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Groundwater resource exploration & development – Focus on groundwater to support surface water supply in the Lower Olifants River, South Africa

Johanna Margaretha van Rooyen [a,*], Sonia Veltman [b], Fanie Botha [c], Johan Matthee [d]

[a] Veltwater Groundwater Specialists, Alberton, Gauteng, South Africa
[b] Veltwater Groundwater Specialists, George, Western Cape, South Africa
[c] Water Hunters, George, Western Cape, South Africa
[d] LORWUA, Vredendal, Western Cape, South Africa

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ABSTRACT

Many South-African towns in the Western Cape Province are dependent on surface water resources to satisfy the ever-increasing water demand. In recent years, the effects of climate change on the environment has challenged these areas continually and recently led to calls for major changes in water management. The Lower Olifants River Water Management Area experienced an extreme drought that persisted from 2016 to 2018, which led to the need for development of groundwater resources. The local economy of the Lower Olifants River is dependent on water releases from the Clanwilliam and Bulshoek Dams, located within the Olifants River Syncline (ORS), where 'megafault' zones form preferred flowpaths for groundwater in the Table Mountain Group (TMG) aquifers. The Lower Olifants River Water User Association (LORWUA) was mandated to proceed with the exploration and development of these aquifers to supplement the existing water use of the LORWUA. This will be available during periods of less rainfall and therefore increase the security of the water supplied. The groundwater project aimed at exploring and developing the fractured rock aquifers of the Peninsula (Op) and Skurweberg (Ss) Formations contained within the TMG. Through a high-level desktop assessment, remote sensing investigations and geophysical ground surveys, several target areas and drilling priorities were identified to obtain high borehole yields that access the resource in proximity to existing surface infrastructure. The projected water need from the groundwater resource was 8.6 million cubic metres per annum (Mm^3/a). Faults/structure zones were the main hydrogeological targets, with drill target depths of structures planned for intersection deeper than 100 m below ground level (mbgl). Down-hole camera work and initial aquifer testing concluded that deep geological contact zones are prone to collapse when flow is induced in water-bearing fractures. This indicated the need for production borehole construction, even prior to aquifer testing for yield estimates. A major concern still to be resolved is the availability of water in storage and the realistic expectations of the well field over time. Although individual borehole testing provided information on the properties of specific water-bearing structures, long-term monitoring will provide a better understanding of the aquifer in response to abstraction and recovery in times of rest. The operating rules for the conjunctive use of the well field developed, with the existing surface water scheme, is still to be defined and modelled for optimisation, pending long-term monitoring.

1. Introduction

The Lower Olifants River Water User Association (LORWUA) manages the distribution of water downstream of the Clanwilliam Dam via a government-owned (approximately 100 years old), 236 km canal system to various communities under the local Matzikama Municipality (approximately 16 996 households), industrial water to the mines, and irrigation water for 9510 ha. The water supplied from this distribution system was restricted from an average of 60–70% per year to 14% in 2017/2018, because of drought conditions.

Without the necessary water, the effect could lead to a decline or possible collapse of the economy, but also risk assurance of water supply to all the water users, including water service providers (local municipalities). Without a functioning agricultural sector, the local Tronox

* Corresponding author.
E-mail addresses: jorettevanrooyen@gmail.com (J.M. van Rooyen), sonia.veltman@gmail.com (S. Veltman), Fanie@waterhunters.co.za (F. Botha), johanm@lorwua.co.za (J. Matthee).

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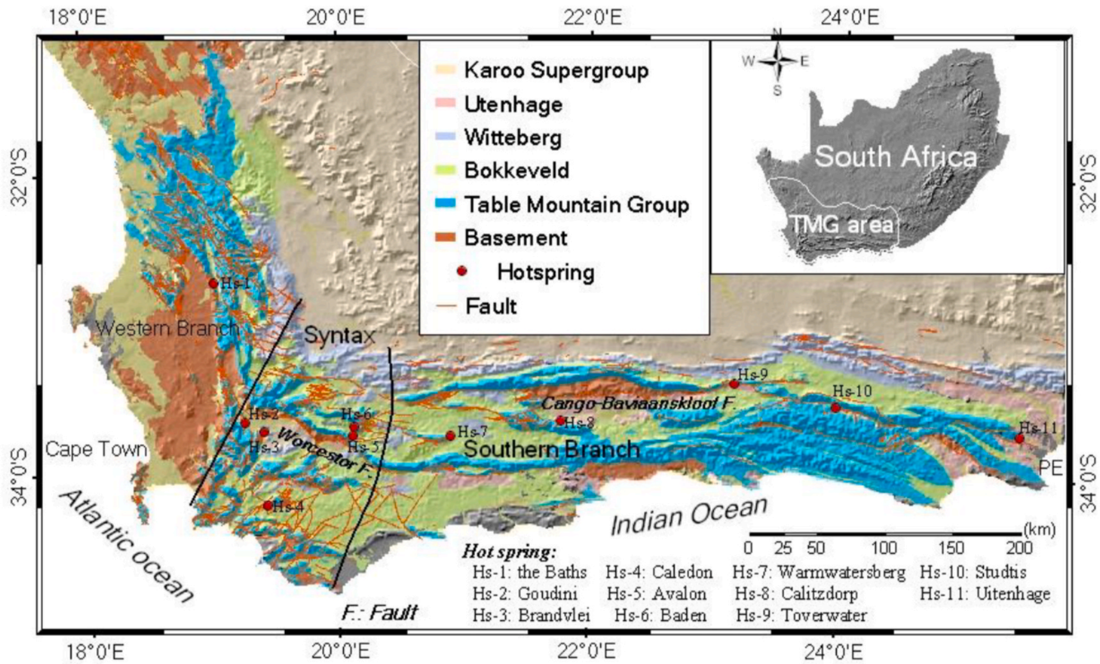

Fig. 1. Map of Cape Fault Belt showing the stratigraphical and faulting distributions of the TMG (after Xu et al., 2009).

Mine (heavy mineral sands) will not be able to solely sustain the economy for the area. The reported economic effect on the GDP of the region for 2017/18 due to the drought conditions in the area was up to 60% less.

The LORWUA was mandated to develop groundwater as a supplement to the existing water supply of the canal system to be available during periods of less rainfall, thereby reducing the risk to the water users and increasing water security. Once the LORWUA's available water supply from the Bulshoek Dam dropped below 50% (60 290 380 m^3/annum) of the demand from the canal, the remaining volume was planned to be augmented from the groundwater resource. The demand versus volume supplied showed that the LORWUA was operating at a water deficit and therefore required the addition from the groundwater resource to augment current and future demands in this sector to secure long-term survival.

Groundwater development was targeted in two (2) key areas, namely Bulshoek (Priority 1) and Klawer (Priority 2); refer to Fig. 3. The Bulshoek (Priority 1) project area was considered first for groundwater exploration and development, due to the proximity of the canal system to a "megafault" zone.

The required development of groundwater was up to 475 l/s from groundwater sources, to be used over a period of 5–7 months of the year, which translated to approximately 8.6 Mm^3/a, of which the operating rules will be dependent on rainfall and surface flows into the Clanwilliam and Bulshoek Dams. This was approximately 5% of the surface water volume listed and was deemed sufficient to alleviate current deficits. However, because of drought fund shortages, only three boreholes in the Priority 1 area (known as the Kromme Valley well field) were converted into production boreholes.

2. Literature review

The Department of Water Affairs and Forestry, now known as the Department of Water and Sanitation (DWS), conducted a dam safety inspection and found that the Clanwilliam Dam wall required strengthening to meet the national safety requirements. Subsequently, a study was commissioned in the early 2000s, and specialists were appointed to investigate the feasibility of conjunctive use options in combination with the rehabilitation of the dam wall (DWAF, 2005). Previous studies and modelling results (2000–2003), where the potential of the Peninsula aquifer was evaluated, resulted in additional volumes available of 30 Mm^3/a from a conjunctive use scenario and 45 Mm^3/a from a storage-based scenario (DWAF, 2005). It was further suggested that groundwater could provide enough water for basic human needs as well as satisfy the allocations for irrigation via a conjunctive use scheme with or without the raising of the Clanwilliam Dam wall (DWAF, 2005).

Projected future water shortages caused by climate variation prompted water management mechanisms and policy development to ensure that existing water supply meet the growing demands, and these measures may need to be introduced earlier than expected (Midgley et al., 2005). Climate change scenarios, should it be a drying and warming effect, could have negative effects on recharge, which will result in reduced abstraction, increased evaporation, changes in groundwater chemistry, and will lead to the drilling of even deeper boreholes (Midgley et al., 2005).

2.1. Geological environment

The Cape Orogeny is largely responsible for the structural framework of the Table Mountain Group (TMG). The Cape Fold Belt is characteristic of large-scale change in general subsidence and sedimentation to deformation and uplift, also known as inversion. The Cape Fold Belt consists of a series of north-west to north-trending folds in the west, stretching from Stellenbosch in the south to Vanrhynsdorp in the north (see Fig. 1). Owing to the compressive stress that was replaced by tensile stress, intraplate movements took place along the existing thrust planes (weakness), which in turn led to the development of half-grabens (Xu et al., 2009). In the western (north-trending) branch of the fold belt, normal faults are common, forming a north-west trending swarm and defining horst and graben structures somewhat oblique to the NNW trend of the folds. The 'arms' of the fold belt meet in the "syntaxis", a domain characterised by complex faulting and folding. Faulting along major fault zones is found to be within a severely brecciated fracture zone. Cementation of this breccia may render these fault zones less permeable for water storage and movement, except where faults may have been subjected to neotectonic reactivation (Xu et al., 2009).

The Clanwilliam Dam is situated within a north-south trending

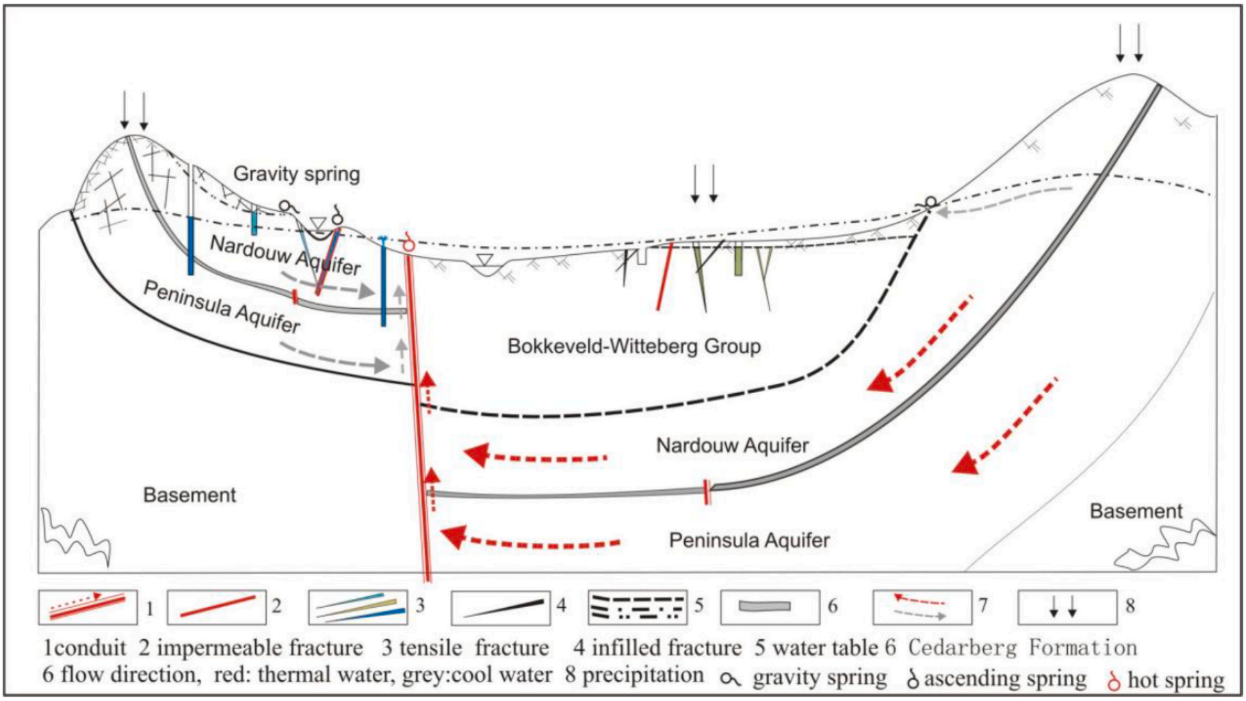

Fig. 2. Generalised model of the fractured rock TMG aquifer system (after Xu et al., 2009).

syncline in the TMG known as the Olifants River Syncline (ORS). Northwest-southeast striking faults form sub-parallel, continuous, and interconnected systems, which stretch over more than 100 km (km). These systems collectively constitute "megafault" zones and are also known as hydrotects, since they form preferred flowpaths for groundwater in the TMG aquifers (Umvoto Africa, 2006). Umvoto Africa (2006) reported that the regional groundwater flow in the vicinity of the Clanwilliam Dam is from east to west and then south to north along the fold axis of the ORS.

2.2. Hydrogeological setting

According to Xu et al. (2009), the TMG can be divided into four categories, namely a horizontal strata aquifer system, a fold strata aquifer system, a fracture zone aquifer system, and a composite aquifer system. Xu et al. (2009) further state that hydro-structural domains exist in which each compartment contains characteristic own flow dynamics and is bound by major discontinuities. The tectonic style within each compartment (overturned synclines, flat anticlines, monoclines, thrust faults, etc.) was developed during the Cape Fold Belt compressional orogeny. Fig. 2 presents a simplified conceptual model of the TMG composite fractured rock aquifer system (Xu et al., 2009).

The quartzitic units of the TMG are well bedded and contain fractures and joints related to regional faulting. These give the formations what is known as secondary permeability that defines a fractured rock aquifer. The TMG aquifer system in the Cape Fold Belt is mainly conceptualised into three aquifer units: the Peninsula Aquifer (1300 m thick), the Nardouw Aquifer (240 m thick), and the Cedarberg Aquitard (Cedarberg Formation) separating the two main aquifers (Umvoto Africa, 2005, 2006). The Piekenierskloof Aquifer and the overlaying Graafwater Aquitard are restricted to the western branch of the Cape Fold Belt (Xu et al., 2009).

3. Case study & methodology

3.1. Study area

3.1.1. Locality of the project area

The Bulshoek (Priority 1) project area (hereafter referred to as 'the site') is located approximately 25 km north north-west of Clanwilliam, within the jurisdiction of the West Coast District Municipality in the Western Cape Province. Fig. 3 presents the locality map of the priority areas for groundwater development.

3.1.2. Topography and climate

The site is situated within the quaternary catchment of E10K. The topography of the study area can be described as mountainous and undulating, whilst the site drainage is toward areas where natural subsidence occurs and ends in the adjoining perennial Olifants River.

The climate is described as Mediterranean with cool, wet winters and warm, dry summers. The Karoo has an arid to semi-arid climate with cold, frosty winters and hot summers with occasional thunderstorms. The rainfall data, obtained from rainfall stations at Bulshoek (E1E001) and the Clanwilliam Dam (E1E004), indicate a mean annual rainfall for the area ranging between 200 and 243 mm/a, with most rainfall typically occurring between the months of June and December. The evaporation data indicate a mean annual evaporation between 1616 to 2380 mm/a. The average precipitation vs. evaporation water balance (1973–2013) showed that the evaporation exceeded the precipitation values for every month of the year. Topographical features are also shown in Fig. 3.

3.1.3. Geology

The site and surrounding areas are underlain by sequences of the TMG. The predominant sequences are the Skurweberg Formation in the east and the Peninsula Formation in the west. The central regions of the sites are also underlain by graphitic and sericitic schist, phyllite, greywacke and quartzite of the Aties Formation, which forms part of the Gariep Supergroup, as well as Quaternary calcareous and gypsiterous soils. Prominent faulting is present in the immediate area of the site, which was expected to act as preferential flow paths for groundwater.

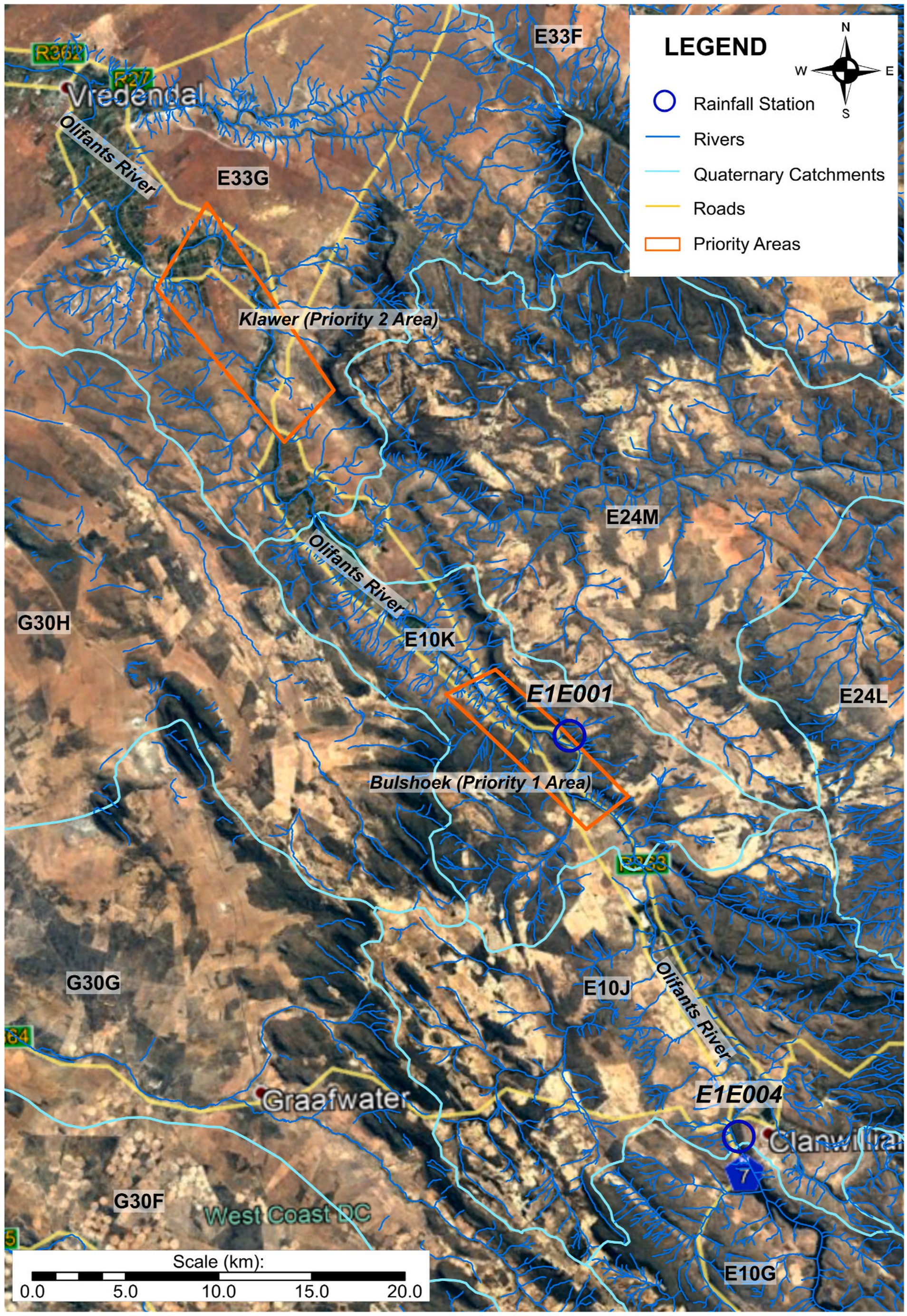

Fig. 3. Locality map.

Fig. 4 presents the geology of the study area, and Table 1 presents the stratigraphical sequences of the study area, as illustrated on the 1:250 000 geological map 3118 (Council for Geoscience, 1978).

3.1.4. *Hydrogeology*

It was evident from the literature review that the most significant hydrogeological unit in the LORWUA priority areas is the Peninsula Aquifer, composed of quartzitic arenites/sandstones, as the preferred target for good quality water with high yields. The two main aquifer types present in the study area are described as follows:

- The weathered zone aquifer: The water level of this aquifer is often shallow and may daylight as springs occasionally when intersected by barriers such as topography.
- A deep fractured rock aquifer formed through secondary fracture/ fault zones: Most of the groundwater flow occurrence is contained in the openings between joints and fractures within the rock mass. Generally, higher yields are expected at intersections of fracture/ fault zones or in transition/contact zones.

3.2. *Methodology*

3.2.1. *Desktop assessment*

Hydrogeological target areas were identified from the desktop study

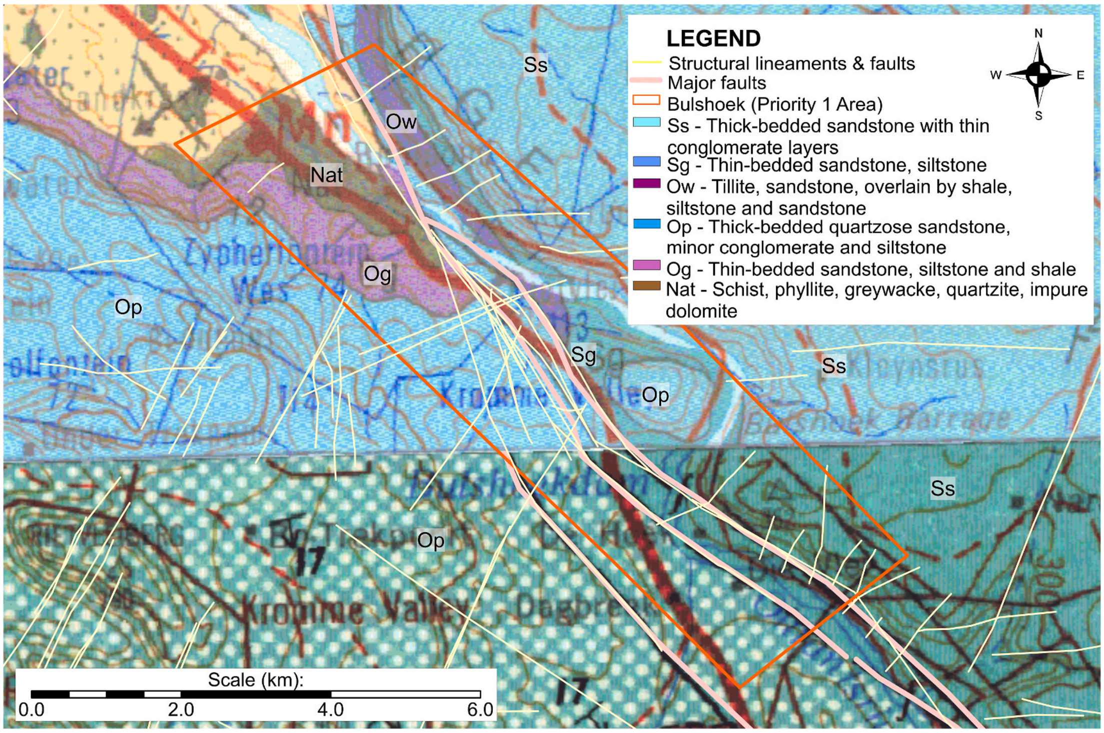

Fig. 4. Geology site map.

Table 1
Stratigraphical sequences (after Council for Geoscience, 1978).

Increasing Age	Cape Supergroup	Table Mountain Group	Nardouw Subgroup	Skurweberg Formation	Ss	Thick-bedded sandstone with thin beds of small-pebble conglomerate
				Goudini Formation	Sg	Orange-grey weathering, thin-bedded sandstone, reddish siltstone
			Winterhoek (OW) Subgroup	Cedarberg, Pakhuis Formations	Ow	Grey-green sandy tillite, sandstone and muddy tillite (Pakhuis), overlain by grey shale, siltstone, and thin-bedded sandstone (Cedarberg)
				Peninsula Formation	Op	Light-grey, thick-bedded, quartzose sandstone, minor conglomerate, and siltstone
				Graafwater Formation	Og	Thin-bedded red to purple sandstone and matrix-supported conglomerate;
				Piekenierskloof Formation	Opi	Light cream-coloured, thick-bedded quartzose sandstone and conglomerate
	Gariep Supergroup	Gifberg Group		Aties Formation	Nat	Graphitic and sericitic schist, phyllite, greywacke, quartzite, impure dolomite, limestone, and marble

and remote sensing utilised, based on the position of the existing infrastructure of the LORWUA scheme in proximity to the occurrence of potential high yielding geological structures within the TMG aquifers, which was confirmed with geophysical techniques. The megafaults within the TMG and subsequently, the Peninsula Formation, were of particular interest, due to the expected higher yields associated with these fault systems, as well as the expected water quality within this lithology.

3.2.2. Geophysics

The surface geophysical assessment was completed using magnetic and electromagnetic methods to define optimal target areas (VSA Leboa Consulting, 2017). Non-intrusive surface geophysical methods informed not only the optimal drilling targets for the exploration drilling phase but also that boreholes should be drilled to 200 mbgl or beyond.

Geophysical remote sensing and fieldwork confirmed the presence of highly developed fault/fracture systems, which indicated deep weathering and/or fracturing within the solid crystalline rocks. The ‘fractured

Table 2
Parameters included in the laboratory analyses.

Physio-chemical parameters:	pH, electrical conductivity (EC), total dissolved solids (TDS) and total alkalinity (T-Alk)	
Inorganic and metal parameters:	major ionic constituents	calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), sulphate (SO4), chloride (Cl) and fluoride (F),
	metals/metalloids constituents	arsenic (As), chromium (Cr), iron (Fe), manganese (Mn) and zinc (Zn)
Nitrogen-species parameters	ammonia (NH4 as N) and nitrate (NO3 as N)	
Bacteriological	heterotrophic plate counts, total coliforms and E.coli	

zone' comprises debris that is removed during the rainy season, and the presence of water in the dry season promotes higher and denser vegetation and is clearly visible on the surface as deep straight lines. These visible structures were validated during the geophysical investigations.

3.2.3. *Exploration drilling*

The methodology employed during the exploration phase was to drill three pilot boreholes on each geophysical traverse in the three areas of the Bulshoek (Priority 1) area, namely Rondeberg, Bulshoek and Kromme Valley. Pilot holes were drilled closer or further from the identified anomaly, structure, or fault, depending on the dip of the structure, which were intended to be intercepted at depths where sufficient drawdown was available for high-yield abstraction to sustain drawdown over time. The groundwater targets were drilled by means of air percussion drilling, of which the highest water-yielding boreholes (based on blow yields) were subjected to short-term aquifer testing to determine borehole efficiency under stressed conditions. The short-term aquifer tests comprised at least three-step drawdown tests (2 h duration each) with a prolonged step at the end of the test (up to 6 h) in order to stress the aquifer sufficiently without allowing the groundwater level to reach the pump inlet, followed by recovery measurements to 95% of the original water level. The exploration boreholes were used to distinguish between higher water-yielding and lower water-yielding structures. The highest yielding boreholes identified from the exploration drilling phase, were converted into production boreholes.

3.2.4. *Hydrocensus investigation*

During the exploration drilling and construction/conversion phases, a hydrocensus was performed with consideration of a larger than 3 km radius surrounding the abstraction boreholes' area, with a site walkover inspection and reconnaissance of the receiving environment, to identify potential sensitive receptors (i.e. springs) and surrounding groundwater users that could be affected.

3.2.5. *Groundwater sampling*

Groundwater samples were collected continuously throughout the project to confirm suitability of water quality. Groundwater samples were collected during the aquifer tests at each borehole tested, at the end of each test. Spring samples were also collected. The analyses were carried out in accordance with methods prescribed by and obtained from the South African Bureau of Standards (SABS), and the results were compared with the SANS 241:2015 standards for drinking water (SANS (South African National Standard), 2015) as well as the DWS, Target Water Quality Range (TWQR) Guidelines for Agricultural Use: Irrigation (South African Water Quality Guidelines, 1996). These standards were chosen, since the water would be used for primarily irrigation, and potentially drinking water. The parameters included in the laboratory analyses are summarised in Table 2.

Through comparisons made from the geochemical make-up of each borehole, distinctions could be made between aquifers. EC measurements were also compared to identify water sources encountered in the field. The water quality results returned showed EC values ranging between 40 and 60 milli-Siemens per metre (mS/m) from water collected within the Peninsula Formation (see Section 4.6).

3.2.6. *Production borehole conversion and pipeline design*

Three exploration boreholes were converted into production boreholes, known as the Kromme Valley well field, where the boreholes were reamed, and casing installed to the required depth (refer to Section 4.4 for details). The well field was intended for conjunctive use, where volumes pumped are dependent on shortages experienced and discharged into the existing water reticulation system via the canal. The well field was designed to function as a delivery system that deals with different rates of flow, depending on the volumes needed. The pipeline was designed in such a way that all boreholes could be pumped simultaneously and/or in any combination thereof.

3.2.7. *Aquifer testing*

Aquifer testing was performed with positive displacement pumps, through industry standard step tests (4 steps, 2 h each), a constant rate discharge test (72 h/3 days) followed by recovery measurements to at

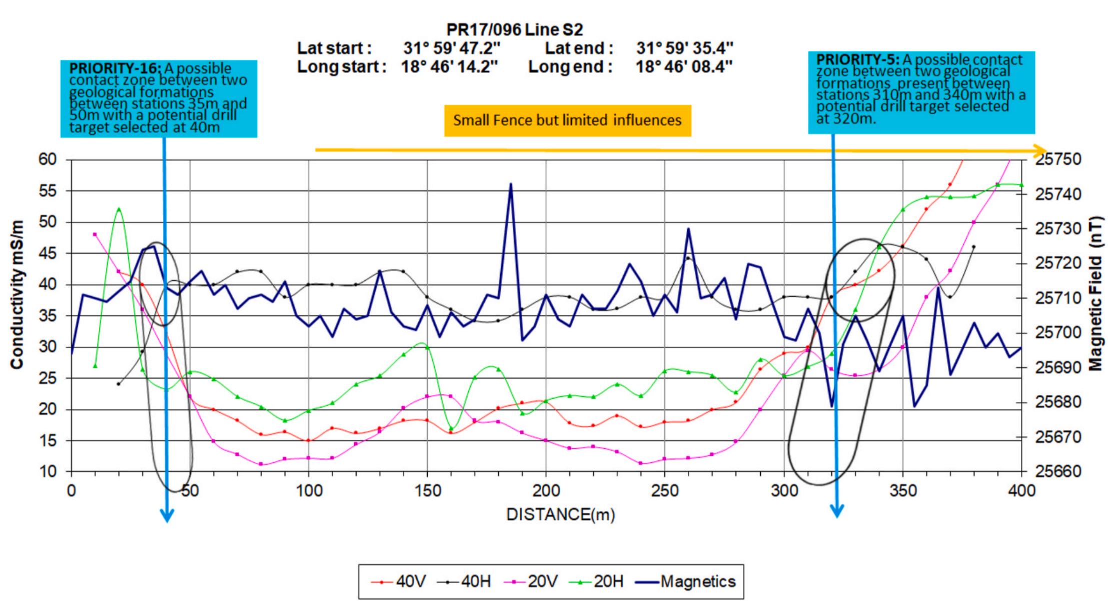

Fig. 5. Traverse S2 Priority 5 and 16 drilling targets (after VSA Leboa Consulting, 2017).

Table 3
Drilling summary.

BH ID	Faults/Structures Targeted	Target	Total Depth (mbgl)	Water Strike (s) (mbgl)	Structure Materials Intersected (mbgl)	Final Blow Yield (l/s)	Field Measurement (EC) (mS/m)	Groundwater Source
S2–P5a	Regional fault system & SW-NE linear structure, steep dip to SE	Main geological structure, fracturing/contact zone within fault zone	181	128; 148; 152, 180/ 181	163	20–40	51	Peninsula Water
S2–P5b			206	105; 173; 177; 180; 183; 186	166 & 193	20–40	50	Peninsula Water
S2–P16a	Regional fault system & SW-NE linear structure,		177	114; 127; 151; 165	111	6	68	Mixed Water
S2–P16b	slight dip to NE		204	52; 113; 117; 131; 140; 170	165	7.4	59	Peninsula Water
L6-P15a	SE-NW striking fault	Fracturing within fault zone	152	90	80	Seepage	–	
L6-P15b			140	93	None intersected	Seepage	–	
L6-P15c			200	83	43	Seepage	–	
S4–P9a	SE-NW Fault zone dip NE	Main geological structure	226	58; 78; 150	None intersected	3.3	70	Mixed Water
L1-P3a	E-W linear structure	Fracturing/contact zone	200	72	49 & 128	Seepage	–	
L1-P3b	dipping slightly SSE	within fault zone	200	42; 90, 144	106	0.3	102	Nardouw Water
L1-P7a			200	162; 169; 177; 181	160 & 180	1.6	98	Nardouw Water
L1-P7b			200	air loss	17; 37; 95 & 145	1.2	87	Nardouw Water
L2-P10	NE-SW linear structure	Fracturing within fault zone	220	air loss	84 & 118	0.7	118	Nardouw Water
S1–P2a	SE-NW Fault zone dip NE	Main geological structure	240	88; 101	136; 141; 171; 175; 202; 208; 226 & 232	Seepage	–	
S1–P2b			107	99	51 & 78	air loss	–	
S1–P2c			200	98; 170	138; 157; 182 & 199	10	49	Peninsula Water
S3-Pa*	NW-SE block fault system & NE-SW linear structures	Main geological structure	171	23; 53; 96; 143; 171	23; 62; 64 & 72	**34.4**	46	Peninsula Water
S3–Pb			148	72; 95; 125	17; 74 & 102	6.8	41	Peninsula Water
S3-Pc			200	72; 90	23; 44; 75; 103 & 114	1.2	46	Peninsula Water
S3–Pd*			180	10; 60; 124	101	**28**	42	Peninsula Water
S3-Pe*			200	56; 76	76; 105; 113; 117; 121 & 131	**20**	50	Peninsula Water

*Kromme Valley well field boreholes.

least 90% of the original water level of each test. Aquifer test data were evaluated to determine various aquifer parameters and characteristics, radius of influence, and sustainable yields expected from single boreholes. Both the Fracture Characterisation (FC) method software and AQTESOLV were used to evaluate all the test data and radius of influence calculations. Only the FC method was deemed most useful for understanding the aquifer, quantification of the aquifer's hydraulic and physical properties, and the interpretation and estimation of sustainable yield and efficiency of the boreholes (Van Tonder et al., 2001, 2002). Log-log and semi-log plots showing the time-drawdown relationships are diagnostic for fracture positions, identification of flow regime, and flow boundaries (Kruseman and De Ridder, 2000).

This analytical information was used to determine the maximum radius of influence, inform the extent of the hydrocensus area, and to support the quantification of numerical effects.

3.2.8. *Environmental compliance*

As per the requirements of the Water Resilience Projects of the Matzikama Municipality, and the Generic Environmental Management Programme (EMP), a detailed method statement for the Kromme Valley well field was completed and approved by the Department of Environmental Affairs and Development Planning (DEA&DP) prior to the construction phase. Weekly site audits/inspections were performed, and all findings and practices observed during the site audits were noted and reported to the Environmental Control Officer (ECO). Further to this, monthly ECO reports on the site findings were compiled and sent to the DEA&DP and Matzikama Municipality.

3.2.9. *Numerical modelling and impact assessment*

The expected impacts were examined for both surface water and groundwater quality and quantity, based on the proposed groundwater use, water quality and results during the aquifer testing phase and evaluation of data and information. The hydrogeological unit of concern is the deep confined fractured rock aquifer of the Peninsula Formation. A conservative, single-layered, three-dimensional finite difference model was constructed and calibrated, with the use of the Processing Modflow for Windows (PMWIN) Version 8 program, to validate the radius of influence obtained from the analytical models used and test well field scenarios. The following aquifer parameters were used as starting parameters from which to calibrate:

- Transmissivity values – calculated aquifer transmissivities varied significantly between 0.01 square metre per day (m^2/d) and 72.2 m^2/d (matrix versus preferential flow paths).
- Recharge – the effective recharge in the area was estimated at between 0.01% (0.0000001 m/d) and 5% (0.0000378 m/d) of mean annual rainfall.
- Specific storage – the storage values assigned ranged from 0.00005 to 0.001.

Two main aspects were tested, namely 1) determination of the combined radius of influence for abstraction boreholes pumping

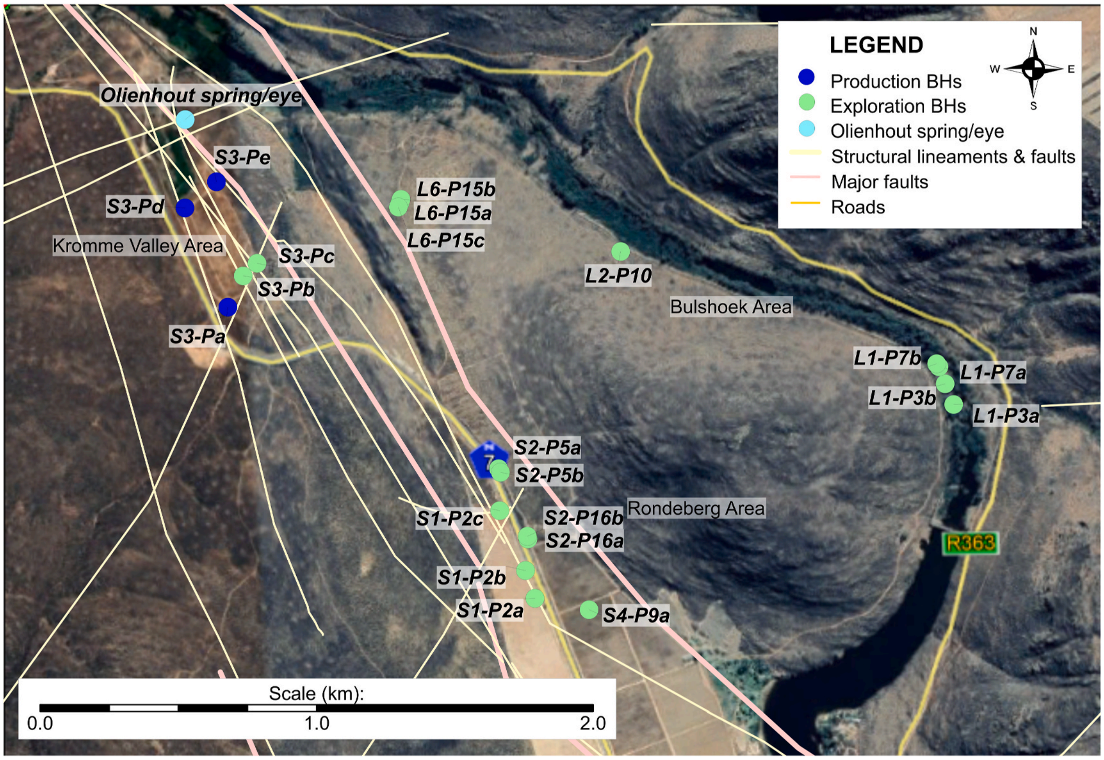

Fig. 6. Borehole distribution map for the Bulshoek (Priority 1) area.

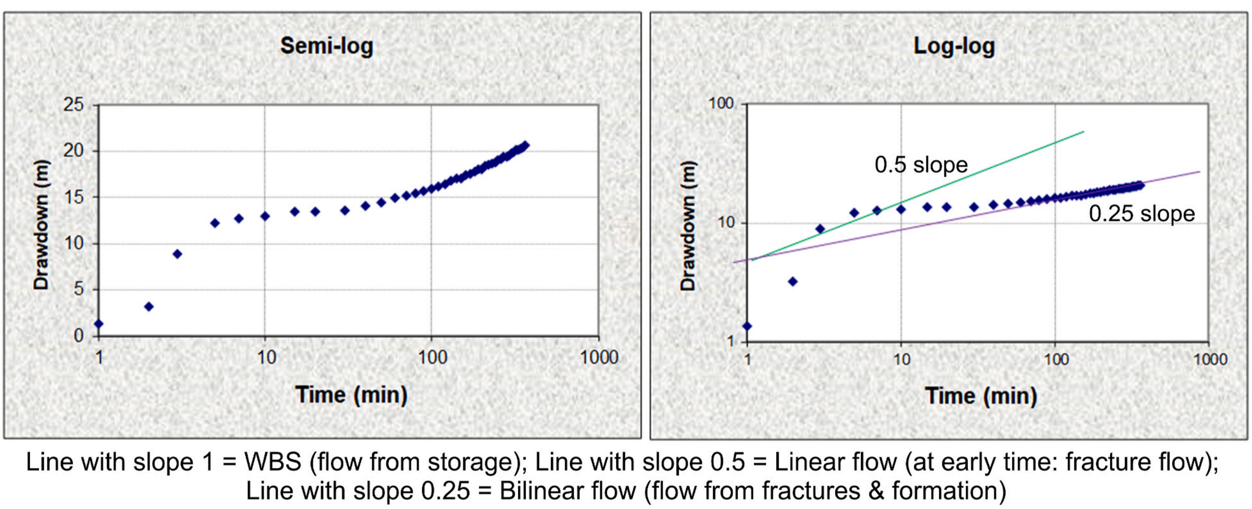

Fig. 7. Representative diagnostic plots (borehole S3-Pa) showing typical aquifer test characterisations (Van Tonder et al., 2001).

collectively over a prolonged period; and 2) the influence on the river system through groundwater abstraction. The initial parameters were selected based on the results of the desktop study and site-specific data collected throughout the project. The model was built on actual results, but aquifer response can vary in the natural system, due to heterogeneities not known at the time.

4. Results

4.1. Geophysics

The results of the field work conducted yielded fourteen completed traverses within the site area. In many cases, one traverse produced more than one drilling target (see Fig. 5), as an example of the different dipping geological anomalies found. The anomalies were prioritised further based on the type and extent of the geophysical anomaly.

4.2. Exploration drilling

The best potential drilling targets were selected based on a combination of magnetic and electromagnetic geophysical anomalies that occurred across the sub-vertical fault zones and geological contact zones (refer to Section 4.1, Table 3 for a drilling summary, and Fig. 6 for borehole distribution). Drilling and installation of twenty-three (23) boreholes in the site area commenced in December 2017. The planned depth of the exploration boreholes was 200 mbgl but ranged between 107 and 240 mbgl. Where boreholes did not reach the planned depths, it was either because of structural instabilities, abrasive formations or

Fig. 8. Borehole S3-Pa as captured by down-hole camera footage: Images showing a geological structure at varying depths.

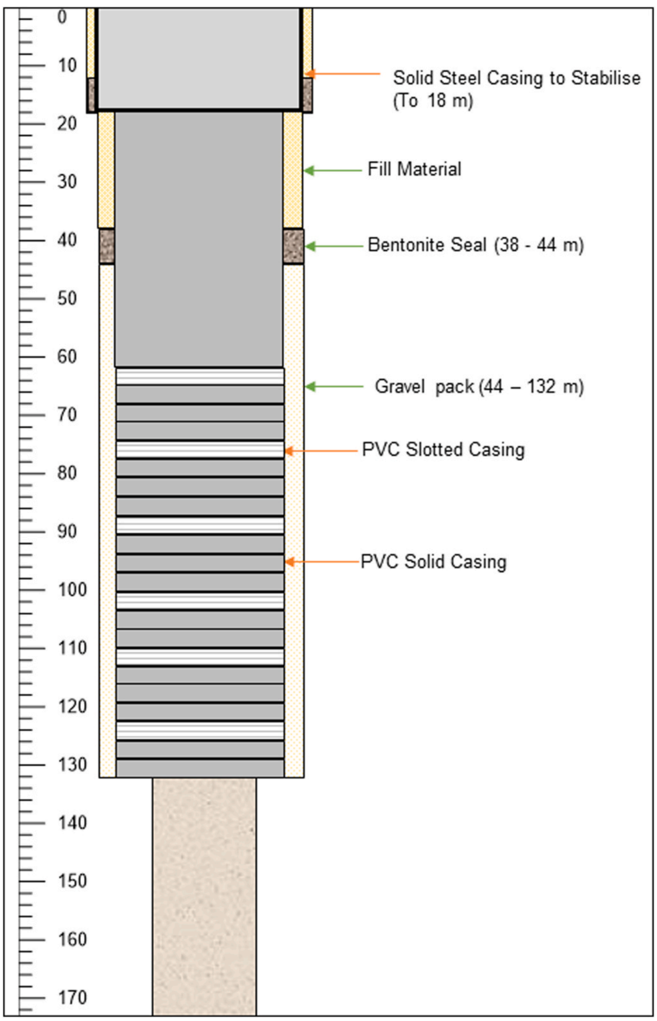

Fig. 9. Schematic illustration of borehole construction.

high-yielding water strikes forcing drilling to stop. Some structures were eliminated as potential water-bearing structures, since no or limited water was observed during the final blow yield. One specific traverse/line drilled on the shear zone of the megafault yielded no effective flow within the structure; targets numbered L6P15. Others were only targeting the smaller structures striking east-west. The megafaults striking north-south, especially where intersected by east-west structures, were identified as major water-producing hydrogeological structures and were therefore the main groundwater targets for high-yielding boreholes. The smaller faults striking east-west and linear features, which were not developed successfully into high-yielding boreholes, were not connected to the north-south megafaults. Remnants of the Skurweberg Formation occur in various thicknesses, depending on the structural geology, and are mostly absent in the Rondeberg area. In the Kromme Valley area, the Skurweberg constitutes the weathered and fractured rock aquifer that was identified during the hydrocensus investigation and supports flow to the spring and wetland on the farm.

In specific borehole geological logs, the Cederberg shale was shown to be absent and, in some areas, the weathered aquifer is in direct connection with the Peninsula lithology. However, the Peninsula is considered massive, unless structural controls developed the aquifer and vertical connections that effectively disconnects the two aquifers exist.

Groundwater flow in the aquifers is in the openings between joints and fractures within the rock mass. The influence of foliation in the groundwater flow direction of the underlying layers is likely to form a preferred direction of flow in the groundwater system in the direction of foliation (referred to as anisotropy). The faulted and fractured contact zones interconnect the strata vertically and horizontally into a highly heterogeneous and anisotropic unit.

Electrical conductivity field measurements within the Nardouw Formation (upper weathered and semi-confined fractured aquifer) were confirmed as much higher than the groundwater sourced from the Peninsula Formation (confined fractured aquifer). The Peninsula aquifer at depth was the aquifer with the best water strikes and best overall water quality.

4.3. Initial aquifer testing

Aquifer tests with positive displacement pumps were conducted on exploration boreholes with yields more than 10 l/s (litres per second), as well as the lower-yielding boreholes drilled in the Bulshoek Dam service road next to the canal. The cumulative results from the higher-yielding boreholes showed that linear and bilinear flow is dominant with good fracture networks, supported by radial inflows from a wider area (see Fig. 7 for typical diagnostic plots). In most of the tests, bilinear flow only started after 60–90 min into the tests, where after borehole efficiency increased. It was inferred that the fracture networks are sensitive to pressure changes before flow becomes optimal; therefore, pumping rates and installation depths will attribute to effective flow from the deeper fracture networks.

Most of the high-yielding boreholes could be tested only up to 15 l/s, after which water strikes at geological contacts became unstable and resulted in pump breakdowns.

4.4. Camera inspections

Down-hole camera work subsequently confirmed the presence of not only horizontal structures within the geological sequences but also sub-vertical structures (refer to Fig. 8). These structures and water-bearing fractures were shown to be unstable, causing the formations within to

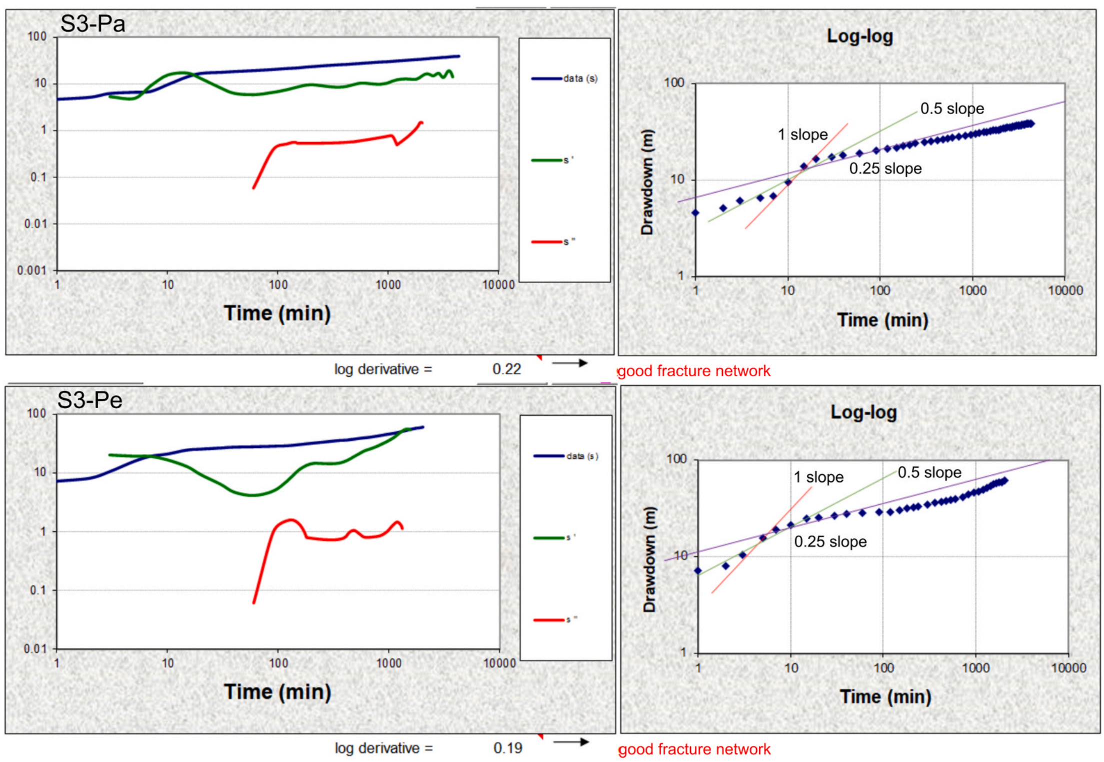

Fig. 10. Representative derivative and diagnostic plots (boreholes S3-Pa and S3-Pe) showing aquifer test characterisation graphs (Van Tonder et al., 2001).

collapse. The footage also showed definite iron precipitation in the upper weathered and fractured Nardouw aquifer. This informed the proper construction of the production boreholes. This construction was not initially in the project plan, and cost increased dramatically as a result.

4.5. Production borehole conversion

Boreholes in the Kromme Valley well field were reamed to diameters of 203 mm/8 inch, followed by the installation of a threaded plain and factory-slotted 200 mm outer diameter (OD) uPVC casing to 132 mbgl. Further to this, a 3–5 mm silica gravel pack was placed in the annulus between the borehole walls and installed casing, to ensure stability and to prevent the entry of fines into the completed boreholes. A bentonite seal was installed at a depth in each borehole to seal off the upper Nardouw shallow aquifer from the lower high-yielding Peninsula aquifer, to prevent Fe-rich shallow Nardouw aquifer water from entering the Peninsula aquifer. Fig. 9 presents a schematic drawing detailing the construction of a typical production borehole at the site.

The head works designed for each of the production boreholes included a bentonite/sanitary seal and concrete slab to protect the boreholes from direct surface infiltration and to secure the permanent pump installations. Owing to the site topography, flow in the pipeline is under gravity from each of the production boreholes to the discharge point at the LORWUA canal. Abstraction will lower water levels in nearby boreholes and is also likely to interfere with groundwater flow towards the spring and associated wetland within the radius of influence while abstraction is ongoing. Recovery is expected during the 5 months that the boreholes will rest.

4.6. Aquifer testing on well field boreholes

The Kromme Valley production boreholes were subjected to aquifer testing with positive displacement pumps. Pumps were installed at 124.5 mbgl, with drawdown limitations in the three boreholes set at pump intake level to test the entire available column. With the use of the FC-method software, calculations of the radius of influence from the 72 h aquifer test data showed that influence of high-yielding boreholes is typically less than 400 m from the abstraction borehole, which will extend over time as abstraction is prolonged.

The 24 h, 7 month, sustainable yields calculated for no recharge (worst-case) scenarios of the single tested boreholes were estimated at 152 m^3/h (42.2 l/s), 67 m^3/h (18.7 l/s), and 30 m^3/h (8.3 l/s) for boreholes S3-Pa, S3–Pd and S3-Pe respectively and subsequently tested in the numerical modelling phase.

The results of the test data confirmed linear and bilinear flow is dominant with good fracture networks, supported by radial inflows from a wider area, and that the fractures are sensitive to pumping rates, and effective flow from the deeper fracture networks will be influenced if over-pumped. S3-Pa and S3–Pd resembled a single plane, vertical fracture type flow with high transmissivity or infinite hydraulic conductivity, and flow becomes pseudo-radial at mid-to late pumping time (horizontal, parallel, and perpendicular to the fracture network). S3-Pe resembles a confined fractured aquifer of a double porosity type with flow occurring entirely through the fractures and that is radial and in an unsteady state. S3-Pe has an additional drawdown limitation due to a major fracture dewatering, as well as a no-flow boundary at late time. Fig. 10 shows the representative derivative and diagnostic plots showing aquifer test characterisations.

Recovery was limited to the confined aquifer, and long-term monitoring will show whether the leaky aquifer causes higher observed water levels in the production boreholes. This showed a large pressure system with quick initial recovery, from where water from the confined storage is flowing, as well as a shallower weathered zone from which the late time recovery leaks over time. The conceptual site model is presented in Fig. 11, which shows cross-sections of the current site understanding. The construction of the cross-sections was based on information about local geology and gathered from project drilling and testing.

4.6.1. Water level trends

A comparison between the static water level elevations of the boreholes drilled showed the presence of a clear step in water levels over the

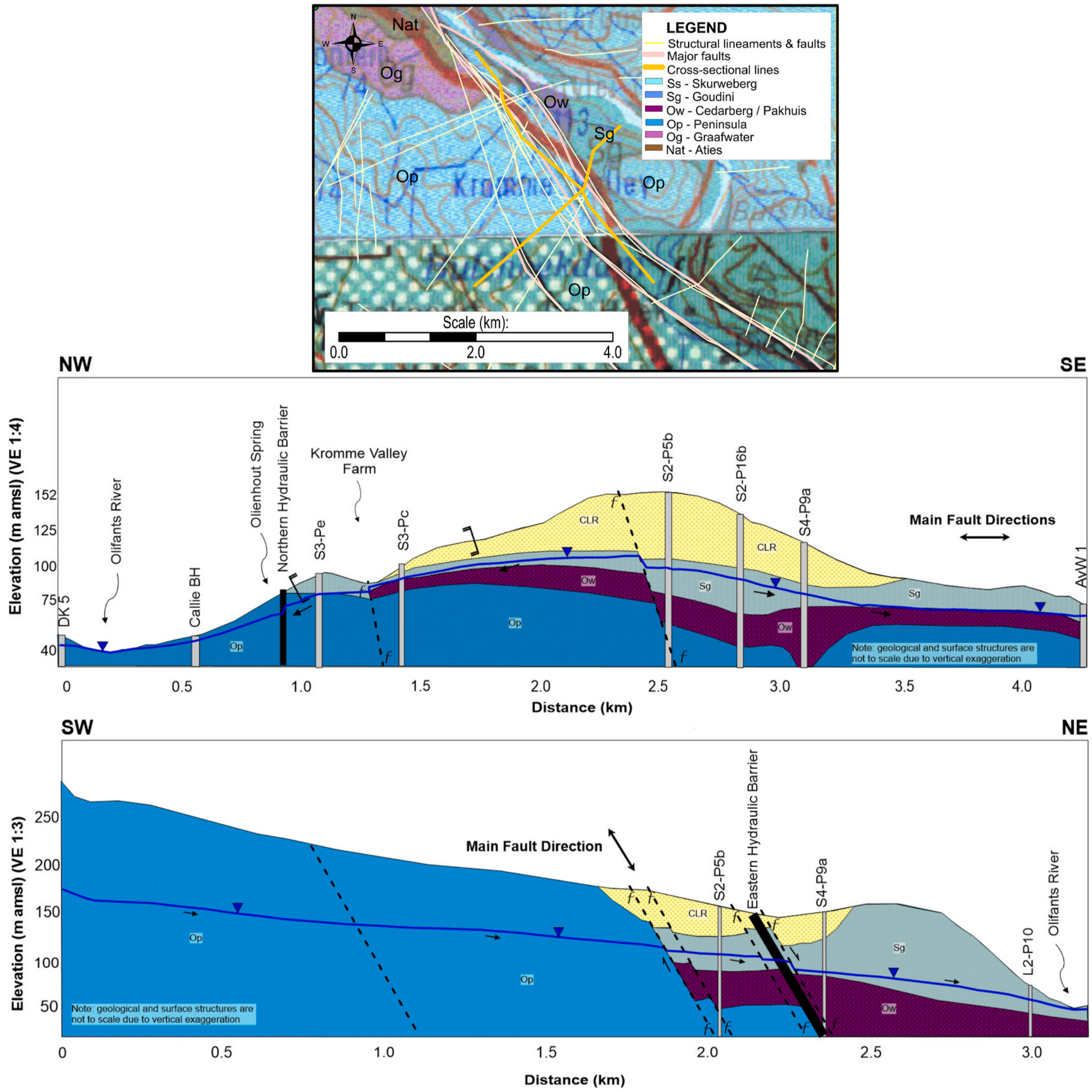

Fig. 11. Conceptual site model for the Bulshoek (Priority 1) area.

main shear zone and a flow boundary between the blocks across the fault systems. There is a water level elevation difference of up to 40 m across the eastern limb of the main fault, with intermediate water levels found at and across flow boundaries (see Fig. 12). The collected data showed that groundwater flows from a higher to a lower topographical point under ambient conditions (i.e. towards the Olifants River). Water level elevations across the Kromme Valley site show a change in gradient over the two east-west linear features just north of S3-Pe, close to the Olienhout spring/eye. This is a strong indication that a hydraulic barrier exists just north of S3-Pe and the Olienhout spring/eye.

4.6.2. *Surface water interaction*

A connection between the Olifants River and the well field boreholes was not observed during aquifer testing (i.e., no recharge boundary was observed in late time pump data). This remains to be confirmed with regular water level monitoring and water quality monitoring at the end of the abstraction periods. However, neighbouring boreholes close to the river have groundwater elevations of 2–4 m above the river head; therefore, it must be assumed that a direct connection could exist.

4.7. *Groundwater quality*

Available water quality analyses show a suitable groundwater quality for domestic and irrigation water, apart from individual parameters that will either precipitate when discharged into the canal system or will blend with volumes of canal water, i.e. chloride, during irrigation periods (refer to Table 4).

Abstraction from the aquifer has no to minimal influence on the confined aquifer water chemistry. Long-term monitoring will show whether aquifer chemistry changes as a result of more oxygen-rich water flowing through at a more rapid rate. Should there be any on-surface spillage in future, the effect on the Peninsula is considered low, due to the deep, semi-confined/confined nature of the aquifer.

4.8. *Impact assessment*

A numerical model was utilised to calibrate and simulate the well field to determine long-term effects on neighbouring boreholes and the river system. First model runs showed the necessity to add geological detail to achieve a suitable fit to the observed water levels. Hydraulic barriers were identified north and east of the well field during single borehole aquifer testing and were included as horizontal flow barriers. The well field was subjected to a two-week pumping test with recovery. The test was conducted to confirm borehole performance, and the data obtained were used to calibrate the transient model. Groundwater abstraction was considered as the main effect on the groundwater

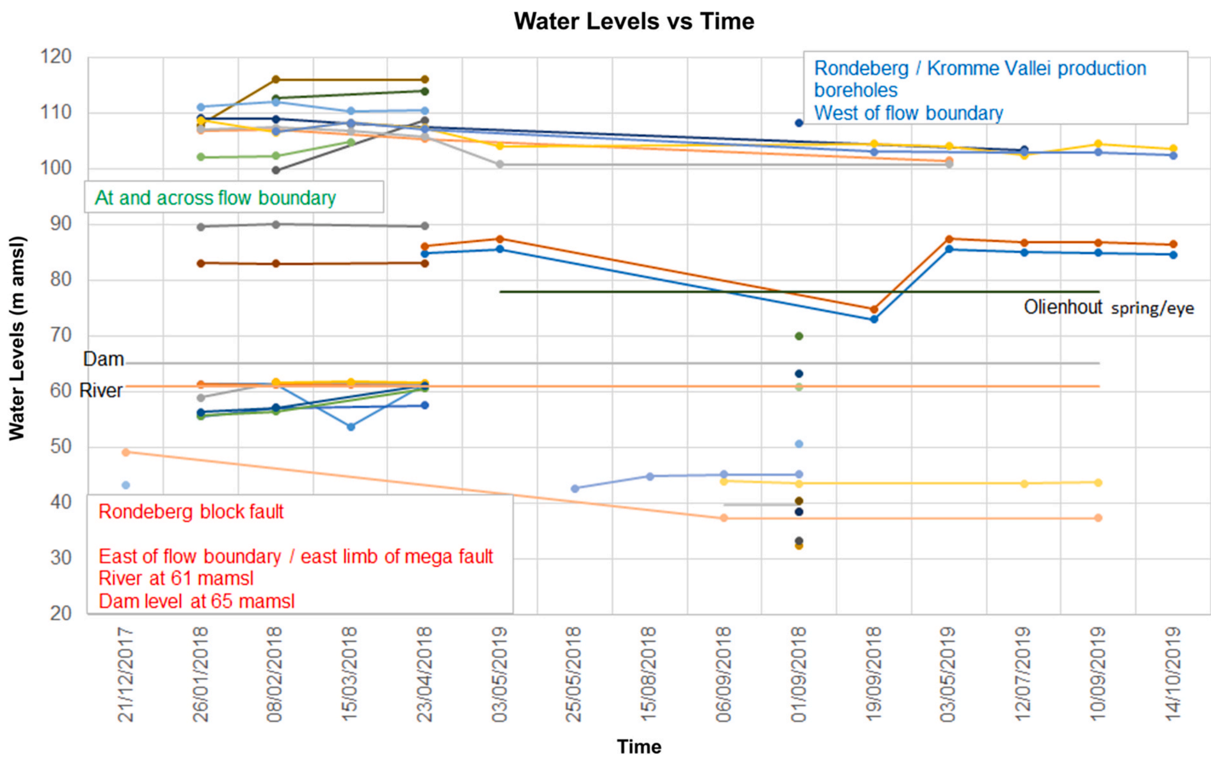

Fig. 12. Water level trends.

Table 4
Water quality comparison.

Variable	EC	Ca	Mg	Na	Cl	Fe	Mn
Unit	mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
SANS	170	-	-	200	300	0.3 - 2	0.1 - 0.4
DWAF TWQR	-	-	-	70	100	5	0.02
Canal	17.60	4.23	3.95	19.40	35.00	0.01	0.04
Olienhout spring/eye	50.00	19.70	10.00	67.00	110.00	1.87	4.56
Peninsula Aquifer	38.00	10.00	7.96	57.00	97.00	0.02	5.38
Nardouw Aquifer	126.00	49.00	24.00	159.00	288.00	0.12	0.17

system. The radius of influence for the worst-case abstraction scenarios: all three well field boreholes combined over 11 months (longest expected continuous abstraction period), ranged from 500 to 600 m, extending longitudinally towards the south-south east, with 3 m (closest neighbour) to 55 m (monitoring borehole S3–Pb) drawdown influence on nearby boreholes. The Olienhout spring/eye showed a maximum groundwater drawdown of 26 m during the simulation.

During the two-week well field test, it was observed that the Olienhout spring/eye stopped flowing. A direct connection to the confined aquifer was also established through chemical analysis of groundwater. The Olienhout spring/eye supplies water to the farm owner, and alternate arrangements were made to supply water directly from the closest production borehole. The numerical model was also used to evaluate the change in flow between the groundwater and surface water systems. From the water balance results, it was evident that the head in the groundwater system near the river remained higher than the river stage. This showed that groundwater flows from the aquifer into the river even during long pump cycles. However, a decrease in groundwater discharge of up to 89 m^3/d was calculated to the river reach.

5. Discussion

Owing to the drought conditions experienced, with an overall increase in water demand, the Kromme Valley well field was designed as a conjunctive use scheme to alleviate the pressures on surface water availability. Exploration drilling informed the optimal drilling depths, and in some instances, drilling deeper boreholes than planned was necessary. Although not all the exploration boreholes have high yields for supply contribution into the canal, it provided valuable information on water-bearing structures and aquifer matrix parameters, i.e. transmissivity and storativity in the wider aquifer.

The TMG geological terrain and structures (faulting and folding) control both the extent of the aquifer and topographical features that affect the aquifer's recharge. The upper weathered aquifer is more prone to recharge from direct rainfall, whilst the confined Peninsula aquifer will be recharged either at outcrops, directly into the aquifer system with longer flow paths, or closer to site where vertical flow paths exist from the surface or weathered aquifer.

Owing to the presence of two aquifer systems, a weathered aquifer and a deeper fractured rock aquifer, a portion of the recharge to the weathered upper aquifer will discharge into springs/rivers contributing to baseflow as interflow, and not as groundwater baseflow. Infiltration of stream flow could occur during times of high rainfall and the associated runoff, at seepage rates dependent on the weathered zone as well as the water level head in the weathered and/or confined aquifers.

The unconfined/weathered Nardouw aquifer acts as either a leaky aquifer to the Peninsula and/or disconnected aquifer where the Cederberg shale effectively seals the connection between the two lithologies.

Based on the conceptual understanding of the Kromme Valley site, the nature of abstraction conditions and volumes, the effects on other water users are considered as small or low. No other abstraction boreholes that are being used actively for domestic purposes exist within the 2 km radius of the site.

6. Conclusions

The completed Kromme Valley well field (Phase 1) can contribute 1 253 750 m^3/a from groundwater sustainably for 7 months scheduled abstraction, and when compared with the initial demands from groundwater, equates to 15% of what was requested. A monitoring network will include on-site monitoring of abstraction volumes and associated water level responses (use and/or rest periods) in both the production boreholes and the surrounding groundwater system at neighbouring boreholes, springs, and rainfall events. Individual borehole testing only provides the information on singular boreholes, whereas the long-term performance of the well field, through monitoring, would provide a better understanding of the aquifer response. Therefore, it was recommended to switch the pumps on occasionally during the winter months as a trial period, in conjunction with Bulshoek Dam releases to the canal, and utilise the monitoring data gathered to refine the response of the groundwater system and adjust pumping schedules if necessary. The ratio of exploration boreholes to production boreholes drilled was 7:1. When planned versus project budgets were compared, it was evident that the cost for exploration and production borehole development surpassed initial budgeting by 200%, and double the time was spent to see the project to completion. However, this may drastically decrease in subsequent phases, where the focus would be production boreholes only, since the exploration phase eliminated smaller structures as potential targets. Phase 2 of the groundwater development plan will likely continue upon availability of funds.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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