

An updated water balance for the Grootfontein aquifer near Mahikeng

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ABSTRACT

The Grootfontein Aquifer, part of the important North West dolomite aquifers, supplies about 20% of Mahikeng's domestic water needs. Over-abstraction caused the large natural spring draining the aquifer to disappear in 1981, and groundwater levels have since fallen nearly 30 m in the vicinity of the former spring. Analysis of water levels and a water balance using recent assessments of groundwater abstractions confirm past work describing the hydrogeological functioning of the aquifer, and suggest that current abstractions need to fall by between 19 and 36 ML/day (7 and 13 Mm³/a) to bring the aquifer back into long-term balance. Continued over-abstraction at Grootfontein implies increasing risk to Mahikeng's water supply, and illuminates the larger challenge of ensuring groundwater use in the North West dolomites that is sustainable and in the public interest.

Keywords: Groundwater, North West dolomites, Mahikeng, over-abstraction, irrigation

INTRODUCTION

The Grootfontein aquifer is of particular interest because it is well studied hydrogeologically, and it is part of the domestic water supply of Mahikeng, the capital of North West Province. The decades of hydrogeological studies at Grootfontein contrast with its poor management, evidenced by falling groundwater levels (see below). The management of the aquifer is the collective outcome of a diverse and complex series of interacting issues, rather than being primarily a question of hydrogeological data. However, the hydrogeology provides a fundamental basis or 'envelope of possibility' for management, and its description is necessary and important.

South Africa's dolomite aquifers are amongst the highest-yielding and most important aquifers in the country (Barnard, 2000). The dolomites of North West Province (Fig. 1), known as the North West dolomites, hold around 5 000 Mm³ of water (about the same as the Gariep Dam), and are recharged at a rate of about 300 Mm³/a (Stephens and Bredenkamp, 2002). The North West dolomites are divided into a number of discrete units or 'compartments' by igneous dykes and faults (Meyer, 2012), making them a patchwork of semi-autonomous aquifers rather than a single hydraulic entity. Under natural conditions, rainfall recharges these compartments / aquifers, and they drain via springs, seeps and wetlands. Some of the springs draining North West dolomite compartments are large and important – for example, the Molopo Eye near Mahikeng and the Maloney's Eye near Mogale City are the sources of the Molopo and Magalies Rivers, respectively. Both have long-term average flow rates exceeding 30 ML/day or 11 Mm³/a (DWS NGA data; Vahrmeijer et al., 2013). Over-abstraction in some of the dolomite compartments is a growing problem, threatening domestic supplies, irrigated agriculture and environmental services.

Whilst most dolomite groundwater is used for irrigation, hundreds of thousands of people also depend on it for domestic water supply. It also supports many springs, wetlands

and associated ecosystems. Bodibe, Lichtenburg, Itsoseng, Ventersdorp, Mahikeng, Ottoshoop and Zeerust, amongst other towns, all rely mainly on dolomite groundwater for municipal water supplies.

Mahikeng is one of the largest and most important groundwater-dependent towns in South Africa. Mahikeng's water demand is about 50 ML/day (18.3 Mm³/a). About 20 ML/day (7.3 Mm³/a) of this water comes from the Setumo Dam, on the Molopo River to the west of Mahikeng. Groundwater from the Molopo Eye spring and from boreholes in the Grootfontein aquifer supply the other 30 ML/day (11 Mm³/a) – roughly 20 ML/day (7.3 Mm³/a) from the spring and 10 ML/day (3.7 Mm³/a) from the boreholes. Both the Molopo Eye spring and the Grootfontein aquifer are located in the North West dolomites, about 30 km east of Mahikeng. The Setumo Dam depends on intermittent flows from the Molopo River (which originates at the Molopo Eye), and on leaks and effluent return flows from Mahikeng. The dam is therefore partly dependent on North West dolomite groundwater too.

Before the early 1980s the Grootfontein aquifer used to discharge naturally at a large spring, the Grootfontein Eye. This spring used to be the primary water source of Mahikeng (and nearby Mmabatho). Municipal officials drilled boreholes around the Grootfontein Eye in the 1970s to augment the municipal water supply. Irrigation from the Grootfontein aquifer also grew rapidly, starting in the 1960s. These combined groundwater abstractions led to the spring disappearing in October 1981, after which groundwater levels in the Grootfontein aquifer fell. Today the water table in the vicinity of the old Grootfontein Eye is more than 28 m below ground level. This fall in groundwater level has led to some of the municipal boreholes failing, and it now also threatens some of the irrigation boreholes. The volume of water that the remaining Grootfontein boreholes yield to Mahikeng has fallen by more than 60% over the past 10 years to today's approximately 10 ML/day (3.7 Mm³/a) (DWS, 2014). Over-abstraction in the Grootfontein aquifer continues today, and it is likely that domestic supply abstractions will decline further. To compensate, Mahikeng increasingly relies on flows from the Molopo Eye spring (located in a different dolomite compartment to the north of Grootfontein), and on the

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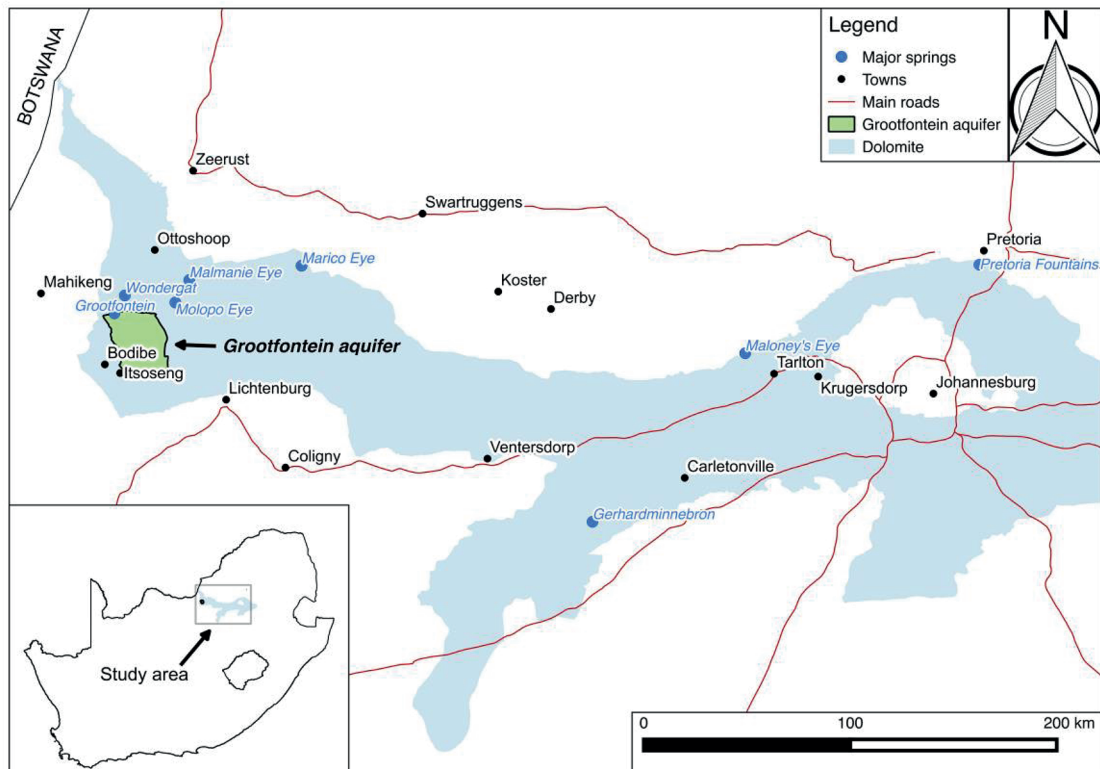


Figure 1
Regional overview (boundaries after Holland and Wiegman, 2009)

TABLE 1 Hydrogeological data used	
Data type	Source and description
Groundwater levels	DWS National Groundwater Archive (NGA) data for 34 water-level measuring stations in and around the Grootfontein aquifer. Confirmed by dipmeter measurements in the vicinity of the former eye.
Former Grootfontein Eye flows	Literature review, personal communications. The Grootfontein Eye has not flowed since 1981, and no single continuous record of its former flow was obtained.
Public water supply borehole pumping rates	Literature review, personal communications, DWS pumping data obtained for 2015.
Irrigation borehole pumping rates	Literature review, personal communications, estimates derived by private consultants obtained for use in WRC Project K5/2429 (Eales, 2015).
WARMS license data	DWS WARMS database representing licensed amounts at Grootfontein. Actual use may be higher or lower.
Major and minor ion chemistry	Sixteen samples were collected in and around Grootfontein in 2015, and analysed for major elements and minor (trace) ion content. See Table 3.
Aquifer properties data	Literature survey, particularly the DWS GH series of reports. Dyke boundaries were estimated by Holland and Wiegman (2009), based on literature review, geophysical data and analysis of water levels.
Aerial photographs	Chief Directorate National GeoSpatial Planning, part of the Department of Rural Development and Land Reform.
Field observations and interviews	Observations made during field visits in 2013, 2014 and 2015.

upgraded water treatment plant at the Setumo Dam. Municipal officials are concerned about the decline in yield from the Grootfontein boreholes since the city then depends more on the remaining sources, and is less resilient during drought. The water from the Setumo Dam is also polluted, and consequently expensive to treat (DWS, 2014). Finally, the dewatered state of the Grootfontein aquifer means that it cannot be used as a backup supply during a prolonged drought, a temporary breakdown at the Setumo Dam, or another crisis.

METHOD AND RATIONALE

Here I use existing and new data for an updated hydrogeological description of the Grootfontein aquifer, in order to anchor and substantiate future discussion of the management of the Grootfontein aquifer, as well as the management of North West dolomite groundwater in the public interest, more generally. The hydrogeological description advanced here largely accords with past descriptions of the aquifer's functioning and confirms the need for better management of abstractions. Discussions of management options at Grootfontein are still dominated by aspects of hydrogeological functioning, and hydrogeological uncertainty is advanced as a reason for management inaction. There is a pressing need to consolidate contemporary hydrogeological knowledge at Grootfontein, including modern water level measurements, to demonstrate that current hydrogeological understanding is sufficient to support better management.

Field data collection, including interviews and meetings with stakeholders, was conducted between 2013 and 2015. Existing and new hydrogeological data for the Grootfontein aquifer used in this analysis is shown in Table 1.

These data were analysed and combined with a literature review to produce the updated conceptual hydrogeological description of the Grootfontein aquifer. The results of the work are described in two sections: an updated conceptual hydrogeological description, and a water balance. These two sections are presented below. The first 'results' section is further divided into sub-sections reflecting the various aspects of hydrogeological functioning.

RESULTS: CONCEPTUAL DESCRIPTION OF THE GROOTFONTEIN AQUIFER

Topography and geology

The Grootfontein aquifer or compartment covers an area of approximately 239 km², based on the boundaries of Holland and Wiegmans (2009). The flat, weathered land surface slopes very gently towards the north, with a gradient of approximately 50 m in 16 km. Average annual rainfall is about 560 mm, falling mainly as summer thunderstorms. The Grootfontein aquifer falls within quaternary drainage region D41A. The course of the Droë Molopo River cuts across the far north-east corner of the aquifer, and former marshland (now dry) associated with this water course indicates that groundwater would once have contributed to the Droë Molopo, along with the flow from the Grootfontein Eye (Fig. 2). Both the Droë Molopo and the unnamed drainage from the Grootfontein Eye join the Molopo River about 6 km due north of the Grootfontein aquifer boundary. A further area of marshy ground existed at Blaauwbank near the centre of the aquifer. No marshy ground occurs today due to the drop in the water table.

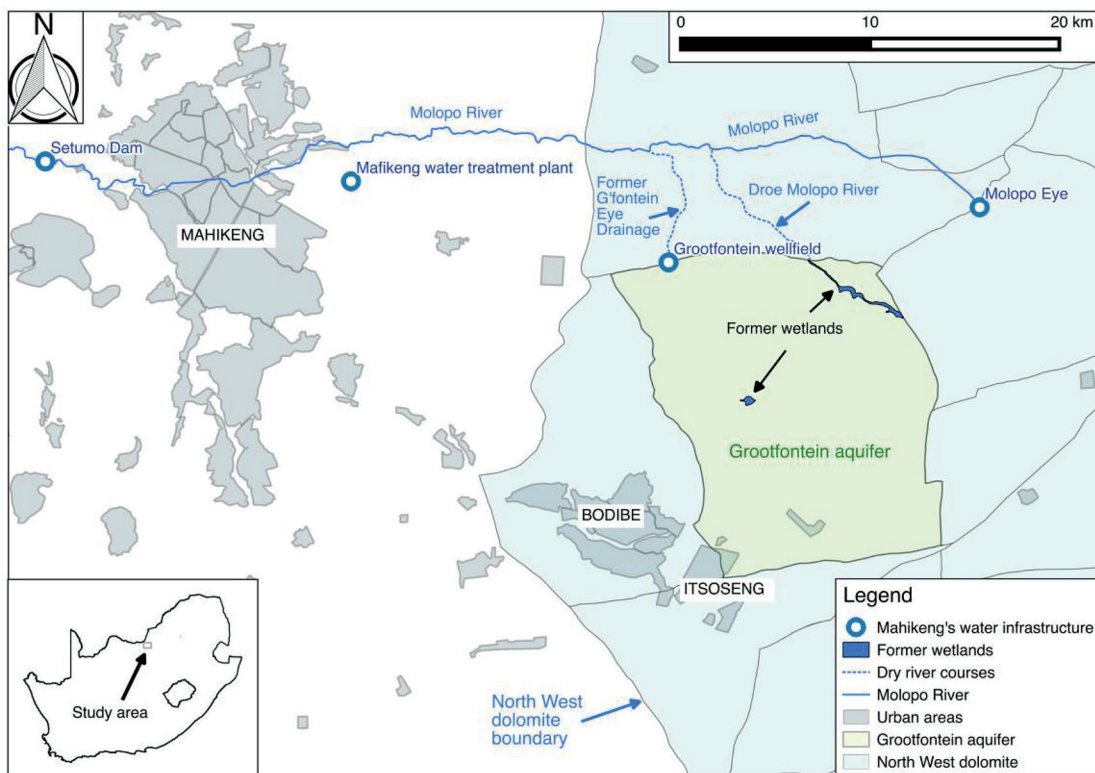


Figure 2
The Grootfontein aquifer and surrounds (compartment boundaries after Holland and Wiegmans, 2009)

Formed around 2.7 billion years ago, dolomites of the Chuniespoort Group (Transvaal Supergroup) have been tectonically deformed and faulted, and are intruded by igneous dykes (Tinker et al., 2002). The dolomite outcrops as a moderately hard, grayish- to brown-coloured rock, often weathering to a surface ‘elephant skin’ texture.

The Malmani Subgroup of the Chuniespoort Group is the main water-bearing unit, and is divided into formations based partly on chert content (Table 2). In the Grootfontein area these formations are the Eccles, Lyttelton, Monte Christo and Oaktree Formations (Johnson et al., 2006). The Eccles and Monte Christo Formations are chert-rich, whilst the Lyttelton Formation is chert free. The chert-rich Eccles and Monte Christo formations are more susceptible to weathering, and the resulting voids are supported by the more resistant chert. As a result, coefficients of storativity and transmissivity are higher, and they are better aquifers (Holland and Wiegman, 2009; Meyer, 2012). The Monte Christo Formation has been further sub-divided into 3 sub-formations or members. The entire sequence dips to the north beneath the Pretoria Group.

The area of the Grootfontein compartment is partly covered by Quaternary alluvium and soils with good agricultural potential (Stephens and Bredenkamp, 2002). This contrasts with areas of poor agricultural potential with thin or absent soil cover, known as ‘klipveld’ (Bredenkamp, 1964).

Compartment boundaries

Vertical to sub-vertical diabase dykes oriented mainly E-W intrude the country rocks of the study area. These dykes vary in thickness from a few metres to tens of metres and show

different weathering profiles. Those dykes that are deeply weathered do not affect groundwater flow appreciably (Cogho, 1982). The dykes vary in age, with the oldest dykes in the study area associated with the Bushveld Complex (± 2 Ga) and the youngest (182 Ma) related to the Karoo Igneous Province (Tinker et al., 2002). A radiometric (Ar-Ar) date obtained by Day (1981) for a sample of dyke material near to the Molopo Eye was $1\,262 \pm 8$ Ma. Dyke exposure in the Grootfontein area is poor, and in general they cannot be identified visually in the field. Aerial photography, magnetic surveys and drilling are used to identify and map dykes.

The Grootfontein aquifer is bounded or compartmentalised by sub-vertical diabase dykes of varying thicknesses and hydraulic properties (Holland and Wiegman, 2009). A detailed study of the geology of the dykes in the area was carried out by Day (1981) who used aerial photography and aeromagnetic data, confirmed by ground magnetic data, to produce a magnetic and photo-lineament map of the area. Day’s work did not establish hydraulic properties for the dykes, however, beyond saying that they are of considerable hydraulic importance (Day, 1981:19). Subsequent studies have estimated aquifer compartment boundaries using dyke thicknesses, pumping tests and changes in groundwater levels (Holland and Wiegman, 2009).

Figure 3 below shows the Grootfontein aquifer with the compartment boundaries as mapped by Holland and Wiegman (2009). The geology, lineaments and dykes are derived from the 1:250 000 scale geological mapping of the Council for Geoscience (CGS, 1981; 1986; 1991; and 1993) and the dyke names are after Day (1981).

Appx. Age (Ma)	Supergroup / Period	Group	Formation	Lithology	
0–2.6	Quaternary / Tertiary	Kalahari	Gordonia	Sands, gravels, alluvium, calcrete	
65–570	Karoo Supergroup	Intrusives	Karoo dolerite	Intrusive dolerite dykes, sills	
		Ecca	Volksrust, Vryheid	Mudstones, shales, sandstones	
		Dwyka		Tillite, shale, mudstone, sandstone	
2050–2700	Transvaal Supergroup	Pretoria	Magaliesberg, Daspoort, Hekpoort, Timeball Hill	Quartzite, shale, andesite	
		Chuniespoort	Penge		Dolomite, chert
			Malmani Subgroup	Frisco	Stromatolitic dolomite, chert-poor dolomite, shale
				Eccles	Interbanded dolomite and chert
				Lyttelton	Chert-poor dolomite, shale, quartzite
				Monte Christo	M1 – Chert-rich dolomite M2 – Interbanded chert & dolomite M3 – Oolitic chert & dolomite
				Oaktree	Chert-poor dolomite, carbonaceous shale
Black Reef	Quartzite, conglomerate				
2700–2800	Ventersdorp Supergroup		Andesite, quartz porphyry, conglomerate, calcareous shale, quartzite, lava		
3090+	Basement Complex	Granite, gneiss			

Most authors agree that the northern boundary of the Grootfontein aquifer is the Grootfontein and Trekrift Dykes. The Grootfontein Dyke is more than 20 m thick and is semi-permeable, with a step change in water level across it of about 6 m reported by Van Tonder et al. (1986). The Trekrift Dyke is narrower and also shows water level changes across it. The point where the two dykes meet is an anomalous depression in the dolomite, interpreted as a fossil sinkhole now filled with low-permeability clay-rich Karoo sedimentary rocks (Van Tonder et al., 1986). The low permeability Mooimeisjesfontein Dyke forms the western boundary of the aquifer, and shows water level changes across it of about 1 m (Van Tonder et al., 1986). The eastern boundary of the aquifer is the Elizabeth Dyke, which also has a low permeability and a water level change of about 2 m (with the higher level on the eastern side) (Van Tonder et al., 1986). In the south this dyke is known as the Elizabeth II Dyke (Day, 1981). The southern boundaries of the aquifer are more controversial. Van Tonder et al. (1986) report that one of at least three dykes may form this boundary (the Blaauwbank, Grasfontein and Stryd Dykes), or some combination of the three. In 1986 the Blaauwbank Dyke showed water levels on its southern side about 12 m higher than those on its northern side. Testing of boreholes in this 80 m wide dyke indicate an extremely low permeability, and it is thought that little water flows from south to north across it (van Tonder et al., 1986).

Following their study of water levels, Holland and Wiegman (2009) placed the southern boundary of the Grootfontein aquifer farther south, extending to the Paarl Dyke, running east-west immediately to the south of the Itsoseng boreholes. Today this dyke is most commonly considered to define the southern boundary of the aquifer.

Groundwater contours, which reveal flow from the south-east towards the north-west, provide some evidence for groundwater flow across the south-eastern boundary of the Grootfontein aquifer. The Verlies Dyke and other un-named dykes and lineaments cut across the aquifer from south-west to north-east (Day, 1981; Cogho and Bredenkamp, 1982) but these are not thought to disrupt groundwater flow substantially (Holland and Wiegman, 2009).

Aquifer physical properties

Whilst the primary porosity and hydraulic conductivity of dolomite rock is poor, weathering and karstification in the North West dolomites makes them prolific aquifers where the thickness of the deposits and the depth of weathering allow. Weathering is limited by overburden, and at depth aquifer characteristics are generally poor.

The Grootfontein aquifer thickness is a function of weathering and karstification, and is thought to vary from about 40 m in the north-west to about 60 m in the south-east of the aquifer (Van Tonder et al., 1986; Cogho, 1982). Transmissivity (T) value distribution is a function of the extreme heterogeneity of the weathered dolomite, with pumping tests showing T values of up to 23 000 m²/d for the dolomites and up to 16 m²/day for the diabase dykes (Van Tonder et al., 1986). The diabase dykes are often presumed to be impermeable for planning purposes (Janse van Rensburg, 1992).

Specific yield values ranging from 1% to 18% are found in the literature (e.g. Enslin, 1967), with most authors quoting values of between 2% and 4% (Mulder, 1982; Cogho, 1982; Bredenkamp and Van Rensburg, 1983; Van Tonder et al., 1986; Janse van Rensburg, 1992).

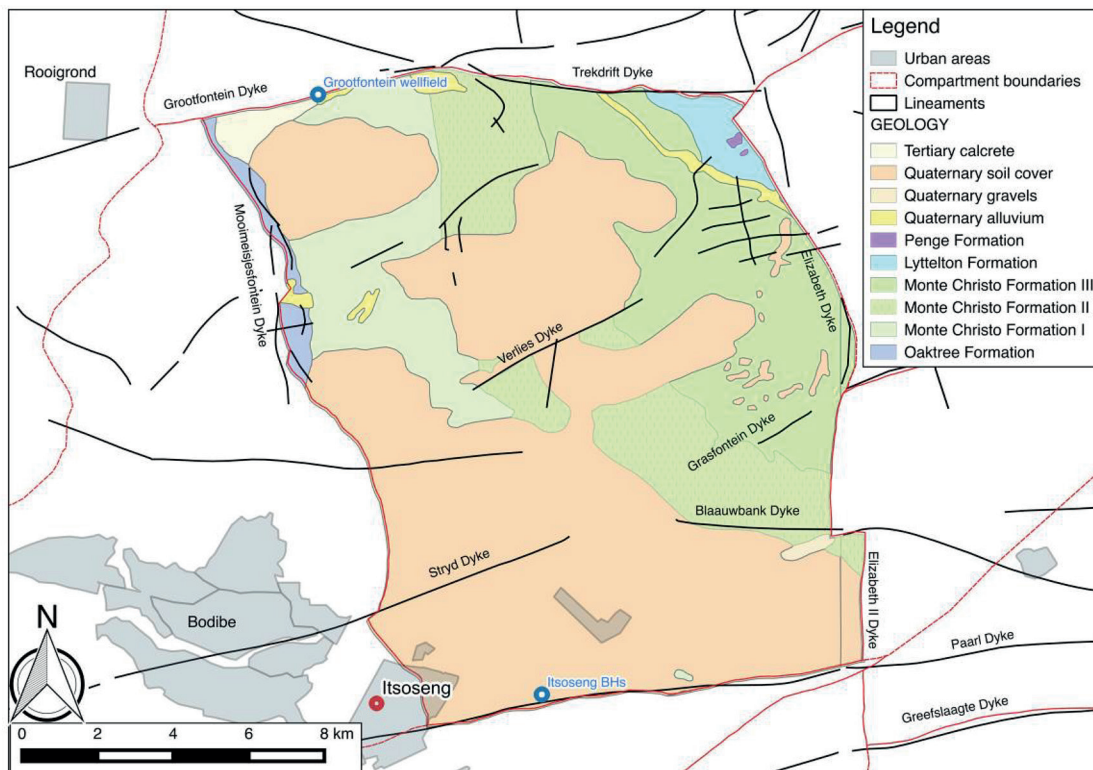


Figure 3

Simplified geology of the Grootfontein aquifer (after Holland and Wiegman, 2009; CGS 1981, 1986, 1991 and 1993; and Day, 1981)

Groundwater quality

Groundwater quality in the North West dolomites generally, and in the Grootfontein compartment specifically, is considered good by several authors. For example, Meyer (2014) reports that more than 95% of analyses on record for the Karst Belt dolomites (i.e. the dolomites stretching from Delmas in the east to the Botswana border in the west) are within the Class 1 electrical conductivity category (< 150 mS/m). Barnard (2000) reports that 223 water samples from the Chuniespoort dolomites falling within the area of the General Series hydrogeology map 2526 (Johannesburg) had a mean EC of 62.9 mS/m, a mean pH of 7.6, and a CaMg-HCO₃ water type. DWS (2006) state that 'groundwater quality is reported as being good and mostly in a pristine state' in the North West dolomites, with electrical conductivities of less than 70 mS/m (DWS, 2006 p 31).

Sixteen water samples were collected in and around the Grootfontein compartment between April and July 2015 (Table 3), at locations where pumping boreholes were available and permission was obtained to sample. The depths of the sampled boreholes were not available.

The samples were collected in 1 L plastic bottles, which were rinsed with sample and then filled to the brim, capped and sealed with tape. The samples were kept cool and submitted to a SANAS-accredited laboratory for analysis. Samples were analysed for a suite of major ions, pH, EC and total alkalinity. An ICP scan for minor constituents was also performed. Sample results were compared with the South African National Standard for drinking water (SANS 241-1:2011; and SANS 241-2, 2011). The SANS 241 standards provide physical, aesthetic and chemical numerical limits based on an assumption of lifetime human consumption. The risk of exceeding these limits falls into 4 categories: aesthetic, operational, chronic health and acute health.

The pH values of the samples are in the expected range for dolomite water, with all samples between 7.3 and 8 (apart from the Setumo Dam sample, which has a high concentration of partially treated wastewater and a pH of 9.2). Electrical conductivities are 100 mS/m or below, well within the SANS limit. Sulphate concentrations are less than 10 mg/L for all except 5 of the samples.

Of the major ion constituents, only nitrate exceeds the guidelines for any of the samples. Samples 3, 7 and 13 all have nitrate ion concentrations greater than 11 mg/L NO₃-N (17, 17 and 19 mg/L, respectively), implying an acute health risk according to the SANS standards. All of the groundwater samples bar one (Sample 2) show levels of nitrate concentration well above the detection limits of the laboratory analytical equipment. In contrast the Molopo Eye sample (Sample 11), from a neighbouring dolomite compartment with little agricultural activity, has a nitrate concentration of 0.9 mg/L. Concentrations of livestock were observed close to several sampling points, and together with fertilizer applications some level of nitrate contamination is to be expected in Grootfontein groundwater. Two of the three samples with high nitrate concentrations (Samples 3 and 7, both with nitrate concentrations of 17 mg/L) also have elevated sulphate concentrations (38 and 34 mg/L of sulphate, respectively) which, whilst well within the SANS guideline value, also suggests anthropogenic pollution.

Of the minor constituents, arsenic concentrations are above the SANS guideline limit for chronic health risk of 0.01 mg/L in 6 samples, and selenium levels are similarly elevated in 4 samples. These results may be related to the leaching of inorganic fertilizers into groundwater (MDH, 1999).

The samples have a CaMg-HCO₃ signature and cluster closely together when plotted as a Piper diagram, apart from the Setumo Dam sample (Sample 5). This suggests relatively homogeneous groundwater and an undifferentiated and

TABLE 3
The Grootfontein sample locations

Sample	Description of sample site	Latitude	Longitude
1	Combined outflow of the 3 DWS public water supply boreholes at Grootfontein	-25.917167	25.860861
2	Domestic water supply borehole	-25.913944	25.872389
3	Domestic water supply borehole	-25.915361	25.868583
4	Public water supply borehole	-26.076389	25.920667
5	Setumo Dam sample near dam wall	-25.856528	25.508611
6	Irrigation borehole	-26.054528	25.954889
7	Domestic water supply borehole	-25.915667	25.869250
8	Irrigation borehole	-25.925611	25.863861
9	Irrigation borehole	-25.925417	25.863833
10	Irrigation borehole	-25.934667	25.910667
11	Molopo Eye taken at eastern end	-25.887528	26.026500
12	Domestic water supply borehole	-26.097167	25.984250
13	Irrigation borehole	-26.087361	25.973500
14	Thusong Hospital borehole	-26.054389	25.949389
15	Irrigation borehole	-26.035611	25.952694
16	Domestic water supply borehole	-25.906722	25.911583

well-connected aquifer. In general, these water quality results confirm previous studies that point towards a high-quality groundwater resource suitable for domestic supply and needing little treatment, even though anthropogenic impacts have been detected in some samples.

The quality of the Grootfontein groundwater can be contrasted with the poorer raw water quality from the Setumo Dam, which requires flocculation, settling, diffused air flotation and filtration, as well as 'ozonation to deal with excessive total organic carbon (TOC) levels in the water and granulated activated carbon (GAC) filters to deal with taste and odour problems arising from the high algal content of the raw water' (DWS, 2014 p 5).

Water level analysis

DWS collects groundwater-level information in South Africa as part of its ongoing monitoring programme. This data is entered into the HYDSTRA database, from where a selection is exported to the publicly accessible National Groundwater Archive (NGA). Data obtained in June 2015 from the NGA indicates that North West Province has 129 groundwater level monitoring stations that are currently active. Most of these stations are monitored manually (i.e. using a hand-held dipmeter) and all except two are monitored quarterly. A subset of 34 groundwater-level monitoring stations was identified for the Grootfontein aquifer. Of these 34 stations, 21 are located within the aquifer whilst the other 13 are less than 3 km outside of its border. All 34 stations are either currently active, or have monitoring records that ended in the past 6 years. All but 3 of these 34 station records began recording in the 14 years between 1972 and 1986, a time of increasing irrigation at Grootfontein. The earliest record is Station D4N0103, which began recording in February 1972. Irrigation is known to have started before the 1960s in the Grootfontein compartment and surrounds (Temperley, 1965), but records showing groundwater levels in the Grootfontein area before the early 1970s are scarce.

A best-fit straight line through the data was added to each record in MS Excel, and the gradients of the lines were compared. An average gradient (or rate of decline in metres per day) of 0.00113 for all 34 records, and of 0.00126 for the 21 records inside the compartment, was calculated. This is equivalent to a fall in water level of 4.1 m per decade for all records, or 4.6 m per decade for those records within the compartment boundaries. Individual record gradients within the compartment boundaries vary by an order of magnitude (i.e. 0.0002 for D4N0838 and 0.0023 for D4N0088). This is expected due to the great heterogeneity of a karst aquifer such as Grootfontein, and the local effects of large-scale abstractions.

The DWS water-level records are confirmed by water-level measurements taken in the field for this research in April 2015. The average water level for 3 boreholes within a few metres of the old Grootfontein Eye site was 27.8 m bgl.

Of the 34 borehole water level records, all but two show a declining water level on average over the record length (Table 4). These two are both outside of the Grootfontein compartment (D4N0833 and D4N0830).

Recharge

Long-term recharge values of between 4.5% and 10% of annual rainfall have been estimated for Grootfontein (Cogho, 1982; Bredenkamp and van Rensburg, 1983; Dziembowski, 1995). However, in semi-arid North West Province recharge

is a function of rainfall intensity, and may only occur in particularly wet years (Beekman and Xu, 2003; Van Wyk, 2010). Some authors (e.g. Janse van Rensburg, 1992) have incorporated this 'threshold effect' into their recharge calculations. Estimating recharge using conventional methods is complicated by its episodic nature, as well as by lack of data on rainfall chloride and stable isotope concentrations; lack of daily water level measurements and local rainfall data; and uncertainty regarding bypass flow and irrigation return flows.

A mass-balance approach to contemporary recharge is complicated by lack of knowledge of irrigation volumes and schedules, leakage across dykes, uncertainty over specific yield distribution, relatively coarse water-level data, and other factors. However, under pre-abstraction conditions, the natural recharge at Grootfontein would have been balanced by the long-term discharge of the Grootfontein Eye and other smaller springs (such as the Kleinfontein), plus evapotranspiration (ET) from vegetation and wetlands, plus any change in aquifer storage (ΔS). This basic mass balance can be expressed as follows:

$$\text{Recharge} = \text{Grootfontein flow} + \text{other spring flows} + \text{ET} \pm \Delta S$$

If a long-term average situation is considered, then changes in aquifer storage can be ignored. Similarly, it is necessary to assume that flows across the boundaries of the aquifer, under natural conditions, are equalised in the long term. It follows that the sum of the long-term flows of the Grootfontein Eye and other springs would be a minimum figure for long-term recharge under natural conditions across the compartment. The evapotranspiration from wetlands that once existed would add to this figure, since they represented zones of groundwater discharge (they have now disappeared since the water table has dropped).

Unfortunately, detailed figures for the flow of the Grootfontein spring before borehole abstractions started are not available. Vipond (1979) reported that the average flow of the Grootfontein Eye at that time was 14.4 ML/day (5.3 Mm³/a), thought to be close to the long-term average flow of the eye. One of the earliest technical reports to mention the Grootfontein Eye, by Temperley (1965 p 2), states:

A study of the records of Grootfontein shows that during the seven years since this spring was gauged, its yield has fallen from 1.5 to 0.75 thousand gallons per minute, a reduction of 50%. This is attributed to a fall in the regional water level consequent on a steady increase in abstraction by boreholes for irrigation.

This implies that the gauging of the Grootfontein Eye began in the late 1950s. Assuming that Temperley (1965) meant imperial gallons, 1 500 gallons per minute is about 9.8 ML/day or 3.6 Mm³/a. Borehole abstractions had already started in the area in the 1950s, however, and were probably already affecting the flow of the Grootfontein Eye by the early 1960s. It seems likely, therefore, that the long-term flow of the Grootfontein Eye was at least 10 ML/day (3.7 Mm³/a), and possibly as much as 20 ML/day (7.3 Mm³/a). The flow of the Kleinfontein and other springs and seeps along the northern boundary of the aquifer also needs to be taken into account – likely at least another 10% of the Grootfontein flow, and possibly as much as a further 25% of its flow, based on discussions with local farmers. In summary, the long-term average of total spring discharges under pristine conditions from the Grootfontein aquifer was probably at least 11 ML/day (4.0 Mm³/a), and possibly as much as 25 ML/day (9.1 Mm³/a).

TABLE 4
Water level summary at Grootfontein

Borehole	Start date	Start wl	End date	End wl	Years	Trend	TrendGrad	AnnualDrop
D4N0103	10-Feb-72	5.42	17-Feb-15	27.27	43.05	decline	0.002	0.56
D4N0037	10-Aug-73	20.62	23-Feb-12	28.85	38.56	decline	0.0018	0.21
D4N0051	5-Apr-74	17.1	23-Nov-09	32.76	35.66	decline	0.0016	0.42
D4N0080	8-Oct-74	6.99	23-Dec-08	26.9	34.23	decline	0.0023	0.59
D4N0088	8-Oct-74	11.37	18-Sep-07	36.8	32.97	decline	0.0023	0.81
D4N0092	15-Jan-75	29.22	24-Apr-13	36.67	38.30	decline	0.0009	0.28
D4N0094	15-Jan-75	21.24	15-Dec-04	33.21	29.94	decline	0.001	0.48
D4N0117	20-May-75	0.93	19-Feb-15	6.58	39.78	decline	0.0002	0.09
D4N0120	20-May-75	17.91	19-Feb-15	42.79	39.78	decline	0.0012	0.55
D4N0102	7-Jul-75	5.39	11-Nov-14	11.23	39.38	decline	0.0002	0.11
D4N0108	9-Jul-75	12.35	17-Feb-15	13.84	39.64	decline	0.0001	0.01
D4N0128	11-Aug-75	1.82	17-Feb-15	12.98	39.55	decline	0.001	0.28
D4N0095	15-Jan-76	28.33	19-Feb-15	38.01	39.12	decline	0.0009	0.17
D4N0111	15-Jan-76	15.7	10-Nov-09	30.75	33.84	decline	0.0016	0.53
D4N0039	10-Sep-76	3.39	17-Feb-15	14.3	38.46	decline	0.0005	0.26
D4N0113	15-Dec-76	5.8	17-Feb-15	22.87	38.20	decline	0.0008	0.37
D4N0129	20-Jan-77	8.94	22-Jun-10	8.96	33.44	decline	0.0001	0.07
D4N0075	30-Aug-79	3.6	17-Feb-15	27.91	35.49	decline	0.0021	0.67
D4N0852	4-Jun-81	11.34	11-Nov-14	28.09	33.46	decline	0.001	0.48
D4N0665	10-Nov-81	9.7	25-Jun-13	41.51	31.64	decline	0.0013	0.87
D4N0697	3-Jan-83	5.21	23-Feb-09	28.97	26.16	decline	0.0014	0.64
D4N0850	3-Jan-83	5.78	23-Feb-09	28.4	26.16	decline	0.0009	0.62
D4N0851	3-Jan-83	5.43	23-Feb-09	27.74	26.16	decline	0.0011	0.67
D4N0854	3-Jan-83	2.73	6-Jun-12	25.89	29.44	decline	0.0013	0.63
D4N0855	3-Jan-83	9.25	17-Feb-15	28.37	32.15	decline	0.0015	0.56
D4N0840	4-Oct-83	23.64	7-Dec-09	30.785	26.19	decline	0.0004	0.11
D4N0833	26-Oct-83	8.5	15-Jul-04	8.85	20.73	RISE	-0.0002	-0.02
D4N0829	28-Oct-83	13.1	17-Feb-15	24.36	31.33	decline	0.0011	0.25
D4N0830	19-Jan-84	17.16	11-Nov-14	24.3	30.83	RISE	-0.0003	0.02
D4N0838	15-Sep-86	28.05	7-Dec-09	31.82	23.24	decline	0.0002	0.01
D4N0839	15-Sep-86	28.88	7-Dec-09	32.65	23.24	decline	0.0003	0.11
D4N1664	31-Oct-97	28.83	3-Mar-15	47.6	17.35	decline	0.0034	1.26
D4N1668	10-Dec-98	33.06	19-Feb-15	37.81	16.21	decline	0.0012	0.22
C3N0653	9-Nov-10	28.31	18-Feb-15	32.46	4.28	decline	0.0033	0.80

Start/End wl: First / last water level recorded for each record, in metres below datum.

Trend: Trend of best-fit straight line through each water level record.

TrendGrad: Gradient of best-fit straight line through each water level record.

Rise: Rising water level: Decline: Declining water level

AnnualDrop: Average annual change (drop) in water level over length of each record

Under natural conditions (i.e. before agriculture and human changes to the landscape), evapotranspiration by natural plant cover and evaporation from wetlands would have removed water from the aquifer, and these volumes would need to be added to the spring discharge volumes for a water balance. Today's evapotranspiration is partly a function of anthropogenic changes such as the modified plant cover or cropping patterns, the deeper water table, and soil moisture

conditions in the soil zone due to irrigation. A reasonable assumption might be that natural evapotranspiration (i.e. not related to irrigation) is much reduced since the water table is considerably lower today, and no wetland areas remain.

There were two main areas of wetland within the compartment boundaries as shown on the old topographic maps: the course of the Droë Molopo River in the north-east, and a smaller area close to the farm Blaauwbank near the centre of the

compartment (Fig. 2). Using GIS, their areas were estimated to be about 1.2 km² and 0.22 km², respectively. Assuming potential evaporation of 1 500 mm/a and standing water all year round, this implies that these areas together might have discharged as much as 5.8 ML/day (2.1 Mm³/a) to evaporation.

This method uses 'pristine' conditions to derive a defensible upper and a lower limit to recharge. The minimum average recharge figure for the Grootfontein aquifer is probably about 13 ML/day (about 4.7 Mm³/a), based on minimum spring discharges and low evapotranspiration, and corresponding to the minimum figures for percentage of rainfall quoted by previous authors. A maximum recharge figure of about 30 ML/day (about 11 Mm³/a) would be based on maximum spring discharges combined with higher rates of evapotranspiration. The maximum figure quoted in the literature (10% of mean annual rainfall, implying recharge of 36.5 ML/day or 13.3 Mm³/a) seems too high when considering likely discharges under 'pristine' conditions. Recharge figures corresponding to averages above 30 ML/day (11 Mm³/a) may however be possible today due to the effects of induced recharge.

Contemporary groundwater abstractions

Current groundwater abstractions from the Grootfontein aquifer can be divided into three categories: the wellfield boreholes supplying Mahikeng, the irrigation boreholes spread across the aquifer, and miscellaneous other uses. Based on data obtained from DWS for 2015, the three remaining public water supply boreholes yield a combined average of 8.7 ML/day (3.2 Mm³/a). Estimating irrigation use is more difficult since licensed quantities are not enforced; however, work done for DWS by private consultants using satellite measurements of irrigated crop areas and knowledge of crop irrigation requirements suggests that about 37 ML/day (13.5 Mm³/a) is being abstracted for irrigation (Eales, 2015). Miscellaneous uses, including the public water supply boreholes in the southern part of the aquifer supplying Itsoeng, are estimated

at about 3 ML/day (1.1 Mm³/a). Combined average outflows are therefore roughly 49 ML/day (17.9 Mm³/a).

A water balance for the Grootfontein aquifer

As described above, a recharge figure of between 13 and 30 ML/day (4.7 and 11.0 Mm³/a) was estimated. (This corresponds to roughly 3% to 8% of average annual rainfall across the aquifer area, respectively.) If zero flux across the aquifer boundaries is assumed, then: Inflows – Outflows ± ΔS = 0, and a contemporary water balance can be constructed for Grootfontein (Table 5).

DISCUSSION AND CONCLUSIONS

Grootfontein currently has a groundwater deficit of at least (49–30 =) 19 ML/day (6.9 Mm³/a), and as much as (49–13 =) 36 ML/day (13.1 Mm³/a), based on estimates of current inflows and outflows. Alternatively, long-term water-level declines averaging 0.4 m/a suggest a long-term average deficit of between about 5 and 26 ML/day (1.8 and 9.5 Mm³/a), based on minimum and maximum estimates of aquifer specific yield. The discrepancy between long-term estimates based on water-level changes, and estimates based on current irrigation abstractions, is partly due to increasing irrigation. Recent sampling confirms that the groundwater quality is good.

Although hydrogeological uncertainty is inevitable, it is clear that the Grootfontein aquifer is being over-exploited. Abstractions must fall if water levels are to recover. Remaining uncertainty should not defer better governance – indeed, uncertainty will diminish as improved governance and monitoring refine the conceptual model (Seward et al., 2006; Cobbing, 2017). Calls to restrict abstractions at Grootfontein have been regularly made in the hydrogeological literature since the 1960s, mainly by DWS hydrogeologists (e.g. Bredenkamp, 1964). South African water law and policy also

TABLE 5
Grootfontein water balance

Inflows	Estimate	Notes
Recharge	Between 13 ML/day and 30 ML/day (4.7 and 11.0 Mm ³ /a)	Based on spring discharges and estimated evapotranspiration under pre-abstraction conditions
Return flows	Assumed to be zero under current conditions	May be a locally significant source of recharge
Inflows across aquifer boundaries	Assumed to be zero under current conditions	May be significant particularly where water levels have dropped and/or dykes are highly weathered
Outflows		
Irrigation boreholes	37 ML/day (13.5 Mm ³ /a), may be higher	Estimated using satellite data (DWS' WARMS licence data implies amount is higher)
Evapotranspiration	Assumed to be zero under current conditions	Falling water tables have eradicated wetland areas, springs and seeps
DWS boreholes	8.7 ML/day (3.2 Mm ³ /a)	Based on DWS 2015 data, was higher up until about 2010 (DWS, 2014)
Other boreholes	About 3.0 ML/day (1.1 Mm ³ /a)	Mainly Itsoeng boreholes for public supply, since other abstractions are small
Δ Storage		
Falling groundwater levels	Between 5.2 ML/day and 26 ML/day (1.9 and 9.5 Mm ³ /a)	Figure based on specific yields of 2% (min) and 10% (max) and average drop in water levels of 0.4 m/a across the aquifer

specify sustainable use, and protection of ecosystems. Yet over-abstraction at Grootfontein continues, with all of the implied risks and costs.

It is sometimes thought or implied that poor knowledge of groundwater resources in South Africa is behind a collective failure to fully utilize this resource, or behind a preference for surface water alternatives (DWA, 2010). However, current hydrogeological understanding of Grootfontein enables a defensible water balance to be constructed from publicly available data as demonstrated above, suggesting that lack of technical knowledge of the aquifer cannot be blamed for poor management. It follows that more hydrogeological work, on its own, will not automatically lead to better management of groundwater – indeed, may even reinforce the regressive notion that the solution to groundwater management lies mainly in further technical work. This would only continue the 50-year tradition of detailed hydrogeological studies being done whilst water levels fell, and the poor coordination between hydrogeological work and management practice. A full discussion of the interaction between the hydrological and social spheres is beyond the scope of this article, but has been discussed elsewhere (e.g. Cobbing, 2017).

The failure to better utilise groundwater in the public interest is not limited to Grootfontein, but appears to be more widespread. In Cape Town, for example, planners are installing desalination plants, whilst at the same time grappling with seasonal flooding and sanitation problems on the Cape Flats – problems that would partly be addressed by pumping this groundwater. Various proposals over the years to use the water (and storage potential) of the well-studied Cape Flats Aquifer (e.g. Maclear, 1995; Wright and Conrad, 1995) have not been adopted. Plans to incorporate the good quality groundwater in the Cape Fold Mountains into Cape Town's supply have also fared poorly. Innovative proposals to use aquifer storage to buffer seasonal demand at Plettenburg Bay and Sedgefield were trumped by costly surface water and desalination options, respectively.

A more holistic view of South Africa's groundwater as a national resource is required, taking into account the wider management, funding, legal, policy, and operational context as well as the hydrogeological realities. Mahikeng is already paying a high price for essentially abandoning the Grootfontein aquifer, since expensively treated dam water must substitute for the decline of Grootfontein. This price will rise further since other sources of water in this semi-arid area are scarce and expensive. Concerns over water in Mahikeng also influence the wider social and economic context, with difficult-to-quantify implications for employment, equity, stability and economic development.

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