Stable isotope constraints on hydrostratigraphy and aquifer connectivity in the Table Mountain Group

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Abstract

The Table Mountain Group is a folded, faulted, quartzite-dominated sedimentary sequence, metamorphosed to lower greenschist facies, that forms steep mountains dominating the topography of the Western Cape and causing orographic rainfall in an otherwise semi-arid region. These quartzites are highly fractured to depths of kilometres and act as a complex aquifer system that supplies groundwater directly and indirectly, through baseflow, essential for sustaining the natural environment and human activity in the region. Hydrogen and oxygen isotope data for rain, rivers and groundwater (boreholes and springs) in the region give typical altitude effects of -1.8‰ δD/100 m and -0.33‰ δ^{18}O/100 m, and a very strong continental effect of -30‰ δD/100 km and -4.7‰ δ^{18}O/100 km. This allows for application of stable isotopes as natural hydrological tracers. Groundwater at several locations had stable isotope compositions different from ambient rainfall, but similar to rainfall at high altitudes in adjacent mountains, indicating recharge at high altitude. The groundwater flow is through the Skurweberg Aquifer, here defined as all three formations of the Nardouw Subgroup. Observations on the Peninsula Aquifer suggest a very well mixed aquifer, due to extensive fracturing. Potential exists to delineate groundwater protection zones, detect overabstraction and understand aquifer connectivity better by applying stable isotope hydrology to the Table Mountain Group.

Introduction

The Table Mountain Group (TMG) dominates the landscapes of the Western Cape, forming the highest mountains, nearly 2500 m, and spine-like ridges of mountainous terrain that separate valleys, towns and other areas of human settlement (see Figure 1). The highest rainfall regions of the Cape also occur on TMG outcrop areas (Beuster et al, 2009) and, if it was not for the mountainous outcrop areas of the TMG, the Western Cape would be semi-arid. The TMG is dominated by lower greenschist facies metamorphosed arenaceous layers (Frimmel et al, 2001) and forms a thick, extensive fractured quartzite aquifer system. The TMG therefore partly controls the abundance and distribution of water across the Western Cape, in turn influencing the ecology and human activity. The hydrogeology of the TMG has been dealt with regularly (Midgley and Scott, 1994; Diamond and Harris, 2000; Pietersen and Parsons, 2002; Wu and Xu, 2005; Xu et al, 2007; CCT, 2008; Miller et al, 2017), although little has been done towards understanding the hydrostratigraphy (Blake et al, 2010). This paper aims to add towards our understanding of the TMG hydrostratigraphy, given the increasing importance of water management in times of increasing population, water usage per capita and changing climate (IPCC, 2014).

Hydrogen and oxygen isotopes of water have been used since the 1950's to understand the hydrological cycle (Epstein and Mayeda, 1953). Major global patterns in stable isotopes were elucidated in the 1960's (Craig, 1961) and by the 1970's onwards detailed hydrological processes, such as evaporation (Dincer, 1968), mixing (Krouse and McKay, 1971), water balance (Zuber, 1983), recharge estimation (Midgley and Scott, 1994) and source delineation (Diamond and Harris, 2000) were being investigated.

Hydrogen and oxygen isotope data are reported using the delta notation, where δD (or $\delta^{18}O$) equals:

$$\delta D = \left((D/H_{sample} - D/H_{SMOW}) \div D/H_{SMOW} \right) \times 1000 ,$$

where SMOW is Standard Mean Ocean Water. Delta values are reported in per mille (‰).

Stable isotope ratios vary in natural waters because of various processes that cause fractionation. Fractionation can occur under equilibrium conditions, in which two substances containing the element of interest interact with sufficient time to reach a state of equilibrium, but due to the bond strength interactions in the two different reservoirs, the isotopes do not partition equally, but are fractionated by some amount, known as the fractionation factor. These substances can be chemically different, (e.g. hydrogen in water and micas) or physically different, (e.g. oxygen in liquid and gaseous water). The second type of fractionation is kinetic, where, due to the dynamics of the system, there is insufficient time for isotopic equilibrium to be achieved and certain isotopes are preferentially removed from one reservoir (e.g. evaporation into windy air preferentially removing H (or ^{16}O) from the liquid water) (Gat and Gonfiantini, 1981). As with equilibrium fractionation, kinetic fractionation can also occur during chemical reactions or physical transformations.

Fractionation in the atmosphere results in several noticeable patterns in meteoric waters. These have been named the temperature effect, the continental effect, the altitude effect and the amount effect (Dansgaard, 1964). These effects often operate in tandem, or are separate components of a single greater effect of rainout. The temperature effect, where delta values tend to be more negative in colder climates, can be ascribed to the negative correlation between the isotope equilibrium fractionation factor and temperature (i.e. as the temperature increases, so the fractionation factor decreases). The altitude effect, where delta values tend to be more negative at higher altitude, is largely due to progressive rainout of heavier isotopes at lower elevations. The continental effect, where delta values tend to be more negative further inland, is largely due to progressive rainout of heavier isotopes closer to the coast. The amount effect, where delta values tend to be more negative with heavier rainfall events, is also due to progressive rainout, as well as saturation of air beneath clouds, reducing evaporative enrichment (Rozanski, 1993). Evaporative enrichment of raindrops is caused by kinetic fractionation as raindrops preferentially lose the lighter isotopes into dry air beneath clouds during their descent to the ground.

The differences in isotope composition of waters of different origins are exploited as natural tracers of hydrological processes. However, few publications exist on stable isotopes in the TMG area, from the 1980's (Mazor and Verhagen, 1983) until present (Miller et al, 2017). Most of these studies come to some conclusion regarding groundwater flow, but little has been said on the hydrostratigraphy of this large aquifer system. This paper contributes to the small, but growing, literature available on stable isotope hydrology of the TMG and draws some conclusions that should aid in further investigation as well as management of the water resource.

Study area

Stratigraphy

The geology of the study area is summarized in the map in Figure 2. The Western Cape basement comprises several lightly metamorphosed groups of varied lithology, including the Malmesbury Group that dominates the south-western Cape, and the Cango, Kansa, Kaaimans and Gamtoos Groups that occur from Outdshoorn to Port Elizabeth, collectively known as the Saldanian Belt (Gresse et al, 2006). Intruded into these Pan-African groups is the Cambrian Cape Granite Suite, mainly found in the Malmesbury Group outcrop area, with minor plutons further east, near George (Scheepers and Schoch, 2006).

Unconformably overlying the basement is the Paleozoic Cape Supergroup, which dominates the geology of the Western Cape, and extends substantially into the Eastern Cape. The Ordovician to Silurian Table Mountain Group (TMG) forms the base and is the thickest group in the Cape Supergroup, being overlain by the Devonian Bokkeveld and Carboniferous Witteberg groups, together totalling up to 10 km thickness (Thamm and Johnson, 2006). The TMG is predominantly arenaceous, whereas the Bokkeveld Group is largely argillaceous and the Witteberg Group somewhat in between. Overlying the Cape Supergroup is the Karoo Supergroup, a glacial, through marine, to continental foreland basin sequence, partly derived from erosion of the uppermost portions of the Cape Supergroup. Deformation, metamorphism to lower greenschist facies, and mountain building of the basement, Cape and lowermost parts of the Karoo Supergroup, took place during the Permo-Triassic Cape Orogeny (Frimmel et al, 2001).

The TMG lithostratigraphy varies somewhat around the basin. In the far south-east, the Sardinia Bay Formation, composed of feldspathic quartzitic sandstones, may belong either to the TMG, or to the Gamtoos Group (Toerien and Hill, 1989). Fortunately, the rest of the formations are better understood, even though their distribution varies. In the north-west, from the Piketberg to the Olifants River mouth, the Piekenierskloof Formation, comprising conglomerate and arenite, forms the base of the TMG, ranging from 0 to 900 m thickness in barely over 100 horizontal kilometres (Theron et al, 1992). In the far west, from Cape Town to Clanwilliam, the Graafwater Formation, generally around 100 m thick and composed of maroon shale and siltstone with minor quartzitic sandstone, forms the base of the TMG sequence where the Piekenierskloof Formation is not present (Rust, 1977). The Peninsula Formation is a light grey, medium to coarse grained, mainly planar but also trough cross-bedded, usually thickly bedded, mature quartzose sandstone with thin pebble lags (Shone and Booth, 2005). Quite remarkable is the consistent nature, the great thickness of 500 to 4000 m (some of which is due to structural thickening) and the extensive geographic

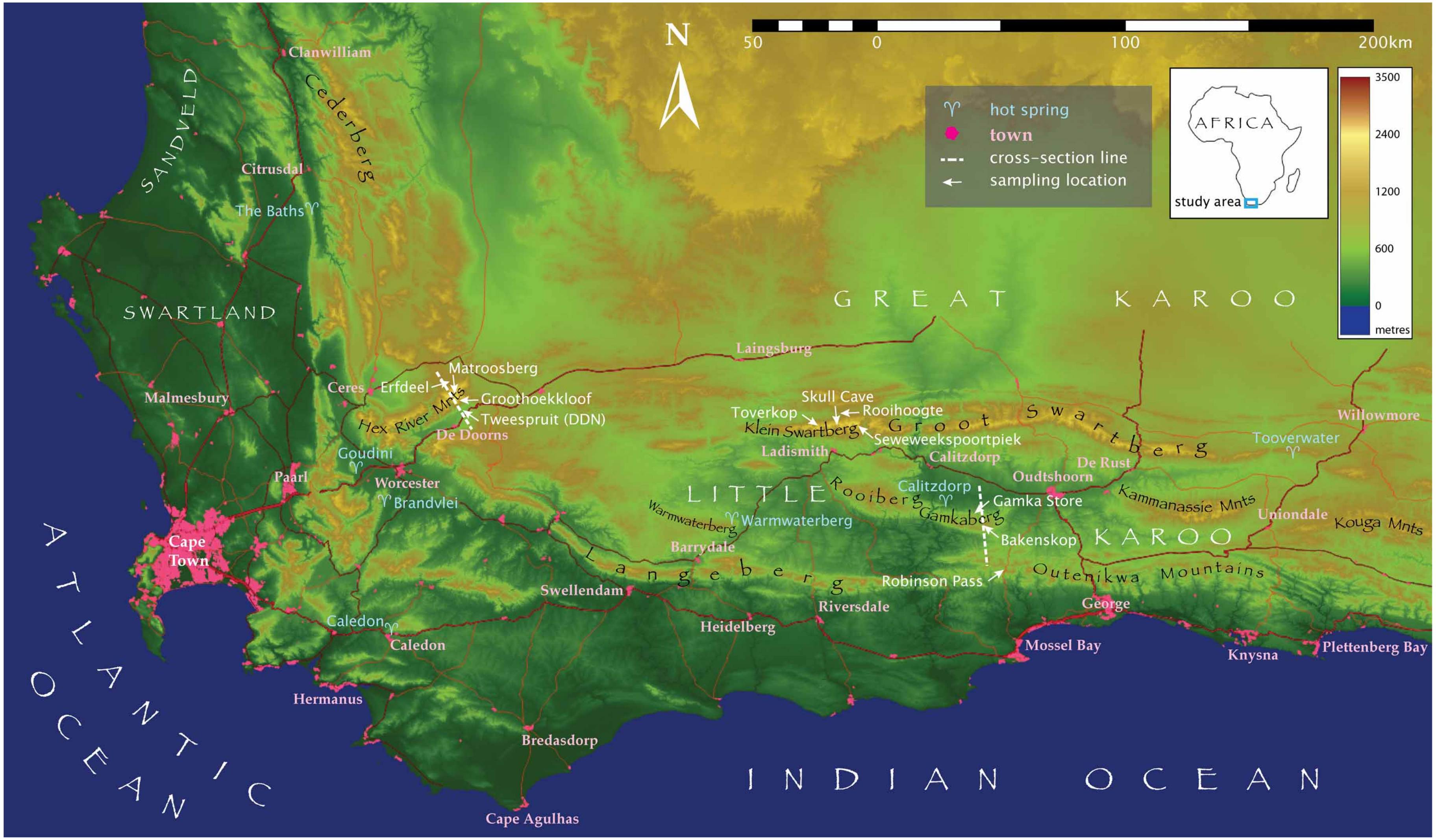

Figure 1. *Map of the study area, showing all major hot springs, cross-section lines (as seen in later figures), rainfall and groundwater collection sites, using the NASA DEM (NASA, 2013) and South African geospatial information (NGI, 2012).*

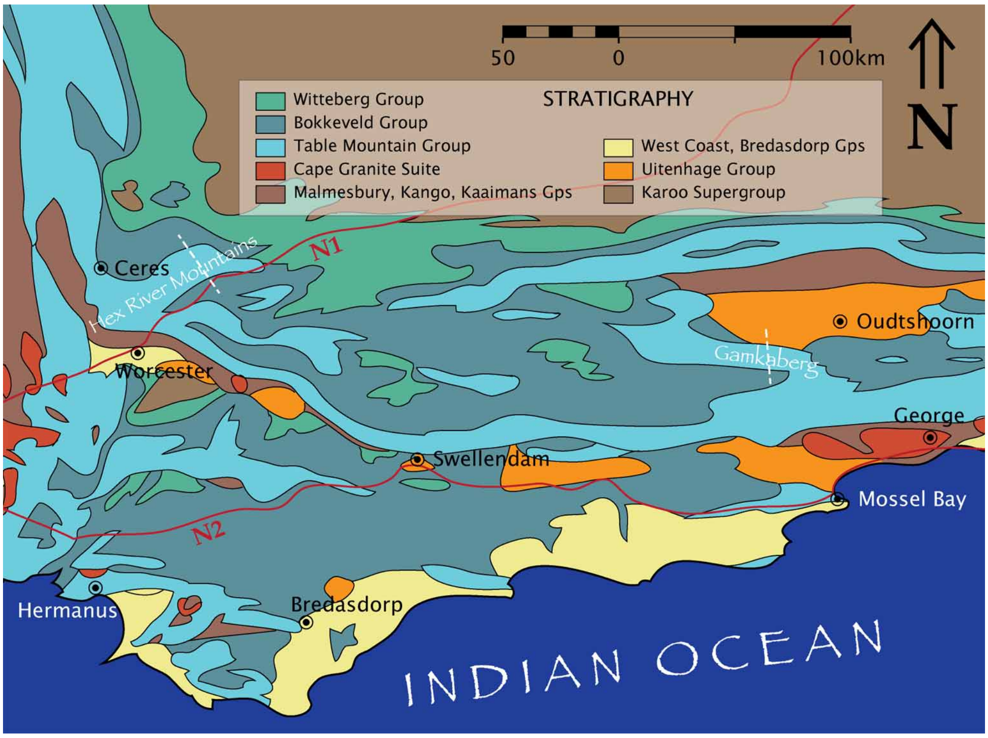

Figure 2. *Geological map of the study area (after Visser, 1984).*

distribution, barring the very northern tip of the basin (Broquet, 1992). The Peninsula Formation makes up the base of the TMG everywhere except the west and perhaps very far east. Overlying the Peninsula Formation in the western half of the basin is the Pakhuis Formation. It has been given thicknesses of 40 to 190 m by different observers, is poorly sorted and often structureless, has four members and is commonly regarded as glacial in origin, but is nonetheless still a quartzose sandstone (Tankard et al, 1982). The 50 to 120m thick Cederberg Formation has a sharp basal but gradational upper contact, ranges from black shale at the base to siltstone at the top and occurs everywhere except in the extreme east (Theron et al, 1990). The upper three formations of the TMG have been lumped into the Nardouw Subgroup, which is continuous throughout the basin, including the very northern extremity where it thins to metres, lying unconformably on basement, with rocks of the Karoo Supergroup above. The Goudini Formation is usually around 200 to 300 m thick, has grey quartzose sandstones, typical of the Peninsula Formation, but these are more thinly bedded, weather to an orange colour, and there is also abundant siltstone and minor shale insterspersed througout the formation (Gresse and Theron, 1992). Next is the Skurweberg Formation, that with thicknesses of 200 to 400 m and highly quartzose medium to coarse grained sandstones that are massive to heavily trough cross-bedded in very thick beds, forms dramatic, steep cliffs capping many mountain ridges or peaks in the Cape (Theron et al, 1991). The uppermost formation of the TMG is the Rietvlei Formation, west of 21.5°E, or Baviaanskloof Formation, east of 21.5°E. The Rietvlei Formation is lithologically similar to the Goudini Formation and may be gradational into the overlying Bokkeveld Group. The Baviaanskloof Formation contains the Kareedouw Member that is similar to the Rietvlei Formation, but has greyish green micaceous sandstone and carbonaceous shale above and below this member (Theron et al, 1991; Toerien and Hill, 1989).

In contrast to the TMG, the Bokkeveld Group is distinctly cyclic and highly argillaceous. It varies from 1 km thick in the north-west near Citrusdal to 4 km in the south-east near Uitenhage (Rust, 1967). The Witteberg Group caps the Cape Supergroup, and is intermediate between the two underlying groups, in that it has some cyclicity like the Bokkeveld Group, although less regular, and is lithologically comprised of more mudrocks than the TMG, but thicker sandstones than the Bokkeveld Group (Broquet, 1992). It also increases in thickness eastwards with a maximum thickness of around 1700 m (Thamm and Johnson, 2006). It it not present in the far north of the Cape Basin, and has been eroded from much of the southern part of the Cape Mountains.

The Karoo Supergroup has the Dwyka Group at its base, dominated by tillite. These only overlie the TMG directly in the far north of the basin, near Niewoudtville. Cretaceous deposits of the Uitenhage Group occupy extensional basins, generated during Gondwana breakup, particularly further east, near Oudtshoorn and beyond, and comprise immature conglomerates, sandstones and finer grained units, totalling thicknesses of around 5 km, very locally (Shone, 2006). Finally, various superficial gravels, sands and other deposits overly or are adjacent to the TMG, particularly in coastal settings, but also in minor inland alluvial and colluvial locations.

Structure

Deformation of the TMG occurred in the Permo-Triassic Cape Orogeny, with pulses of deformation having been dated from 278 to 230 Ma (Hälbich, 1992). Three structural domains are present: the western limb with moderately folded north-south striking folds and faults; the southern limb with strongly folded, northwards verging overturning and thrusting, and duplexing causing much thickening, mostly with east-west strike; the syntaxis where the two regions meet, with chaotic folding and faulting that is somewhat less intense than the southern limb, but still strongly deformed, with a northeast - southwest strike in less intensely deformed parts (De Beer, 2002).

The compressional tectonic regime during the Cape Orogeny was inverted during Gondwana breakup and many previously reverse faults became normal (De Wit and Ransome, 1992). Displacement up to several kilometres vertically can be observed and repetition of the TMG stratigraphy occurs on either side of fault defined valleys, for example at the Worcester and Kango Faults.

Climate

The study area has a climate that ranges from Mediterranean in the west to cool subtropical in the east (see Figure 3). The western region has warm to hot, dry summers and cool, wet winters with snow on the mountain summits; daily maximum temperatures are around 25ºC (Cape Town) to 30ºC (Calvinia) in summer and 17ºC (both) in winter, with daily minimums of 15ºC to 12ºC in summer and 8ºC to 5ºC in winter, similarly. In the eastern end of the study area, daily maximum temperatures are around 25ºC (Port Elizabeth) to 30ºC (Oudtshoorn) in summer and 20ºC (both) in winter, with daily minimums of 17ºC in summer and 8ºC to 5ºC in winter, similarly (CSAG, 2013). As these statistics show, temperatures are similar across the whole region, but with greater extremes further inland away from the moderating effect of the sea, and added warmth in the east, due to the influence of the warmer sea temperature from the Agulhas Current.

Rainfall amount in the study area is influenced by several factors, including distance from the sea, altitude, proximity to high mountains and windward or leeward relations to high mountains. As a result, extreme microclimates result, with rainfall gradients up to 100 mm/a per horizontal kilometre. For example, in Cape Town, mean annual rainfall (1961 to 1990) ranges from 1600 mm at Kirstenbosch Gardens to 540 mm at the airport, 10 km away (SAWB, 1996). Rainfall distribution over the year varies from a distinct winter peak in the west with most rain falling from April to October, to a steady year-round rain pattern in the east.

Hydrogeology

Burial of the TMG during the Cape Orogeny was sufficient to cause lower greenschist facies metamorphism, turning the sandstones to quartzites (Frimmel et al, 2001), in which partial recrystallisation of quartz grains and precipitation of a quartz cement has given the rocks great strength, but reduced the porosity to almost zero (Rosewarne, 2002). The highly competent nature of these recrystallized rocks has led to a high degree of brittle failure, resulting in abundant secondary porosity (Kotze, 2002). Highly fractured zones can become very permeable, however, it has been noted that some faults have had subsequent silicification and sealing of the openings (De Beer, 2002), leading to faults becoming barriers to groundwater flow (Blake et al, 2010).

Boreholes near Citrusdal deliver water at different rates at different depths, for example 5 L/s blowyield at less than 200 m, until at 220 m a water strike of 100 L/s blowyield, both in the Peninsula Formation, suggesting abundant minor fractures and occasional major fractures (Hartnady and Hay, 2002). Furthermore, the commonly held belief that fracture density decreases with depth was not clearly observed, as only a slight decrease in fractures was recorded by Lin et al (2007) in 750 m of drilling into the Piekenierskloof Formation.

Hydraulic parameters for the TMG are problematic because the porosity is secondary and the fractures are anisotropic.

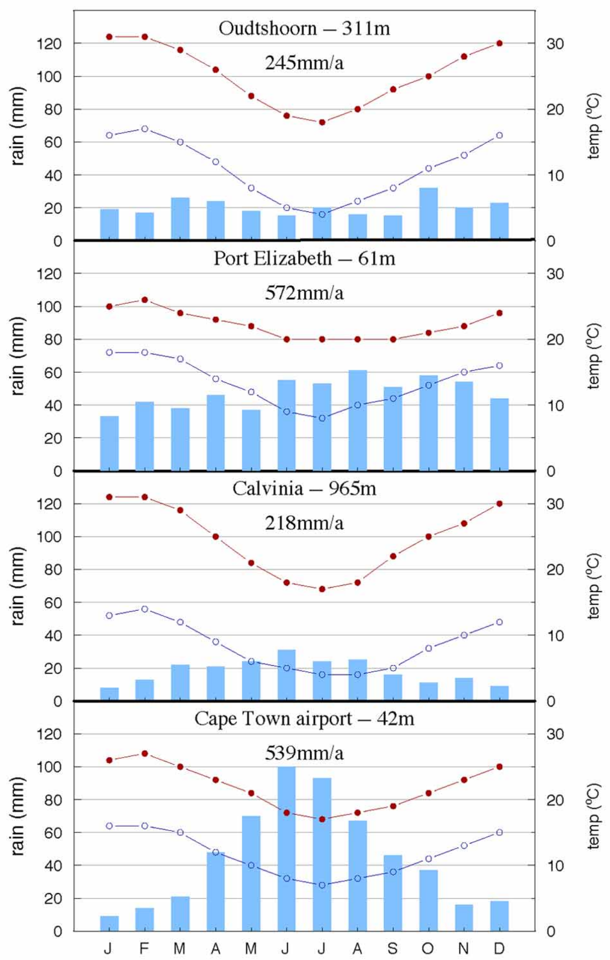

Figure 3. *Climate information for towns around the study area, showing altitude above sea level, mean monthly rainfall, and mean daily maximum and minimum temperatures per month (CSAG, 2013).*

Full aquifer penetration is seldom possible (financially), and the aquifer geometry, including dip and boundaries with other aquifers and aquitards is complex. However, several measurements have been made, as summarised by Rosewarne (2002), and extended by Lin et al (2007). The results of these studies suggest approximate values for hydraulic conductivity (K) are 0.01 to 0.2 m/d for either the Peninsula or Skurweberg aquifers, with storativity (S) of 0.0001 to 0.05 for Peninsula and/or Skurweberg, or the whole TMG.

Methods

Samples of water collected at several locations over 2010 to 2012 included rain, spring water and borehole water. Locations of the rainfall stations are listed in Table 1 and indicated on the map in Figure 1. Sample preparation for hydrogen was according to methods described by Coleman et al (1982), where water is reduced by reaction with Zn in a glass tube at 450°C, before attachment to a vaccuum line and collection of pure hydrogen gas in a glass tube ready for analysis. Sample preparation for oxygen was according to methods described by Socki et al (1992) as originally developed by Epstein and Mayeda (1953), where water is allowed to reach isotopic exchange equilibrium with CO_2 in glass vials being shaken in a water bath at 25°C, before separation of CO_2, water vapour and atmosphere is done on a vaccuum line, collecting all the CO_2 to be ready for analysis. Water samples were analysed for their hydrogen and oxygen stable isotope composition at the University of Cape Town stable isotope laboratory using a Thermo Delta Plux XP mass spectrometer. Laboratory standards Cape Town Millipore Water (δD = -7.4‰, δ^{18}O = -2.74‰; long term averages) and Rocky Mountain Water (δD = -131.4‰, δ^{18}O = -17.38‰; long term averages) were used to correct raw data to the SMOW scale. Analytical precision is within 1‰ for δD and 0.2‰ for δ^{18}O.

Results

All data are given in Table 2 (groundwater) and Table 3 (rain water).

Table 1. Locations of rainfall collection stations.

Name	Detail	Latitude	Longitude	Altitude
Bakenskop	summit of Gamkaberg	33º43'07.8"S	21º55'28.4"E	1101 m
Robinson Pass	crest of pass	33º52'26.3"S	22º01'54.7"E	885 m
Gamka Store	store near office	33º40'20.0"S	21º53'15.5"E	350 m
Conical Peak	nek south of peak	33º22'27.2"S	19º39'53.1"E	1910 m
Tweespruit	farm in Hex River Valley	33º26'34.3"S	19º40'30.9"E	482 m

Gamkaberg

Gamkaberg Nature Reserve straddles the Little Karoo and the Gamkaberg, ranging in altitude from 300 to 1100m. The Little Karoo is a semi arid area and the nature reserve office, staff quarters and accommodation get their water from boreholes that are drilled into the Rietvlei Formation. Rain water was collected at three stations: the Gamka Store at the park office, Bakenskop on top of the Gamkaberg, and at Robinson Pass in the Langeberg, 20 km to the south. These are located on Rietvlei Formation, Peninsula Formation and Skurweberg Formation, respectively. Both Bakenskop and Robinson Pass receive considerably more rain than the Little Karoo. The δD and δ^{18}O results are plotted in Figure 4, along with data from three hot springs in the Little Karoo, the Global Meteoric Water Line (GMWL) and local MWL (Diamond and Harris, 1997).

There is a strong separation of the weighted means for the three stations, due to a combination of factors. The higher altitude stations, Robinson Pass and Bakenskop, both have more negative values than the Gamka Store, and of the two mountain stations, the further inland one, Bakenskop, has even more negative isotope ratios. These patterns conforms to the well known altitude and continental effects (Rozanski et al, 1993).

Klein Swartberg

The Klein Swartberg includes the highest mountain, Seweweekspoort Peak (2327 m), and several other of the highest peaks in the Western Cape. Interestingly, there are three perennial water points near the east-west trending summit ridge of this range: a bedding plane in the lower layers of the Skurweberg Formation on the east face of Nels Buttress on Toverkop at 2060 m (see Figure 5), at a small fold hinge in the Peninsula Formation at Seweweekspoort Peak Cave, on the southern slopes of the range at 2020 m, and from the soil floor of Skull Cave in the Goudini Formation on the northern slopes of the range at 1880 m (although the Skull Cave water point has dried up in recent years). Samples from two boreholes drilled into the Rietvlei Formation at the farm Rooihoogte, north of the range at 960 m and downslope of Skull Cave, were also taken. In Figure 4 it can be seen that the Rooihoogte boreholes have a stable isotope composition as negative as any rainfall collected in the region, and as negative as the hot springs in the region. The samples from the high altitude seeps record a variety of isotope compositions, but interestingly, the sample from Skull Cave, a mere few kilometres from the Rooihoogte boreholes, yet a kilometre higher in elevation, and in a different geological formation, have identical stable isotope composition to that of the boreholes.

Hex River Mountains

The Hex River Mountains study area straddles the 15 km wide anticline of the eastern Hex River Mountains, from the cooler, higher and wetter Ceres Valley on the north-west, over the mountains to the semi-arid Hex River Valley on the south-east. Rain was collected at two stations, one at the nek between

Table 2. Stable isotope results for surface water and groundwater. Groothoekkloof samples were taken in 2012 - 02.

sample type	sample description	elevation m amsl	δD ‰	$\delta^{18}O$ ‰
river	Groothoekkloof 1: main stream	1800	-27.7	-5.15
river	Groothoekkloof 2: main stream	1600	-32.4	-5.73
river	Groothoekkloof 3: main stream	1350	-30.1	-5.28
river	Groothoekkloof 4: tributary	1170	-23.6	-5.29
river	Groothoekkloof 5: seep from soil/scree	990	-29.9	-5.70
river	Groothoekkloof 6: main stream	980	-26.1	-5.17
river	Groothoekkloof 7: tributary	980	-29.1	-5.22
river	Groothoekkloof 8: spring from rock	880	-31.5	-5.62
river	Groothoekkloof 9: main stream	870	-30.0	-5.48
river	Groothoekkloof 10: tributary	730	-30.9	-5.14
river	Groothoekkloof 11: tributary	700	-30.0	-5.33
river	Groothoekkloof 12: main stream	575	-29.7	-5.43
cold spring	Toverkop drip (2010/09)	2060	-25.2	-4.56
cold spring	Toverkop drip (2011/03)	2060	-27.4	-5.21
cold spring	Skull Cave seep (2011/03)	1880	-39.7	-6.83
cold spring	Seweweekspoort Peak Cave drip (2011/03)	2020	-31.5	-6.86
hot spring	Brandvlei (2011/02)	220	-32.2	-5.79
hot spring	Goudini (2011/02)	290	-24.1	-4.80
hot spring	Warmwaterberg (2010/09)	500	-37.7	-6.78
hot spring	Calitzdorp (2011/05)	200	-39.4	-7.02
hot spring	Tooverwater (2011/05)	800	-38.6	-7.11
borehole	Tweespruit upper (2012/06)	505	-32.7	-4.91
borehole	Tweespruit lower (2012/06)	490	-35.6	-5.74
borehole	Erfdeel (2012/02)	1170	-34.6	-6.44
borehole	Erfdeel Grootvlak 1 (2012/02)	1160	-45.0	-7.77
borehole	Erfdeel Grootvlak 2 (2012/02)	1160	-35.2	-6.89
borehole	Gamkaberg house (2012/06)	330	-36.3	-6.70
borehole	Gamkaberg Tierkloof (2012/06)	380	-34.4	-7.19
borehole	Rooihoogte east (2012/07)	960	-40.6	-6.79
borehole	Rooihoogte west (2012/07)	960	-39.4	-7.09

Matroosberg (2249 m) and Conical Peak (2045 m) and one in the Hex River Valley at Tweespruit farm. These are located on the Pakhuis Formation and Rietvlei Formation respectively. Boreholes are used for irrigation and domestic supply at farms on either side of the Hex River anticline and samples were taken from Erfdeel on the north-west and Tweespruit on the south-east. The river flowing down Groothoekkloof was also sampled from where the river starts flowing until its exit from the range. The stable isotope results are plotted in Figure 6, along with data from two hot springs in the nearby Worcester Valley, the GMWL and local MWL. In addition, the weighted means (using monthly precipitation amount) of the two rainfall stations have been plotted.

As with the Gamkaberg study area, there is a marked difference in isotope composition between the two rainfall sites. Here the cause is primarily the altitude difference, where rain over Tweespruit (482 m) has a greater column of dry air beneath the cloud base for evaporation to take place, as compared to Conical Peak nek (1910 m), which in most cases will be in the cloud when precipitation is occurring. The continental effect may also apply as rainout will increase towards Tweespruit, as air blows over the Hex River Mountains during a north-west wind when a frontal depression is causing the typical winter rain of the region (SAWB, 1996).

There are 12 samples from Groothoekkloof, from the point where water starts flowing at 1750 m until the river's exit from the kloof and into the Hex River Valley, at 575 m, a downstream distance of 8 km. These include samples of the main stream, tributaries and some seeps and springs adjacent to the river. The isotope compositions are remarkably similar given the large altitude gradient.

Discussion

Gamkaberg

Differences exist between the weighted means for precipitation at Robinson Pass, Bakenskop and Gamkaberg, which are at similar altitudes. The continental effects based on these

Table 3. Stable isotope results for cumulative monthly rainfall samples. Missing values were either not collected (before or after study, or collection problems) or were months with no rainfall, the latter particularly at the semi-arid Gamka Store and Tweespruit sites.

	Robinson Pass			**Bakenskop**			**Gamka Store**			**Conical Peak**			**Tweespruit**		
	rain mm	**δD ‰**	**$\delta^{18}O$ ‰**	**rain mm**	**δD ‰**	**$\delta^{18}O$ ‰**	**rain mm**	**δD ‰**	**$\delta^{18}O$ ‰**	**rain mm**	**δD ‰**	**$\delta^{18}O$ ‰**	**rain mm**	**δD ‰**	**$\delta^{18}O$ ‰**
2010 - 05										80	-24	-5.4			
2010 - 06	120	-6	-0.3	60	-14	0.7									
2010 - 07	150	-33	-6.1	50	-53	-9.0									
2010 - 08	70	-23	-5.6	20	-22	-5.4									
2010 - 09	30	-6	-2.2	5	-17	-3.9									
2010 - 10	200	-33	-5.8	50	-38	-7.1									
2010 - 11	50	-10	-2.1	20	-17	-3.9									
2010 - 12															
2011 - 01							1	11	0.5	5	-45	-8.0			
2011 - 02							21	-8	-1.4	10	-42	-7.9			
2011 - 03							20	14	0.8	5	-32	-4.7			
2011 - 04				22	-31	-7.1	15	-23	-3.7	20	-42	-8.0			
2011 - 05				75	-39	-8.2	59	-30	-6.1	180	-53	-9.3			
2011 - 06				133	-34	-6.6	73	-26	-6.2	250	-44	-8.2	60	-27	-4.20
2011 - 07	200	-22	-6.7	50	-29	-7.8	22	-16	-4.7	30	-44	-8.1			
2011 - 08				60	-21	-5.0	14	-13	-2.5	80	-43	-8.0	17	-6	-2.71
2011 - 09				6	-6	-3.5				40	-45	-8.2			
2011 - 10				10	-37	-6.4				10	-31	-5.9			
2011 - 11				40	-11	-4.9	15	-15	-2.6	20	-31	-6.0	10	-1	-1.50
2011 - 12				30	-18	-3.4	10	0	0.5	15	-42	-7.4	5	11	2.43
2012 - 01							7	1	0.1	10	-26	-5.3	5	1	-0.20
2012 - 02															
2012 - 03							51	-9	-0.6						
2012 - 04							15	-7	-2.4						
2012 - 05							7	-6	-2.3						
2012 - 06							26	-10	-2.4				60	-23	-3.19

differences are: δD of -30 ‰/100 km inland, and $\delta^{18}O$ of -4.7 ‰/100 km inland.

In comparison to those for the Amazon of -0.075‰/100 km for $\delta^{18}O$ (Salati et al, 1979), or Europe of -2.3‰/100 km for δD (Rozanski et al, 1982), or western Canada of -11‰/100 km for δD and -1.3‰/100 km for $\delta^{18}O$ (Yonge et al, 1989), these are large. The Canadian study, the highest of the three, even attributed its high rates to the combination of an altitude and continental effect. Clearly, isotope gradients in the Cape Mountains are extremely high and provide great potential for hydrological tracing.

The altitude effects at Gamkaberg, between the Gamka Store and Bakenskop stations, a horizontal distance of 6 km apart and 750 m vertically (Figure 7), are: δD of -1.8 ‰/ 100 m, and $\delta^{18}O$ of -0.33 ‰/ 100 m. These are more typical of altitude effects measured in other parts of the world (Clark and Fritz, 1997, p.71), however, they are still extremely useful and allow tracing of the source of the groundwater from the Gamka Store and Tierkloof boreholes.

The groundwater sampled at Gamkaberg displays a very different isotope composition to that for the weighted mean of ambient rainfall. Instead, the groundwater is isotopically more similar to the rain falling on top of the Gamkaberg at Bakenskop. There is a small, but significant difference between the Bakenskop weighted mean and the Gamkaberg boreholes. This could be due to a process of selective recharge, where heavier rainfall events with more negative delta values tend to overcome runoff losses, saturate the soil and be responsible for groundwater recharge (Vogel and Van Urk, 1975; Dogramaci et al, 2012). Alternatively, the two-year-long record from Bakenskop may not be representative of the long term mean isotope composition of rain, as the isotope composition of rain varies from year to year by up to 10‰ δD and 1.2‰ $\delta^{18}O$ (Harris et al, 2010). However, the discharge at these boreholes is convincingly close to that of rain collected at Bakenskop and suggests that the groundwater is being recharged near the top of the mountain. Groundwater must therefore flow from the Goudini Formation, through the Skurweberg Formation and discharges into the boreholes in the Rietvlei Formation (see Figure 6). The Nardouw Subgroup is acting as a single aquifer. The definition of the Skurweberg Aquifer according to Blake et al (2010) excluded the Goudini Formation, but the evidence here points to its inclusion. At this location, recharge into the Peninsula Formation would have similar isotope composition to

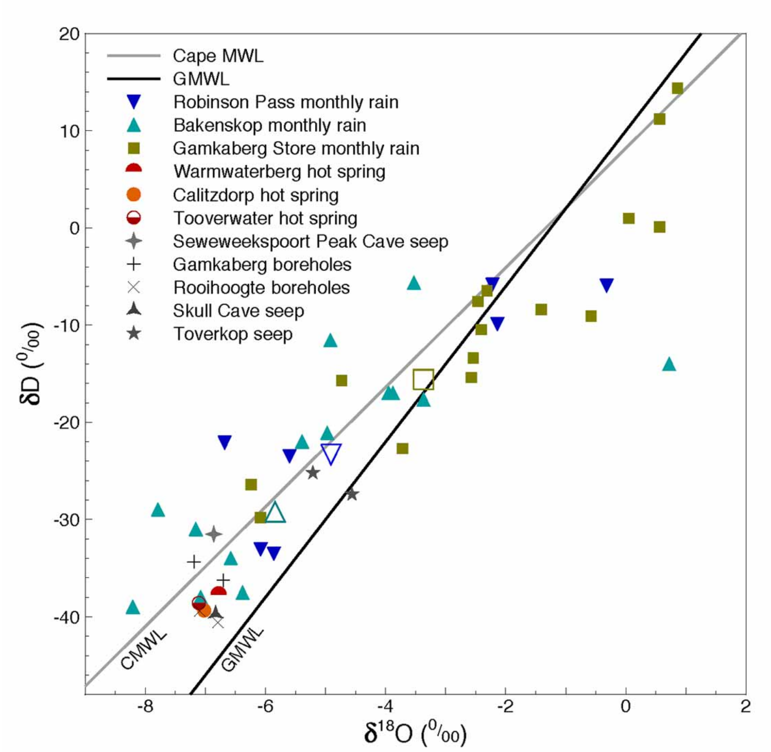

Figure 4. *Stable isotope data for the Gamkaberg region. Weighted means for the three rainfall stations are plotted as larger, hollow symbols. Analytical errors are approximately the size of the symbols. The local and Global Meteoric Water Lines are also plotted (Diamond and Harris, 1997; Craig, 1961).*

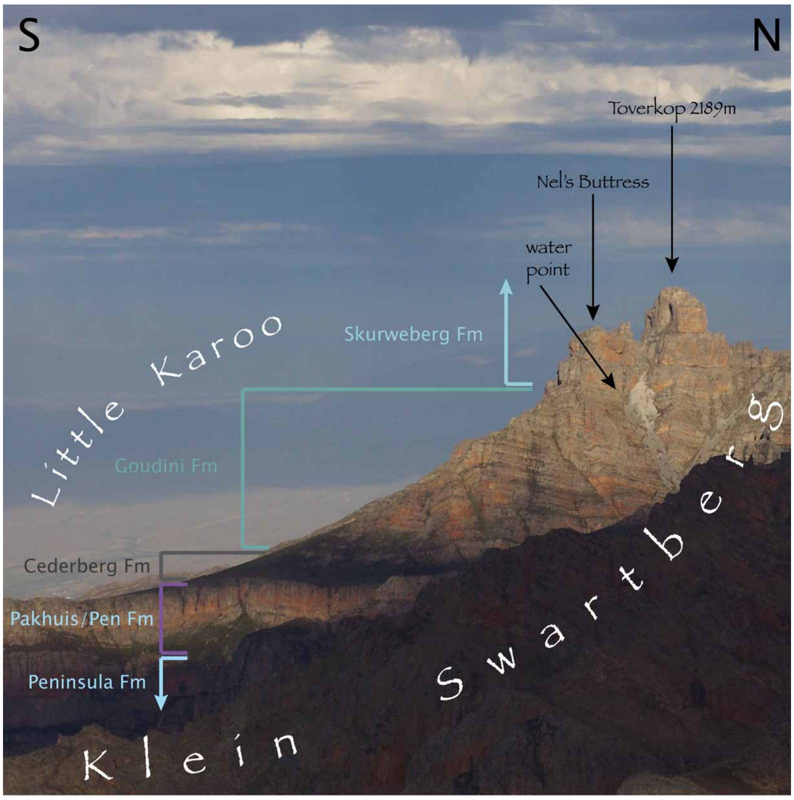

Figure 5. *Photograph looking west from Peak Wood (2240 m) on the Klein Swartberg ridge, showing the Toverkop water point in relation to most of the formations in the Table Mountain Group. The highly fractured, blocky nature of the TMG quartzites is apparent.*

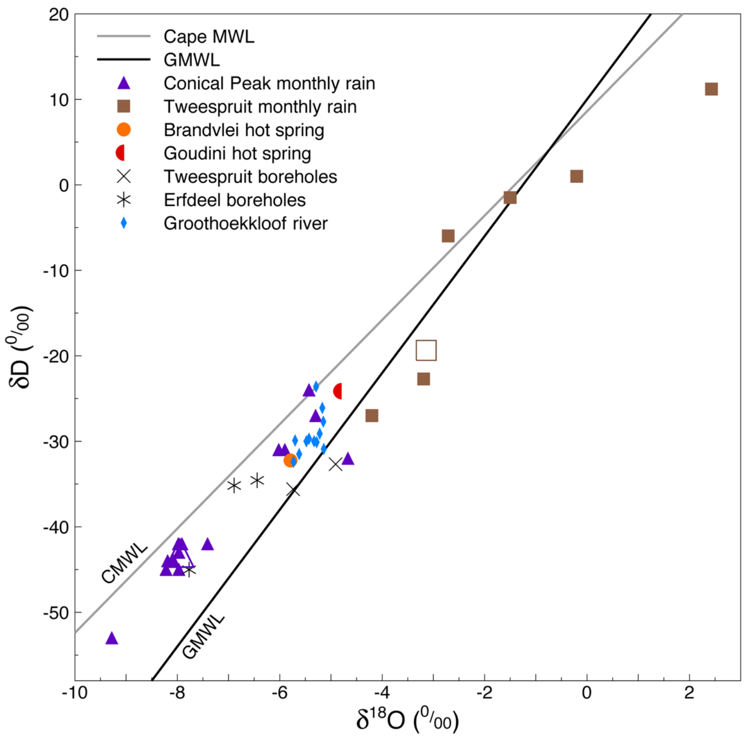

Figure 6. *Stable isotope data for the Hex River Mountains region. Weighted means for the Conical Peak and Tweespruit rainfall stations are plotted as larger, hollow symbols. Analytical errors are approximately the size of the symbols. The Cape and Global Meteoric Water Lines are also plotted (Diamond and Harris, 1997; Craig, 1961).*

that of the Nardouw Subgroup, so any leakage from the Peninsual Formation into the Goudini Formation would not be detectable. Therefore, although it seems the formations of the Nardouw Subgroup are hydraulically linked at this location, there is no evidence to exclude flow from the Peninsula Formation upwards stratigraphically.

Klein Swartberg

A similar situation appears to exist in the Klein Swartberg as at Gamkaberg, although without rainfall to compare the mountain and valley isotope compositions. However, the high altitude seeps, as seen in Figure 5, because of their limited groundwater flow paths, are effectively samples of the long term rainfall at the same elevation as the seep. The coincidence of isotope composition for Rooihoogte boreholes and the Skull Cave seep is evidence that rain recharging into the Goudini Formation at nearly 2000 m flows through the Skurweberg Formation and into the Rietvlei Formation, descending a kilometre in the process.

The isotope compositions at the other two seeps, Seweweekspoort and Toverkop, are somewhat less negative than Skull Cave. All three seeps occur near the top of mountains and have their own, small groundwater circulation systems. The drying up of the Skull Cave seep is supporting evidence for the limited groundwater resource supplying these seeps. Variations between the seeps are therefore to be expected.

Interestingly, the isotope compositions for the Rooihoogte and Gamkaberg boreholes are similar to those for the three hot springs that emerge in very different geological settings: they are over 200 km apart east-west (Figure 1); two emerge on a cross-fault at the TMG-Bokkeveld Gp contact (Warmwaterberg and Calitzdorp) and one at a regional Cretaceous basin bounding fault between the Peninsula Formation and Uitenhage Gp (Tooverwater). This confirms that groundwater recharge for regional flow takes place at high altitude (e.g. Diamond and Harris, 2000) and during specific heavy rainfall events that have the most negative isotope compositions seen in the region. The less negative isotope compositions of the Toverkop and Seweweekspoort Peak Cave seeps shows these shallow systems are recharged during various rainfall events and not only regionally significant rains.

Hex River Mountains

The altitude effects based on the different isotope compositions of the weighted means of the two rainfall stations, Conical Peak and Tweespruit, 10 horizontal kilometres and 1430 vertical metres apart are: δD of -1.6 ‰/100 m, and $\delta^{18}O$ of -0.34 ‰/100 m. These are very similar to those of the Gamkaberg area, probably because of the similar contrast between semi-arid valley bottom and wet mountain slope at the two sites.

The isotope results from this region differ from the two other regions in that the high altitude rainfall at Conical Peak has more negative delta values than the groundwater found in boreholes on either side of the Hex River Mountains anticline, except for the Grootvlak 1 borehole on the Ceres side. The initial interpretation is that recharge for the boreholes is occurring somewhere on the mountain slope inbetween the valley and mountain top. The geology and landscape are somewhat complex, with the Hex anticline, several faults and the deep canyon of the Groothoekkloof, as seen in Figure 8, but unfortunately, a single cross-section does not capture this complexity.

Using the altitude effect calculated, recharge of groundwater being abstracted at Tweespruit is taking place around 1 200 m, and Erfdeel 1300 to 2000 m. In both cases recharge is either into the Goudini or Skurweberg Formations, and discharge from the Rietvlei Formation, similar to findings of Weaver et al (1999) for the Agter Witzenberg Valley about 40 km to the west-north-west.

Perhaps the most intriguing results for this region are the Groothoekkloof river samples, taken over an altitude range of 1 800 to 575 m, along 15 km, in a three day period. The river flows through Peninsula Formation most of the way, only passing across Pakhuis, Cederberg, Goudini and into Skurweberg formations in the last few kilometres of the gorge. The similarity of the isotope compositions along the length of the river is somewhat surprising given the range in altitude. At the time of sampling, no significant rain had fallen to supply any overland runoff, and very shallow groundwater (soil water) flow would be minimal. The river is probably being sustained by baseflow from deep within the Peninsula Aquifer. The results suggest that groundwater within the Peninsula Aquifer is well mixed, which is plausible given the extensive, deep fracturing observed in rocks of the TMG (Lin et al, 2007).

Conclusions

Very strong continental and normal altitude isotope effects result in substantial variation in the isotope composition of rainfall at different locations in the Western Cape, allowing the use of stable isotopes as natural tracers of hydrological flows. Groundwater from boreholes and hot springs tends to have more negative delta values than that of the weighted means for precipitation in likely recharge areas, indicating recharge takes place during heavy rainfall events or seasons with very negative delta values, a process known as selection (Vogel and Van Urk, 1975). Similarity between all groundwater (boreholes and hot springs) in the Little Karoo region suggests rare, heavy rainfall events are widespread and cause significant recharge for the TMG aquifers. Such dependence on rare events warns against overuse of water resources in a world of changing climates.

At both Gamkaberg and the Hex River Mountains, borehole water has an isotope composition that does not match that of ambient rainfall, but rather that falling in the mountains, at elevations up to a kilometre higher. For this to occur, groundwater flow must be through all three formations of the Nardouw Subgroup, here defined as the Skurweberg Aquifer.

Groundwater discharge from the Peninsula aquifer is isotopically very similar over several kilometres of distance and more than 1 km of altitude, suggesting well mixed groundwater caused by well connected discontinuities, comprising bedding and joints. No clear evidence has been found for connections or the lack thereof between the Peninsula and Skurweberg

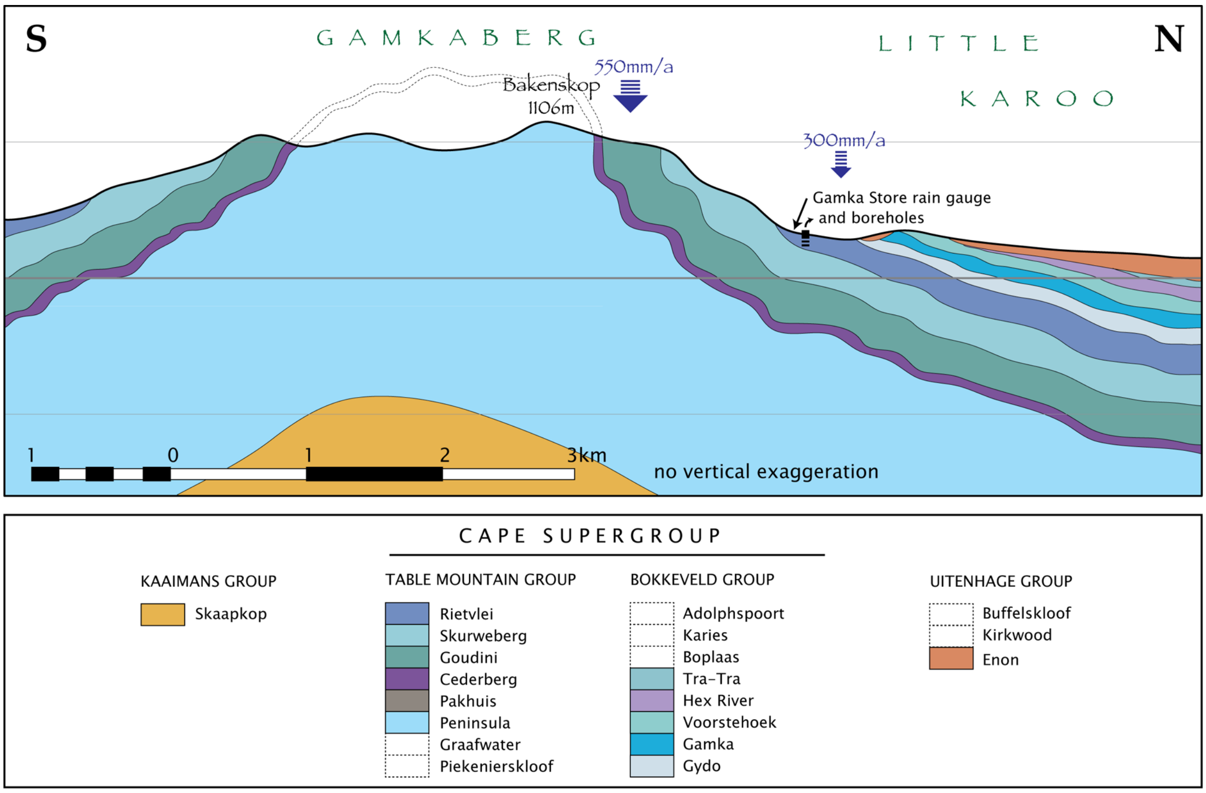

Figure 7. *Cross section through the Gamkaberg area, showing the mean annual rainfall variations between Gamka Mountain and the Little Karoo.*

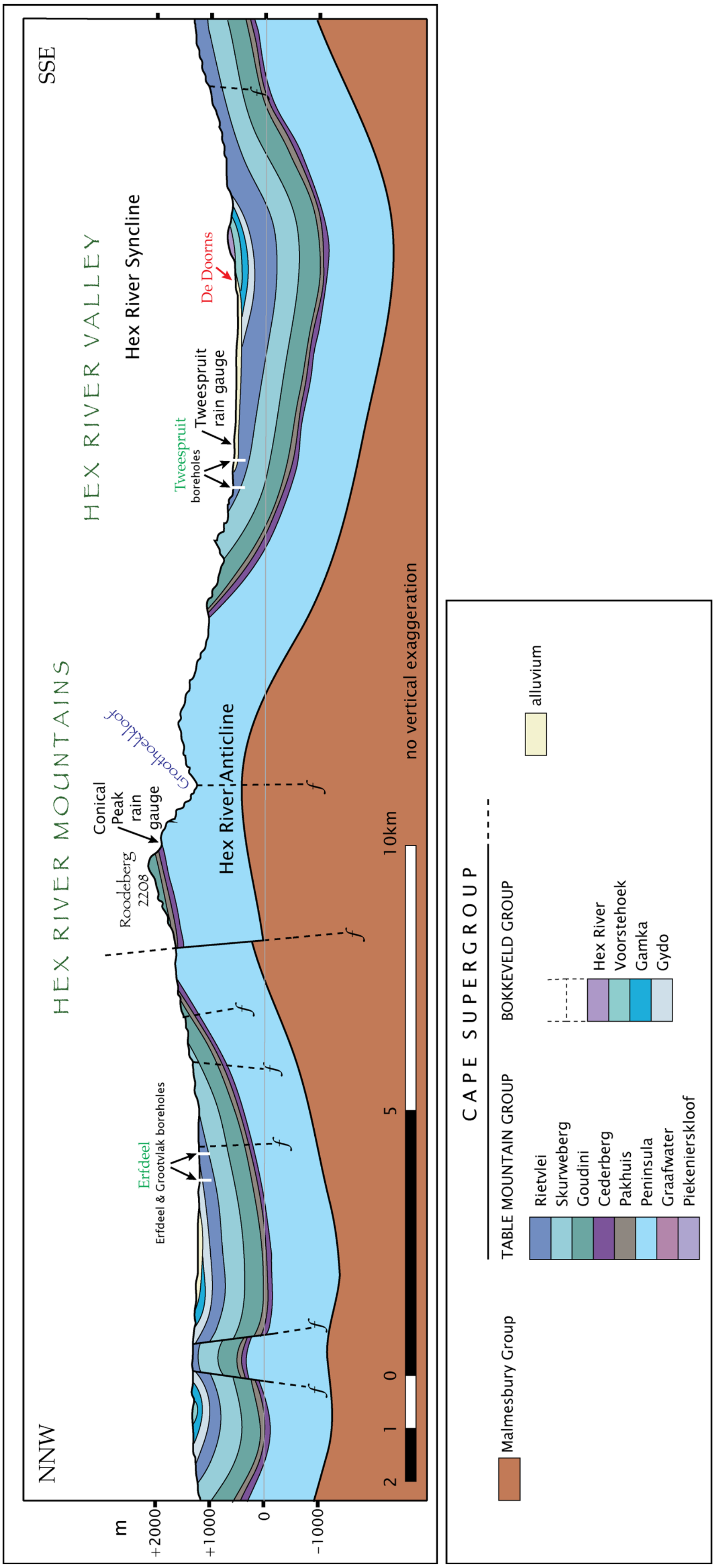

Figure 8. *Cross-section through the Hex River Mountains area.*

Aquifers. In locations where both aquifers occur and each has a recharge area with different stable isotope precipitation compositions, stable isotopes should detect hydraulic connections.

The ability to detect recharge areas allows for the establishment of groundwater protection zones. Overabstraction may also be detectable with a change in isotope composition of groundwater over time. Further investigations using stable isotopes need to employ precipitation measurements at a range of locations over periods of years, and sample groundwater periodically from a range of sources.

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