Towards defining a baseline status of scarce groundwater resources in anticipation of hydraulic fracturing in the Eastern Cape Karoo, South Africa: salinity, aquifer yields and groundwater levels

DIVAN H. STROEBEL1,2*, CHRISTIEN THIART1 & MAARTEN DE WIT1
1AEON-ESSRI (African Earth Observatory Network - Earth Stewardship Science Research Institute), Faculty of Science, Nelson Mandela University, PO Box 77000, Port Elizabeth, 6031, South Africa
2Department of Geosciences, Faculty of Science, Nelson Mandela University, PO Box 77000, Port Elizabeth, 6031, South Africa

*Correspondence: divan.stroebel@mandela.ac.za

Abstract: The Eastern Cape Karoo region is water stressed and will become increasingly so with further climate change. Effective and reliable groundwater management is crucial for a development such as the proposed hydraulic fracturing for shale gas. This is especially critical across this region of agriculture and protected ecosystem services. The research, as part of baseline data gathering, aims to characterize the hydrochemistry for both the shallow groundwater (<500 m) and saline groundwater closer to the c. 2–5 km deep shale gas. The classification will be used to determine possible vertical hydraulic connectivity between the shallow and deep aquifers, prior to anticipated hydraulic fracturing. This paper reports on the baseline framework that includes the sampling design and a hydrocensus with field-recorded parameters shown as interpolated maps. This includes electrical conductivity, groundwater level and borehole yield. Together with completed sampling results, these data provide a record against which the environmental impact of hydraulic fracturing and the reinjection of production water can be determined. The research is a critical first step towards the successful governance of groundwater in light of proposed shale gas development in the Karoo. In its absence, effective regulation of the sector will not be effective.

Unconventional gas is found in shale formations within the Karoo. The depth to main target formation, known as the Whitehill Formation, varies from surface in the Western Karoo Basin to near 5 km in the eastern sector of the Karoo Basin. Recent technical reports have advised that shale gas development should only proceed where the gas-shale is deeper than 1.5 km below surface (ASSAf 2016). This limits much of the gas development potential to the Eastern Karoo, which is the region covered by this study.

The Karoo shale-gas-bearing formations exhibit a very low permeability with the gas ‘tightly’ trapped within the rock (de Wit 2011; Geel et al. 2013, 2015). In order to determine whether gas can be liberated and economically harvested from these formations requires fracturing of the shale in situ. Drill holes are initially drilled vertically towards the target formation, followed by horizontal drilling within the target formation. This is followed by the pumping down of high volumes of water, sand and chemicals under pressures down the drill holes to induce controlled brittle failure. This technique, known as hydraulic fracturing, creates additional permeability through the fractures, which allows gas to flow more readily to the well head (ASSAf 2016). There is much debate whether or not such artificial fracturing at depth may also induce out-of-formation and upwards fluid leakage that may penetrate shallower groundwater systems.

The need for effective monitoring and regulation during and after hydraulic fracturing related to shale gas development in the Karoo is indisputable (ASSAf 2016). Essential to the effectiveness of any long-term monitoring system is the need for the acquisition of a natural baseline: an understanding of the existing framework prior to the introduction of an intended intervention or critical process such as shale gas harvesting through hydraulic fracturing. This has been advocated in the United Kingdom (e.g. Healy 2012; Talbot & Morris 2012), Asia (e.g. Enoe et al. 2012), Australia (e.g. ACOLA 2013), Europe (e.g. EASAC 2014) and Canada, especially in Quebec (e.g. Council of Canadian Academies 2014), with repeated calls in the US (e.g. Palacios 2012; Jackson et al. 2013; Penningroth et al. 2013; Reig...
et al. 2014) and most recently in South Africa (ASSAf 2016; CSIR 2016) for similar research to be undertaken prior to any further development of unconventional oil and gas. Without robust scientific evidence of the current state, that is, the baseline state of the Karoo, as is the case currently, effective future monitoring of shale gas development will be difficult (de Wit 2011; Vermeulen 2012).

The National Development Plan (NDP) of South Africa has prioritized the call for economic growth that includes sustainable energy production, skills and job creation. To contribute towards achieving this goal, the South African government is now considering the option of shale gas development in the Karoo, an area with a relatively pristine, unique and iconic ecosystem and local agriculture, devoid of previous oil and gas exploitation. The anticipated exploration and exploitation of Karoo shale gas through hydraulic fracturing has raised considerable debate about the benefits and risks associated with this process for both the Karoo, and the country as a whole (NDP 2030 2013; ASSAf 2016). To date much of the discourse has been locked in the seemingly intractable conflict between economic development and environmental concerns. At the centre of both narratives is the attempt to base decisions on the science behind it. However, there are a lot of unknowns as the science behind the future of shale gas development has not yet been fully explored and tested in the South African context, and in the Karoo in particular (e.g. de Wit 2011).

Focus has been placed on the potential impact of hydraulic fracturing where the chemicals used could result in the contamination of the critical zone, its ecological and agricultural systems, and especially their reliance on the relatively scarce water resources across the Karoo.

Specifically, potential impacts that have been linked to shale gas extraction and hydraulic fracturing in the Karoo are as follows.

1. Additional water demand from shale gas exploitation could exceed that available for agriculture, ecosystems and human consumption.

2. Groundwater and surface water quality could be compromised through (Fig. 1):

   a. spills and leaks of chemicals and/or fuels on and around the well pad;
   b. improper disposal of returned frack-fluid and production water;
   c. contamination of groundwater by drilling fluids and gas through faulty drill casings, poor cement, as well as the associated risk of saline water contamination of fresh water sources through these casings;
   d. upwards and lateral leaks of highly saline groundwater into shallower freshwater aquifers via geological structures along dolerite sills and dykes, faults and fractured zones (all prominent geological features of the Karoo along its northern and southern prospective margins, respectively) and possibly the regional shape of the basin that may induce artesian flow (e.g. Vermeulen 2012); and
   e. induced fluid flow and seismic activity along dormant faults triggered by the drilling, hydraulically fracturing or subsurface wastewater disposal (e.g. ASSAf 2016).

It has also been indicated that as much as 90% of fracking fluids injected into the shale does not return to the surface in USA shale gas plays (Vidic et al. 2013). This poses the question of where do those injected fluids go, and what may be the impacts of the potential reinjection of production fluids (e.g. Guglielmi et al. 2015; ASSAf 2016)? The possibility exists that these fluids may enter the shallow groundwater supply and induce deep earthquakes (Walsh & Zoback 2016). The Karoo region is highly dependent on fresh groundwater as an important water resource and, with anticipated climate change, it will become increasingly so (e.g. Vermeulen 2012). Sustainable groundwater management is therefore of prime importance.

The South African Department of Water and Sanitation (DWS) administers the National Water Act (NWA) (Act 36 of 1998). At the core of the act is the unity of sustainable development and the Karoo’s hydrological cycle (ASSAf 2016; Morkel & de Wit 2017). The act formulates a regulatory regime for the sustainable use of water, including groundwater. Central to this regime is water licensing. The minister published a notice in the Government Gazette during August 2013 classifying hydraulic fracturing as a controlled activity. This enables the regulating authority to add conditions in addition to the standard water license, such as specifying the waste treatment, pollution control and monitoring equipment to be installed, maintained and operated, and specifying the management practices to be followed to prevent the pollution of any water resource (ASSAf 2016). The regulatory regime commits to the sustainable use of the water resources of South Africa and therefore the Karoo.

**Purpose of paper**

The aim of this paper is to supply an overview of groundwater within the Eastern Cape Karoo, South Africa and describe the need for baseline data along with initial results towards defining its baseline status. This is a crucial step towards the main objective: to characterize the hydrochemistry of both the shallow groundwater (<500 m) and deeper saline groundwater in an area most likely to be selected
for early shale gas exploration in the Eastern Cape Karoo. Our results can be used to test possible natural hydraulic connectivity between the shallow and deep aquifers, particularly in those areas where dolerite intrusions, as well as fault systems, may act as conduits for the preferential flow of water.

A record of the natural state of Karoo prior to any intrusive exploration and exploitation activities will also be of significant value globally, because the region is one of the most pristine basins identified for shale gas development.

**Karoo as a baseline region**

Although there have been regional studies on groundwater sources within the Karoo (e.g. Woodford & Chevallier 2002; Usher et al. 2006; Murray et al. 2012), only limited studies have attempted to characterize these groundwater sources based on hydrochemistry. Furthermore, limited knowledge exists on the interaction between potential deep contaminant sources and shallow groundwater resources, which has been identified to be an environmental risk with shale gas development elsewhere (e.g. in Pennsylvania, USA; Myers 2011; Warner et al. 2012). This should be considered a great risk in the Karoo due to the fractured nature of Karoo formations and its local seismicity (Dhansay et al. 2017), as well as the presence of dolerite intrusions which can serve as preferred flow pathways for potential contaminants between deeper and shallow groundwater sources (Vermeulen 2012).

**Karoo geology**

**Main Karoo Basin**

The Karoo Basin of South Africa covers approximately 600 000 km² and comprises sedimentary
strata belonging to the Karoo Supergroup; the latter represents a period of approximately 100 Ma of sedimentation from the Late Carboniferous (c. 291–288 Ma) to Early Jurassic (c. 182 Ma) (Fig. 2) (Linol et al. 2016).

Numerous models have been proposed for the tectonic setting of the basin; however, recent findings support a southwards-directed subduction and collision between the Patagonian landmass and the Rio de la Plata–Kalahari Shields (Linol & de Wit 2016; Miller et al. 2016). This led to the formation of the Cape Fold Belt (CFB) at around 250 Ma, as a Jura-type fold-and-thrust belt formed through arc-continent collision. The Karoo Basin formed as a flexure foreland basin to the CFB (Lindeque et al. 2011; Miller et al. 2016).

Karoo Supergroup

The Karoo Supergroup conformably overlies the Cape Supergroup in the south and unconformably the Archean Kaapvaal Craton in the north (Linol et al. 2016). The strata of the Karoo Supergroup are generally horizontal to very gently dipping and undeformed, except in the south of the basin where the strata is deformed into mainly north-vergent folds adjacent to the Cape Fold Belt (Booth & Goedhardt 2014; Linol et al. 2016).

Glacial sediments, mainly tillites and diamicites known as the Dwyka Group, were deposited in the southern part of the Karoo Basin into the newly formed basin containing a widespread glacial melt lake, forming the base of the Karoo Supergroup (Linol et al. 2016; Schulz et al. 2016). The Dwyka Group is overlain by the lower Ecca Group. It consists predominantly of multiple layers of mudstone and shale (Linol & de Wit 2016). These shales are rich in organic matter and are believed to be unconventional gas reservoirs (ASSAf 2016; Linol & de Wit 2016).

The overlying strata of the Ecca and Beaufort groups (maximum 5 km thick) were deposited during and following the Cape Orogeny (252 Ma; Blewett & Phillips 2016). They comprise abundant mud rocks and cross-beded sandstones attributed to lacustrine and floodplain deposition. Mudstone grades into sandstone towards the top of the Ecca and Beaufort groups (Geel et al. 2013; Chukwuma & Bordy 2016; Schulz et al. 2016). The succeeding and uppermost Karoo red-bed sediments (Stormberg Group) varied from ephemeral arid fluvial near the base to aeolian sand dune deposition at the top (Geel et al. 2013; Black et al. 2016).
The sedimentary Karoo depositional sequence was terminated by the emplacement of the Karoo large igneous province (Karoo LIP; c. 182 Ma), which includes the Drakensberg Group volcanics and the Karoo dolerite-gabbro sills, some of which may have affected the shale gas potential either by insulating the gas (thus ‘trapping’ it) or causing thermal degassing (Fig. 2) (e.g. Moortcroph & Tonneller 2016; Nengovhela et al. 2016; Scheiber-Enslin et al. 2016).

Karoo shale gas potential

Field and core analyses suggest that regions of the Southern Karoo Basin exhibit favourable features for the occurrence of shale gas (e.g. Geel et al. 2013, 2015; Chere 2015). The extensive size, appropriate host rocks (shales belonging to the Ecca Group) and the potentially large resources of gas make it a potentially attractive target (Geel et al. 2015).

There are a considerable number of estimates of the potential Karoo shale gas resources. However, due to limited knowledge of the deeper geometry of the basin, a high degree of uncertainty prevails (ASSAf 2016). Initial estimates of potential shale gas resources have been between 10 and 500 trillion cubic feet (Tcf). However, subsequent studies have suggested that these numbers are overoptimistic (ASSAf 2016). Initial estimates of potential shale gas (e.g. Geel et al. 2013, 2015) suggested as a realistic number and 10–20 Tcf as a likely reserve (ASSAf 2016).

Reliable economic reserve figures for Karoo shale gas are not available, largely because there has been little to no exploration since the mid-1960s when exploration for oil was terminated by SOEKOR (Southern Oil Exploration Corporation) since no oil was found due to over-maturity of the basin. At the time, there was no interest in gas despite significant detections (ASSAf 2016).

The South African Government had received three applications for shale gas exploration in the Karoo Basin, namely Shell International, Falcon Oil and Gas, and Bundu Energy (Fig. 2). However, while these applications include permitting for activities such as stratigraphic drilling and seismic surveys, they exclude hydraulic fracturing. To date, the regulatory authority has not pronounced on these applications. Since 2009, when the first Technical Cooperation Permits (TCPs) were awarded to these applicants, their exploration activities were restricted to desktop studies (inclusive of reviewing existing geological and core data from SOEKOR wells previously drilled in the Karoo) and community consultations in the basin (Morkel & de Wit 2017). Considering that Mossgas (conventional natural gas harvesting offshore off the south coast of South Africa) was developed on 1 Tcf, the Karoo reservoirs hold huge potential (Geel et al. 2015; ASSAf 2016).

Karoo hydrogeology

Aquifers that occur in the Karoo Supergroup exhibit secondary porosity/permeability to form so-called Karoo fractured-rock aquifers (Woodford & Chevallier 2002; Usher et al. 2006; Vermeulen 2012). They owe their storage and transmission capabilities to weathering, jointing, fracturing, faulting and the intrusion of dolerite dykes and massive sills (Vermeulen 2012).

A dual porosity model is considered appropriate, where most of the water is stored within the porous matrix of Karoo formations with the transmission of groundwater along fractures (Woodford & Chevallier 2002; Botha & Cloot 2004; Usher et al. 2006; Vermeulen 2012). A complex aquifer geometry results in heterogeneous and anisotropic aquifers that exhibit variability over short distances (Botha & Cloot 2004; Vermeulen 2012).

The aquifers are generally of low permeability with very low yields, often less than 1 L s–1 (Usher et al. 2006). Large volumes of water are, however, withdrawn from well fields for water supply from Karoo formations (Woodford & Chevallier 2002; Botha & Cloot 2004). This does indicate that Karoo formations have high storage potential (high porosity) and may contain large quantities of water, not readily released due to the low permeability/effective porosity. For this reason, numerous closely spaced (<20–30 m) wells (often yielding approximately 1–3 L s–1) are commonly required to abstract significant water volumes for agriculture (Usher et al. 2006).

The average annual rainfall within the Karoo varies between 50 and 400 mm, but can reach 400–600 mm on mountains, with most of the rainfall during summer months (December–February) (Fig. 3). The annual rainfall increases from west to east, from as little as 50 mm in the west to as much as 600 mm in the east (Schulze et al. 1997).

Methodology

Areas with the highest potential for shale gas development throughout the Eastern Cape Karoo (e.g. Geel et al. 2013) cover an area of approximately 66 000 km2 (Fig. 2). To enable sufficient groundwater sample coverage across the area, a regular sample distribution was determined to cover quaternary catchments (a fourth-order drainage basin in a hierarchical classification system in which a primary catchment is the major drainage basin) with a minimum of two sites per catchment. Boreholes are predominantly situated on privately owned farm land within the Karoo region, accessible by mostly gravel roads. Access was gained through a rigorous engagement process with all relevant stakeholders.
Fig. 3. (a) Map showing mean annual precipitation across the research area (modified from Schulze et al. 1997). (b) Mean annual rainfall above 400 mm seen in high elevated, mountainous areas. Topography map across the research area. Areas of lowest elevation (green) at c. 200 m above mean sea level (mamsl) with highest elevation (purple and white) at c. 1800 mamsl. Meteoric water derived from the escarpment is an important source of recharge within lowland aquifers and springs.
A hydrocensus, an in-field process of obtaining information about access, borehole location, pump type (if any), borehole diameter and depth, purging rates, turbidity and anything of relevance to facilitate the future sampling of a borehole, was completed. This information was used to establish the sampling procedure and design. All data collected were entered into a GIS-linked database for processing and management.

All unequipped (no pump installation) boreholes identified during the hydrocensus were vertically EC (electrical conductivity) profiled using a probe to determine plume movement and water salinity stratification. This was used to identify the sampling depths, where either an increase or decrease in EC represents the groundwater inflow from which a sample was taken. Slug tests were completed to determine the hydraulic conductivity (K) of the aquifer, as well as to estimate the yield of all unequipped boreholes. The acquired data were interpreted using the FC (flow characteristics) programme, interactive software which is available as an Excel workbook on the website of the Institute for Groundwater Studies at the University of the Free State, South Africa (http://www.uovs.ac.za/faculties/igs). Systems used include the derivative, Barker and Cooper–Jacob methods. This was followed by groundwater sampling of all shallow (<500 m) sites covered during the hydrocensus.

Sampling was receptor-focused (active groundwater users/active boreholes), being the end-user of groundwater which may encounter possible contaminants introduced by the proposed hydraulic fracturing (e.g. O’Brien et al. 2013). Sampling was also conducted at inactive boreholes to ensure samples were taken that have not been affected by pumping processes (i.e. samples from undisturbed groundwater sources). The combination of samples from active and inactive boreholes provides robust information on the baseline chemical properties of groundwater.

Boreholes equipped with pumps were sampled at the surface directly from the pump. Samples at unequipped boreholes were collected by use of a discrete interval sampler (DIS). This allows for the collection of high-quality samples without significant disturbance of the water column and contamination from the water column above the sampling point. DIS also allows for the collection of high-quality organic samples, as the samples have minimal contact with air and do not undergo pumping; this limits the risk of loss of organics, especially regarding volatile organic carbon (VOC).

The collected samples are currently being analysed by the use of four AEON instruments (see Section ‘Selection of chemical determinands and hydraulic connectivity’ below for determinands to be analysed):

- PICARRO cavity ring-down spectrometer (CRDS) analyses of CH$_4$ and CO$_2$ concentrations, as well as stable isotope ratios of the carbon of both gases;
- OL Analytical Aurora 1030W total organic carbon (TOC) analyser, to determine the concentration of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) in water and which can be coupled to the PICARRO CRDS for determination of C isotope ratios of DIC and DOC;
- THERMO SCIENTIFIC ICAP-Q inductively coupled plasma mass spectrometer (ICP-MS) to measure the concentrations of trace elements in water and other solutions; and
- Dionex ICS-2100 ion chromatograph (IC) to measure concentrations of anions in water, and which can be coupled to the ICP-MS.

Isotope analysis of $^18$O and $^2$H of water are currently being conducted at iThemba LABS, Johannesburg (http://www.tlabs.ac.za).

Data collected during the hydrocensus were spatially visualized. Inverse distance weighting interpolation was used to populate measurements. This technique was selected for its simplicity and sufficiency for the current dataset. Other interpolation techniques will be investigated as more data and results are generated. Parameters visualized are the recorded electrical conductivity, measured groundwater depth and determined borehole yields. Measurements at both unequipped and equipped boreholes were included in the interpolation of EC, with EC values of unequipped boreholes taken at identified inflow horizons. Only measurements at unequipped boreholes were included for yield and groundwater level interpolation, as installed pumps in equipped boreholes obstructed the probes.

The electrical conductivity interpolation was not based on a specific depth, as sampling depth was either determined through profiling or dependent on user pump depth installation, which varies throughout the area. It is only used as the interpolated salinity of groundwater currently being extracted, and shallower than 500 m below ground level. The measured electrical conductivity values were grouped and classified according to the publication Quality of Domestic Water Supplies, DWAF, Second Edition 1998 (Department of Water Affairs and Forestry 1998). An explanation of the classification scheme is provided in Table 1.

**Sampling frequency**

The Department of Water Affairs (DWA) recommends that groundwater be sampled twice yearly, as groundwater is generally stable in pristine areas such as the Karoo (Department of Water Affairs and Forestry 2000). A similar sampling frequency
includes a sampling phase to be conducted during a hydrocensus prior to the onset of biannual sampling (e.g. O’Brien et al. 2013). This research follows such a sampling frequency, with the samples collected so far serving as initial samples prior to the planned biannual sampling. Only identified samples, as identified by geospatial statistics (see the following section), will be sampled in future phases.

Sampling of the identified sites (through the statistics) will be undertaken after winter (i.e. October/November 2018), with a second sampling phase to be conducted six months later (after summer in April/May 2019) (e.g. O’Brien et al. 2013). This is done to allow for the detection of any seasonal variance in the hydrochemistry. If required, additional and intermittent sampling will be undertaken should significant variance be observed.

Geospatial statistical analyses

Geospatial statistical analyses was performed to identify a manageable sampling design without losing spatial coverage of the area. Data collected during the hydrocensus was used for this purpose. The sampling design was based on a two-stage approach. The first stage encompassed the validation of the hydrocensus (NMU) database where it was ensured, for example, that units of measurement are uniform, site names and coordinates are correct. Ambiguous records were omitted from the database. A total number (population N) of 756 sites (boreholes and springs) were incorporated into the statistical analyses.

The second stage involved the selection of a sample size (n) from which various variables (location, EC and depth) can be measured as baseline parameters. Based on geostatistical literature guidelines, a sample size (n) of 250 was selected. Not only is a sample of 250 manageable, but it also satisfies geostatistical guidelines. This stage can be described as a nested multi-criteria approach. The main criterion is based on the continuous variables latitude (X1), longitude (X2) and EC (X3) and is based on conditional Latin hypercube sampling (cLHS, after Minasny & McBratney 2006). With cLHS, the sample size of 250 is formulated in such a way that for each variable the sample is marginally stratified.

The range of each variable (X1, X2 and X3) in the population (the 756 sites) is divided into n (=250) equally probable intervals (strata) (equivalent to setting up a histogram with 250 bins). A random sample for each variable is then drawn in such a way that it minimizes the criterion:

\[ cLH_{\text{criteria}} = \sum_{i=1}^{n} \sum_{v=1}^{3} \left| \#(q_{v}^i \leq x_v \leq q_{v}^{i+1}) - 1 \right| \]

where \#(q_{v}^i \leq x_v \leq q_{v}^{i+1}) is the number of \( x_v \) that falls between \( q_{v}^i \) and \( q_{v}^{i+1} \) (the count in a specific bin). The minimization of \( cLH_{\text{criteria}} \) is obtained via an annealing schedule, and we use the Minasny & McBratney (2006) Matlab code with 10 random starts, finding 100 optimal designs (each based on 10 000 000 iterations). The term ‘design’ refers to a specific sample (250 selected sites) and the term ‘optimal design’ refers to a sample that yields the minimum \( cLH_{\text{criteria}} \); the design is optimal (best) in terms of the \( cLH_{\text{criteria}} \).

The first 25% best optimal designs, based on cLHS, were selected (main criteria). From these designs, three secondary criterions (nested) were calculated based on the borehole depth (Bordepth), the spatial coverage (Cover%) and a correlation measure (Cor3) based on the three continuous variables (latitude, longitude and EC).

The depth of the boreholes data were transformed into categorical data, deep (>30 m) and shallow. Bordepth is then defined as:

\[
\text{Bordepth} = \left| \frac{\#(X_{\text{deep}}) - \pi_{\text{deep}}}{250} \right| + \left| \frac{250 - \#(X_{\text{deep}})}{250} - (1 - \pi_{\text{deep}}) \right|
\]
where \( \#(x_{\text{deep}}) \) is the number of sites with boreholes that belong to class ‘deep’ in the sample and \( \pi_{\text{deep}} \) is the proportion of deep boreholes in the population. The aim again is to mimic the same proportions in the sample as in the population; a design with a small value for Bordepth is therefore desirable.

The spatial coverage criteria is defined as the percentage of quaternary catchment areas in the sample compared to those in the population (Cover%); a design with a higher Cover% is desirable. The correlation measure (Cor3) based on the three continuous variables (latitude, longitude and EC) is defined:

\[
\text{Cor3} = \frac{3}{\pi_1} \sum_{i=1}^{3} \sum_{v=1}^{3} |c_{iv} - t_{iv}|
\]

where \( c_{iv} \) are the elements of C, the correlation matrix of the three continuous variables (X1, X2, X3) in the population, and \( t_{iv} \) is the elements of T, the correlation matrix of the three continuous variables in the sample; a design with a small Cor3 is desirable.

The four criteria (main and nested) were combined for the 25 best cLHS designs upon which an efficiency index \((E)\) was defined in order to identify the four best sample designs. For each design we identify the ‘best’ value under each criteria. This was then used to set an efficiency index for each design:

\[
E = \frac{cLH_{\text{criteria}}}{\text{best}'} cLH_{\text{criteria}} + \frac{\text{Cor3}}{\text{best}'} \text{Cor3} + \frac{\text{bordepth}}{\text{best}'} \text{bordepth} + \frac{\text{Cover%}}{\text{best}'} \text{Cover%}
\]

Note that this actually includes the reciprocal of Cover% (as nearest to 100% is the best).

Selection of chemical determinands and hydraulic connectivity

Very little detailed information exists on which determinands should be analysed for a baseline groundwater study, with respect to shale gas development (O’Brien et al. 2013). A defined list of determinands that cover South Africa’s groundwater user quality requirements, as outlined by the Department of Water and Sanitation, South Africa (http://www.dwa.gov.za/IWQS/wq_guide/index.asp), were set up to provide a scientific record of pre-drilling quality in the event of possible contamination (Table 2), following methodology described by O’Brien et al. (2013).

The selection was also guided by studies in the USA (e.g. Stoessell & Prochaska 2005; Warner et al. 2012, 2013), where results of deep and produced (water produced as result of hydraulic fracturing of shale formations containing gas) water analysis data have shown that water \( \delta^{18}O \) and \( \delta^{2}H \), methane \( \delta^{13}C \) and \( \delta^{2}H \), Ba, Br, Cl, F, K, Na U, Sr and Li (and/or their ratios) possibly represent indicators of deep-seated saline groundwater, as the concentration of these elements differs considerably when compared to shallow groundwater.

It was determined that such fluids migrate naturally into shallow aquifers. The natural migration of saline fluids into shallow aquifers may also occur in the Karoo along conduits such as faults and fracture systems along dolerite intrusions (e.g. Vermeulen 2012).

Results and discussion

As indicated above, a considerable amount of work has already been done on groundwater sources within the Karoo (e.g. Woodford & Chevallier 2002; Usher et al. 2006; Murray et al. 2012). However, these results are outdated when keeping in mind the goal of this baseline research, which is to determine the current state of groundwater conditions. Furthermore, earlier studies have not incorporated a comprehensive set of chemical parameters to conclusively characterize the groundwater chemistry needed for robust baseline analyses.

The density of sample distribution, as covered during the present hydrocensus, allows for the presentation of initial groundwater baseline conditions. Coverage was achieved with 98% of catchment areas surveyed to quaternary level with a minimum of two sites per catchment (Fig. 4). The number of sites decreased to a manageable sample size of 250 sites achieved through geospatial statistics without the loss of significant spatial coverage (Fig. 5). The sampling design allows for approximately 90% coverage to quaternary catchment level. However, 100%
coverage has been achieved to tertiary catchment level. As mentioned, these sites will form part of future, seasonal sampling phases.

Borehole construction and depth as determined during the hydrocensus and EC profiling indicate that boreholes are typically drilled to a depth of 42 mbgl. Well casing is generally only installed to a depth of 3–12 mbgl to prevent caving from shallow soil/unconsolidated rock. Groundwater plume movements are typically identified between 20 and 30 mbgl, where either sharply increased or decreased EC values are observed. This represents the contact between the unsaturated strata and saturated, ‘hard’ rock. This indicates that groundwater abstraction within the area is commonly taken from the highly fractured, weathered and unsaturated strata from a depth down to 30 mbgl or shallower. It is therefore evident that recharge linked to precipitation is a key factor influencing EC, groundwater depth and aquifer yield.

It should be noted that fewer boreholes are drilled into the saturated strata beyond depths of 42 mbgl. These boreholes vary in EC and yield, with water levels linked to water table depth since there is no mechanisms in place (such as deep well casing and screening) separating the unsaturated and saturated strata.

Based on electrical conductivity, the groundwater within the research area is predominantly classified as ideal to marginal in quality (Fig. 6a). Similar results have been reported for the Eastern Cape Karoo (Department of Water Affairs and Forestry 2010; Murray et al. 2012; SRK Consulting 2012). However, this research has also identified increased areas where water exhibits a considerably lower quality (poor to unacceptable).

Ideal to good water quality is seen in areas of higher elevation with higher annual precipitation, and also throughout the immediate surface water runoff zones in such areas. The higher precipitation...
results in higher groundwater recharge values, causing increased dilution with the fresher meteoric water.

In contrast, poor to unacceptable water quality is seen in areas at low elevation with lower annual precipitation. The lower rainfall results in lower groundwater recharge rates, with limited to no dilution with fresher meteoric water. Furthermore, regional groundwater typically flows along the hydraulic gradient from areas of higher elevation (e.g. Freeze & Cherry 1979). We therefore interpret that groundwater present at low-lying areas exhibits lower quality because these have typically undergone extended periods of water–rock interactions due to lengthier recharge flow paths.

Distance to groundwater level is presented in mamsl (Fig. 6b) and mbgl (Fig. 6c). Groundwater presented in mamsl confirms that the regional groundwater level is linked to topography and, as mentioned, flows down-gradient from higher elevations (e.g. Freeze & Cherry 1979). The regional groundwater flow direction can therefore be determined and is depicted to flow in a NW–SE-aligned direction within the study area.

The depth to groundwater level in mbgl is mostly between 10 and 20 mbgl. Similar groundwater depths have been observed for the Eastern Cape Karoo (Department of Water Affairs and Forestry 2010; Murray et al. 2012; SRK Consulting 2012).

However, regions with deeper water levels (below 30 mbgl) have been identified, and areas of water levels deeper than 20 mbgl are seen to be more extensive. Areas with groundwater below 20 mbgl are seen predominantly in areas of lower annual precipitation. We interpret that to reflect that the lower recharge volumes result in a deeper water table.

Groundwater shallower than 10 mbgl is seen in areas of higher elevation with higher annual precipitation (higher recharge), as well as in the immediate runoff zones of these areas. The higher recharge volumes equates to a shallower water table. The presence of dolerite sills and dykes in these areas may also be a contributing factor, where the dolerite sills act as aquitards to form possible perched aquifers.

Areas with groundwater levels deeper than 10 mbgl are seen in areas of high elevation/high
Fig. 6. Inverse distance weighting interpolated maps of (a) groundwater electrical conductivity (mS m$^{-1}$), where blue and purple indicate low- and high-salinity domains, respectively; (b) groundwater level (m amsl), where blue and red indicate low- and high-elevation groundwater level, respectively.
Fig. 6. (Continued) (c) groundwater level as metres below ground level (mbgl), where blue and red indicate shallow and deep groundwater level, respectively; and (d) aquifer yield (L s$^{-1}$) where red and blue indicate low- and high-yielding aquifer domains, respectively. Hydrocensus sites (a) and boreholes (b–d) are depicted as green coloured dots.
rainfall. This is possibly an indication of overabstraction of groundwater by farmers and municipalities. The potential overabstraction of groundwater is seen throughout the region, where isolated areas exhibit a groundwater level deeper than 30 mbgl. The possible overabstraction is highlighted by the increasing size of areas exhibiting a groundwater level below 20 mbgl when compared to previous observations (Department of Water Affairs and Forestry 2010; Murray et al. 2012; SRK Consulting 2012). Aquifer yield has been interpolated from the calculated yield of individual boreholes (Fig. 6d).

Yields are predominantly between 1 and 5 L s$^{-1}$. Similar results have been observed for Eastern Cape Karoo aquifers (Woodford & Chevallier 2002; Department of Water Affairs and Forestry 2010). This research has however identified more extensive areas where aquifer yields are below 1 L s$^{-1}$. It is within these regions that possible overabstraction is common. It is expected that the hydrochemistry for initial samples collected will be received during the first half of 2018. This will be followed by sampling and results from future seasonal samples to be collected from the 250 sites identified by the geospatial statistics, including deep sites. This will include the isotopic research as outlined here. Water $\delta^{18}$O and $\delta^2$H and methane $\delta^{13}$C and $\delta^2$H values will be used as indicators to distinguish between shallow and deep groundwater (e.g. Kaplan et al. 1997; Osborn et al. 2011; Tilley et al. 2011; Palacios 2012; Tilley & Muehlenbachs 2012; Molofsky et al. 2013; O’Brien et al. 2013; Penningroth et al. 2013; Vengosh et al. 2013; Talma & Esterhuyse 2015). The validity of this, along with the major and trace hydrochemistry, needs further investigation in the Karoo which will be conducted during this research.

Ongoing geophysics will aid the interpretation of the groundwater chemistry, especially to identify possible hydraulic pathways connecting the deep and shallow aquifers. The ongoing geophysical surveys include passive seismic profiling, magnetotelluric (MT) geophysics and airborne geophysics (magnetic and radiometric analyses). Electrical conductivity measurements during MT surveys have identified the existence of possible highly saline waters at depth (c. 2 km below surface and deeper) within the Karoo (Weckmann et al. 2012). These surveys indicate that the fresher, shallower groundwater gradually salinizes down towards these depths, with possible hydraulic connectivity with shallow groundwater shown as isolated vertical plumes within the fresher water. Groundwater samples will be taken at the suggested areas of hydraulic connectivity to test the presence of deep-water mixing. The results will be added to data collected so far towards a final baseline of groundwater conditions within the selected area in the Eastern Cape Karoo, South Africa.

**Conclusion**

There is a growing interest in baseline research in the Karoo ahead of potential shale gas development because this basin is globally one of the very few with potential unconventional reserves of oil/gas that have not yet been disturbed by hydraulic fracturing. As such, the Karoo can act as a global example of the best natural state for basins for scientific and legislative purposes before it becomes disturbed through intrusive exploration and exploitation practices. It is therefore likely that there will be global interest in the results of Karoo baseline research prior to exploration.

It is also imperative to understand that this research must proceed within a dynamic framework. Hydraulic fracturing technology is rapidly improving, and it is likely that exploration will begin across parts of the Karoo within the next 5 years, leaving only a small time window for robust natural baseline research before the onset of a new age of energy production in South Africa.

Initial results as reported in this paper have yielded valuable insights towards defining a final baseline status of the Eastern Cape Karoo. Measurements from the hydrocensus have again emphasized the need to gather up-to-date good-quality scientific information needed to classify baseline conditions. Based only on EC, groundwater depth and aquifer yield, changes have been observed in groundwater conditions throughout the research area when compared to previous observations (Department of Water Affairs and Forestry 2010; Murray et al. 2012; SRK Consulting 2012). Areas where groundwater exhibits higher, unacceptable EC values indicate increased salinization and possible decreased quality. Aquifers within the area are also being increasingly stressed due to possible overabstraction. This is evident due to an increased groundwater level to below 30 mbgl in certain areas and also the expansion of areas where groundwater levels are below 20 mbgl. These observations will have to be included when identifying a robust, but evolving baseline condition.

The identification of the 250 sites through the geospatial statistics is key to establishing the baseline groundwater conditions. It represents a manageable sample size which can be seasonally sampled. Furthermore, due to a spatial coverage where 90% quaternary catchments are covered, these sites can serve as a monitoring network should gas harvesting take place.

**Acknowledgements** We would like to thank the post-graduate colleagues from AEON involved in the hydrocensus and sampling. This is AEON contribution number 166 and Iphakade number 165.
Funding The Karoo baseline research project is financed through the government of the Eastern Cape and AEON’s Iphakade programme (DST/NRF – Global Change Initiatives).

References

Academy of Science of South Africa (ASSAf) 2016. South Africa’s Technical Readiness to Support the Shale Gas Industry. Academy of Science South Africa, ISBN 978-0-9946852-7-8, http://research.assaf.org.za

Australian Council of Learned Academies (ACOLA) 2013. Engineering Energy: Unconventional Gas Production. Australian Council of Learned Academies, Project 6, ISBN 978-0-9875798-1-2, https://www.acola.org.au

Black, D.E., Booth, P.W.K. & de Wit, M.J. 2016. Petrographic, geochemical and petro-physical analysis of borehole cores of the lower Ecca Group in the Upper Karoo. South African Journal of Geology, 119, 171–186, https://doi.org/10.2113/gsaajg.119.1.171

Blewett, S.C.J. & Phillips, D. 2016. An overview of Cape Fold Belt Geochronology: implications for sediment provenance and the timing of Orogenesis. In: Linol, B. & de Wit, M.J. (eds) Origin and Evolution of the Cape Mountains and Karoo Basin. Springer International Publishing, Switzerland, pp. 45–54, https://doi.org/10.1007/978-3-319-40859-0

Booth, P.W.K. & Goedhardt, M.L. 2014. Thrust faulting in the northernmost foreland zone of the Cape Fold Belt, Fort Beaufort, Eastern Cape South Africa. South African Journal of Geology, 117, 301–315

Bordy, E.M. & Catuneanu, O. 2001. Sedimentology of the Upper Karoo fluvial strata in the Tuli Basin, South Africa. Journal of African Earth Sciences, 33, 605–629, https://doi.org/10.1016/S0899-5362(01)00090-2

Botha, J.F. & C loot, A.H. 2004. Karoo Aquifers – Formations, Hydraulic and Mechanical Properties. Water Research Commission, South Africa Research Report No. 936/1/04, http://www.wrc.org.za

Chere, N. 2015. Sedimentological and geochemical investigations on borehole cores of the lower Ecca Group Black Shales, for their gas potential – Karoo Basin, South Africa. Dissertation (Master of Science in Geology degree), Faculty of Science, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

Chukwuma, K. & Bordy, E.M. 2016. Spatiotemporal sedimentary facies variations in the lower Permian Whitehill Formation, Ecca Group, Karoo Basin. In: Linol, B. & de Wit, M.J. (eds) Origin and Evolution of the Cape Mountains and Karoo Basin. Springer International Publishing, Switzerland, pp. 101–109, https://doi.org/10.1007/978-3-319-40859-0

Council of Canadian Academies 2014. Environmental Impacts of Shale Gas Extraction in Canada. The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction. Council of Canadian Academies, Ottawa (ON), ISBN 978-1-926558-78-3.

Council for Scientific and Industrial Research (CSIR) 2016. Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks. Council for Scientific and Industrial Research, ISBN 978-0-7988-5631-7, http://www.csir.co.za

Department of Water Affairs and Forestry 1998. Quality of Domestic Water Supplies. Water Quality, 2nd edn. Department of Water Affairs and Forestry, Pretoria, South Africa, http://www.wrc.org.za

Department of Water Affairs and Forestry 2000. Quality of Domestic Water Supplies, Volume 2: Sampling Guide. Department of Water Affairs and Forestry, Pretoria, South Africa. http://www.wrc.org.za

Department of Water Affairs and Forestry 2010. Groundwater Strategy 2010. Department of Water Affairs and Forestry, Pretoria, South Africa. http://www.wrc.org.za

De Wit, M.J. 2011. The Great Shale Debate in the Karoo. South African Journal of Science, 107, 9, Article #791. https://doi.org/10.4102/sajs.v107i7/8.791

Dhansay, T., Navabpour, P., de Wit, M. & Ustaszewski, K. 2017. Assessing the reactivation potential of pre-existing fractures in the Southern Karoo, South Africa: evaluating the potential for sustainable exploration across its critical zone. Journal of African Earth Sciences, 134, 504–515, https://doi.org/10.1016/j.jafrearsci.2017.07.020

European Academies’ Science Advisory Council (EASAC) 2014. Shale Gas Extraction: Issues of Particular Relevance to the European Union. http://www.easac.eu

Enoe, E., He, Y. & Pohanan, E. 2012. Lessons Learned: A Path toward Responsible Development of China’s Shale Gas Resources. Natural Resources Defence Council (NRDC), Beijing, August 2012. http://www.nrde.cn

Freeze, R.A. & Cherry, J.A. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ, http://hydrogeologistswithoutborders.org

Geel, C., Schulz, H., Booth, P., de Wit, M.J. & Horsfield, B. 2013. Shale gas characteristics of Permian Black Shales in South Africa: results from recent drilling in the Ecca Group (Eastern Cape). Energy Procedia, 40, 256–265.

Geel, C., de Wit, M.J., Booth, P., Schulz, H. & Horsfield, B. 2015. Paleo-environment, diagenesis and characteristics of Permian Black Shales in the lower Karoo Supergroup Flanking the Cape Fold Belt near Jansenville, Eastern Cape, South Africa: implications for the shale gas potential of the Karoo Basin. South African Journal of Geology, 118, https://doi.org/10.2113/gssajg.118.3.0

Guglielmi, Y., Cappa, F., Avouac, J.P., Henry, P. & Elsworth, D. 2015. Seismicity triggered by fluid injection-induced aseismic slip. Science, 348, 1224–1226, https://doi.org/10.1126/science.aab0476

Healy, D. 2012. Hydraulic Fracturing or ‘Fracking’: A Short Summary of Current Knowledge and Potential Environmental Impacts. Department of Geography & Petroleum, University of Aberdeen, https://www.epa.ie

Jackson, R.E., Gorody, A.W., Mayer, B., Roy, J.W., Ryan, M.C. & van Stempvoort, D.R. 2013. Groundwater Protection and Unconventional Gas Extraction: The Critical Need for Field-Based Hydrogeological Research. National Ground Water Association, Westerville, Ohio, USA, https://doi.org/10.1111/gwat.12074
monitoring. In: Sublette, K. & Veil, J. (eds) 19th International Petroleum Environmental Conference, 30 October 2012–1 November 2012, Denver, Colorado, USA. http://www.ionscience.com

Talma, S. & Esterhuyse, C. 2015. Isotopic clues to the origin of methane emissions in the Karoo, South Africa. South African Journal of Geology, 118, 45–54, https://doi.org/10.2113/gssajg.118.1.45

Tilley, B. & Muehlenbachs, K. 2012. Isotope reversals and universal stages and trends of gas maturation in sealed, self-contained petroleum systems. Chemical Geology, 339, 194–204.

Tilley, B., McElllan, S., Hiebert, S., Quatero, B., Veilleux, B. & Muehlenbachs, K. 2011. Gas isotope reversals in fractured gas reservoirs of the Western Canadian Foothills: mature shale gases in disguise. AAPG Bulletin, 95, 1399–1422.

Usher, B.H., Pretorius, J.A. & van Tonder, G.J. 2006. Management of a Karoo Fractured-rock Aquifer System – Kalkveld Water User Association (WUA). Water SA, 32, 9–19, January 2006. ISSN 1816-7950, http://www.wrc.org.za

Vengosh, A., Warner, N., Jackson, R. & Darrah, T. 2013. The effects of shale gas exploration and hydraulic fracturing on the quality of water resources in the United States. Procedia Earth and Planetary Science, 7, 863–866.

Vermeulen, P.D. 2012. A South African perspective on shale gas hydraulic fracturing. In: McCullough, C.D., Lund, M.A. & Wyse, L. (eds) International Mine Water Association Symposium, 30 September–4 October 2012, Bunbury, Western Australia, http://www.imwa.info

Vidic, R.D., Brantley, S.L., Vandenbossche, J.M., Yoktheimer, D. & Abad, J.D. 2013. Impact of shale gas development on regional water quality. Science, 340, 1235009, https://doi.org/10.1126/science.1235009

Walsh, F.R. & Zoback, M.D. 2016. Probabilistic assessment of potential fault slip related to injection-induced earthquakes: application to north-central Oklahoma, USA. Geology, 44, 991–994, https://doi.org/10.1130/G38275.1

Warner, N.R., Jackson, R.B. et al. 2012. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. PNAS, 109, 11961–11966, https://doi.org/10.1073/pnas.1121181109

Warner, N.R., Kresse, T.M., Hays, P.D., Down, A., Karr, J.D., Jackson, R.B. & Vengosh, A. 2013. Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville Shale development, North-Central Arkansas. Applied Geochemistry, 35, 207–220.

Weckmann, U., Ritter, O., Chen, X., Tietze, K. & de Wit, M.J. 2012. Magnetotelluric image linked to surface geology across the Cape Fold Belt, South Africa. Terra Nova, 24, 207–212, https://doi.org/10.1111/j.1365-3121.2011.01054.x

Woodford, A.C. & Chevallier, L. 2002. Hydrogeology of the Main Karoo Basin: Current Knowledge and Future Research Needs. Water Research Commission, Pretoria, South Africa. WRC Report No TT 179/02. http://www.wrc.org.za