Earth Stewardship Science Research Institute

# The Grootfontein aquifer at Mahikeng, South Africa as a hydro-social system


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Thesis submitted in fulfilment of the requirements for the PhD degree in the Faculty of Science at Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

March 2017

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## DECLARATION

I, Jude Edmund Cobbing, Student Number 212473468, hereby declare that the thesis for PhD (Geology) is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

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This thesis is the work of Jude Edmund Cobbing and has not been previously submitted to another university.

ACKNOWLEDGEMENTS

My supervisor, Professor Maarten de Wit, and staff and fellow students at AEON, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

All of the interviewees for sharing their time generously and patiently, and for going out of their way to assist with the fieldwork and data collection.

The Water Research Commission in Pretoria for supporting this research, and Shafick Adams and Eiman Karar for their guidance and advice.

Mike Butler and iThemba LABS in Johannesburg for analysis of the stable isotope samples.

Theo Rossouw, Kathy Eales and Karabo Lenkoe-Magagula for assistance with fieldwork in and around Mahikeng, North West Province.

Friends and acquaintances at the Department of Water and Sanitation in Pretoria, Hartbeespoort, Mahikeng, Polokwane and East London for assisting with this research in many different ways.

Friends and colleagues in the professional water and engineering community in South Africa, particularly former staff of Water Geosciences Consulting, for encouragement, discussions, sharing of data and information, assistance, and friendship.

My family and especially my wife, Cleo, for all their encouragement and support.

*"Umuntu Ngumuntu Ngabantu" – "A person is a person through other people"*

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All geographic data and maps use the WGS84 ellipsoid. The 1:50 000 scale topocadastral map backgrounds, road networks and town locations shown in some figures are derived from raster imagery published by the Chief Directorate: Surveys and Mapping of the Department of the Department of Rural Development and Land Reform, Pretoria, South Africa and available from www.ngi.gov.za

# Abstract

The Grootfontein aquifer is located about 20 km south east of Mahikeng, North West Province, South Africa, and currently supplies about 20% of Mahikeng's water. Formed in weathered Malmani Subgroup dolomites, the aquifer contains good quality groundwater that could potentially supply more of Mahikeng's water, as well as provide a strategic reserve of water for use during droughts. Over-abstraction of groundwater from the aquifer, mainly by irrigating farmers but also by the boreholes supplying Mahikeng, has caused the natural groundwater level to drop at a rate of about 0.4 m per year since the 1970s, leading to water level declines of as much as 28 m in parts of the aquifer. Although the Grootfontein aquifer is one of the best studied aquifers in South Africa hydrogeologically, efforts to address these declines since the 1970s have largely failed. This research combines hydrogeological evidence with social research (interviews and participant-observation) and the principles of Earth Stewardship Science to argue that the aquifer functions as a hydro-social system, and that institutional characteristics are the root cause of a collective inability to restore the aquifer to its full potential as a water resource. A sub-optimal and undesirable Nash equilibrium prevails, in which major groundwater users are unable or unwilling to reduce abstraction. The situation has significant cost and risk implications for the environmental, economic and social sectors, and contributes to insecurity, pessimism, inequality and mistrust. An effective local forum with appropriate powers, supported and mandated by the Department of Water and Sanitation, is needed to begin the work of dismantling the sub-optimal equilibrium to realise the potential of the Grootfontein aquifer. Such a forum would require a shared understanding of the hydrogeological mechanisms of the aquifer as well as its social and institutional functioning, since these influence each other in complex ways.



**Key Words**

Groundwater, hydrogeology, Grootfontein, institutions, transdisciplinarity, Earth Stewardship Science

# Abbreviations

| Abbreviation | Definition |
|---|---|
| **CGS** | Council for Geoscience |
| **CMA** | Catchment Management Agency |
| **CMF** | Catchment Management Forum |
| **CSIR** | Council for Scientific and Industrial Research |
| **DM** | District Municipality |
| **DWA** | Department of Water Affairs (formerly DWAF) |
| **DWAF** | Department of Water Affairs and Forestry |
| **DWS** | Department of Water and Sanitation (formerly DWA or DWAF) |
| **EC** | Electrical Conductivity |
| **GH** | Geohydrology Series reports published by DWS |
| **GIS** | Geographical Information System |
| **GMA** | Groundwater Management Area |
| **GMU** | Groundwater Management Unit |
| **GRA1 / GRA2** | Groundwater Resource Assessment Phase 1 and Phase 2 |
| **GRIP** | Groundwater Resource Information Project |
| **GW** | Groundwater |
| **GWD** | Ground Water Division of the Geological Society of South Africa |
| **Ha** | Hectares |
| **HDI** | Historically Disadvantaged Individual |
| **HYDSTRA** | DWS' main Hydrological Database |
| **IWRM** | Integrated Water Resources Management |
| **L/s** | Litres per second |
| **LM** | Local Municipality |
| **$m^3$/day** | Cubic metres per day (i.e. thousand litres per day) |
| **Ma** | Million years |
| **masl** | Metres above sea level |
| **mbd** | Metres below datum |
| **mbgl** | Metres below ground level |
| **mg/L** | Milligrams per litre |
| **ML/d** | Mega-litres per day (i.e. million litres per day) |
| **$Mm^3$/a** | Million cubic metres per annum |
| **MRCC** | Magalies River Crisis Committee |
| **MS** | Microsoft |

| | |
|---|---|
| **mS/m** | Millisiemens per metre |
| **NGA** | National Groundwater Archive |
| **NGS** | National Groundwater Strategy |
| **NMMDM** | Ngaka Modiri Molema District Municipality |
| **NMMU** | Nelson Mandela Metropolitan University |
| **NORAD** | Norwegian Agency for Development Cooperation |
| **NWA** | National Water Act of 1998 |
| **NWRS** | National Water Resource Strategy |
| **NWRS2** | National Water Resource Strategy (Second Edition) |
| **O&M** | Operation and Maintenance |
| **PSP** | Professional services provider |
| **RDP** | Reconstruction and Development Programme |
| **S** | Storativity |
| **SANAS** | South African National Accreditation System |
| **SANS** | South African National Standard |
| **SMOW** | Standard Mean Ocean Water |
| **SOF** | Stakeholder Operating Forum |
| **T** | Transmissivity |
| **TU** | Tritium units |
| **UGEP** | Utilisable Groundwater Exploitation Potential |
| **UNESCO** | United Nations Educational, Scientific and Cultural Organisation |
| **USD** | United States Dollars |
| **V&V** | Verification and validation |
| **VLOM** | Village-level operation and maintenance |
| **WAR** | Water Allocation Reform |
| **WARMS** | DWS' Water Use Authorisation Management System database |
| **WASH** | Water, Sanitation and Hygiene |
| **WMS** | DWS' Water Management System water quality database |
| **WRC** | Water Research Commission |
| **WSA** | Water Services Authority |
| **WSP** | Water Service Provider |
| **WUA** | Water User Association |

# 1. Introduction

## 1.1. The dolomites and water supply in South Africa

Dolomite rocks of the Transvaal Supergroup form three major regions in South Africa. A thin, bow-shaped area hugs the escarpment to the east, and includes the towns of Sabie and Pilgrim's Rest where the discovery of veins of gold in the dolomite led to South Africa's first gold rush in the early 1870s. A wedge-shaped dolomite plateau, the Ghaap Plateau, is found in the arid north-centre of South Africa around the town of Kuruman in the Northern Cape Province. The third major area of dolomite stretches from Gauteng Province in the east towards the Botwana border at Lobatse in the west, covering a swathe of North West Province (Figure 1-1).

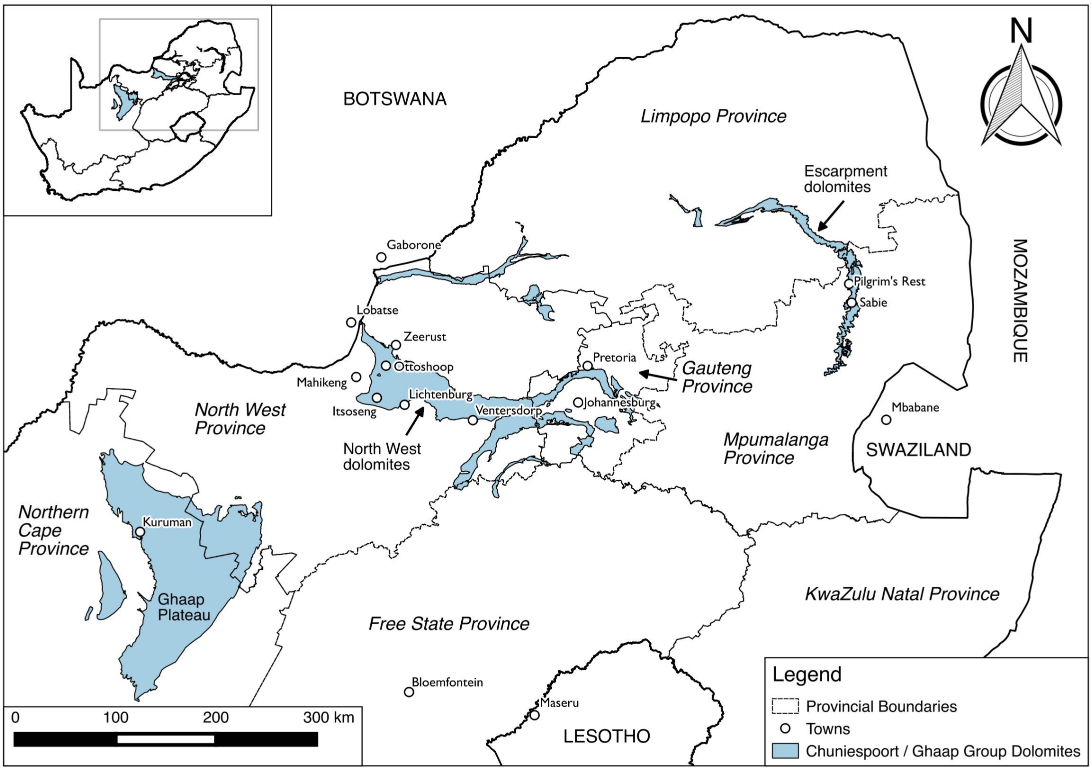


**Figure 1-1 Main Transvaal Supergroup dolomite outcrops in South Africa (geology after CGS, 1997)**

These dolomites of North West Province have weathered to form flat, monotonous landscapes that contrast with the krantzes and ridges of the Magaliesberg Mountains to the north formed by overlying quartzite rocks. The North West dolomites have little in the way of mineral wealth, but they do hide a secret: weathering and solution processes over millions of years have caused channels, caves and other secondary structures to form, giving rise to some of South Africa's most prolific and important aquifers, and holding one of the nation's largest water resources. The volume of groundwater stored in the North West dolomites is similiar to the water stored in South Africa's largest dam, the Gariep Dam on the Orange River[1]. Recharged by rainfall, under natural conditions this dolomite groundwater feeds wetlands and a series of large springs or "eyes".

The town of Kuruman is located due to the Kuruman Eye spring issuing from the Ghaap dolomites nearby, which still supplies part of Kuruman's water today. The Pretoria Fountains are another large dolomite spring, found just south of Pretoria city centre at the contact between the dolomites and the quartzites. The Fountains are the source of the Apies River, and were Pretoria's original water supply. The Fountains still supply a portion of Pretoria's water, and the natural water quality is excellent (Dippenaar, 2013). The Marico Eye, Maloney's Eye, the Malmanie Eye, the Molopo Eye and the Gerhardminnebron[2] are other notable North West Province dolomite "eyes" (shown on Figure 1-4). The Wondergat, a collapsed sinkhole forming an eerie, circular lake in the otherwise semi-arid landscape south of Ottoshoop, is used by scuba divers and is more than 50 metres deep. It is a rare window into the vast dolomite groundwater reservoirs of North West Province (see photographs in Appendix F).

This research is concerned with one dolomite spring or eye in particular, which no longer flows. It was located about 20 km south east of Mahikeng[3], the capital of North West Province, where it was an early water source for the town. Once a popular weekend picnic spot and a haven for wetland birds, this spring was known as the "Great Spring" or Grootfontein before it stopped flowing in the early 1980s due to nearby pumping boreholes. Some of these boreholes still supply water to Mahikeng today.

The site of the Grootfontein eye is located in a dolomite aquifer or "compartment" called the Grootfontein aquifer. This Grootfontein aquifer is the subject of this research. A similar dolomite aquifer, the Steenkoppies aquifer, lies near the town of Krugersdorp. The Steenkoppies aquifer is used as corroborative evidence in this research. (The locations of these two aquifers are shown in Figure 1-4.)

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1 See Section 4.2.2 in Chapter 4.

2 The pioneering geologist Alex du Toit described water "gushing forth" from the Gerhardminnebron "at the rate of between 21 and 26 cubic feet per second" (du Toit, 1939:113).

3 Also known as Mafikeng.

Towns in North West Province that rely mainly on dolomite groundwater for their municipal water supplies include Lichtenburg, Ventersdorp, Ottoshoop, Mahikeng, Zeerust and Itsoseng (Figure 1-1). This water comes either from natural springs or eyes, or from boreholes drilled into the dolomite. There is usually no practical alternative to dolomite groundwater since surface water resources are scarce and over-allocated. The dolomite groundwater is mostly of excellent quality and can be used for domestic supplies with only basic treatment. Despite widespread reliance on the resource, in general groundwater is undervalued and overlooked in North West Province, and in South Africa more generally.

Work on the water supply to Mahikeng and the Grootfontein aquifer by this researcher began in early 2012, as a NMMU PhD student and researcher on a two-year Water Research Commission (WRC) project that initially aimed to provide local municipal authorities in the most deprived parts of South Africa with more detailed maps and other information about their local groundwater resources. This WRC project (WRC project K5/2158) arose in response to requests from local government officials who said that they did not know where to find groundwater in their areas of jurisdiction.

This WRC research project showed that reluctance to use groundwater, and the perceived unreliability of groundwater supplies, was due to a wide set of issues that included budgets and funding, protocols for operation and maintenance, divisions of responsibility, existing habits and practices, and other "non-hydrogeological" issues (Cobbing et al., 2014 and 2015). A second WRC project, also part of this PhD research, examined reasons for the failure of the legally-specified local water management organisations, or Water User Associations (WRC project K5/2429). The water supply to Mahikeng was used as a case study in both of these WRC research projects.

## 1.2. The Grootfontein aquifer and water supply to Mahikeng

### *1.2.1. Overview*

Mahikeng is the capital of North West Province and the seat of both Ngaka Modiri Molema District Municipality, and Mahikeng Local Municipality. It is also historically significant. The Siege of Mafikeng (1899-1900) was one of the defining battles of the second Anglo-Boer war. Sol T. Plaatje, the South African journalist, polymath and founding member of the precursor organisation to the African National Congress, was a newspaper editor in Mafikeng and kept diaries of the time (Plaatje, 1973). Part of

Mahikeng, known as Mmabatho, was the capital of the "homeland" parastatal of Bophuthatswana during the years of apartheid. Mahikeng today has a population of about 66 000 people, and the surrounding peri-urban villages are home to a further 170 000 people (DWS, 2014b).

Mahikeng's water supply depends mainly on groundwater – it is probably the largest and most important groundwater-dependent South African town. Mahikeng has three main sources of raw municipal water: the Molopo Eye spring about 40 km to the east of the town; the boreholes at Grootfontein about 20 km to the south east (replacing the former Grootfontein Eye); and the Setumo Dam about 10 km west of Mahikeng. Currently the Molopo Eye and the Setumo Dam each supply about 20 ML/day (mega-litres per day), whilst the Grootfontein boreholes supply about 10 ML/day (Figure 1-2). The Setumo Dam however relies for at least 50% of its inflow water on poor-quality effluent from Mahikeng's two waste water treatment plants, and on leaks in existing water reticulation infrastructure. The Setumo Dam therefore depends indirectly on the groundwater sources - if these groundwater sources were to fail the dam's potential yield would drop.

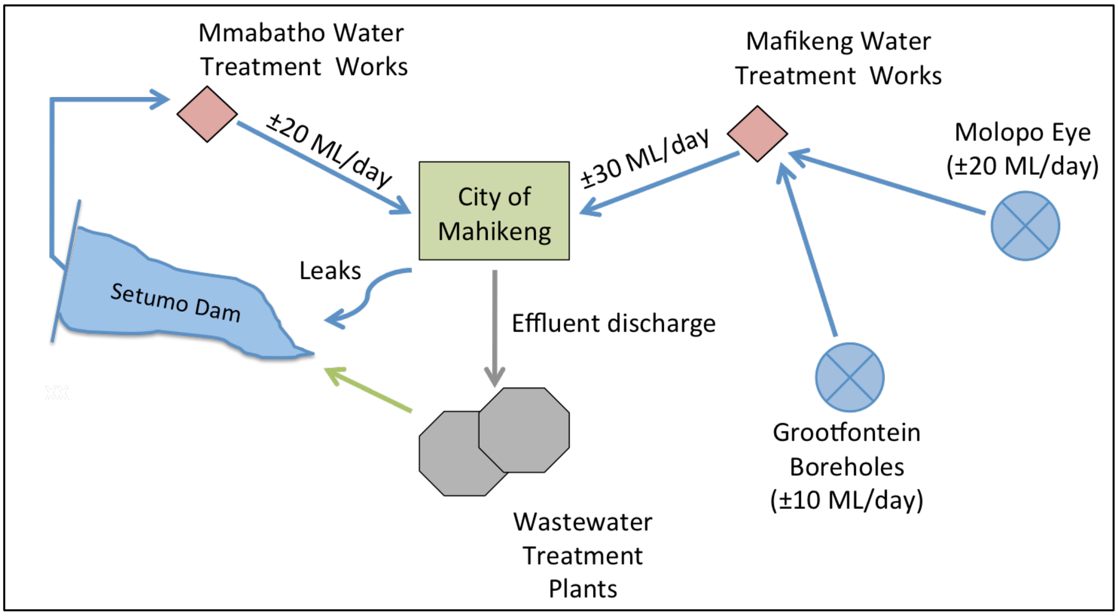


**Figure 1-2 Schematic diagram of Mahikeng's water infrastructure**

Although the Grootfontein boreholes only supply about 20% of Mahikeng's water today, before the mid-1980s Grootfontein was Mahikeng's main water source. At first, Mahikeng took a proportion of the Grootfontein Eye's natural flow. The spring waters flowed over a weir, where they were divided by a mechanical device into a quantity for local farmers, and a share for Mahikeng's supply. The town's proportion then flowed via a concrete channel and pipeline to Mahikeng. Over time, the natural spring flow proved too little for Mahikeng, and in the 1970s the Department of Water Affairs and Forestry or DWAF (as it was then called) began to install boreholes around the Grootfontein Eye to augment its flow. (The boreholes around the site of the Grootfontein Eye are collectively known as the Grootfontein wellfield.) These water supply boreholes, together with increasing irrigation abstractions and a drought, caused the Grootfontein Eye flow to diminish, and eventually, in 1981, to dry up completely. Whilst further boreholes have since been drilled around the old site of the Eye, the total supply from the boreholes at Grootfontein to Mahikeng has steadily declined to today's 10 ML/day or less, and groundwater levels (the water table) in the vicinity of the Eye have fallen to about 28 m below ground level. The Grootfontein Eye has not flowed since 1981 (see Section 4.3.8), and many of the water supply boreholes at the old Eye site have also now failed due to the falling water table - only three boreholes remain operational today.

In 1985, as demand increased, Mahikeng began to also use groundwater from the Molopo Eye spring to the east of Grootfontein (the source of the Molopo River). A new pumping station and treatment plant, the Mafikeng Water Treatment Works, was opened in August 1987 to receive the combined groundwater flow from the Grootfontein boreholes and the Molopo Eye spring. Minimal treatment was needed (precautionary chlorination) as the groundwater quality was very good.

Further demand for water led to the construction of the Setumo Dam to the west of Mahikeng in 1996. The Setumo Dam began supplying water to Mahikeng via the newly-built Mmabatho Water Treatment Works in 1997 (DWS, 2014b), supplementing the flows from the two dolomite groundwater sources. Originally designed to supply 20 ML/day, the capacity of the Mmabatho Water Treatment Works had halved to about 10 ML/day by mid 2012 due to poor raw water quality and inadequate maintenance (DWS, 2014b). In 2015 the Mmabatho Water Treatment Works was restored to its original design capacity of 20 ML/day. A second phase of work scheduled to end in August 2017 will increase this capacity still further, to 30 ML/day. The Mmabatho Water Treatment Works is a sophisticated water treatment plant using flocculation, settling, diffused air flotation and filtration, ozonation and granulated activated carbon filtration, all necessary to deal with the poor dam water quality (DWS, 2014b).

Supplying groundwater to Mahikeng is considerably cheaper than an equivalent surface water supply from the Setumo Dam, since the latter requires expensive infrastructure (the dam and water treatment works) and ongoing staff, energy and materials costs[4].

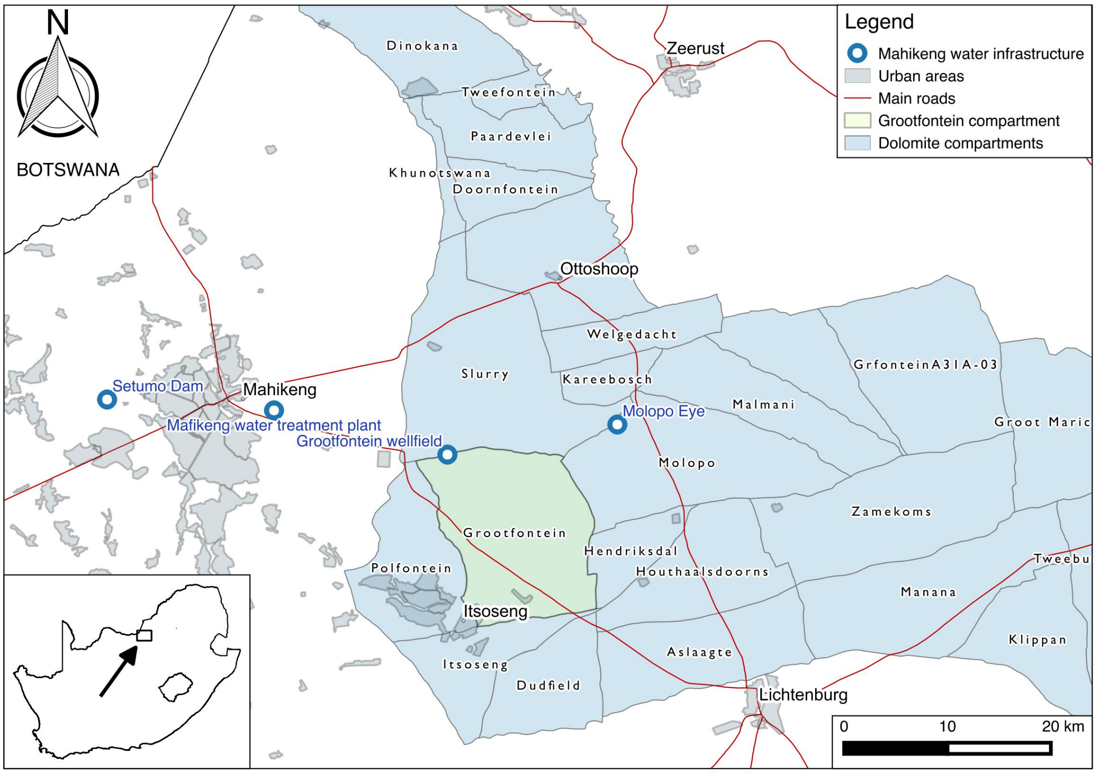


**Figure 1-3 The Grootfontein compartment, neighbouring compartments (after Holland and Wiegmans, 2009), and Mahikeng's water infrastructure**

### *1.2.2. Dolomite compartments, and the potential of the Grootfontein aquifer*

Mahikeng itself lies just to the west of the North West dolomite outcrop, which is why its two major dolomite groundwater sources, the Molopo Eye and Grootfontein, are both to the east of the city. Hydraulically speaking, the dolomites do not form a continuous aquifer. They are divided into smaller blocks or units by sub-vertical igneous dykes, faults and geological contacts. These smaller dolomite units are conventionally known in South Africa as "compartments" (Vegter, 2001; and Meyer, 2012). Much work has gone into defining their boundaries, and today a distinction is made between groundwater management units, and larger groupings of these compartments into groundwater management areas (Holland and Wiegmans, 2009). See Figure 1-3 above,

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[4] Funding for the upgrade of the Mmabatho Water Treatment Works at the Setumo Dam allocated between 2012 and 2015 exceeded R33 million, with completion of Phase 2 of the work expected by August 2017 (DWS, 2014b).

and Section 4.2 for more details. The groundwater in each compartment, originating mainly as rainfall recharge, often discharges at the downstream edge of the compartment as a spring, seep or wetland, or some combination of these. Each compartment can be thought of as a stand-alone aquifer, separated from its neighbours to a greater or lesser extent by dyke boundaries. Pumping from one compartment may not affect the groundwater in an adjacent compartment, or if it does the effect is diminished and delayed. The term "Grootfontein aquifer" is used in this thesis in preference to the more technical term "Grootfontein compartment". These terms are considered synonymous. The Grootfontein aquifer / compartment is sometimes also known as the Kliplaagte compartment.

The Grootfontein Eye was the primary natural discharge point of the Grootfontein dolomite compartment or Grootfontein aquifer. The Grootfontein compartment is roughly rectangular in shape, and covers about 239 $km^2$ (Holland and Wiegmans, 2009). Unlike the Molopo compartment which has poor agricultural potential, the Grootfontein compartment is partly covered by fertile alluvial soils. In the 1960s, as borehole drilling expertise grew and rural electrification proceeded, more and more farmers drilled boreholes to abstract Grootfontein groundwater for irrigation. The area was soon declared a "subterranean groundwater control area" under the legislation then prevailing, and various policies aimed at controlling groundwater abstraction were introduced. However, groundwater abstraction for irrigation rapidly outpaced the natural recharge of the Grootfontein compartment, contributing to the demise of the Grootfontein Eye in 1981. Today, irrigating farmers remain the major users of Grootfontein groundwater (see Section 5.8), although as described above groundwater is also abstracted for public supply to Mahikeng via boreholes drilled around the old eye site and operated by the Department of Water and Sanitation (DWS).

The Grootfontein aquifer, if it was full, could hold more than three times as much water as the Setumo Dam (see Section 5.5). If the Grootfontein aquifer were to be managed so that the water table remained high, it could yield a larger and more reliable supply to Mahikeng. This would necessarily involve reducing allocations for some other users, to bring abstraction as a whole back into balance. The aquifer's huge storage potential could also be exploited by temporarily over-abstracting groundwater during droughts, in the expectation of replenishment during wetter years. Grootfontein could act not only as a steady and more predictable source of excellent quality water, but would also be a potential "insurance policy" in case other sources (e.g. the Setumo Dam) failed.

In summary, the Grootfontein aquifer, via the Grootfontein boreholes, is no longer the main source of domestic water to Mahikeng because over-abstraction of groundwater has caused the water table to drop and the Grootfontein borehole yields to fall to around a third of the quantities pumped when they were first operating (DWS, 2014b). The Molopo Eye, and more recently the Setumo Dam, have compensated for the partial loss of the Grootfontein source in the overall water supply to Mahikeng. Water levels in the Grootfontein aquifer have fallen by an average of more than 12 m across the compartment, and by nearly 30 m in the vicinity of the old Grootfontein Eye (see Section 5.5) since the early 1980s. The aquifer can no longer provide a predictable and reliable supply to Mahikeng, and its storage potential is not used. Planners see the future of Mahikeng's water supply in the expensive upgrade of the Mmabatho Water Treatment Plant at the Setumo Dam. Yet, the potential of the Grootfontein aquifer remains and much could be achieved with better management of the Grootfontein groundwater.

## 1.3. Management of the Grootfontein aquifer

### *1.3.1. Organisations and institutions*

A distinction is made in this research between organisations and institutions. This distinction is important when discussing management provisions. Institutions are the customs, habits, informal rules, formal prescriptions and other modes of behaviour that govern all interactions between people, groups and organisations. Many institutions are defined by custom or culture, and they are a type of learned behaviour. Institutions can be bundled together into groups – and a group of more finely specified institutions may be "nested" together to constitute a larger, over-arching institution. Institutions can change or evolve over time, but some are very persistent.

Organisations on the other hand are taken to mean formally constituted groupings of people, often with staff, a legal mandate, a budget and a building or offices. The Department of Water and Sanitation is an organisation, for example. The water management literature does not always clearly distinguish between institutions and organisations. This is partly because organisations are also institutions, in the sense that organisations depend on multiple sets of rule-based interactions between people and groups. The common use of the term "institute" to mean an academic or research organisation can also confuse matters. The study of institutions, or the use of institutional structures as a means of analysis, is found in the field of water management (e.g. Ostrom, 2005), in economics (e.g. Hodgson, 2013) and in other fields requiring insights based on more than relatively simple models of individual utility maximisation.

### *1.3.2. Stakeholder organisations at Grootfontein*

Responsibility for the water supplies to Mahikeng and the management of the Grootfontein aquifer is shared between several organisations and groups. These are introduced below, discussed in more detail in Section 6.2, and shown in Figure 6-1.

The Department of Water Affairs and Forestry (DWAF) was originally responsible for the operation of the Grootfontein Eye boreholes, the Molopo Eye, and other aspects of bulk water supply to Mahikeng. Today, its successor the Department of Water and Sanitation (DWS) still runs the public water supply boreholes at the Grootfontein Eye site; operates the weir system at the Molopo Eye; and maintains all channels, pipelines, boreholes and other infrastructure upstream of the Mafikeng Water Treatment Works. DWS is legally the custodian of all water in South Africa, ultimately responsible for the conservation and appropriate management of water (DWA, 2013). DWS is devolving some of its water assessment and management functions to regional organisations known as Catchment Management Agencies (CMAs). Nine CMAs will ultimately cover the whole of South Africa, replacing some of the functions of the DWS regional offices.

Ngaka Modiri Molema District Municipality and Mahikeng Local Municipality also have important functions in providing domestic water in Mahikeng and treating waste water. Sedibeng Water Board, a regional water utility, also has significant responsibilities, particularly providing and operating infrastructure, and running the two water treatment works that supply clean water to Mahikeng.

Private sector service providers and consultants are also an important group in Mahikeng, but they are not homogeneous. They include large engineering consultancies, banks providing finance, policy and management experts, and independent groundwater consultants advising on technical options for water supplies. Multilateral development policy organisations, some of them international, influence the range of policy options and the final choices made regarding water supply options and the nature of the organisations mandated to manage water supplies.

Local groundwater users, particularly irrigating farmers who are the main users of Grootfontein groundwater, are also an important group with interests in the Grootfontein aquifer. The South African National Water Act of 1998 provides for local-level organisations known as Water User Associations (WUAs), designed for the day to day management of water at the local level. These WUAs do not exist, there is currently a moratorium on their formation, and DWS is reconsidering its policy as it applies to WUAs (DWS, 2014a). Local interests are inadequately represented in the interim by other organisational structures such as the Catchment Forums convened by DWS, or the various commercial farming groups and lobbies.

Other organisations, whilst perhaps not directly involved with water supply or groundwater abstraction, nevertheless have a stake in water related outcomes and the capacity to influence water related decisions. These include other national government departments (such as the National Treasury, the Department of Health, or the Department of Rural Development and Land Reform), or regional government structures such as the provincial Office of the Premier. Other organisations might include citizens groups, non-governmental organisations (NGOs), trade unions, political parties, religious organisations, student bodies, and others.

The decisions and interactions of these different organisations (either by legal mandate, or less formally) greatly influence the management of the Grootfontein aquifer. The influence of any one organisation may be disproportionate to its size, funding, legal or social mandate, or organisational coherence. Some organisations, whilst having little real influence on water policy, may still have the capacity to halt a particular course of action. The absence of some organisations also influences outcomes – for example the lack of the relevant Catchment Management Agency and the relevant Water User Association in the Grootfontein area contributes to lag and uncertainty and hinders water management. In other cases, matters unrelated to water impact on water policy and planning indirectly, sometimes in unexpected ways. For example, emergency diversion of funding towards a priority area by a municipality may have the unintended effect of decreasing funding for water infrastructure maintenance. Poor relationships between organisations are common, and can hinge on disagreements or misunderstandings regarding jurisdictional matters. Even small disagreements can have disproportionately large impacts on water resources, since they can stall key management interventions.

## 1.4. The relevance of this case study

The Grootfontein aquifer is not the only dolomite compartment that is under stress – towns such as Lichtenburg and Zeerust that are also dependent on dolomite groundwater have equally serious water supply challenges. The Grootfontein aquifer was chosen as a case study for several reasons:

1. The Grootfontein aquifer (prior to 1981 the natural flow of the Grootfontein Eye, today the pumped Grootfontein boreholes) provides part of the domestic water supply to the important South African city of Mahikeng. Other boreholes that also draw groundwater from the Grootfontein aquifer support a valuable irrigated agriculture industry. (These are the two major categories of groundwater users at Grootfontein.) The financial stakes are high – finding alternatives to the Grootfontein groundwater supplies, should they fail, would be expensive.
2. Grootfontein has a long history of hydrogeological research, and it is one of the best studied aquifers in South Africa. Water levels and other hydrogeological parameters are regularly monitored, and the availability of hydrogeological data for Grootfontein is relatively good. The past hydrogeological research reduces digressions linked to hydrogeological uncertainty. Nevertheless, it is still sometimes thought or implied that a lack of hydrogeological knowledge is the main reason for poor groundwater management at Grootfontein.
3. The Grootfontein aquifer is spatially well defined. It is bounded by igneous dykes that have been mapped geologically and/or geophysically, and their effects have been confirmed by a study of water levels (Holland and Wiegmans, 2009). This does not mean that the dykes are impervious, nor that they are continuous. But it simplifies the consideration of the Grootfontein aquifer as a physical and conceptual entity.
4. The Grootfontein aquifer invites comparison with another North West dolomite groundwater compartment with which it shares many similarities, the Steenkoppies compartment. Steenkoppies is located close to Krugersdorp on the West Rand, and also supports a large irrigated agricultural industry. Steenkoppies also drains naturally via a large spring or "eye", known as Maloney's Eye, which unlike the Grootfontein Eye is still flowing (Figure 1-4, and see Appendix F). There is good hydrogeological data available for Steenkoppies, including long records for the flow of the eye. Steenkoppies groundwater is not however used for municipal supply. Steenkoppies stakeholders made better progress towards a WUA compared with Grootfontein, but they too were ultimately unsuccessful, and Steenkoppies today also lacks a formal local management organisation. The comparison of Grootfontein and Steenkoppies reinforces the research findings at

Grootfontein, helps engage with rival hypotheses, and addresses the possibility that Grootfontein is unrepresentative or an aberration.

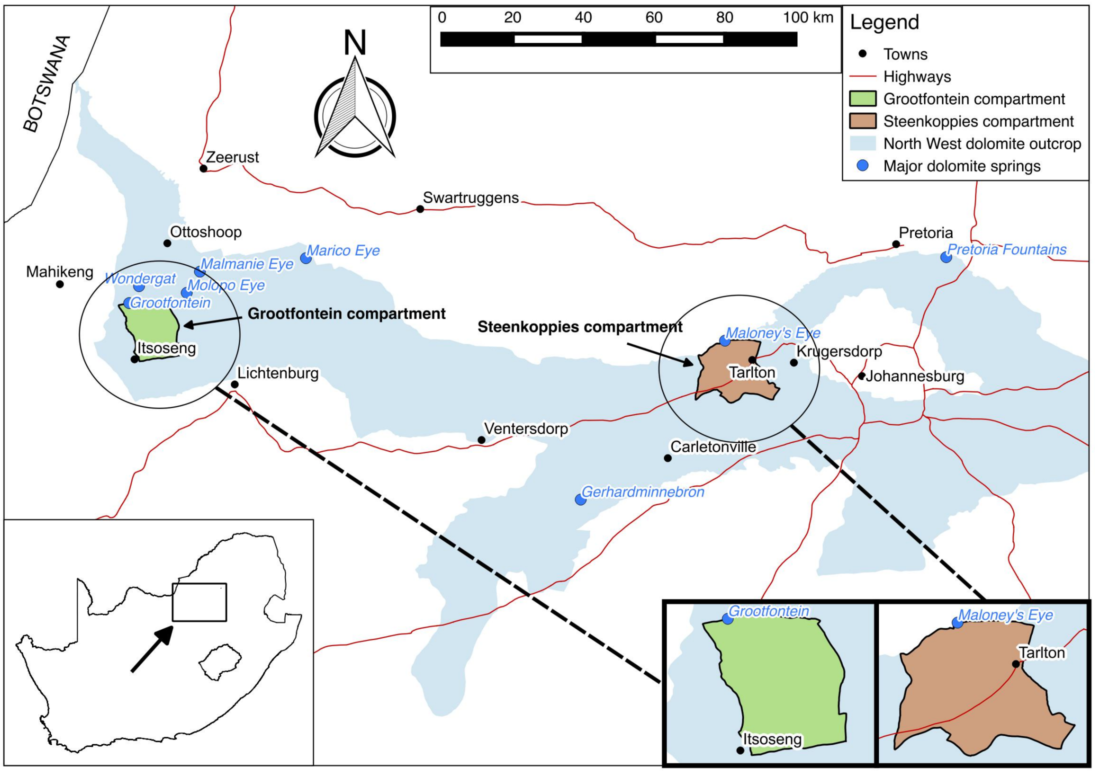


**Figure 1-4 Locations of the Grootfontein and Steenkoppies compartments, with selected major dolomite springs (boundaries after Holland and Wiegmans, 2009)**

Grootfontein has wider implications for natural resource stewardship in South Africa. Management failures at Grootfontein share characteristics with other natural resource management challenges. Water has always been a challenge in the development of South Africa, and lessons from Grootfontein may help resolve future water challenges and questions of environmental stewardship, sustainable development and social equity.

## 1.5. The research question

Better management of the Grootfontein aquifer will lower costs and increase assurance of water supply, and deliver a drought insurance policy and other benefits. It is however difficult to define and quantify the series of actions most likely to bring this about. Better management of Grootfontein needs individuals and organisations to cooperate, backed by appropriate funding and policy. Any realistic course of action will need to take multiple issues into account, necessitating a broad view of the problem.

This has led to the main research question of this study:

> "What is necessary for the successful management of the Grootfontein aquifer?"

There are various organisations with a stake in the Grootfontein groundwater, some of which are legally mandated to be involved in its management (e.g. the Department of Water and Sanitation) and others with a strong vested interest in the outcome (such as Mahikeng Local Municipality). As described, the local level Water User Association (WUA) was never constituted. Actions by individuals and organisations with an interest in Grootfontein groundwater are currently not leading to better management of the aquifer, particularly a reversal of the falling water level trend. In fact, these organisations and institutions appear to be interacting in ways that perpetuate or maintain the over-abstraction problem.

Fully investigating groundwater management at Grootfontein involves integrating geological and hydraulic issues with organisational and institutional issues. This lead to the primary hypothesis of this study, which is that:

> An understanding of both the technical and the institutional aspects of the Grootfontein aquifer, and how they interact, is required.

Related to this primary hypothesis are "sub-hypotheses" which include:

1. The technical and institutional aspects of the Grootfontein aquifer are not usually studied or viewed as an integrated whole.
2. The technical and institutional aspects influence each other, sometimes in unexpected or non-linear ways.
3. Due to the potential complexity of the interactions, outcomes can be counter-intuitive.

There are also certain assumptions that have been made in this research, which will be addressed. These are related to the main research question, and to the primary hypothesis (above). They are as follows:

1. The Grootfontein aquifer is being managed poorly, and this is not a natural or inevitable process. The hydrogeological conditions are such that it is technically possible to better manage the aquifer.

2. There is currently adequate technical or hydrogeological knowledge of the Grootfontein aquifer for better management to proceed, and the lack of such knowledge is not in itself a major impediment to better management.
3. Aquifer management, and in particular the institutional interactions between organisations and individuals, is poorly studied compared with the technical hydrogeology. These issues receive too little research interest when compared with their importance to groundwater management outcomes.

This thesis argues that consideration of both Grootfontein's hydrogeology and its institutional context is required, suggesting that techniques from both the physical and the social sciences are necessary. This raises potential problems of compatibility. For example, how can quantitative and qualitative data best be combined? What research techniques might shed light on institutions, and how can these be incorporated into the research strategy? These issues are discussed in the next chapter. Working across disciplinary boundaries has major advantages because it allows a researcher to study a complex "whole" rather than a more detailed part of it. There is a recognition in the literature that research approaches that cross disciplinary boundaries are useful, particularly when it comes to what are sometimes known as "complex" or "wicked" problems (Munnik and Burt, 2013).

## 1.6. Layout of this thesis

Following a one-page abstract, Chapter 1 introduces the Grootfontein aquifer. It describes why the Grootfontein aquifer has been chosen as a case study, and why it is relevant to groundwater resource stewardship in South Africa. Chapter 2 introduces the methodology including the challenge of combining different data types and research methods into a "mixed methods" case study. It describes the research methods and how the resulting data has been treated and analysed.

A literature review is described in two parts, Chapter 3 and Chapter 4. The first part examines the wider context of groundwater in the world and in South Africa. The second part focuses on the North West dolomites and particularly on the Grootfontein aquifer. Chapter 5 discusses the hydrogeology of the Grootfontein aquifer, and presents an updated hydrogeological description and water balance. Chapter 6 describes the institutional structure and the main interest groups or "participants" at Grootfontein.

Chapter 7 summarises the findings of the research work derived from each of the three main research methods, revisits the hypotheses, and discusses sub-questions related to the main research question. It discusses alternative hypotheses, and revisits the main research question. It uses the Steenkoppies aquifer as corroborating evidence. It also describes the potential implications of the research for groundwater governance and natural resource stewardship in South Africa.

## 1.7. Conclusions

The Grootfontein aquifer, a potentially prolific source of excellent quality water located in a dry part of South Africa, is poorly managed. Water levels in the aquifer have been falling for many years, but effective management measures have never been implemented. The research question of this study is "What is necessary for the successful management of the Grootfontein aquifer?". The primary hypothesis is that an integrated understanding of both the technical and hydrogeological dimension, as well as the social or institutional dimension, is required in order to make progress. These technical and institutional dimensions interact, producing unexpected outcomes. Aquifer management is often seen either as a mainly hydrogeological issue, or as a question of water allocation - but these are two sides of the same coin.

Not only do institutional features frequently determine the range of possible management outcomes, but aspects of the social and institutional system control physical characteristics such as available yield (through siting of boreholes or changes in water levels), groundwater quality (through pollution or intrusion of poorer quality water due to pumping) or even recharge (for example recharge changes caused by lower water tables, or changing land-use). It is necessary to move beyond the idea that the physical aquifer should be described first, after which management interventions can be tailored to fit the physical aquifer. The range of possible outcomes is partly or even mainly controlled by institutional structures, and not the hydrogeology. These institutional structures, however, partially respond to the hydrogeology and evolve as the hydrogeological conditions change. The Grootfontein aquifer therefore needs to be seen as a hydro-social system for the best management outcomes. The term "hydro-social system" used here emphasises the interdependence of institutional and hydrogeological features, and does not imply that the groundwater dynamics are dependent on the wider social or institutional context (see Section 3.3.4).

# 2. Methodology

## 2.1. Introduction

This chapter describes the analytical approach of this research. It describes the different sources of data used in this study, and the ways in which these sources have been integrated in a mixed methods case study approach to answer the research question. It includes a list of interviewees and a case study database showing the data types used (Table 2-2). The principles used in the analysis of the data are then described, together with the strategies used to maintain logical consistency.

The different study areas of the physical and social sciences, together with the different research methodologies, have contributed to a divide between the two in the modern world, famously described by CP Snow is his lecture and writings on the "two cultures" of the sciences and the humanities (Snow, 1961). This divide has echoes on contemporary university campuses world-wide, where the sciences and the humanities have separate faculties and buildings, different criteria for entry, and confer differently titled qualifications. Although misunderstandings between the two may well be over-emphasised and even caricatured, differences do persist. Some scholars of the humanities may become exasperated by what they perceive as the narrow focus and materialism of physical science, whilst some physical scientists are uncomfortable with the metaphysical nature of some research areas in the social sciences.

Such "cultural" differences between the physical and the social sciences make it harder to integrate knowledge from both, particularly in fields such as water management where complex or "wicked" problems require understanding and insights drawn from both (Rubenstein et al., 2016). Recognition of this has contributed to a movement emphasising the crossing of disciplinary boundaries, including the degree of integration between disciplines captured by a hierarchy of terms from "multidisciplinary" to "cross-disciplinary", "interdisciplinary" and "transdisciplinary"(Munnik and Burt, 2013). In the earth sciences, movements such as Earth Systems Science integrate knowledge from fields such as geology, hydrology, biology and atmospheric physics to better understand the earth as a functional whole (de Wit and Booth, 2016). The notion of the "Anthropocene" (Waters et al., 2016) and James Lovelock's "Gaia hypothesis" (Lovelock, 1979) emphasise the growing recognition that human activities and earth systems are interdependent and should be considered together. Transdisciplinary cooperation is however more common between disciplines related by their approach and generally sharing the same university faculty (such as hydrology and microbiology, politics and economics, or psychology and medicine). Earth Stewardship Science (de Wit and Booth, 2016:7) recognises this, and emphasises dialogue across "traditional natural and social science divides" to tackle complex trans-disciplinary problems[5].

## 2.2. Research approaches at Grootfontein

Previous research into the groundwater resource and its management at Grootfontein and other similar South African aquifers can be grouped along disciplinary lines as described above. One approach emphasises the physical science characteristics of the aquifer, whilst another concentrates on social science, policy and the law.

A physical science research approach focuses on the hydrogeology of the Grootfontein aquifer and the delineation of its physical parameters. The Grootfontein aquifer is notable for the large amount of hydrogeological work that has been done there, and the consequently good hydrogeological understanding. This hydrogeological work continues today – for example, in 2015 the Department of Water and Sanitation began a study of the water levels and abstractions at Grootfontein based on available water level and abstraction data. There are numerous studies of recharge, compartmentalisation, water quality and other physical characteristics of the North West dolomites (see Chapters 3 and 4). There is an implicit assumption that this work – and the knowledge it produces – will inform policy and help manage the groundwater resources (the technical work is not, after all, done for its own sake). Conversely, where policy appears to be failing, it is often assumed that technical information is lacking. For example, lack of knowledge of volumes pumped by irrigating farmers may be (correctly) identified as a constraint on managing falling water levels, but discussion of how this knowledge would be used in a practical effort to reduce abstractions is less common. At its worst, the physical science approach sees the solution to management failings at Grootfontein in further technical

[5] Earth Stewardship Science is "a new, broad intellectual field in tune with contemporary global perspectives of the world and its complexities; it provides a far broader focus of study than that of 'Climate Change', 'Sustainability Science', 'Development Studies', or 'Earth System Science'. Its consilience approach seeks a deeper understanding of people and planet issues of both local and global significance; and has the potential to make a major impact on the way Africa manages its resources and how it responds to the many pressures on diversity, environment, and society; and how it relates to poverty and well-being" (de Wit and Booth, 2016:8).

work or more precise technical definition of the problems, with the issue of how this would inform policy seen as outside of the scope of enquiry, or even relatively trivial.

A social science research approach tends to emphasise policy, organisations, funding and other resources, and interactions between people and groups. Whilst little social science or policy work has been done at Grootfontein specifically, a body of social and policy research exists for the North West dolomites, for groundwater in South Africa, and for South African water resources in general. At its worst this can resemble a generic set of prescriptions that ignores how local water resources physically exist or integrate into the wider economy, even where there is a stated commitment to local knowledge and expertise. For example, water management policy in South Africa still suffers from a bias towards surface water (DWA, 2010a), one outcome of which is that the major units of water management in North West Province (as elsewhere) are surface water catchments, even though these are mostly irrelevant to the groundwater aquifers that constitute the province's most important water resource (see Figure 3-2). What are seen as technical distinctions or engineer-led initiatives may be minimised or disparaged. For example, Allan (2003), Wester et al. (2009), and others describe the "hydraulic mission" or techno-centric attempts to control water, and its apparent eclipse by more modern practices that emphasise sustainability and the environment[6]. This is echoed in contemporary developed-world opposition to the building of large dams and other hydraulic infrastructure in poor countries (Muller, 2014). The discourse of water allocation reform (WAR) sees water problems in South Africa as fundamentally those of equitable allocation and therefore amenable to state or macro policy, rather than local (and more technical and procedural) problems concerned with pollution, distribution, operation and maintenance, funding, and data availability (e.g. Van Koppen and Schreiner, 2014a).

If the natural sciences sometimes wrongly assume that research findings will be seamlessly translated into policy, then the social science view is that policy can be implemented with relatively little regard for the hydrological realities. Obviously, neither (caricatured) approach is particularly helpful and the generally poor state of the North

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[6] David Blackbourn's book "The Conquest of Nature: Water, Landscape and the Making of Modern Germany" describes the evolution of hydraulic policy in Germany, from the early draining of swamps for agriculture through to "hydraulic mission" style control of rivers, to today's more holistic views such as accomodating rather than preventing flooding. Acknowledged by Blackbourn, but not always by others, is the way in which engineering-led approaches underpinned the modern developed world and provided the vantage point from which the "hydraulic mission" could be criticised (Blackbourn, 2006).

West dolomite aquifers illustrates the limitations of current approaches. The issue is complicated by the interdependence of the social / policy side and the natural science side – whilst the fundamental hydrogeology might govern what is possible in terms of groundwater use, it is policy or ideology (and social science) that determines where scientific efforts should be concentrated, ranking and ordering scientific problems according to policy and the democratic mandate, and allocating resources accordingly.

This researcher argues that a combined research approach is necessary instead, and that neither a physical science approach nor a social science approach on its own improves water management. Falling groundwater levels and other problems at Grootfontein, despite sound technical knowledge and widely-respected South African water laws and policies, suggest the need for a broader view. This research aims to understand more of the full spectrum of technical, social, policy and institutional issues that seem to apply.

## 2.3. The Grootfontein mixed-methods case study

It has been assumed that the management failings at Grootfontein may be due to any one of a range of technical, policy and institutional factors, or more likely some (unknown) combination of these. A mixed-methods approach, combining quantitative and qualitative techniques and methods, has therefore been selected to investigate the Grootfontein case-study (Yin, 2009). Although the methods may differ, for example water sample collection versus attending stakeholder meetings as a participant-observer, each method retains a focus on the research question. Methods of investigation may also overlap and complement one another – for example, water sampling in the field may lead to a conversation with an irrigating farmer about sustainability, or a presentation in a policy meeting may have information on the flow rate of an important spring. This mixed-methods approach helps the researcher to address broader or more complicated research questions (Yin, 2009). However, the mixed methods approach, and the incorporation of qualitative evidence, raises questions of epistomology and bias.

A major philosophical or epistomological question is "what do we know, and how do we know it?" This has not been satisfactorily resolved (della Porta and Keating, 2008). In the social sciences, the logical positivist tradition emphasises the clear distinction between myth and truth, and sees the task of the researcher as discerning and describing an objective, knowable, external reality (della Porta and Keating, 2008). This is a familiar approach to natural scientists. Neo-positivists accept probabilistic approaches and a degree of uncertainty, an approach also familiar to natural scientists (e.g. quantum physics, or numerical techniques in groundwater and climate modelling). Constructivists, interpretivists and humanists accept increasing degrees of subjective interpretation when it comes to describing reality, and focus increasingly on meaning rather than some (in any case impossible to define) external reality (della Porta and Keating, 2008). These gradations have echoes in the distinction between realist and post-modern art and literature, or in the divide between economic behaviourists and institutionalists.

These matters are important in any study where subjective views or approaches are a necessary part of the work, since they encompass people's perceptions, motives, normative drivers and other institutional characteristics as well as the less controversial (from an epistomological and ontological standpoint anyway) study of the physical characterists of the Grootfontein aquifer. The issue also raises the question of "units of analysis" (della Porta and Keating, 2008) – in other words, should the study focus on individual actors, or on groupings of individuals?

Economic behaviourists and positivists would see the individual as the fundamental unit of analysis, possessed of "free will" and able to make independent decisions based on "facts". A more constructivist approach would see value in grouping individuals on the basis of institutional characteristics (e.g. by class, profession or organisational affiliation), since these to a greater or lesser extent determine the normative worldview of individuals and largely define their range of options. Both approaches probably have their place in this study. However, it would seem foolish to ignore the strong influence of social institutions on human behaviour, and the extent to which such institutions are formed and perpetuated by the groups to which an individual may belong. This study therefore takes a standpoint somewhere between the logical positivists on one side, and the humanists on the other – there is indeed an objective reality, and on aggregate it is a prime driver of human behaviour, but institutional strategies for dealing with reality vary between individuals, groups and over time and space. Just as human behaviour (institutions) can alter physical reality (e.g. overpumping an aquifer), so the objective physical reality can influence human institutions (e.g. behaviour such as economic strategies may change in response to a lack of water). Once a degree of subjectivity is accepted, due both to the institutional background of this researcher, as well as the difficulties inherent in investigating abstract concepts such as trust, the problem of bias becomes important.

This researcher comes from a particular socio-cultural background in South Africa – white, male, English-speaking, relatively affluent, and tertiary-educated. A friendly professional relationship also exists between this researcher and some of the other people (or "participants") in this study – for example, with professional hydrogeologists at the Department of Water and Sanitation (DWS) in Pretoria and Mahikeng. These relationships in some cases pre-date the study, and in others developed during the study. A complex web of institutions, based partly on some mixture of these identity characteristics, governs not only how this researcher may see and evaluate other participants in the study, but also how these participants perceive this researcher.

It is easy to appreciate some of these issues – for example the difference it can make being a first-language Afrikaans speaker as compared with being an English speaker when interviewing white commercial farmers – and strategies can be developed to overcome potential misunderstandings such as working together with an Afrikaans speaking hydrogeologist colleague. In other cases, one's own bias and the bias of other participants may be hidden or sub-conscious – for example the difference in being an older, male researcher as opposed to a younger female researcher changes the way one is perceived, but it is not always easy to keep this in mind[7]. One's professional background or perceived links to a professional establishment also carry weight and meaning. Rural African participants may place a greater emphasis on age than an urban white participant might. Ultimately, even if one's own bias could be known and overcome, the response of participants to questions and to the study in general is determined to some (unknown) extent by these things.

A further source of bias would be the documents, datasets and interviewees available to the researcher. These sources are themselves mediated and even primarily constructed by institutional structures, and even the most wide-ranging and even-handed survey of documents, datasets and informants would likely reproduce the institutionally-determined bias inherent in these sources. For example, the long history of hydrogeological work by DWS and others on the Grootfontein aquifer, and the numerous reports produced as a consequence, can be contrasted with the relative lack of

[7] This issue became clearer during discussions with a visiting British female researcher working on groundwater at Dendron in Limpopo Province during 2014 and 2015. Some of the problems that she experienced in accessing data and interviewees highlighted the potentially complex institutional issues that partially control this kind of research.

studies on other aspects of the aquifer (e.g. the economic or the socio-political contexts), and as a consequence a researcher might be tempted to stress the former and minimise the importance of the latter.

An "unbiased" approach is therefore an ideal to be aspired to, and very difficult to achieve in practice. Alternative strategies for dealing with inbuilt bias must be found. The most important of these is "triangulation" (Yin, 2009), useful in a mixed-methods approach, in which different strands of evidence are used to underpin a research finding. For example, rather than wholly trust interviewees who maintain that a particular aquifer is over-exploited, water level readings as well as official reports published by DWS can corroborate this. A related method is to use the absence of something to triangulate a finding. This is helpful when dealing with more abstract issues. For example, if interviewees state that levels of trust are low, then the absence of institutions that might indicate trust (such as well attended water management meetings) could be taken as supporting evidence. Clearly, a mixed-methods study in which the different methods could be used to triangulate or bolster findings related to the main research question would be most useful. The actual methods used in the mixed-methods study (i.e. the design of the study) are therefore important, and are dicussed in the next section.

## 2.4. Methods of investigation

Three main methods have been used in this study to investigate the research question. These are a comprehensive literature review, a hydrogeological study and conceptual model, and institutional analysis carried out by interviews and participant-observation.

### *2.4.1. Literature review*

The literature review illuminates the general background to the study, including the choice of a mixed-methods case study as a research technique and the identification of possible pitfalls. It was fundamental to defining the research question and the main hypothesis. The literature review is also a research technique in itself, since the opinions and findings of other researchers, where they overlap with this research question, are important and provide insights into this study and additional evidence for findings made. It helps to focus the other research methods, and in some cases eliminates rival hypotheses without the need for further work. The literature review is also important in describing the wider context important to this study (e.g. groundwater occurrence in South Africa, theory of institutions, or water management policy).

Work on the literature review began as part of Water Research Commission (WRC) project K5/2158 "Favourable Zone Identification for Groundwater Development: Options Analysis for Local Municipalities" (Cobbing et al., 2014), in which the hypothesis that groundwater supplies to local municipalities were threatened or mistrusted due to poor hydrogeological data was questioned. The groundwater-based water supply to the town of Mahikeng was used as a case-study. However, work on the general question of the role of groundwater in South Africa and its contribution to rural domestic water supplies in particular goes back to 2005 to a WRC project aimed at assessing groundwater research needs in the eastern part of the Karoo Basin, including much of the former Transkei (Murray et al., 2006).

The literature review has been split into two separate chapters. The first literature review chapter (Chapter 3) concentrates on the wider context of groundwater in the world and in South Africa. It also covers the various policies, planning documents and tools, and organisations that pertain to groundwater in South Africa. Both technical or hydrogeological, and policy and institutional matters, are covered.

The second literature review chapter (Chapter 4) focuses in on the North West dolomites, and on the Grootfontein aquifer in particular, describing them technically but also discussing their current governance arrangements and the various relevant organisations and groups. Both chapters comment critically on some of the key literature and ideas, and show how these have impacted on the study area.

The literature review aims to cover the main documents and other sources of information on groundwater occurrence and availability nationally and in the North West dolomites, as well as major documents and ideas relevant to modern groundwater governance both internationally and in South Africa. Some of the over-arching philosophies or ideologies behind current approaches to water governance in South Africa, particularly integrated water resource management (IWRM) and decentralisation, are derived from a still wider array of sources. It was not possible to review all of these sources, but a significant sub-set of the most influential sources is covered.

The literature on the Grootfontein aquifer described in Chapter 4 is covered in more detail, with the aim of assessing every available published paper or report on the groundwater resources or groundwater governance initiatives of Grootfontein.

Published documents on broader groundwater occurrence and governance come from a wide variety of sources including journal and book publishers, research organisations such as the CSIR and the Water Research Commission (WRC), the World Bank and United Nations organisations, the Department of Water and Sanitation (DWS), and South African white papers, parliamentary proceedings and acts of parliament. Technical material on the Grootfontein aquifer, on the other hand, is mostly confined to journal papers and conference proceedings, WRC reports, and the Geohydrology[8] Report (GH) Series of the Department of Water and Sanitation.

### *2.4.2. The hydrogeological conceptual model*

One of the main assumptions of this study is that there is sufficient hydrogeological or technical information to underpin defensible management decisions or policy. This is based on the Grootfontein aquifer being one of the best studied aquifers in South Africa. In order to test whether the current hydrogeological understanding of the aquifer is indeed broadly correct – and to demonstrate that it is a sufficient basis for management policy – it is necessary to describe an up to date conceptual hydrogeological model of the aquifer. A conceptual model describes the hydrogeological parameters of the aquifer (recharge, abstraction, storage, groundwater quality, etc) so that a water balance can be derived and the potential impacts of management interventions can be assessed. New data collected during fieldwork for this research has been combined with existing data for the conceptual model.

Collection of new data for the Grootfontein aquifer included water level measurements, and the collection of sixteen water samples for major and minor ion content, as well as stable isotope ratio measurements. This field sampling was done over a series of five visits to the study area between April and July 2015. Existing data from other individuals and organisations was also obtained during 2014 and 2015. In some cases this data is freely available (e.g. water level measurements made by DWS), but in many cases it was less easy to obtain and access had to be negotiated with the data holders (e.g. irrigation abstraction estimates). A knowledge of DWS and existing relationships with DWS staff members was essential here. Existing data obtained and collated for this study included rainfall and evaporation data, abstraction volumes from the Grootfontein wellfield, estimates of abstraction volumes from irrigation boreholes, estimates of municipal water use by Mahikeng, flow rates of the Molopo Eye spring, water level measurements from

[8] In South Africa the words geohydrology and hydrogeology are used synonymously to mean the study of groundwater.

the DWS water level monitoring network, stable isotope data from the early 1980s, topographic maps and satellite images, geological maps, hydrogeological maps, and digital data for the compartment boundaries, farm boundaries, geological and hydrogeological boundaries, settlement areas, town locations, and political and administrative boundaries. (See Table 5-1 in Chapter 5 for an inventory of hydrogeological data used.)

Time-series data and water sample results were put into MS Excel format for comparison and analysis. Spatial data, or data with a spatial component, was converted to shapefile format (.shp) and initial analysis was done using ESRI's ArcGIS software. In 2015 the spatial database was moved from ArcGIS to the freeware software product QGIS (version 2.8.1 "Wien"), which was also used to produce the maps in this thesis. Apart from being free, QGIS was found to be more flexible than ArcGIS and better at integrating a variety of vector and raster data formats. Google Earth software was used to locate certain spatial features, to plan sampling and other fieldwork, and to assist in identifying irrigated areas. Where required, .kmz files exported from Google Earth were added to the QGIS spatial database.

The new data collected, and the collated existing data, were supplemented by information from the literature for key parameters (e.g. some recharge estimates, and hydraulic parameters such as transmissivity and storage). The literature review also provided historical estimates of spring flow volumes and irrigation abstraction data, as well as previous conceptual and numerical models of Grootfontein.

The hydrogeological data is described and interpreted in Chapter 5, with the aim of arriving at a defensible conceptual aquifer model and water balance. This conceptual model then brackets or defines the range of management options in a physical sense – i.e. what is physically or quantitatively possible. It also shows the contemporary state of hydrogeological knowledge of the Grootfontein aquifer, and allows discussion of the extent to which remaining hydrogeological uncertainty might contribute to poor management outcomes. The conceptual model and discussion also serve to show that current management outcomes at Grootfontein are indeed poor, based on an analysis of water level changes and the water balance.

### *2.4.3. Institutional analysis and the interviews*

A major contention of this research is that the institutional structure of the Grootfontein aquifer is a key part of understanding why management outcomes are poor. How do the individuals and organisations in and around Grootfontein interact, and what appear to be the drivers of this? How important are abstract issues such as trust and reciprocity? What are the drivers of poor management? As mentioned, it is not easy to obtain information on institutions (especially informal institutions not codified in law), compared with physical parameters such as water levels. They are subject to interpretation and bias, they change in response to external events and to other institutions, and they are difficult to rank and to document.

Yin (2009) describes six sources of evidence commonly used in case studies: documentation, archival records, interviews, direct observations, participant-observation and physical objects. Documentation, archival records and physical objects (i.e. water samples) are particularly important to the literature review and hydrogeological methods of investigation. All six sources shed light on the institutional background.

Interviews were a particularly important part of the institutional analysis study method. When the WRC project K5/2158 "Favourable Zone Identification for Groundwater Development: Options Analysis for Local Municipalities" (Cobbing et al., 2014) began, field interviews were chosen as a research tool. A series of interviews carried out in 2013 for K5/2158 are an important contributor to this current study and constitute the first interview data set. These interviews were carried out in the Eastern Cape, Gauteng, North West and Limpopo Provinces, and included interviews in Mahikeng (see Table 2-1 below). The combined interview data helped to provide initial answers to questions such as "Do municipalities favour groundwater?", or "What are the main reasons for groundwater supply unreliability?", questions that would be difficult to answer using other research techniques. As mentioned, interview data needs to be supported by other sources of information (corroboration or triangulation).

Interviews for K5/2158 were initially designed as a rigid series of questions, whose answers could be compared easily and objectively – ideally by converting them to numerical scales or yes/no formats. It soon became clear that the questionnaire format was preventing interviewees from commenting on what they thought was important – a problem since interviewees were generally experts in their field. The questionnaire format also tended to reflect initial assumptions and bias on the part of this researcher. The interview format was therefore modified to provide a more flexible basis for discussion, and a more general conversation was encouraged that allowed interviewees to expand on what they considered important whilst still focusing on the research questions. This technique is referred to by Yin (2009) as "guided conversation", and by other authors as "semi-structured" interviews (e.g. Mjoli et al., 2009). All told, 25 interviews were done in this early phase of the work, taking place between 11 March and 22 November 2013.

This semi-structured interview approach was exclusively used when fieldwork centred on Grootfontein began in earnest, in mid-2014.

Interviews were solicited initially based on this researcher's knowledge of the study area, by phone call or email. In some cases it took many phone calls or emails to arrange an interview, and in one or two cases interviews were refused or cancelled at the last minute by the interviewee. Recommendations by interviewees formed an important way of finding new people to interview, and in some cases (e.g. some of the irrigating farmers, or DWS technical staff) an introduction by a first interviewee was the key to obtaining permission to interview further participants. A primary aim was to interview stakeholders or participants in all of the identified groups or organisations with a stake in the groundwater at Grootfontein. However the selection of actual interviewees themselves also depended on one interviewee recommending another, the availability of interviewees, the willingness of interviewees to be interviewed, logistical considerations, and several other factors. The participants interviewed do not therefore constitute a "representative" sample; rather the interviews reflect as wide a set of viewpoints as could be obtained within the boundaries of funding, time and luck.

The early interviews for K5/2158 (and forming a part of this research) were all recorded using a digital recording device, although this was later stopped in the belief that interviewees were more reluctant to speak freely when they were being recorded. However, the value of recording interviews soon became apparent, and where possible all of the one-on-one interviews done after early 2015 were recorded. A smartphone replaced the digital recorder in later interviews, being easier to use and less intimidating. Both devices allowed recordings to be stored in .wav format. In certain cases interviewees were reluctant to be recorded and recording was not carried out, since at the time this researcher judged that, on balance, more value could be derived by not recording. In one case an interviewee agreed to be recorded, but it was so obvious that s/he was uncomfortable with the process that the recording was stopped after about fifteen minutes and the interview proceeded more easily. In at least four cases interviews were conducted outdoors, and recording was not possible for some of these (e.g. standing in a barn).

Notes were taken during all interviews whether recorded or not, and in many cases further notes were taken as soon as possible after the interview to document impressions and background information that is easily forgotten. In many cases notes were made before each interview too, to help in focusing the interview and in tailoring interview questions. Along with the interview transcripts, these notes form one of the data sources for this research (see Table 2-2 below). This researcher was accompanied by research colleagues for some of the interviews, and in these cases the recollections of the colleagues added value to the notes made.

In some cases interviews took the form of meetings with a group of respondents. These were not recorded, but notes were always taken. In some of these meetings this researcher was a recognised participant in the meeting, for example a water infrastructure tender briefing in Mahikeng, or a meeting deliberately called to discuss this research at DWS. These can be classified as "participant-observation" (Yin, 2009) since this researcher took part in the meeting, was able to ask questions, and to some extent steered the direction of the meeting. In other meetings this researcher was an observer only, having first gained permission to attend and observe the meeting as a researcher and student. An example of this would be attending a Molopo Stakeholder Operating Forum meeting or a Dam Operating Rules meeting convened by DWS in Mahikeng.

Where interviews were recorded, the recorded data was downloaded and backed up in .wav format as soon as possible. Transcription of interview data is time consuming (Yin, 2009) and was done in late 2015 after all of the interviews were completed. In hindsight immediate transcription after each interview would have been better, since the transcription process raised questions and allowed connections to be made that would have informed subsequent interviews. The freeware software product "Transcriptions" (version 1.1) was used to transcribe the interviews. This software allows the interview playback to be slowed down enough for typing to keep up, without distorting voices. The software also has pause and playback features, and the transcriptions are time-stamped at the end of every paragraph, making it easier to find specific parts of recordings.

Three of the interviews were carried out mainly in Afrikaans (but with questions asked mainly in English), and two or three others partly in Afrikaans (the home language of many of the irrigating farmers in the Mahikeng area). These interviews were transcribed in the original Afrikaans, and were then translated into English, with each paragraph of Afrikaans being followed by its English translation. With hindsight it would have been valuable to allow all interviewees to use their home language (only a minority spoke English as a first language) because this would have allowed interviewees to express themselves more clearly and easily. However, since this researcher speaks only English and limited Afrikaans, the transcription and translation challenges would have been daunting.

In total, 63 interviews were carried out, including meetings where this researcher was either a participant-observer or an observer. Of these 63 interviews, 25 were recorded and transcribed for a total of 866 minutes of recorded time, yielding 139 326 transcribed words (including translation). In some cases interviews continued after the recording device was switched off, and information from these was captured as notes.

Details of the interviews carried out for this research, including those done during K5/2158, are shown in Table 2-1. The interview transcripts are provided as a separate document. Names of interviewees have been removed, but this (confidential) information has been provided to the examiners of this thesis.

Yin's (2009) "direct observation" covers a range of activities and was an important source of data for this study. These included attending meetings as an observer (see above), making field visits to infrastructure such as public water supply boreholes, the Molopo Eye, the Itsoseng boreholes, and the Setumo Dam, viewing irrigation and land-use practices, visiting the offices of important stakeholder groups such as municipalities and observing working practices, and spending time driving on roads and being "in the landscape" at Mahikeng and surrounds. Visits to the workplace of important interviewees or informants, where the working conditions can be observed, emerged as a valuable source of information that would not have been available if interviews had been carried out by telephone or on-line questionnaire, for example.

Where and how people work, the physical circumstances of their office or professional environment, have a bearing on their priorities and the work that they do. A technical professional such as a hydrogeologist, working in a windowless temporary office without access to the computer server, to maps, to field transport or other essential tools, is much less efficient than a well-resourced individual, particularly when one considers the psychological as well as material affects of these things. It is only by meeting such informants in their professional surroundings that one can gain a nuanced appreciation of the particular challenges that they might face. This information was captured in notes following the direct observation.

### *2.4.4. Ethical considerations*

Human subjects of contemporary (i.e. not historical) studies require protection from any unforeseen or unintended consequences of the research (Yin, 2009). This is particularly important when the issue may be seen as controversial, or could be interpreted as having a bearing on how well certain participants are performing their professional functions or even whether they are obeying the law. All persons involved in such a research study must give their informed consent. They must be protected from any harm, including the use of any deception, and their privacy and confidentiality must be protected (Yin, 2009). Nelson Mandela Metropolitan University Ethics Clearance procedures are particularly clear for vulnerable groups such as the handicapped or children, and in cases where individual interviewees, respondents or other participants might be identified.

When making contact with potential interviewees, a letter describing the study and listing the contact details of this researcher and his supervisors was made available (Appendix A). This letter states that interviewees will not be identified to anyone apart from the study supervisors. This confidentiality requirement has been observed in this thesis. During interviews, previous interviewees were not identified, except in cases where an interviewee was aware already of the previous interview (e.g. a farmer who had been recommended by a previous farmer interviewee). Where water samples were taken, a copy of the water sample results was sent to the owner of the sampled borehole. All respondents were informed that this researcher was working on a PhD study, partially supported by the Water Research Commission, and had no affiliation with any state organisation or authority. None of the outputs of the research are confidential, apart from the identities of the interviewees.

Considering the potentially controversial topic, the groundwater management difficulties and the mistrust between some of the organisations, the response of almost all potential participants was very positive. Many participants went out of their way to assist this researcher and gave up their time willingly and graciously.

## Table 2-1 List of Interviewees

| No | Province | Date | Rec'd? | Location | Interviewee Role | Affiliation | Main interest |
|---|---|---|---|---|---|---|---|
| 1 | E Cape | 11 March 2013 | **Y** | East London | Consultant engineer | Private consultancy | Water scheme operation |
| 2 | E Cape | 11 March 2013 | N | East London | Consultant engineer | Private consultancy | Small-scale irrigation |
| 3 | E Cape | 12 March 2013 | **Y** | East London | Borehole O&M technician | Private consultancy | O&M of small schemes |
| 4 | E Cape | 12 March 2013 | **Y** | East London | Consultant hydrogeologist | Private consultancy | General GW, water scheme data |
| 5 | E Cape | 13 March 2013 | **Y** | East London | Municipal engineer | District Municipality | Water scheme operations, planning |
| 6 | E Cape | 13 March 2013 | **Y** | East London | Scientist | Government Department | Rural asset management |
| 7 | E Cape | 14 March 2013 | **Y** | East London | Engineer | Water Board | Water supply operations |
| 8 | E Cape | 15 March 2013 | **Y** | Port Alfred | Consultant hydrogeologist | Private consultancy | Small town water supplies |
| 9 | Limpopo | 19 March 2013 | N | Polokwane | Hydrogeologist | Government Department | GW supply and management |
| 10 | Limpopo | 19 March 2013 | N | Polokwane | Hydrogeologist | Private Consultancy | GW supply and management |
| 11 | Gauteng | 26 March 2013 | N | Midrand | Municipal officials (meeting) | Municipalities | Water supplies |
| 12 | NW | 12 June 2013 | N | Mahikeng | Consultant engineer | Private consultancy | Urban & rural water supplies, planning |
| 13 | NW | 12 June 2013 | **Y** | Mahikeng | Consultant engineer | Private consultancy | Water supplies in rural areas |
| 14 | NW | 13 June 2013 | **Y** | Mahikeng | Engineer | Water Board | Water supply operations |
| 15 | NW | 16 July 2013 | N | Kathu | O&M technical manager | Private consultancy, formerly water board | Rural GW supplies, O&M |
| 16 | NW | 17 July 2013 | N | Mahikeng | Technical manager | District Municipality | O&M and water supply operations |
| 17 | Gauteng | 22 July 2013 | N | Pretoria | Scientist | Government Department | Rural water supply backlogs, planning |
| 18 | Limpopo | 24 July 2013 | N | Mokopane | Hydrological technician | District Municipality | Rural GW supplies |
| 19 | Gauteng | 6 August 2013 | N | Pretoria | Economist | Government Department | Infrastructure funding |
| 20 | Gauteng | 6 August 2013 | N | Pretoria | Soil scientist and farmer | University and Water User Association | GW irrigation, Water User Associations |
| 21 | Gauteng | 6 August 2013 | N | Pretoria | Hydrogeologists | Private consultancy | GW supplies & technical evaluation |
| 22 | Gauteng | 13 August 2013 | N | Pretoria | Hydrogeologist | Private Consultancy | GW supplies |
| 23 | Gauteng | 7 October 2013 | N | Pretoria | Manager | Government Department | Municipal water supplies |
| 24 | Gauteng | 21 Oct 2013 | N | Pretoria | Policy specialist | Multilateral development partner | Water policy |
| 25 | Gauteng | 22 Nov 2013 | N | Pretoria | Hydrogeologist | Government Department | GW assessment and management |
| 26 | NW | 6 March 2014 | N | Hartbeespoort | Hydrogeologists (meeting) | Government Department | GW assessment and management |
| 27 | Gauteng | 17 March 2014 | N | Pretoria | Hydrogeologist | University | GW assessment and management |
| 28 | Gauteng | 11 June 2014 | N | Pretoria | Soil scientist and farmer | University and Water User Association | GW irrigation, Water User Associations |
| 29 | NW | 10 April 2015 | N | Hartbeespoort | Hydrogeologist | Government Department | GW assessment and management |
| 30 | Gauteng | 22 April 2015 | N | Pretoria | Hydrogeologist | Government Department | GW assessment and management |
| 31 | NW | 30 April 2015 | N | Mahikeng | Hydrogeologist | District Municipality | GW assessment and management |
| 32 | Gauteng | 4 May 2015 | N | Pretoria | Engineer | Government Department | GW licensing |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 33 | NW | 12 May 2015 | **Y** | Lichtenburg | Farmer | Agricultural union | Water and farming |
| 34 | NW | 13 May 2015 | **Y** | Mahikeng | Engineer | Private consultancy | Municipal water supplies |
| 35 | NW | 13 May 2015 | N | Mahikeng | Hydrogeologists (meeting) | Government Department | GW assessment and management |
| 36 | NW | 13 May 2015 | N | Rooigrond | Farmer | Farmer | Grootfontein water use |
| 37 | NW | 13 May 2015 | N | Rooigrond | Farmer | Farmer | Grootfontein water use |
| 38 | NW | 14 May 2015 | **Y** | Rooigrond | Farmer | Farmer | Grootfontein water use |
| 39 | Gauteng | 26 May 2015 | **Y** | Pretoria | Engineer | Government Department | GW and licensing |
| 40 | Gauteng | 8 June 2015 | N | Johannesburg | Engineers (meeting) | Private consultancy | Dam operating rules |
| 41 | NW | 9 June 2015 | N | Mahikeng | Various (meeting) | Government Department | Dam operating rules |
| 42 | NW | 10 June 2015 | **Y** | Zeerust | Water expert | Government Department | Municipal water supply to Mahikeng |
| 43 | NW | 10 June 2015 | **Y** | Groot Marico | Farmer | Farmer | Agricultural water planning |
| 44 | Gauteng | 15 June 2015 | **Y** | Pretoria | Hydrogeologist | Private consultancy | GW assessment and management |
| 45 | NW | 22 June 2015 | **Y** | Mahikeng | Engineer | District Municipality | Urban water supplies |
| 46 | NW | 23 June 2015 | N | Mahikeng | Engineer | Water Board | Urban water supplies |
| 47 | NW | 24 June 2015 | **Y** | Mahikeng | Farmer | Farmer | Agricultural water use |
| 48 | NW | 7 July 2015 | **Y** | Hartbeespoort | Hydrogeologist | Government Department | Water management |
| 49 | NW | 9 July 2015 | N | Mahikeng and Zeerust | Various (meetings) | Water Board | Rural GW supplies |
| 50 | NW | 21 July 2015 | **Y** | Hartbeespoort | Hydrogeologist | Government Department | GW assessment and management |
| 51 | NW | 21 July 2015 | N | Mahikeng | Hydrogeologist | District Municipality | GW assessment and management |
| 52 | NW | 22 July 2015 | **Y** | Mahikeng | Engineer | District Municipality | Urban water supplies |
| 53 | NW | 22 July 2015 | N | Mahikeng | Hydrogeologists (meeting) | Government Department | GW assessment and management |
| 54 | NW | 22 July 2015 | N | Mahikeng | Engineer | Water Board | Urban water supplies |
| 55 | NW | 22 July 2015 | **Y** | Rooigrond | Farmer | Farmer | Agricultural water use |
| 56 | NW | 23 July 2015 | **Y** | Rooigrond | Farmer | Farmer | Agricultural water use |
| 57 | NW | 23 July 2015 | **Y** | Rooigrond | Farmer | Farmer | Agricultural water use |
| 58 | NW | 23 July 2015 | N | Rooigrond | Farmer | Farmer | Agricultural water use |
| 59 | NW | 24 July 2015 | N | Mahikeng | Various (meeting) | Government Department | Regional water managment |
| 60 | NW | 24 July 2015 | N | Rooigrond | Farmer | Farmer | Agricultural water use |
| 61 | Gauteng | 11 August 2015 | N | Pretoria | Hydrogeologist | Government Department | Water use licensing |
| 62 | Gauteng | 12 August 2015 | N | Pretoria | Various (meeting) | Government Research Agency | Grootfontein GW |
| 63 | NW | 17 August 2015 | **Y** | Lichtenburg | Farmer | Farmer | Water management by farmers |

*Rec'd? = Recorded and Transcribed?*

*GW = groundwater.*

*O&M = Operation and Maintenance.*

## 2.5. The Case Study Database

Yin (2009) stresses the value of organising all of the data or evidentiary base of a case study into a formal case study database. This should include all of the data collected for a case study, and on which the final analysis or thesis is based. The four main classes of data for a case study database are notes, case study documents, tabular materials, and narratives (Yin, 2009). Notes include all notes made during the research, including the interview recordings, notes made during interviews, and notes made following discussions with research collaborators. Case study documents are reports, published papers, theses, and similar documents relevant to the research. Tabular materials include quantitative digital data such as water level records and rainfall records, and also (for the purposes of this study) spatial digital data such as vector and raster shapefiles. Narratives are preliminary analytic attempts on the part of the researcher to understand or interpret parts of the ongoing research work, and include items such as journal papers, conference papers, formal talks and emails to colleagues and research collaborators. Table 2-2 below summarises the case study database of this study:

**Table 2-2 Case Study Database**

| **1 - NOTES** | |
|---|---|
| **Description** | **Format** |
| Notes made during field interviews, 2013 to 2015. | Paper, stored chronologically. |
| Notes made before and after interviews and meetings, 2013 to 2015. | Paper, stored chronologically. |
| Interview recordings and transcripts (where interview recorded), transcribed in 2015. | Digital files (.wav for recordings, .doc for transcripts). |
| Notes following discussions with colleagues and research associates, 2007 to 2015. | Paper, stored chronologically, and digital files (.doc). |
| Notes following meetings with research supervisor, 2013 to 2016. | Paper, stored chronologically, and digital files (.doc). |
| Notes on ideas and theories, made during analysis of research material and during general study (e.g. reading journal papers), 2013 to 2016. | Notebook. |
| Photographs taken in the field, 2013 to 2015. | Digital files (such as .jpeg). |
| **2 - DOCUMENTS** | |
| **Description** | **Format** |
| Digital copies of journal papers, research reports, guidelines, summaries, policy documents, and similar documents. | Stored mainly in .pdf format and organised by topic (e.g. "water governance", or "drought"). Approximately 3100 items. |
| Hard copies of journal papers, published reports, grey literature reports and sets of guidelines. | Hard copy. Many of these are also held digitally, as above. Approximately 400 items. |
| Combined bibliography of relevant books, journal papers and reports. | MS Word format. Approximately 300 items. |
| Summary database of important reports and papers with short description, keywords and relevance ranking. | MS Word table (.doc) containing more than 200 items. |
| Hydrogeological, topographical and geological maps. | Hard copies. |

| 3 - TABULAR MATERIALS / DATA | |
|---|---|
| **Description** | **Format** |
| Water level data for monitored boreholes in and around the Grootfontein aquifer. | MS Excel and .csv files. |
| Spring flow data for Molopo Eye spring. | MS Excel and .csv files. |
| Field measurements (e.g. water levels or GPS readings) taken during fieldwork in 2015. | Paper, converted to MS Excel format. |
| Estimates of flows, pumping rates and water levels from interviewees, 2013 to 2015. | Paper, converted to MS Excel format. |
| Rainfall data from rain stations near Grootfontein. | MS Excel. |
| WARMS borehole abstraction data from DWS WARMS database | MS Excel. |
| Meter readings of the three remaining Grootfontein abstraction boreholes maintained by DWS for 2014. | .pdf converted to MS Excel. |
| Ion sample analyses and isotope results (collected for this study, and historical analyses). | MS Excel. |
| Irrigation and crop type estimates derived from satellite observations. | MS Excel. |
| Water level and spring flow data from historical reports such as DWS GH Series. | .pdf converted to MS Excel. |
| Spatial data files on farm boundaries, dolomite compartment boundaries, geology, hydrogeology, topography, satellite imagery, borehole locations, administrative boundaries, former homeland boundaries, human settlement boundaries, land-use, transport links, surface water courses, rainfall stations, town locations, surface water catchments, aquifer regions and evaporation. | Vector and raster digital files mostly converted to .shp format. |
| **4 - NARRATIVES** | |
| **Description** | **Format** |
| Formal reports written for the Water Research Commission (projects K5/2158 and K5/2429). | Hard copy and .pdf. |
| Journal papers (Cobbing et al., 2015, and Adams et al., 2015) and popular article in Water Wheel magazine on water supply to Mafikeng. | Hard copy and .pdf. |
| Conference papers and presentations (2014 2nd ChinAfrica Dialogue Forum on Water Resources, Guilin, China, and 2015 GWD Conference, Muldersdrift, Gauteng). | MS Powerpoint and .pdf. |
| Email correspondence with research colleagues on WRC and other research projects, 2007 to 2016. | Digital emails. |

## 2.6. Analytical approach

The three research methods described above (literature review, hydrogeological study, and institutional analysis) produce sets of data or sources of evidence as listed in the case study database above (Table 2-2). These different sources must be combined together to support a logical argument that addresses the main research question. As mentioned, it can be difficult to combine different sources that are qualitatively different (e.g. water level measurements and field interviews). Five main principles have been followed in the analysis of the data in an attempt to overcome this problem, as follows:

### *2.6.1. Principle 1: Focus on the research question*

A focus on the main research question allows the sources of evidence to be compared logically with respect to how they answer the question. Without this there is a chance that the study, with its different methods, might emerge as a (biased) description of the Grootfontein aquifer and its users. "How?" and "why?" type questions are useful in this regard (Yin, 2009). Each source of data can be evaluated partly by how well it contributes to addressing the research question.

This approach assumes that the primary research question is more important than alternative research questions (and their answers) posed by interviewees or bundled up as institutional assumptions in the data sources (e.g. a focus on technical hydrogeology in much of the available literature). Considering alternative explanations or hypotheses partly compensates for this focus on the primary research question (see below).

Computerised methods for identifying topics or keywords from interview transcripts and other documents, and formal Grounded Theory methods for developing new theories or themes during the analysis of data (Yin, 2009; and Glaser and Strauss, 2006) have therefore not been chosen as research strategies for the same reason.

### *2.6.2. Principle 2: Triangulation*

Combining multiple sources of evidence to answer important research questions is known as triangulation (Yin, 2009). The main research question and the sub-questions answered by this thesis should therefore be supported by more than one strand of evidence – preferably by all three main research methods, and by both qualitative and quantitative sources of evidence. Triangulation requires understanding the assumptions underlying each source of evidence (della Porta and Keating, 2008). As mentioned above, the related technique of using the absence of something as evidence is also useful.

### *2.6.3. Principle 3: Logic models and explanation building*

This thesis seeks to build logical explanations or answers to questions by stipulating sets of causal links between phenomena, that can be defended using the evidence (Yin, 2009). This can be an iterative process, in which plausible and rival explanations are tested and either accepted or discarded based on the evidence. The evidence base or logic should be such that the argument can be followed by an outside reviewer or examiner. The different sources of evidence should be linked by a shared logical treatment and relevance to the particular explanation or answer that is being argued. As discussed, this researcher accepts that institutional assumptions are built into the notion of "logic", but it is nevertheless a powerful technique. These approaches help to ensure what is known as the "internal validity" of the study (Yin, 2009) – in other words, does the study have an inherent, internal logic that can be easily followed?

### *2.6.4. Principle 4: Rival hypothesis testing*

A potential weakness with the predominant focus on the research question is that it might exclude plausible rival hypotheses or explanations at the outset, before the evidence is considered. This study therefore explicity examines plausible rival hypotheses and explains, with reference to the evidence, why they are not full answers to the research question. The primary hypothesis of this thesis is that an integrated understanding of the hydrogeological and the institutional aspects of the Grootfontein aquifer is required. This leads to a number of sub-hypotheses, and has the basic assumption that the groundwater management at Grootfontein is poor and that this poor management is not inevitable. Rival hypotheses, however, might include the assertion that hydrogeological knowledge is lacking, or that groundwater management policy provisions are inadequate, or that local government in South Africa is structurally unable to manage groundwater, or even that the Grootfontein groundwater resource will inevitably and irreversibly decline despite management efforts. Some of these rival hypotheses are implicit in various strands of the literature and the suggested policy responses to the situation. These rival hypotheses should be discussed and tested.

A second potential weakness is that a single case study (i.e. Grootfontein), chosen partly because it has an unusually rich history of hydrogeological research, is unrepresentative. This is a form of rival hypothesis, suggesting that research findings apply only to Grootfontein. It is countered partly by logical explanation building – i.e. it is shown that it is not the unique characteristics of Grootfontein that make management difficult. It is also countered by reference to a second case study, the Steenkoppies aquifer, which shares many characteristics with Grootfontein and anchors the Grootfontein findings.

These strategies help to promote what is known as the "external validity" of the study – i.e. can it be defended against external, rival theses? (Yin, 2009)

#### *2.6.5. Principle 5: Use of Ostrom structure for the institutional framework*

Despite the focus on the main research question, and the use of logical "explanation building" relying on the different sources of data, the analysis of the institutional background to the Grootfontein aquifer remains a challenge. Which abstract institutions should be discussed? Should people be discussed as individuals, or as groups? If they are grouped, then what characteristics should be used? How should institutions be treated that appear to overlap? The political economist Elinor Ostrom (1933-2012) has produced a body of influential work on water governance and "common pool" resource theory (discussed in Section 3.4). Ostrom (2005) defined "attributes" of both common pool resources and their appropriators, which if present make it more likely that institutions that promote local self-governance will arise. There is considerable scholarly consensus on these attributes (Ostrom, 2005). Whilst it is argued that not all of Ostrom's analysis applies to groundwater in South Africa, these resource and appropriator attributes are a convenient, succinct and defensible framework for the analysis of social institutions at Grootfontein. They underpin the structure of Chapter 6 of this thesis.

## 2.7. Conclusions

This chapter has described the techniques used to address the research question "What is necessary for the successful management of the Grootfontein aquifer?". The three primary research methods are the literature review, the hydrogeological assessment, and the institutional assessment. These form the basis of the next four chapters. The data types have been described, and the potential difficulties of reconciling both quantitative and qualitative data discussed. The five main principles of analysis broadly followed in this research have been described. The next chapter, the first part of the literature review, introduces groundwater world-wide and in South Africa, and its wider context of policy and ideas.

# 3. Groundwater policy and management

## 3.1. Introduction

All disciplines, including hydrogeology, are underpinned by a range of ideas, policies, laws, traditions and other relevant norms, habits or institutions; as well as the organisational forms that these take. This wider context governs the work and priorities of hydrogeologists. Although it may seem immutable this context is itself dependent on changing ideas and theories regarding how society is organised and evolves, what constitutes progress, and how this is to be achieved.

This literature review begins by describing the wider context of groundwater policy and management, and associated norms and habits. It describes Ostrom's (2005) institutional framework and introduces the resource and appropriator attributes. It summarises the organisations managing water in South Africa, and the technical groundwater assessment and planning tools available to them. The literature review ends with a discussion of operation and maintenance of groundwater supply systems. These topics help to explain underlying drivers of outcomes at Grootfontein, and possible options for intervention.

Groundwater is a "hidden resource" which can't usually be seen. As a result it is often overlooked by policy makers, including those in South Africa[9]. Margat and van der Gun (2013:120) state: "Most people have at best an incomplete notion of the groundwater resource they use and influence". Groundwater is more important in South Africa and worldwide than usually thought (UNESCO, 2004), with over half of South Africa's population dependent on groundwater for their domestic needs (Braune and Xu, 2006).

Around 98% of the world's available fresh water is groundwater[10], and estimates of the global total volume of fresh groundwater in storage range from 7 million $km^3$ to as much as 60 million $km^3$ (Price, 1996). Groundwater is the world's most extracted raw material,

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[9] The first version of this general introduction to groundwater was developed during Water Research Commission (WRC) project K5/2158 "Favourable Zone Identification for Groundwater Development: Options Analysis for Local Municipalities" (Cobbing et al., 2014). The findings of project K5/2158 were an outcome of this PhD research, and this researcher was designated as a PhD student at NMMU by the WRC when working on K5/2158.

[10] According to Margat and van der Gun (2013:8), 97.5% of the world's water is seawater. Of the remaining 2.5% that is fresh water, groundwater makes up 30.1%, with the inaccessible ice caps, glaciers and permafrost comprising 69.5%. Only 0.4% of the world's fresh water is found as lakes, rivers, wetlands, soil moisture, atmospheric water, and water in plants and animals.

with withdrawal rates in the region of 600 to 800 $km^3$ a year (UNESCO 2004; Shah et al., 2000). When that world figure is broken down into types of use, it is distinctly different from surface water use, and is biased towards more valuable potable water as follows: potable / domestic water (65%), irrigation and livestock (20%) and industry and mining (15%) (IAH, 2003). At world level (and in proportions that vary widely from one country to the next) groundwater supplies approximately 50% of drinking water needs, 20% of the demand for irrigation water, and 40% of the needs of self-supplied industry (UNESCO 2004). Groundwater supplies almost all drinking water in countries such as Austria, Bangladesh and Denmark; and in mega-cities such as Mexico City and Dhaka.

## 3.2. Groundwater in South Africa

People have used groundwater in southern Africa for millennia, both directly from springs, and indirectly as baseflow to rivers and lakes. Johannesburg's earliest safe water supply was groundwater, first from springs on the Witwatersrand and then pumped from the dolomite aquifers to the south-west of the city (the Zuurbekom dolomite compartment). Pretoria is located close to the prolific Pretoria Fountains spring to the south of the city centre, the town's earliest water source. Both Pretoria and Johannesburg still rely on groundwater for a proportion of their water supply today (Dippenaar, 2013). Perhaps the most important role of groundwater is that it is critical to ecosystems and "environmental goods and services" – an area often ignored in the past. As Burke and Moench (2000:1) state: "Groundwater is an often unnoticed and unacknowledged cornerstone in the foundation of many economic and environmental systems".

Groundwater is also vital to development and poverty alleviation, especially in rural areas. Professor Richard Carter of the international non-governmental / non-profit organisation the Rural Water Supply Network had the following to say:

> "Of the 780 million [of the global population] not yet served [with a safe water supply], the majority of these predominantly rural people will need to be supplied from groundwater. Groundwater matters to the human race. We misunderstand or mismanage groundwater at our peril. The dispersed nature of groundwater and the generally large quantities in natural storage in aquifers make it particularly suitable for serving rural communities in times of uncertainty about the climate and the natural environment." (RWSN, 2012:1)

Surface water resources in South Africa are nearly fully allocated for the country as a whole, and already over-allocated in some catchments (DWA, 2013). There is frequent mention of a potential "water crisis" in the South African media and elsewhere (e.g. Hedden and Cilliers, 2014). It is a fact that the average annual rainfall in South Africa of around 500 mm is well below the international average, and that about a fifth of the country by area receives less than 200 mm of rain per year[11]. Despite this context planners are deterred from wider groundwater development partly by questions of groundwater availability and sustainability.

In South Africa only about half of the available, renewable groundwater resource is used. According to DWA (2010a) the total Utilisable Groundwater Exploitation Potential or UGEP in South Africa is about 10.3 $km^3/a$ under non-drought conditions, or about 7.5 $km^3/a$ under drought conditions. UGEP represents the maximum groundwater yield that may be abstracted on a sustainable basis, given an adequate distribution of boreholes (Middleton and Bailey, 2009). Vegter (2001) estimated that in 1999 between 3.3 and 3.5 $km^3/a$ was used in South Africa (Figure 3-1). Both DWA (2010a) and Woodford et al. (2006) estimated South African groundwater use at between 2 and 4 $km^3/a$, most of it for irrigation. A more recent estimate is that of Margat and van der Gun (2013:123), who estimate that 2.84 $km^3$ of groundwater is abstracted annually in South Africa, 10% of this volume for public water supply, 6% for industry and 84% for agriculture, mostly irrigation. Exact figures are hard to establish for the many thousands of groundwater sources across South Africa since only larger abstractions require licenses, and in many cases these license volumes are not enforced or verified.

Groundwater in South Africa is therefore in the same league, volumetrically, as its stored surface water resources. South Africa's dams have a total capacity of about 32 $km^3$ when they are full (DWA, 2004a). However, the "assured yield" of South Africa's surface water resources is considerably less at about 12 $km^3$ per year, and more than 80% of this is already allocated (Middleton and Bailey, 2009). South African hydrogeologists have long acknowledged that groundwater is underutilised in South Africa (e.g. Barnard, 2000). Under these circumstances groundwater would appear to be a viable option for expanding water supplies across the country in general, and the argument that

[11] Domestic water supply problems in South Africa are however only rarely caused by an absolute lack of physical water resources – this is more an expression of the misleading "discourse of shortage", as will be discussed.

groundwater is insufficient to meet requirements (particularly for the relatively small volumes needed for domestic supplies) can be challenged. Groundwater is however rarely available in the huge quantities that a dam can provide, being limited by the yield of boreholes or wellfields and the properties of the relevant aquifers. Problems with operation and maintenance (O&M) also hamper the sustainable operation of groundwater sources in South Africa, leading to misconceptions about the reliability of the resource (Cobbing et al., 2015; and discussed in Section 3.7).

The exact groundwater availability in a given local area is often very different to the aggregate national average. Much work has been done in the past thirty years to estimate groundwater availability at national, district and local levels, relating groundwater occurrence to aquifer type, to recharge, to baseflow and environmental requirements, to natural groundwater quality, and to other hydrogeological or "technical" factors (see later in this literature review). Several of these efforts have also tackled the issue of "sustainability" – in other words, trying to quantify not only an expected borehole or aquifer yield, but also whether than yield can be maintained indefinitely without unacceptable environmental or other impacts.

Physical or hydrogeological groundwater sustainability is a study in its own right (e.g. Kalf and Woolley, 2005; Middleton and Bailey, 2009; or Sophocleous, 1997) and is more complex than it might appear. Abstracting groundwater from an aquifer means that the volume of groundwater stored in the aquifer will decline, or that adjacent surface water resources and environments will be impacted, or some combination of these things. However impacts might take years to manifest themselves, due to the large storage potential of many aquifers, and may in any case be acceptable from a management point of view in the same way as drawing water from a river or dam. There is no question that aquifers can be managed sustainably, and can continue to deliver reliable water supplies indefinitely, provided that a source of modern recharge is available. Even aquifers with ancient or "fossil" groundwater that are no longer being recharged can deliver reliable groundwater supplies for decades or longer – a good example being the regional Nubian aquifer system of North Africa (Voss and Soliman, 2014). Sustainability becomes particularly important where larger volumes of groundwater are required (e.g. for irrigation, or for urban water supplies).

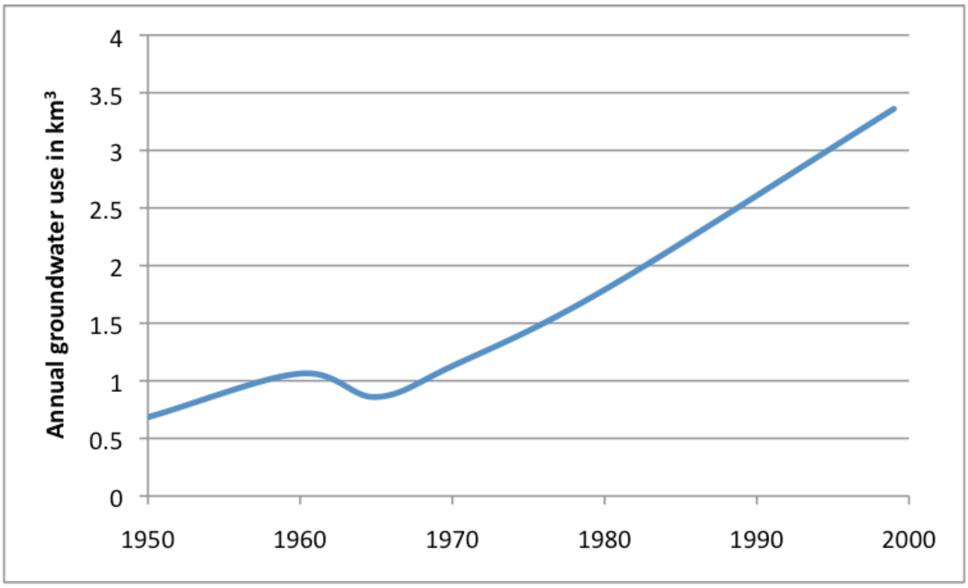


**Figure 3-1 Estimated increase in groundwater use in South Africa, 1950 to 2000 (after Vegter, 2001)**

### *3.2.1. Ambivalence towards groundwater in South Africa*

In the 1970s Raymond Nace of the United States Geological Survey referred to the tendency amongst government officials and planners to overlook groundwater and to skew planning resources and expertise towards surface water as "hydroschizophrenia" (Llamas, 1985). The Spanish hydrogeologist MR Llamas wrote in 1985 "until recently, groundwater was something of a mystery to most Spanish engineers and scientists, almost a kind of occult science, within the province of water diviners" (Llamas, 1985:161). The same can be said about contemporary South Africa. A practical outcome of "hydroschizophrenia" is the neglect of groundwater assessment and management at the planning level[12]. South Africa is still geared towards surface water solutions or surface water management approaches, tailored for phenomena such as relatively rapid changes in response to rainfall (Riemann et al., 2012).

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12 The publication "Overview of Water Resources availability and utilisation in South Africa" published by DWAF in 1997 (DWA, 1997) is a good example of South African institutionalised surface water bias at the time. Written by senior DWAF planners, the detailed descriptions and pictures of the major rivers and dams contrast with the lack of information on groundwater. A map of municipal groundwater supplies does not show Mahikeng, and the "Future Options" chapter at the end discusses desalination, weather modification and even the tapping of icebergs, but not better use of groundwater. As Xu and Beekman put it (2003:64), "Groundwater has a history of neglect and unsustainable utilization in South Africa. Despite recent developments in policy, and the importance of groundwater as a strategically important resource on which many rural communities depend, water management in South Africa remains largely determined by surface water systems".

This surface water bias echoes international practice. Previous South African water laws also made regional groundwater management difficult. Most resources have gone to large surface water schemes (e.g. the Lesotho Highlands Water Project or the Vaal Dam), and to inter-basin transfers linking surface water sources to urban areas (Braune et al., 2014). A recent example of this emphasis is the attention and funding given to the upgrading of the Mmabatho Water Treatment Works at the Setumo Dam outside of Mahikeng, of massive scale compared with the resources provided for local (and more important) groundwater resources. There are relatively few qualified South African hydrogeologists (DWA, 2009), and municipal hydrogeologists are rare (even though most rural South Africans depend on groundwater for their domestic supplies). The South African water planning unit – the catchment – reflects surface water flow, not groundwater. Figure 3-2 below shows how quaternary[13] surface water catchments ignore the dolomite outcrop, springs and the compartment boundaries in North West Province:

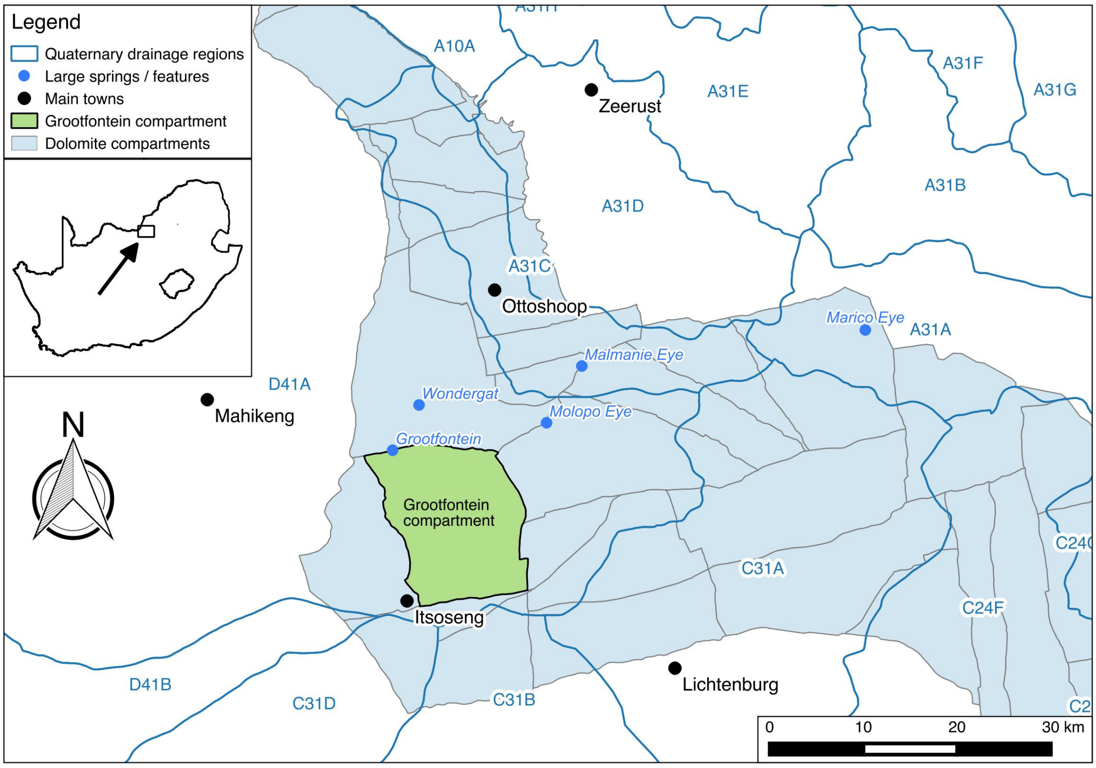


**Figure 3-2 Quaternary drainage boundaries (blue) cross dolomite compartments (grey) near Mahikeng (compartments after Holland and Wiegmans, 2009)**

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[13] South Africa's 22 primary surface water drainage basins can be subdivided into 148 secondary basins; and further into 278 tertiary basins, and 1 946 quaternary basins. The quaternary drainage basins average about 650 km² in area and are often used as the basis for local water resource assessment and planning. They are sometimes further divided into quinary drainage basins.

Groundwater sources are also seen as less desirable or "sophisticated" than surface water sources in South Africa, particularly where the groundwater source is a hand pump and surface water is delivered via a tap direct to a dwelling (Harvey and Reed, 2004). Reliance on groundwater in rural settlements is still associated with the former 'homelands', where boreholes were the default rural water source in a context of severe under-development. Management and maintenance by the designated authorities was profoundly under-resourced, and reliable supply was often a function of local initiative rather than formal management.

A driver of early hydrogeological research into the dolomites in South Africa was their proximity to the gold-bearing Witwatersrand Supergroup and the technical and engineering problems that large volumes of groundwater posed to deep gold mining (Vegter, 2001). Dolomite groundwater was a potential danger, and getting rid of it was a major cost. Vegter (2001:19) reports that:

> "By 1956 pumpage from Venterspost mine, the first mine to be established along the so-called West-Wits line, had reached 50 000 $m^3$ per day. The profitability of the mine was threatened".

The ingress of pumped groundwater back into mining voids was minimised by dewatering whole dolomite compartments. Government bodies were established to deal with the resulting problems of dry springs, lowered water tables and land subsidence. Nevertheless, the externalised environmental and social costs of gold mining were (and are) high, and only partially met by compensatory policy (Adler et al., 2007). The current problem of groundwater rebound and associated acid mine drainage is a good example. For these reasons and others, dolomite groundwater can seem an expense or a problem, rather than a resource.

Taken together, the issues discussed above predispose planners in South Africa towards surface water resources. It is rare to find investments in groundwater matching those for surface water, even where groundwater quality, volumes and potential are equivalent to or exceed surface water resources (such as at Mahikeng, Lichtenburg and several other parts of the country). South African hydrogeologists joke that "a pipeline" from a distant surface water resource is all that is needed to solve any water supply problem[14].

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[14] The problem is not confined to smaller towns. In Cape Town planners are considering a multi-billion rand seawater desalination plant, whilst at the same time facing sanitation and flooding

The South African tendency to undervalue or overlook groundwater unfortunately still reflects contemporary practice world-wide. For example, the latest publication by the World Bank's Water Global Practice group focuses on the cross-cutting role of water in world-wide economic security, food security and poverty alleviation (World Bank, 2016). Groundwater is central to these focus areas, but the report concentrates on surface water and runoff, and the tiny section on groundwater mistakenly states that groundwater comprises 30% of available fresh water, rather than about 98%. The authors confuse groundwater's proportion of total world water resources, including icecaps and glaciers (inaccessible because frozen), with the proportion of available *liquid* fresh water – a serious error that reflects widespread misunderstanding of the resource.

### *3.2.2. Advantages of groundwater for domestic water supplies*

Groundwater has advantages over surface water that can make it suitable for domestic water supply, particularly in rural areas and small towns requiring relatively small quantities (Pietersen, 2005). Firstly, groundwater is a "proximal resource", meaning it is often found close to where it is needed – a major advantage where settlements are scattered and the logistics and costs of pipelines from a central source are daunting. Secondly, groundwater is resistant to the effects of drought, relative to surface water, because large volumes are in storage and it is much less susceptible to evaporation. This is usually only recognised when droughts become severe, and under these circumstances emergency borehole drilling programmes are not as effective as they should be. Thirdly, the natural microbiological quality of groundwater is usually good due to long residence times and the filtering effects of the aquifer. Precautionary treatment is nevertheless usually recommended for groundwater when it is used for domestic supplies, and all groundwater needs to be checked for safety in the same way as surface water. Finally, groundwater can be developed incrementally as funds and skills permit and as increasing demand dictates. This is in contrast to the larger initial investment usually needed for a surface water source (e.g. a dam, pipeline or treatment plant). Groundwater sources can however require more expensive and logistically complex ongoing operation and

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problems on the Cape Flats caused partly by high water tables – problems that would be reduced by pumping this groundwater. Various proposals to increase the use of Cape Flats Aquifer groundwater have not found policy traction (e.g. Maclear, 1995). Plans to use the good quality groundwater from the Cape Mountains for public supply have also been tabled for years, but have not progressed.

maintenance expenditure, and this funding can be difficult to secure and sustain (see Section 3.7).

These advantages do not mean that groundwater is a "cheap option", or requires lower levels of skills and planning compared with surface water supplies. Both surface water and groundwater have advantages and disadvantages, which need to be understood in the particular context of each scheme. Groundwater remains vital for domestic water supplies in South Africa, particularly in rural areas. As Hassan et al. put it in their analysis for the World Bank, groundwater in South Africa "…represents a key source of water supply especially in rural semi-arid areas and mainly for irrigation and domestic use" (Hassan et al., 2008:5).

## 3.3. Management of groundwater

Since groundwater has distinct differences with surface water, its management requires a tailored approach. Groundwater is usually invisible, it responds slowly to pumping or to recharge compared with surface water, and the boundaries of aquifers may be indistinct. Groundwater is naturally protected from surface pollution, but once polluted can be very difficult to remediate. The sub-surface geochemistry means that groundwater's hydrochemical characteristics can differ from surface water. Despite – or perhaps because of – these distinctive characteristics, groundwater management is a new field.

A century ago borehole drilling and pumping technology was primitive and "management" of groundwater resources as understood today was uncommon, since only small amounts of groundwater were abstracted from shallow aquifers. In most places shallow wells were dug, springs were tapped, and coping strategies were developed for dry periods and natural variations in groundwater levels. But in the last fifty years a huge boom in global groundwater development has taken place, most of it for irrigation purposes (Mukherji and Shah, 2005; Shah, 2009). Improved drilling technology, wider access to electricity, and growing demand for water have all contributed to this boom. Konikow and Kendy (2005:317) state that:

> "In the past half-century, ready access to pumped wells has ushered in a worldwide 'explosion' of groundwater development for municipal, agricultural and industrial supplies".

In 2000 it was estimated that 750 to 800 km$^3$ of groundwater was abstracted globally per annum (Shah et al., 2000). More recently, Margat and van der Gun (2013) estimate that

986 $km^3$ per annum of groundwater is being abstracted worldwide. In South Africa as much as 4 $km^3$ is being abstracted annually, compared with less than 1 $km^3$ in the 1950s[15]. There is a growing recognition of the necessity for groundwater management:

> "By far the most serious groundwater challenge facing the world, then, is not in developing the resource but in its sustainable management" (Shah et al., 2000:8)

Over-abstraction, salinisation and pollution of groundwater are now serious problems in many parts of the world, leading to debate about how best to manage groundwater and a growing literature on groundwater management or governance. Saline intrusion, land subsidence and ecological damage are other downsides to this "explosion". But the benefits to people and societies have also been immense[16]. Today most agree that better groundwater management is needed to address deterioration of the resource. Growing populations and climate change complicate the picture.

A recent publication by the United States Agency for International Development (USAID) describes the problem as follows:

> "Subterranean water resources pose particularly acute governance challenges. They require sophisticated technology and significant knowledge to be sustainably managed. By contrast, even when surface water is not systematically measured it can, at a minimum, be visually monitored. As a result, groundwater resources are at heightened risk of unsustainable consumption, pollution, and uninformed perceptions with regard to quantity and quality of available resource." (USAID, 2014:12).

Shah et al. (2000) urge a global move towards better groundwater management, pointing to numerous examples of over-abstraction, pollution, salinisation and other negative impacts. One essential pillar of management is a physical understanding of the resource.

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15 This figure is still only around half of the estimated sustainable total amount of groundwater that could be abstracted in South Africa, and most of it is abstracted for irrigation (DWA, 2010a).

16 The South Asian "green revolution" in agricultural productivity depended on a massive increase in groundwater abstraction, helped by access to cheaper pumps and electricity and carried out mostly by small-scale farmers (Shah, 2009).

> "A major barrier that prevents transition from the groundwater development to management mode is lack of information. Many countries with severe groundwater depletion problems do not have any idea of how much groundwater occurs and who withdraws how much groundwater and where." (Shah et al., 2000:14).

Put another way, "you can't manage what you don't measure". Whilst South Africa already has considerable groundwater data holdings (see Section 3.6), a series of recommendations were made with respect to improving monitoring of groundwater systems in South Africa as part of the work done towards the National Groundwater Strategy (DWA, 2010a). Recommendations for this work included the better delineation of the lateral and vertical heterogeneity of aquifer systems, and the collection of related data. Rainfall station coverage was recognised as deficient, and higher densities for important catchments recommended[17]. Better construction of monitoring boreholes, and a more strategic approach to monitoring of groundwater generally, was also recommended. In many parts of South Africa monitoring of groundwater resources is declining (Pietersen and Lenkoe-Magagula, 2013). DWS and the consulting company AECOM are currently (2016/2017) developing a strategy towards a new, integrated hydrological monitoring system that aims to reverse earlier setbacks and refine hydrological data collection.

Most specialists acknowledge that groundwater monitoring and data collection are important in South Africa, but the conversion of groundwater data into information products that are relevant to decision makers[18] is given less attention (Seward, 2015). The further question of how to optimally use such information products is very rarely discussed. The perceived lack of tangible benefits from large-scale collection of groundwater data has led to questioning of the purpose of such data collection programmes, one of the reasons for the DWS/AECOM project mentioned above.

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[17] The WR2012 study being conducted by the Water Research Commission will be completed in 2016 and will update previous estimates of Southern African water resource availability. The study has identified recent deterioration of relevant data sources including streamflow estimates, reservoir records and water quality analyses. The most serious deterioration in data availability has been in terms of the number of rainfall monitoring stations (Pitman and Bailey, 2015).

[18] A good example of such a product is the annual "London Basin Report" produced by the British Geological Survey. Intended for decision makers, the Report shows updated groundwater piezometric contours and rates of change for the London Basin, part of the important Cretaceous Chalk aquifer of South East England.

### *3.3.1. Groundwater management and groundwater governance*

Hydrological literature distinguishes between "management" and "governance" of water, with the former indicating a narrower range of issues including hydrogeological modeling and the application of laws and regulations, and the latter implying a broader range of issues at different levels with a bearing on all stakeholders (Mukherji and Shah, 2005). Another way to think of this is that management is "*de jure*" – following formal laws and procedures, whilst governance is "*de-facto*" – a focus on what really happens in the chaotic business of groundwater, and of which formal laws are only a part.

The project "Groundwater Governance. A Global Framework for Action" is the most recent and important international programme investigating mechanisms for better groundwater governance (it ended in 2015). It was funded by the World Bank's global environment fund (GEF) and implemented by the Food and Agriculture Organization of the United Nations (FAO) together with UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrologists (IAH) and the World Bank (GWG, 2014). The 4.5 M USD project, which started in June 2011, was "designed to raise awareness of the importance of groundwater resources for many regions of the world, and identify and promote best practices in groundwater governance as a way to achieve the sustainable management of groundwater resources" (GWG, 2014). After a first project phase in which a review of the global situation with respect to groundwater governance was carried out, a second phase led to the main project outcome which is a "Global Framework for Action". The first phase included case studies, thematic papers and five regional consultations. The second phase consists of a set of policy and institutional guidelines, recommendations and best practices aimed at various geographical levels. Resources and outcomes of the project are available on the project website (www.groundwatergovernance.org) (GWG, 2014).

Groundwater governance, as investigated by Groundwater Governance project members, shares with other water governance a need to be "accountable, transparent and participatory" (GWG, 2012a), but does have requirements that are particular to groundwater, based on the distinguishing characteristics of groundwater and aquifers. These include the common perception that groundwater is a private resource (ironically, groundwater is usually viewed as a classic "common pool" resource (e.g. Ostrom, 2005) by institutional experts), the need for groundwater management to consider baseflow to rivers, the susceptibility of groundwater to diffuse land-use practices, and longer timeframes (GWG, 2012a). The inherent complexity of groundwater and the sub-surface calls for management approaches that take uncertainty into account such as adaptive management (Seward et al., 2006), but which do not necessarily dovetail with management of other water resources. The Groundwater Governance project has distilled the following definition of groundwater governance:

> "Groundwater governance is the process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global." (GWG, 2012a:14).

The definition goes on to state that:

> "Accordingly, 'groundwater governance' could be interpreted as the set of policies or decisions that moderates groundwater use and promotes aquifer protection. Governance can be distinguished from 'government' (who decides) and 'management' (what is done to implement decisions)…. Broadly, groundwater management is the set of actions to implement decisions that derive from the process of governance." (GWG, 2012a:14).

It is acknowledged that the definition does not capture "the wider context of political and power relations or social drivers that determine outcomes" (GWG, 2012b: 4). A set of groundwater governance principles are presented and discussed in the synthesis paper, as follows:

- Sustainability – more complex than it might first appear, and goes beyond the idea of "safe yield". Aquifer response time is a consideration, for example.
- Transparency – especially important in the case of groundwater, which is mostly invisible and subject to various "fallacies".
- Participation – considered necessary to reach agreement and implement management actions.
- Accountability – need to determine who is accountable for e.g. pollution, who benefits and who loses from groundwater abstractions, and reach agreement on management response.

- Integration – groundwater management needs to be well integrated into other water sector governance, including consideration of long-term buffering and storage advantages.
- Precautionary Principle – especially around issues such as injection of pollutants.
- Knowledge Management Principle – need to promote the use of groundwater knowledge more widely.

These principles of groundwater governance as defined by the GWG project refer to and draw on ideological principles or underpinnings that have been accepted by most water management practitioners in the last twenty or thirty years or so. Two of the most important of these principles are the set of ideas that are collectively referred to as "integrated water resource management", or IWRM; and the principle of subsidiarity or decentralisation. The latter is often seen as bundled within the former. Both of these principles have had tangible effects on local groundwater management in South Africa, including on management approaches at Grootfontein. They particularly affect the nature of the organisations mandated to manage groundwater, and the sphere of governance where these are located (see Section 3.5).

### *3.3.2. Integrated water resource management*

In the late 1970s and especially following the UN International Water Decade for Clean Drinking Water of the 1980s, it was increasingly recognised world-wide that water needed to be managed in a more holistic way, taking into account all of the various uses, benefits, costs and trade-offs of using water as well as the different components of the water cycle[19]. The impact of water use on other sectors such as agriculture, energy, health, transport or mining also needed to be better understood. The 1977 UN water conference at Mar del Plata in Argentina recognised the multiple linkages between water, food and energy (Muller, 2015). Together these increased support for the concept of "integrated water resources management" or IWRM. IWRM is today a major or even dominant concept in water resource allocation or management worldwide (Allan, 2003; Giordano and Shah, 2014). Biswas (2004) points out that IWRM is not a new concept, however – just that support for it has increased greatly in recent years. There are various

[19] The "Dublin Principles", released following the International Conference on Water and the Environment in Dublin in 1992 included the principle that "water has an economic value in all its competing uses and should be recognised as an economic good".

definitions of IWRM, but one of the most common is provided by the Global Water Partnership as follows:

> "Integrated Water Resources Management (IWRM) is a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment." (GWP, 2012; and Biswas 2004).

This definition (and the concept of IWRM generally) has been criticized for being vague, amorphous and difficult to achieve (e.g. Biswas, 2004). However, IWRM is still generally regarded as a very useful concept in water governance, and in groundwater governance (Foster and Ait-Kadi, 2012; Riemann et al., 2010; Riemann et al., 2012). IWRM-influenced thinking can be seen in the South African National Water Resource Strategy (DWA, 2004a), the Water for Growth and Development Strategy (DWA, 2009), and even in the National Water Act of 1998 (RSA 1998) that stipulates that water must be managed in a holistic way as a common good, with ownership vested in society as a whole. The requirement for decentralisation of water management to local level, and the necessity for the involvement of local communities in water management, is also commonly regarded as supporting IWRM thinking (see Section 3.3.3). IWRM has also contributed to organisational changes within South African water management and research organisations such as the disbandment of a separate Directorate of Geohydrology in the Department of Water Affairs in the early 2000s or the dissolving of the Groundwater Research Group at the CSIR in 2007, partly on the grounds that water resources are best managed holistically rather than in "silos". As Foster and Ait-Kadi put it: "…past 'compartmentalized' approaches to water management have generally failed to achieve sustainable outcomes" (2012:1). As Riemann et al. (2012:4) put it: "IWRM is universally recognized as a people- and environment-focused, holistic paradigm by which to regulate and manage water".

IWRM is however more usefully seen as a loose collection of related ideas, which in their most basic manifestation (e.g. fairness, environmental integrity, consideration of all uses of water) are uncontroversial. In its more strict application IWRM can, however, drive a radical restructuring of the water planning and organisational landscape. In South Africa the coincidence of the end of apartheid and the opportunity to rewrite the water laws, and the pre-eminence of IWRM in the early to mid 1990s, contributed to the South African National Water Act and particularly its emphasis on entirely new water management organisations, together with the (surface water) catchment as the basis for water management. Few other countries have implemented IWRM thinking to this extent[20]. The benefits of the IWRM approach have still to be conclusively proven in South Africa, but the institutional challenges inherent in creating new organisations such as Catchment Management Agencies (CMAs) and Water User Associations (WUAs), and dissolving or shrinking the predecessor organisations, are clearly substantial.

There is growing acknowledgement of these challenges in South Africa today, and the way in which IWRM is linked to them. For example, Muller (2014:12) calls for less of the IWRM-inspired "river basin fetishism" and a more practical approach to water management. Giordano and Shah (2014) argue that a focus on IWRM can become an end in itself and distract from actual problem-solving, and that a more pragmatic approach is required. Van Koppen and Schreiner (2014b) highlight what they see as the shortcomings of an emphasis on IWRM, including its focus on "second generation" issues of resource allocation at the expense of basics like infrastructure, and its faith in the corporate sector and push for reduced state capacity.

IWRM is amorphous politically as well as in its practical prescriptions, and can hide a variety of reformist political agendas on both sides of the political spectrum. Some view IWRM as a Trojan horse for a centre-right ideology that sees water as an economic commodity, central government planning as inefficient and undesirable, and the individual as the source of innovation and progress. Managerialism, "third-way" politics and a focus on "change" and "choice" may also be prominent[21]. This could be summed

[20] Countries in the developed world who were proponents of IWRM and influenced South African water policy in the late 1990s have not implemented these principles to the extent that South Africa has, particularly the requirement for separate, independent water management organisations at catchment rather than state or province level (Mehta et al., 2016).

[21] Harrison (2007) discusses the influence of New Public Management on Integrated Development Planning in the early days of South Africa's democracy. Harrison quotes the definition of "integrated planning" provided by the RDP office in South Africa as follows "… a participatory approach to integrate economic, sectoral, spatial, social, institutional, environmental and fiscal strategies in order to support the optimal allocation of scarce resources between sectors and geographical areas and across the population in a manner that provides sustainable growth, equity and the empowerment of the poor and the marginalised". This is similar to the definition of IWRM. Harrison confirms the influence of then-current developmental thinking on South African policy and planning in the mid-1990s: "The accepted international discourse on

up as the "Washington Consensus" as it applies to water. The idea that clean water should be paid for and not free is usually considered intrinsic to IWRM thinking, and most water professionals accept this[22]. This does not rule out subsidies, nor mean that the indigent be denied clean water if they cannot pay[23]. Water cross-subsidisation and free basic water are government policy in South Africa today (Muller, 2008).

Defenders of IWRM on the left-of-centre of the political spectrum often maintain that failures to adopt IWRM in South Africa, and elsewhere, are due to insufficient zeal in implementation, rather than to a flaw in the IWRM ideology itself. For example, it is DWS's ambivalence towards local or catchment-level IWRM organisations and other IWRM measures that is behind their apparent failure. In this view, DWS prefers centralised power and has not whole-heartedly supported IWRM. This argument has a chiliastic ring to it, but it is true that DWS has dragged its feet in implementing some of the IWRM-inspired provisions of the National Water Act, and still appears reluctant to decentralise responsibilities. On the other hand, the scarcity of truly local, participative, authoritative, self-funded, grassroots IWRM-style water management organisations anywhere in the world, even where impressive financial and human resources are available, suggests that IWRM is a concept best treated with caution.

### *3.3.3. Decentralisation*

Along with IWRM, decentralisation has become an important idea in the global discourse of water governance, partly because it is thought to promote efficiency, transparency, democracy and accountability. Decentralisation underpins much of the approach to water provision and management in South Africa. For example, the National Development Plan calls for "catchment management agencies to undertake [water] resource management on a decentralised basis" (RSA, 2012:183). Decentralisation has

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governance and development forcefully constrained the horizon of possibilities for policy innovation after apartheid" (Harrison, 2007:188).

22 For example a statement by the United Nations following a 1990 conference on water and sanitation included the words "Further, there must be widespread promotion of the fact that safe water is not a free good" (UN, 1990:6).

23 The "privatisation" or corporate commodification of water goes well beyond the idea of paying the state a fair price for a safe water supply, and is not usually seen as intrinsic to IWRM. Protests against the commodification of water are not the same as advocating for universally free water.

historical, economic, religious and ideological roots that are rarely acknowledged in the water management literature.

Decentralisation accords with post-1980s free-market orthodoxy, which with Fukuyama's 1992 "The End of History" and the rejection of inefficient Soviet centralised bureaucratic planning informs modern public-sector management theory (Fukuyama, 1992). Decentralisation is often seen as reducing the role of the centralised state in favour of lower transaction costs at local levels (Bardhan, 1996), particularly in complex interconnected systems (Helbing, 2013). The economist Friedrich von Hayek endorsed decentralisation as a way of reducing the perceived power of the state over the individual, and wrote in The Road to Serfdom (von Hayek, 1944:51):

> "There would be no difficulty about efficient control or planning were conditions so simple that a single person or board could effectively survey all the relevant facts. It is only as the factors which have to be taken into account become so numerous that it is impossible to gain a synoptic view of them that decentralisation becomes imperative."

This has its echoes in current orthodox economic thinking urging governments to "cut red tape" or "get out of the way" of the economy[24]. To be fair to von Hayek, he did concede that the central state still had a limited role to play in areas where the free market did not function well, such as in environmental legislation, and it could be argued that his work (and that of others) has been used in recent decades to justify ideological positions which he did not contemplate[25]. Nevertheless, it would be strange if the currently dominant economic ideologies did not influence planning and management in a variety of specialist fields, including water and hydrogeology. In the words of another great economist, JM Keynes:

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[24] As Ronald Reagan once quipped, "The nine most terrifying words in the English language are: *I'm from the government and I'm here to help.*" The view that "big government" is undesirable, or that the state should not "pick winners" still has wide contemporary political appeal.

[25] An influential 1974 paper by the economist Anne Krueger, later chief economist at the World Bank, coined the phrase "rent-seeking" as it applied to large state bureaucracies in the developing world, and argued against government intervention in the economy (Krueger, 1974). The "Berg Report" (World Bank, 1981) linked slow growth in Sub-Saharan Africa to ineffective central bureaucracies and advocated trade liberalisation and deregulation, helping to usher in "structural adjustment" policies following the oil shocks of the 1970s.

> "The ideas of economists and political philosophers, both when they are right and when they are wrong, are more powerful than is commonly understood. Indeed the world is ruled by little else. Practical men, who believe themselves to be quite exempt from any intellectual influence, are usually the slaves of some defunct economist." (Keynes, 1936:383).

Decentralisation also has roots in the legal Principle of Subsidiarity, which holds that issues should be decided upon or managed at the lowest or most devolved level practical. This is considered a founding principle of European Union law, and echoes a late 19th century Papal encyclical "*Rerum novarum or Rights and Duties of Capital and Labour*" which gave attention to "the enormous fortunes of some few individuals, and the utter poverty of the masses". According to the encyclical:

> "The limits [of the aid and authority of the law] must be determined by the nature of the occasion which calls for the law's interference - the principle being that the law must not undertake more, nor proceed further, than is required for the remedy of the evil or the removal of the mischief" (LEV, 2014)[26].

The need to address water issues across multiple scales and a range of stakeholders is a cornerstone of Integrated Water Resource Management (IWRM) thinking (USACE, 2014). The recognition of the essentially local nature of much groundwater, and the way in which local, private interests shape demand for groundwater (GWG, 2012b), have contributed to the common idea that the administration and governance of groundwater should also be as local or "decentralised" as possible. As GWG (2012b:20) put it:

> "If an environment of good conduct is to be extended to fill the apparent groundwater governance gaps, the need for this to apply at the point of abstraction or the point of pollution will always implicate local institutions who have an interest in maintaining public goods."

[26] Ironically, considering the association of decentralisation with today's right-of-centre political and economic thinking, the original Papal endorsement was aimed at addressing the high levels of "Gilded Age" inequality prevalent at the time.

A local focus can of course have drawbacks too if it gives preference to a narrow set of local interests at the expense of broader interests, and a pragmatic approach is often recommended (Foster and Ait-Kadi, 2012).

In South Africa decentralisation is important to water resource planners because it underpins the constitution as well as water laws and policies. It was adopted with the intention of increasing public participation in local decision-making, and of promoting democracy and accountability more generally (Ntsebeza, 2002). Decentralisation has been widely supported in the South African water sector – as Lazarus (1998:18) writes:

> "There is general agreement in the [water] sector that devolution of groundwater management functions to the lowest technically competent level should be encouraged while retaining a strong central authority for overall management of all water resources".

Decentralisation has also been extensively criticised as a system that *de facto* places the greatest administrative burdens on those least able to carry them[27], which can fail to separate the political from the administrative, and which draws on and reinforces right-of-centre policies and doctrines such as the New Public Management (Siddle and Koelbe, 2012; and Galvin and Habib, 2003). Manor (2001) maintained that three things are essential for decentralisation to deliver on its promises, and that serious doubts existed about all three in South Africa:

- Substantial resources (financial and other) must be available to local authorities
- Substantial powers must be devolved to local authorities
- Accountability mechanisms must exist which ensure that bureaucrats are accountable to elected representatives, and that elected representatives are accountable to voters.

[27] Decentralisation can also be linked with "community participation", whereby poor rural people take partial or full responsibility for their water supply systems. Community participation gained prominence in the 1980s partly as a crisis response to drought, population movement and state capacity shortfalls, but later came to be seen by some development specialists as a model for rural water supplies in Africa, and a welcome change from top-down, engineer-led approaches. Somewhat out of fashion today, the approach was criticized by Feachem as early as 1980: "Community Participation is not, and never has been, a major component of water supply or sanitation development in [industrialised countries]. Why then are we so ready to urge it upon others?" (Feachem, 1980:22).

Fifteen years after Manor wrote about these three things, doubts continue. As far back as the early 1980s, Rondinelli et al. (1983) acknowledged that decentralisation in developing countries required careful planning and incremental institutional capacity building to be successful.

Whilst decentralisation is intertwined with many of the current groundwater management challenges in South Africa – and is worth understanding as a result – there is no space for a full discussion of it here. Decentralisation of government and associated administrative duties is a complex issue with many forms, with clear advantages and potential drawbacks. The devil lies in the details (Galvin and Habib, 2003), a feature it shares with IWRM. What are often seen as neutral and logical policies are in fact malleable, highly ideological and subject to contestation and change. Decentralisation and IWRM are major reasons why this research focuses on municipalities and the local sphere of government, when considering groundwater management. A frank appraisal of the successes and failures of decentralised or locally-managed water supply does appear to be leading to a more nuanced discussion in South Africa today, with partnerships between central and local levels being increasingly emphasised (DWS, 2013).

The danger is that, being rather vague and amorphous when it comes to practical implementation, IWRM and decentralisation can function as the conduits of any particular set of dominant political-economic ideas. That the dominant ideas in water management have political and ideological roots is beyond doubt (e.g. Allan, 2003). Muller (2015) writes that the IWRM consensus may in fact now be giving way to a "nexus" consensus, in which water is seen as indivisible from certain related fields – for example the water-energy nexus, or the water-food nexus. A recent report by the World Bank confirms this, calling for "an expanded water nexus" (World Bank, 2016:viii). This may be a partial return to the idea that water does in fact have a hierarchy of uses, and that local, decentralised and participative structures are not always the best place to decide these[28]. Whatever happens, hydrogeologists and other technical specialists need to be prepared for the various nested political, institutional and organisational implications that such ideological changes imply.

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[28] An article in Business Day in 2012 by Mike Muller, former DWS Director General and National Planning Commission member, entitled "Living with water scarcity and Ma Vilakazi's cabbages", lampooned the view of the draft second edition of the National Water Resource Strategy (DWA, 2013) that if assurances of water supply to key sectors such as power generation were reduced, water supplies to the poorest South Africans would improve (Muller, 2012).

### *3.3.4. Resilience, adaptive governance and hydro-social systems*

An influential literature concerned with environmental governance and centred around the concepts of resilience and adaptive governance has come to prominence in the last fifteen years or so (Chaffin et al., 2014). Ecological studies recognised that the capacity of complex ecological systems to absorb shocks or adapt to external changes was an important feature, and could also indicate the health of such systems (Folke, 2006). Resilience is not only the capacity to absorb shocks, but also to renew, adapt and develop. Resilience characteristics explain why systems can have multiple stable states, and can move quickly or unexpectedly between states (Folke, 2006). Ecosystem responses to change (often brought about by humans) can be non-linear and unpredictable, and such systems are better characterised as social-ecological systems (Folke et al., 2002; Burns et al., 2006). This approach contrasts with the view that human activities are separate from nature, and that humans can or should "control" the response of natural ecosystems to human impacts. Humans are in fact intimately dependent on wider ecosystems, and the health (and governance) of such ecosystems is therefore of central importance. The interdependence of human societies with ecological systems, and the consequent central importance of environmental or ecosystem functioning, supports "ecological modernisation", a movement arguing that ecological functioning or integrity is necessary for future economic growth (Mol, 2002).

Swyngedouw (2009) has recognised the circulation of water as both a physical and a social process (a "hydro-social cycle") arguing that management of the water cycle is a dialectical, politically-mediated process closely related to existing power and material hierarchies in society. Meissner and Turton (2003) use the term "hydrosocial contract theory" to argue that societies go through two transitions, with increasing water stress and consequent dependence on "hydraulic mission" engineering. Boelens (2014) links the "hydrosocial cycle" to cultural and environmental questions. These uses all acknowledge the links between hydrological and social (institutional) features. The use of the term in this thesis differs from some existing uses in its emphasis on the interdependence of the social (institutional) and the hydrological aspects, rather than the dependence of the hydrological on the wider social context.

Ecological resilience includes the capacity to change and adapt, sometimes unpredictably, and contrasts with "engineering resilience" which refers to technologies that are designed to remain stable and predictable (Folke, 2006). Recognition of multiple nested sets of complex interdependent ecosystems, the capacity for resilience, and the importance of multiple ecosystem indicators rather than a single indicator (e.g. cod fish stocks) has given rise to the concept of "panarchy", or the recognition that humans are embedded in multiple ecosystems which may respond unpredictably to change, especially top-down attempts to control single variables (Folke, 2006). This has links with the Gaia hypothesis (Lovelock, 1979). Indicators of resilience, and early warning signals of "tipping points" or thresholds between ecological states, have been studied by Carpenter et al. (2011) and Carpenter (2013), who emphasise that such signals may be subtle and may not involve macro-variables of obvious interest to humans. Increasing connectivity and complexity can imply unpredictable risks and cascading failures (Helbing, 2013; Perrow, 1999).

A governance approach based on adaptive capacity is suggested as the best way to promote the resilience of social-ecological systems, harnessing local knowledge and including multiple stakeholders at different levels (Folke et al., 2002). Such a governance approach itself has higher levels of resilience, and can adapt as conditions change. Social institutions, particularly those that have developed over time to manage natural resources, are an important component of adaptive governance (Dietz et al., 2003). In this way, resilience and complexity in ecosystem studies have come to influence natural resource management theories. In particular, adaptive governance is seen as an alternative to both top-down government control, and the privatisation of resources – both implied by Hardin in his "Tragedy of the Commons" paper (Hardin, 1968; see Section 3.4.2; and Dietz et al., 2003).

The unpredictability of natural systems and the necessity for management approaches to be flexible and able to incorporate feedback, is important to groundwater governance. Such an "adaptive management" approach, summarised by Chaffin et al. (2014:56) as an approach "…where experiments become policy and results are continously monitored to further inform that policy…", has been recommended for the South African groundwater context by Seward et al. (2006). Adaptive groundwater management allows for new monitoring data to inform and refine initial conceptual models, and influence policy, particularly in determining sustainable aquifer yields. It implies that management actions will change as groundwater abstraction proceeds, and that yields and associated impacts cannot be predicted with great accuracy beforehand (Vegter, 2001). Groundwater abstractions, groundwater management, and the refinement of the conceptual groundwater model must proceed together.

Resilience, complexity in social-environmental systems, the interdependence of humans and the environment, and the need for adaptive governance in general, favour local, distributed, flexible and collaborative governance arrangments (Folke et al., 2002; Dietz et al., 2003). This lends support to both decentralised governance, and IWRM (see Sections 3.3.2 and 3.3.3). Social capital (e.g. high levels of trust) and a forum or platform for collaboration are also important (Stockholm Resilience Centre, 2012). An accountable authority is necessary to break logjams and ensure legitimacy, and it is suggested that a democratically mandated organisation take this role of "traditional accountability" (Stockholm Research Centre, 2012). The recognition of multiple stakeholders, various nested scales and systems, and the need for collaboration also accords closely with Earth Stewardship Science (de Wit and Booth, 2016).

## 3.4. Elinor Ostrom and the Institutional Analysis and Development (IAD) Framework

Institutions are fundamental to how and why water resources are governed, including groundwater. Essentially, institutions are the rules that govern all behavior. As Elinor Ostrom (2005:3) puts it:

> "Broadly defined, institutions are the prescriptions that humans use to organise all forms of repetitive and structured interactions, including those within families, neighbourhoods, markets, firms, sports leagues, churches, private associations, and governments at all scales. Individuals interacting within rule-structured situations face choices regarding the actions and strategies they take, leading to consequences for themselves and for others".

The tools used by institutionalists are useful in examining and delineating the relationships, assumptions, powers and other characteristics of organisations managing groundwater resources in South Africa. After years in the doldrums, the ideas of institutional economists are again making headway (Hodgson, 2013).

Crawford and Ostrom (1995:582) summarise institutions as "enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world". Institutions and institutional analysis can be a powerful way of analysing social behavior and the collective "behaviors" (customs, habits, formal rules, etc) that underpin formal organisations. Institutions can be formal, informal, tangible or abstract. Languages, moral and social norms, customs etc (informal institutions) are given expression in laws (formal institutions). Organisations on the other hand are formally constituted, funded and staffed entities, usually with a legal mandate and official tasks.

The Department of Water and Sanitation is an organisation that anchors existing institutions (formal and informal) as well as promoting new ones that have been formalised (e.g. the South African Constitution, the National Water Act) elsewhere. Individuals create institutions, and are in turn shaped by them. The choices of individuals may appear more important than the institutions (often the codified choices of individuals around them) that shape, guide and direct them – but this is not so[29]. Nevertheless, individual decisions are often given more prominence or may be easier to understand and debate than the relevant underlying institutions. "Institutional structures constrain or empower individuals, and frame their incentives and disincentives" (Hodgson, 2009). For any complex administrative system, it is valuable to understand how different institutions function and interact. Water planning and management in South Africa involves the interaction and change of many nested sets of institutions.

Some of the resource management literature does not distinguish clearly between "institutions" and "organisations" and the two terms are sometimes used synonymously. All organisations are institutions (comprising nested sets of formal and informal institutions) but only a few institutions can be called "organisations". This research uses the word "institution" in the sense of a rule guiding repetitive social behavior (formal or otherwise), and "organisation" to refer to formal, bricks-and-mortar entities usually with staff bodies or memberships, budgets and premises.

One of the most important institutionalists or institutional economists studying water management was Elinor Ostrom, whose ideas and principles have been valuable to this research.

Elinor Ostrom (1933-2012) was a Nobel Memorial Prize winning American political economist. Amongst her research interests were issues of collective action, equity and trust as they applied to "common pool" resources such as groundwater resources (Ostrom, 2002). Ostrom worked on the systematic analysis of social institutions as they

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[29] It is also tempting to make "right and wrong" judgments about institutions, or to assert that they are amenable or analogous to logic, but these tendencies too are institutions, and codified by other institutions in turn.

applied to resource governance and other questions, and put substantial research effort into developing a universal or systematic framework for understanding, categorising and describing social institutions. In Ostrom's own words, she was interested in "an underlying set of universal building blocks" as they applied to social institutions (Ostrom, 2005:5). She wrote (Ostrom, 2005:7):

> "As a scholar committed to understanding underlying universal components of all social systems, I do not introduce complexity lightly. I view scientific explanation as requiring just enough variable to enable one to explain, understand, and predict outcomes in relevant settings."

In effect, Ostrom and colleagues were working on what they referred to as an underlying "grammar" of institutions (Crawford and Ostrom, 1995). Ostrom's system of organising institutions, known as the Institutional Analysis and Development (IAD) Framework (Ostrom, 2005), has been applied in a variety of settings and by many scholars to understand problems of governance, particularly where cooperation and collaboration are required. It has links with game theory, in that governance situations can be described as interacting classes of institutional types, with sets of outcome possibilities to which probabilities may be applied.

Aspects of Ostrom's work have been very useful to this research. In particular, Ostrom has defined sets of attributes of both common-pool resources (resource attributes) and sets of attributes of the appropriators of such a resource (appropriator attributes), which, if present, substantially "increase the likelihood that self-governing associations will form" (Ostrom, 2005:244). When considering the analysis of social institutions as they apply to the Grootfontein aquifer, it became clear that some kind of logical framework was needed to assist in categorising and describing the institutions. Ostrom's resource and appropriator attributes are used because they are a widely supported framework for describing and discussing water management related institutions, such as the institutional situation at Grootfontein. Grootfontein's resource attributes are discussed in Section 6.3 and its appropriator attributes in Section 6.4.

The complete application of Ostrom's IAD Framework to the Grootfontein aquifer would have required a different approach to this thesis and its fieldwork. An important reason for not applying Ostrom's full IAD framework in this research is that Ostrom appears to advocate a high degree of self-organisation or self-regulation, exceeding that envisaged by the 1998 National Water Act. The Water Act does call for decentralisation and a measure of self-organisation, but it is also clear that the Department of Water and Sanitation should facilitate and if necessary enforce the organisational structures that are specified (DWA, 2013). Grootfontein is not a completely self-governing situation, only one with an important element of self-organisation.

Related to this issue is Ostrom's emphasis on the ability of rational individuals to self-organise (Economist, 2012). Ostrom was well aware that self-governing situations involving common pool resources did sometimes need external, state-sanctioned inputs to enforce fairness or punish free-riders (what Ostrom called "holdouts"). For example, in an early study of the West Basin aquifer in California, Ostrom describes how legal sanctions by an outside authority are needed to enforce collectively agreed decisions (Ostrom and Ostrom, 1972). However, Ostrom believed in the tendency of humans to collectively agree on strategies to avoid "tragedy of the commons" (Hardin, 1968) situations (Tucker, 2013). Since Grootfontein appears to bear many classic traits of the tragedy of the commons and has none of Ostrom's appropriator attributes (see Section 6.4), the full application of Ostrom's framework seemed inappropriate. At Grootfontein, incentives to over-abstract dominate tendencies towards self-organisation, implying that a central authority is needed to bolster local governance initiatives (see Section 6.5).

In a paper written in 2011, Ostrom describes and discusses an early 1911 article by Katharine Coman about the hardships faced by settlers in the mid-west of the United States and their attempts to collectively organise irrigation (Ostrom, 2011). Ostrom compiles Coman's conclusions, and assesses the impacts of the various laws passed at the time to assist irrigators. Ostrom concludes that collective action problems such as building irrigation systems are complex and have no simple answers – in other words, the government versus private sector debate is too simplistic. However Ostrom's paper does describe "government officials who lacked information" and goes on to state, "This problem continues into the present time" in the mid-west of the USA (Ostrom, 2011:50). Ostrom writes that "many scholars presume that an external government must intervene" (Ostrom, 2011:50) in collective action problems, implying that this is not necessarily the case, and that smaller associations of motivated individuals may be better placed to understand and address local problems.

In summary, Ostrom's insights emphasise local organisation, often self-organisation, by motivated, rational individuals or groupings of individuals with high levels of institutional characteristics held in common. Central government is important, but ideally only intervenes when absolutely necessary. These views support decentralised, collaborative approaches to common pool governance, in keeping with most definitions of IWRM and in accordance with contemporary South African water law and policy, and explain Ostrom's popularity amongst South African water policy makers[30]. However, this model appears not to apply at Grootfontein, and is unraveling in numerous other natural resource governance situations across South Africa. It may be that more time is needed, that a firmer commitment to IWRM and "true" or fundamental decentralisation is required, or that the numerous severe political and economic imbalances inherent in South African society need to be addressed first. But it is hard not to see a more active role for regional or central government in South Africa than Ostrom may have envisaged. Taken together, these reasons explain why Ostrom's framework has not been adopted in its entirety for this research, but is rather used as a starting point for the institutional analysis as discussed in Chapter 6.

### *3.4.1. Common pool resources*

A concept that Ostrom refers to frequently, and one that is common in resource economics, is the idea of common pool resources. Common pool resources are natural or man-made resources (or "goods") that are shared by multiple users, for example a communal grazing area, a fishery or a groundwater aquifer. The characteristics of common pool resources (e.g. physical size or ease of access) make it inherently difficult to exclude beneficiaries from them, or to stop people from using them. This makes them different to private goods which can be fenced off, locked or otherwise restricted. Common pool resources are also "subtractible", in other words each additional user removes a part of the resource, and too many users can exhaust the resource (Figure 3-3). This is in contrast to non-subtractible public resources such as a park bench, pavement or beach known as "public goods", where additional users (within limits) do not detract from the resource or good.

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[30] Evidence of the esteem in which Ostrom is held by South African water policy and planning experts is the minute of silence held for her at a plenary session of the International Conference on Fresh Water Governance for Sustainable Development that took place at the Champagne Sports Resort in the Drakensberg in November 2012, not long after her death.

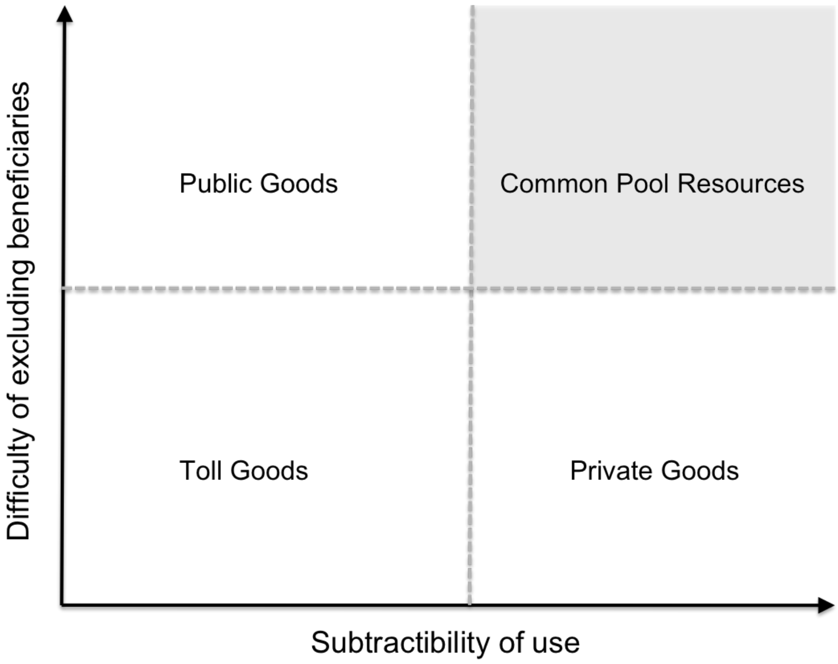


**Figure 3-3 Common Pool Resources (after Ostrom, 2005)**

### *3.4.2. The tragedy of the commons*

A famous paper dealing with the idea of common pool resources is Garrett Hardin's "The Tragedy of the Commons" (Hardin, 1968). Hardin describes herdsmen sharing a common grazing area. Each individual herdsman gains more by adding an additional grazing animal to the commons than he loses, since the gain accrues entirely to the individual whereas the loss (of grazing) is shared between all the herdsmen. Eventually the common grazing area is overwhelmed, to the detriment of all. Hardin writes: "Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit – in a world that is limited" (Hardin, 1968:1244). Hardin also applies this logic to the issue of pollution: "The rational man finds that his share of the costs of the wastes that he discharges into the commons is less than the cost of purifying his wastes before releasing them." (Hardin, 1968:1245). Hardin later discusses methods of "coercion" such as taxes or rules necessary to prevent tragedies of the commons, and argues that population growth is a major threat to the collective "commons".

Hardin's paper is often cited in studies of natural resource management, since natural resources are often "common pool" resources and are also vulnerable to pollution. Many authors have studied the mechanisms, policies or conditions necessary for preventing tragedies of the commons, including those that have evolved to fit the specific characteristics of local common pool resources (e.g. Ostrom, 1990). Diverse social and regulatory systems have developed or evolved in various places to manage potential tragedies of the commons. Local tragedies of the commons are therefore arguably rarer than Hardin's paper might suggest, but contemporary large-scale atmospheric and oceanic pollution bear out his warnings at regional and global scale.

The tragedy of the commons idea has also been criticised for implying that top-down control, coercion or even privatisation of common resources is necessary, and this informs political debate (Dietz et al., 2003). In many cases, solutions for avoiding local tragedies of the commons have been developed by local common-pool appropriators, using local knowledge of resource conditions. This supports ideas such as decentralisation and IWRM, and links water governance to some of the over-arching debates on the position and freedom of the individual in society, and the appropriate role of the state. It also illuminates a tendency to look for wider rules and principles, encapsulated in easily communicable narratives (e.g. Hardin's herdsmen and their cows, or Krueger's "rent-seekers") that underpin attitudes or stances towards complex situations such as governance of the Grootfontein aquifer[31].

## 3.5. Organisations managing water in South Africa

Many of the ideas and philosophies outlined above have impacted the nature and powers of the organisations that manage water resources and water supplies in South Africa. This section of the literature review introduces the contemporary water management organisations in South Africa at the three spheres of government – national, provincial and local, and starts with a short summary of the law as it applies to groundwater[32].

South African law provides for a number of interlocking organisations mandated to manage domestic water supplies and sanitation as well as the overall assessment and management of the national water resource. These include the Department of Water Affairs, Water Services Authorities, Water Boards, Water Service Providers, and

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[31] Easily communicable over-arching narratives that promise progress may be an important component of the modern Western world's collective institutional outlook, including ideas such as "freedom", the "nation-state", "human rights", or "the free market". Trust in the transformative potential of these ideas, particularly that they have an inherent capacity for progress and change rather than being themselves reliant on complex institutional frameworks, has informed the West's response to global events such as the emergence of post-1989 Russia, the development crisis in Africa, or reconstruction challenges in the aftermath of the Iraq war.

[32] These organisations are discussed in more detail in Section 6.2, and their sphere of government and potential influence on Grootfontein are shown on Figure 6.1.

Professional (water) Services Providers. Some of these organisations are currently constituted, funded and effective, and some are not. Catchment Management Agencies (CMAs) and Water User Associations (WUAs) as envisaged in the National Water Act are very important, yet are absent in many parts of South Africa including in the Grootfontein area. A variety of water plans, spatial development plans, and other planning documents are intended to ensure that all of these organisations work together, both in the provision of water services, and in spatial and economic development more generally (Murray et al., 2006). Other government departments, such as Environmental Affairs and Minerals and Energy, are also important to water planning and provision.

South African law and policy concerning groundwater has greatly changed since the first democratic elections in 1994 (Braune et al., 2014). Earlier groundwater legislation (e.g. the Water Act of 1956) was based on the principles of Roman-Dutch law. The owner of the overlying property held the rights to groundwater, and could essentially abstract groundwater at will (DWA, 2010a). In 1912 the Irrigation and Conservation of Waters Act, dealing mainly with irrigation, gave priority to agricultural activities. The Water Act of 1956 established the principle that most groundwater (as well as "private" surface water such as streams) was a private resource, with no obligation to share these resources equitably (Pietersen, 2004). The state had little control over private groundwater except where groundwater had been declared part of a "subterranean government water control area", a classification applied to relatively few locations[33]. Taken together, these measures complicated regional groundwater assessment and management, since they had the effect of defining groundwater as a local and "private" resource in law if not in reality (DWA, 2010a). Today, South Africa's groundwater is recognised as a common asset whose ownership is vested in the state (Braune et al., 2014). The National Water Act (RSA, 1998) recognised groundwater as public water, and refuted the principle of private ownership. Groundwater is now legally seen as part of the water cycle, and therefore as connected to other water resources, with the state as the final custodian (DWA, 2004a). Larger groundwater sources (e.g. boreholes abstracting more than an amount for basic household use) must be licensed, and these licensed quantities can be adjusted by the responsible authorities to control over-abstraction.

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[33] The area around the Grootfontein aquifer was declared a subterranean government water control area in 1963, the Upper Molopo Underground Water Control Area (RSA, 1977).

A distinction is made between the management of water resources in the environment, including bulk water resources such as dams and aquifers; and the provision of domestic water supplies and wastewater services to towns and communities. These are largely governed by the National Water Act of 1998 (RSA, 1998), and the Water Services Act (RSA, 1997), respectively. Environmental and bulk water are primarily the responsibility of the Department of Water and Sanitation, and mandated organisations such as Catchment Management Agencies (CMAs) and Water User Associations (WUAs). Provision of domestic water supplies and wastewater services is seen as the responsibility of the most local of the three spheres of government (RSA, 1998), and this responsibility is therefore primarily in the remit of municipalities. DWS at national level does have the power and obligation to intervene in cases of serious water services failure at local level, but municipalities in South Africa are of primary importance in water service provision.

**WSAs and Water Boards**

District municipalities and many local municipalities are legally designated as "Water Services Authorities" (WSAs). WSAs have a duty to "progressively ensure efficient, affordable, economical and sustainable access to water services" (RSA, 1997:18)[34]. Where a local municipality does not have WSA status, due to capacity or other constraints, the relevant district municipality assumes the WSA duties. A WSA may appoint a Water Service Provider (WSP) or other specialist "water services intermediaries" to enable it to meet its water services obligation (RSA, 1997). Increasingly in South Africa, water services are provided to WSAs by Water Boards, mandated by the relevant WSA. A Water Board is a body corporate established by the Minister of Water Affairs. They tend to be financially self-reliant, but are wholly owned by the state and do not make profits for private shareholders. The primary activity of a Water Board, according to the Water Services Act, is to "provide water services to other water services institutions within its service area." (RSA, 1997:31).

There has been a tendency towards the consolidation of Water Boards, with smaller Water Boards being taken over by larger ones. The recent absorption of Botshelo Water Board by the larger regional Sedibeng Water Board in the Mahikeng area is an example. There is currently discussion in South Africa of further increasing the responsibilities of

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[34] South Africa has approximately 44 district municipalities and 226 local municipalities. Together with the 8 metropolitan municipalities these cover the entire country and constitute the local sphere of governance.

Water Boards, at the expense of the operational independence of those municipalities who attempt to perform the various water services tasks themselves (the "wall to wall Water Boards" debate). Large regional Water Boards serve most of the major metropolitan municipalities in South Africa (e.g. Rand Water Board in Gauteng Province).

**Catchment Management Agencies**

Catchment Management Agencies (CMAs) are envisaged as the organisations with the mandate to manage water resources on a regional scale, yet with sufficient local input. Originally their boundaries of jurisdiction followed South Africa's 19 main surface water catchments in keeping with IWRM principles, and therefore cutting across municipal, provincial or other "political" boundaries. CMAs were also originally envisaged as being self-funding through administrative and licensing charges, and would progressively take over many of the responsibilities of the regional offices of the Department of Water and Sanitation.

The roll-out of CMAs has been plagued by problems including a lack of political support, and only two CMAs have been fully established since the 1998 Water Act. Some years ago, the overall number of CMAs envisaged was reduced from 19 to 9 (DWA, 2013; and Braune et al., 2014). There is now a renewed effort to establish these 9 CMAs - for example the National Development Plan stated that water resource management institutions should be implemented by 2015 at the latest (RSA, 2012).

In the absence of the CMAs, the DWS regional offices at provincial level are mandated to carry out the tasks that would otherwise fall to the CMA (DWA, 2004a). The establishment of the CMAs has not been a political priority over the last decade and a half – the problem is a complicated one, but it has harmed water management functions at local and regional level. The DWS regional offices do not, *de facto*, have the independence and authority to carry out all of the tasks envisioned for the CMAs.

**Water User Associations**

The most important organisational form of cooperative local management of water resources provided for by the National Water Act are Water User Associations - cooperative bodies of local water users. A Water User Association (WUA) is "a co-operative association of individual water users who wish to undertake water-related activities for their mutual benefit." (DWA, undated). A WUA is legally a body corporate, able to borrow money, open bank accounts and enter into legal proceedings. WUAs may represent one sector (e.g. irrigating farmers), or many sectors (e.g. farmers, miners and forestry workers). The Minister of Water and Sanitation must formally approve a WUA, once s/he is satisfied that it is in the public interest and that wide public consultation has taken place (DWA, undated). It was originally envisaged that WUAs would be funded through charges to their members, but in certain circumstances the state may assist with funding. Former irrigation boards and subterranean water control boards as defined by the old Water Act of 1956 are required to become WUAs, and this process must incorporate a measure of transformation in terms of management structure (DWA, 2004a). The final powers and functions of a WUA, once established, are delegated by the Minister, who may also remove functions and even dissolve the WUA under certain circumstances (DWA, undated).

WUAs were intended to facilitate better control of joint finances and equipment; simplify negotiation with regulators and other stakeholders; facilitate debate and collective decisions; and consolidate joint interests. Where over-abstraction is a problem and there is potential for conflict between different groups of water users (e.g. dolomite compartments), a WUA would help to resolve problems as soon as they arose, drawing on the local experience and interests of its members.

A major problem that has beset WUAs is the time and effort needed to set one up – and partly as a consequence relatively few viable WUAs exist today. The reluctance of the Minister to approve new WUAs seems to be mainly because they are often seen as reproducing past race and gender hierarchies and not therefore contributing to the transformation of society as originally envisaged (see Section 6.4.4). WUAs in consequence do not exist in many areas where they would be beneficial, such as around Mahikeng. In fact, there is not a single WUA in existence in the whole of North West Province (DWS, 2014a). This is despite efforts over many years by local stakeholders, mainly irrigating farmers, to establish them.

**The number of management organisations and rising complexity**

The National Water Act and other water policy documents envisage water management organisations collaborating to ensure fair and equitable outcomes. This collaboration, between different spheres of government, would allow for a degree of top-down expertise and guidance when needed, but also give local knowledge and needs a strong voice. Consultation, representation and collective decision-making are emphasised.

However, the various water management organisations can also resemble a chain, which is only as strong as its weakest link. Weakness or absence of any organisation disrupts management since it removes an important component envisaged in over-arching policy.

Furthermore, relationships *between* water management organisations are important, since collective decision-making relies on joint problem solving and reciprocity. Just as the absence of an organisation (e.g. a local level WUA) disrupts groundwater management efforts, poor links between organisations can have the same effect. A poor relationship between two management organisations, such as between DWS and a district municipality, or between a WUA and a CMA, can greatly slow down collective decision-making and implementation (see Section 6.4.4).

Obviously, as the number of management organisations rises, each with a constituency or sphere of governance to represent, the possibility of a poor relationship between any two of them also rises. If each organisation governing a particular aquifer must cooperate with every other organisation involved in that aquifer's governance, the number of good relationships required between the organisations is defined in the following way:

If N = the total number of groundwater management organisations required to collaborate, then the total number of good relationships "R" needed is:

**R = (X(X+1)/2), where X = N-1**

Each new stakeholder organisation joining an existing group of stakeholders therefore implies additional good relationships equal to the number of stakeholders already in the group[35]. The numbers of relationships go up in a triangular number sequence: doubling the number of management organisations from 3 to 6 implies not a doubling but a five-fold increase in the number of good relationships needed (i.e. from 3 to 15). Excluding all other considerations therefore, as new organisations are added the chance of a "poor" relationship rises disproportionately. The advantages of better representation and more expertise that a new organisation can bring must be balanced by the additional new relationships needed (which also take time to build) and the rising chance that a "poor" relationship might hinder the process (Figure 3-4).

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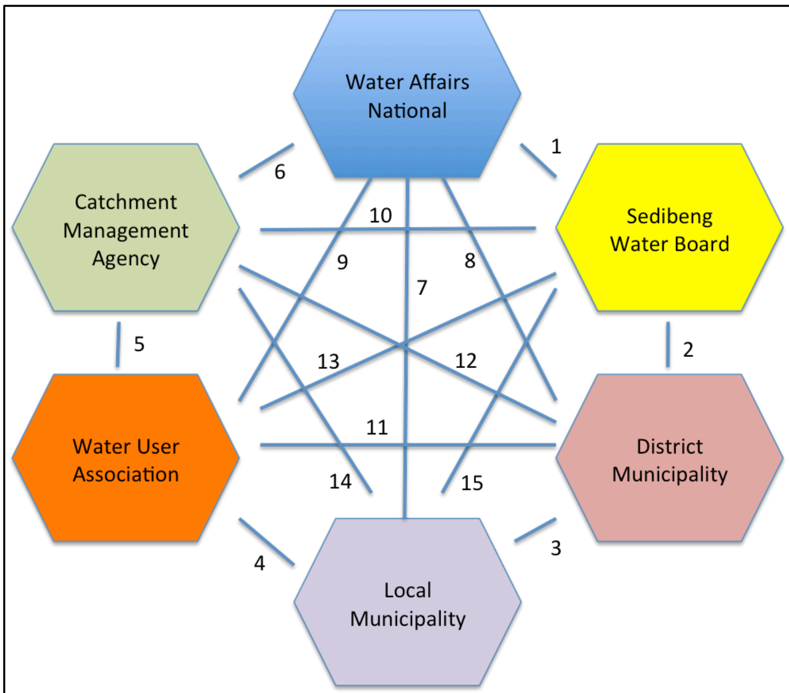
[35] This is sometimes known as the "handshake problem" – the same as the number of handshakes "R" needed in a room full of "N" strangers getting to know each other. At Grootfontein, at least 6 organisations must cooperate to ensure water management, implying 15 "good relationships" (Figure 3-4). A seventh organisation joining would imply 21 relationships.




| Collaborating organisations | Relationships needed |
|---|---|
| 2 | 1 |
| 3 | 3 |
| 4 | 6 |
| 5 | 10 |
| 6 | 15 |
| 7 | 21 |

**Figure 3-4 Organisations mandated to collaborate at Grootfontein and the number of relationships implied**

### *3.5.1. Discussion of water management organisations*

The water management landscape consisting of various interlocking organisations legally obliged to manage water and provide domestic water services is now changing in South Africa. The Department of Water and Sanitation favours a new, single water law that will supersede the old National Water Act and the Water Services Act (DWS, 2014a). This will lead to "developmental water management" governing the "entire water value chain" (DWS, 2014a:3). One organisational implication of this is the renewed effort to establish the Catchment Management Agencies (CMAs). Another is that DWS has elected not to approve any more Water User Associations (in fact it never approved any in North West Province) and to begin disbanding existing WUAs. It is envisaged that the functions of the WUAs will be carried out by the newly established nine CMAs. This is presented by DWS and others as a form of decentralisation, but will in fact transfer the local governance of water resources envisaged for WUAs to the provincial level (the new CMAs will cover areas similar to the size of provinces, although their boundaries will be surface water catchments). It is likely that these measures will collectively amount to a re-centralisation of power, because the CMAs will depend on DWS for funding, will employ mainly ex-DWS personnel, and will fall under the jurisdiction of the Minister of Water and Sanitation. These developments are partly in response to what is seen as the failure of local government (municipalities) to manage water services, and the tendency of local water governance initiatives (the WUAs) to perpetuate apartheid divisions.

It is not clear how these new provisions for water management, and their implications for water management organisations, will develop over time. They follow more than fifteen years of indecision and inaction on establishing the organisations provided for the in the National Water Act, particularly the CMAs and the WUAs. Much literature on South African water governance is nevertheless written as if these organisations already exist, or will exist very soon. For example, Seward et al. (2015:7) discuss the rules that apply to WUAs in South Africa in the context of groundwater governance, and the tension between WUA autonomy and centralised control, without mentioning the rarity of groundwater WUAs and the lack of DWS support for these organisations.

In practice this lack of clarity feeds short-termism, as well as the cynicism of many local stakeholders. The danger inherent in the proposed new DWS framework is that it will further prolong broad agreement about, and establishment of, water management organisations at the various levels in South Africa. It may be better to have water management organisations in existence and deal with their inevitable flaws, than to devote more time and energy to the theoretical organisational structure. At worst, a belief exists that there is a perfect formula for water governance, despite all international evidence to the contrary. This issue has roots in the wider contest between national government and the municipalities, or the national and local spheres of government. It also has roots in the water allocation reform (WAR) debate, which emphasises demographic equity of access to water resources and its balance with economic or strategic uses of water (see Section 7.6). It is an issue that may well take many years to resolve. In the meantime, water governance efforts and organisations (formal and informal) continue to lack legitimacy and long-term security, and aquifers such as Grootfontein remain effectively ungoverned.

## 3.6. Groundwater assessment and planning tools in South Africa

It is sometimes argued that South African groundwater resources are not properly quantified or are unreliable, so justifying other water supply choices such as desalination (Riemann et al., 2012). The Water for Growth and Development Framework published in 2009 by the Department of Water Affairs stated "Although groundwater is widely accessible and often close to the point of use, planners and consumers frequently either do not recognise it as a resource, or shun it as inferior to surface water" (DWA, 2009:29). The Framework goes on to say (DWA 2009:29) "At present, the country lacks the depth in skills and leadership in hydrogeology to drive the understanding and acceptance of groundwater from national down to local management level. Steps must be taken to strengthen geohydrological skills and build technical training capacity at institutions across the country." This implies that it is "technical" skills in groundwater or similar issues that underlie a preference for surface water and the under-utilisation of groundwater. However, this research argues that the problem is considerably more complex than a lack of technical capacity alone – in fact focusing on the technical issues can derail necessary work into the real reasons for the under-utilisation and mismanagement of groundwater in South Africa.

Some of the major past efforts to quantify groundwater resource availability in South Africa are summarised below, including a description of the associated reports, software, maps or other products. Many are essentially tools for decision makers to use in assessing the physical sustainability of groundwater. Most of these resources are available free of charge on the internet. The maps can be purchased directly from the Department of Water and Sanitation. These products show the presence of sophisticated groundwater planning and assessment tools in South Africa, as well as the expertise to develop them.

**Groundwater databases (Late 19th Century to present)**

Much of the public borehole and related data collected by the Department of Water and Sanitation and its predecessors such as the South African Geological Survey (now the Council for Geoscience) over many years has been consolidated into the on-line DWS National Groundwater Archive (NGA). Groundwater licensed abstraction data and groundwater quality data is held in separate databases including the WARMS and WMS databases. Also important are DWA's Geohydrology (GH) series of groundwater reports, dating back to 1906, many of which are available on-line on the DWA website (at http://www.dwaf.gov.za/ghreport/filter.aspx). The NGA currently stores around a quarter of a million borehole records, with the number growing annually. Considerable groundwater data and information is also held by the private sector (e.g. drilling companies, mines and environmental consultants), but this is often inaccessible – despite numerous calls to "register" drilling contractors and require them to submit their drilling records to the public database. A current three-year project led by the international consulting company AECOM is examining DWS's data collection and hydrological databases, and will make recommendations for improving and consolidating these resources (including an implementation strategy) when it is complete (expected in 2017). As mentioned, the conversion of groundwater data into useful data products for decision makers is not routine.

**The Groundwater Regions (Late 1980s to present)**

A long-term project based on the division of South Africa into a series of "Groundwater Regions" was initiated and led by the renowned former Director of Geohydrology at DWS in the 1980s, JR Vegter (Vegter, 2001). These regions are based on the *occurrence* of groundwater (mainly type of opening – i.e. primary or secondary) as well as on lithostratigraphical, physiographical and climatic considerations (Vegter, 2001). Groundwater in a region is not necessarily part of the same hydraulic or hydrological unit. It is intended that each region will ultimately have a separate groundwater report and map or maps, explaining and depicting groundwater occurrence and conditions in the region in detail. Full reports for 5 of the 64 Regions are complete and work is slowly progressing, coordinated by the Water Research Commission in Pretoria. The latest of these "Vegter reports" to be released is the one covering Groundwater Region 10: The Karst Belt, including the Grootfontein aquifer (Meyer, 2012).

**National Groundwater Maps (1995)**

The first comprehensive national estimates of how much groundwater is available in South Africa were provided by a set of national groundwater maps in 1995, accompanied by an explanatory document (Vegter, 1995). These maps were supplied as two A2 sized sheets, and included information on borehole prospects, saturated indices, mean annual recharge, groundwater component of river flow, depth to water table, groundwater quality, and hydrochemical types (Vegter, 2001). It is surprising that, in a country so dependent on groundwater irrigation and supply, South Africa's first official hydrogeological maps were produced as late as 1995[36]. The lack of such maps prior to

[36] In the 1930s Alex du Toit wrote "An uncommonly large proportion of this country is without supplies of surface water except for a limited period during the rainy season, while perennial streams are few. Although advantage has been taken by the settler of springs and shallow wells, it is through boring that the salvation of South Africa has been effected." (du Toit, 1939:484). The first reliable topographic map of South Africa was completed by the Department of Irrigation in 1938 at a scale of 1:500 000 to meet their "dire need for maps". This was at a time when the Trigonometrical Survey Office considered this mapping task practically impossible, cementing an

the 1990s indicates that groundwater was seen more as a local, disconnected, private resource, rather than a public or national asset.

**The Harvest Potential Map (1998)**

The first national groundwater maps (Vegter, 1995) did not provide estimates of sustainability or long-term groundwater availability regarding abstractions, and so further work led to the development of a national "Harvest Potential Map" which estimates total groundwater availability (i.e. not just borehole yield) per unit area in South Africa (Baron et al., 1998). Vegter himself did not agree with the methodology used in the Harvest Potential Map (Vegter, 2001) and did not recommend its use, but the map is nevertheless one of the first attempts to answer questions by water planners in South Africa regarding long term sustainability of groundwater supplies. Hydrogeologists today mostly recognise that precise figures for "assurance of supply" are difficult to provide before groundwater exploitation begins, and that some kind of feedback or adaptive system to refine management is usually recommended once abstractions begin (Seward et al., 2006).

**Groundwater Resource Assessment Phase 1 (GRA1) (Late 1990s to 2003)**

A project led by the Department of Water and Sanitation gave rise to the production of a set of 21 hydrogeological maps (sometimes known as the General Map Series or the "hydrogeological map series") at a scale of 1:500 000 covering the whole of South Africa. (It was intended that each map have an accompanying explanatory booklet - to date about half of the booklets are complete, but production of the rest has stalled). The maps are based on the standard and internationally accepted UNESCO hydrogeological map legend (UNESCO, 1983) and classify borehole yield and aquifer type using an alpha-numeric code. This differs from the system used by Vegter in his "regions" (above) – each system has advantages and drawbacks (see Vegter, 1994). The General Map Series is a significant achievement that allows South African groundwater resources to be more easily compared and contrasted with groundwater resources elsewhere in the world. The project leading to the production of the General Map Series is sometimes known as the Groundwater Resource Assessment Phase 1 (GRA1), to contrast it with the later GRA2 efforts (see below).

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early link between mapping and hydrology (Liebenberg, 2014). Vegter himself documented the huge growth in borehole drilling in South Africa, from about 2 000 boreholes drilled in 1910, to 12 000 drilled per annum by 1955, and 56 000 drilled per annum in 1985 (Vegter, 2001:10).

**The NORAD Toolkit for Water Services (2004)**

The Toolkit for Water Services was published by DWS in 2004 (DWA, 2004b), and was the outcome of a collaborative project supported by the Norwegian Agency for Development Cooperation (NORAD). The NORAD Toolkit (as it has become known) consists of a series of guideline documents, maps, computer programs and other outputs aimed at more appropriate use and management of groundwater in South Africa. Each output was tailored for a particular target audience (e.g. a municipal manager, or a local hydrogeologist). The Toolkit is freely available on-line for download (e.g. at http://intertest.dwaf.gov.za/groundwater/noradtoolkit.asp). The Toolkit has much useful information, including groundwater vulnerability maps and advice, but it represents the outcome of a mode of thinking more common at the time in which "community-led" groundwater projects were seen as most appropriate, and decentralised grassroots self-organisation was esteemed (see Section 3.3.3). This approach has somewhat fallen out of favour as it is recognised that "communities" are often unable to organise and maintain their own water resources, and a mixed approach is better except for countries where the state and its resources are practically non-existent. The Toolkit is unfortunately little used in South Africa today, but remains a useful resource containing much relevant information.

**The Assessment, Planning and Management Guideline (2008)**

A "Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa" was published by DWS in 2008 (DWA, 2008a). The objectives of the guideline are to provide assistance and guidance to those involved with the assessment, planning and management of groundwater resources in South Africa, particularly with regard to the correct processes to follow (DWA, 2008a). Assessment, Planning and Management of groundwater are related steps, each one of which has a bearing on the others in an iterative way. This generic guideline was based on an earlier DWA guideline aimed exclusively at dolomite aquifers (DWA, 2006a). Both documents were produced following the growing realisation that groundwater planning and management were being neglected at the local sphere of government, where water supply decisions are often made. As with the NORAD Toolkit, it is rare to find references to either guideline or to see them used for aquifer management at local government level today.

**Groundwater Resource Assessment Phase 2 (GRA2) (2005)**

The Groundwater Resources Assessment Phase 2 (GRA2) process, which began in 2003 and was led by DWS, aimed to update the Harvest Potential Map (Baron et al., 1998) as well as producing a "planning potential" map, quantifying recharge and groundwater/surface water interaction, classifying aquifers, and making more accurate estimates of groundwater use. Estimates of groundwater availability, recharge, baseflow, and numerous other factors are given per quaternary catchment, having been aggregated up from a 1 $km^2$ grid developed from existing databases. Doubts about the resulting dataset for certain functions and in certain catchments (e.g. it does not satisfactorily account for episodic recharge in arid catchments – see Van Wyk, 2010) has meant that is has not been "officially" released by DWS, but it is nevertheless still used in various ways by South African hydrogeologists as the best currently available dataset. The GRA2 database extrapolates existing spatial data for South African groundwater beyond justifiable limits in some cases, and early hopes that it would provide a groundwater planning tool to rival surface water models have been tempered. Attempts were made at a "GRA3" methodology, led by DWS in about 2009, but these also ran up against the limits of existing groundwater spatial data. Essentially, any remote tool for quantifying South African groundwater at a detailed local scale will need much denser groundwater data coverage. Such attempts are rare elsewhere in the world, even where groundwater data coverage is considerably better, and GRA2 probably says as much about a latent tendency to remotely quantify and classify groundwater down to a quaternary catchment level without field investigations, as it does about the resource itself.

**The GRIP Database (2002 to present)**

The Groundwater Resource Information Project (GRIP) was originally conceived as a national project to improve data holdings by accessing unpublished or "private" data as well as "new" groundwater data collected by visiting boreholes in the field – particularly in priority areas. GRIP would also develop systems and procedures for the collection and verification of unpublished data. GRIP was originally started in the Eastern Cape and Limpopo Provinces, with later roll-out in KwaZulu-Natal and the Free State (Botha, 2005). It was intended that all GRIP data be entered into the relevant DWS national databases (e.g. the NGA) to ensure its accessibility, although to date this has not been done. GRIP has been most fully implemented in the Limpopo Province, where more than 2 500 villages were visited and 24 000 boreholes were added to the GRIP database

(See www.griplimpopo.co.za). It seems unlikely that GRIP will proceed in the other provinces now, and the project has effectively stalled. The commitment in terms of staff, budgets and time that completing GRIP would require is very considerable.

**The South African Groundwater Decision tool (SAGDT) (Late 1990s onwards)**

The SAGDT is a set of software tools with a spatial (GIS) interface aimed at better assessment and management of groundwater resources in any given area in South Africa (DWA, 2006b). The project website states: "The South African Groundwater Decision Tool (SAGDT) is designed to provide methods/tools to assist groundwater professionals and regulators in making informed decisions concerning groundwater use, management and protection, while taking into account that groundwater forms part of an integrated water resource." (http://www.usersupport.co.za/SAGDTabout.php). The tool is freely available to download, and was rolled out in 2006 with a national road show and training course for interested parties, including DWS staff members. The SAGDT is based partly on the GRA2 data (see above) and takes remote assessment of South African groundwater to an unprecedented level. It is little used today and suffers from similar flaws to the GRA2 data on which it partly relies[37].

**The National Groundwater Strategy (2010)**

The output of this three-year project was a national strategy document produced by the Department of Water Affairs in 2010 (DWA, 2010a), following a process of consultation, and building on earlier strategy documents. The National Groundwater Strategy contains recommendations for groundwater management and development in South Africa, an economic assessment of the cost of *not* implementing the strategy, and tables of actions aligned with DWA's 2010-2013 strategic plan. The strategy was also intended to inform the second edition of the National Water Resource Strategy, published in 2013 (DWA, 2013), and it later attracted renewed interest at DWS (Braune et al., 2014). However, it has also been criticised for insufficient consultation (e.g. Seward, 2015). A major flaw of the National Groundwater Strategy was its failure to be recognised throughout the Department of Water Affairs – there was disagreement over whether it was *the* national groundwater strategy, or whether it was just *a* groundwater

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[37] South African hydrogeology has traditionally favoured a strong mathematical focus, with a history of emphasis on numerical modelling techniques and other mathematical methods at the universities where hydrogeology is taught.

strategy. This was tied to the question of how much responsibility DWS would legally assume for the actions prescribed in the final document. The Strategy is quoted fairly often nowadays, but its recommendations are mostly unmet and it does not constitute a core part of contemporary DWS thinking regarding groundwater.

**The Artificial Recharge Strategy and Atlas (2004 to present)**

In 2007 DWAF published an Artificial Recharge Strategy (Murray et al., 2007), a comprehensive document covering artificial recharge[38]. The strategy describes the technique, appraises its application in South Africa using examples, and presents a strategy for the roll-out of artificial recharge in South Africa. The strategy followed the publication of booklet introducing the topic in 2004 (Murray, 2004), and was itself followed by a comprehensive atlas showing areas of artificial recharge potential across South Africa (Murray et al., 2009). Resources on artificial recharge of groundwater in South Africa are collected on the website www.artificialrecharge.co.za and are free to download. The technique has huge potential in South Africa, particularly in arid regions where rainfall is sporadic and surface water storage limited. It has been used successfully at locations such as Atlantis, Kharkhams and Prince Albert in South Africa, and is a mainstay of the water supply system to Windhoek in Namibia. Unfortunately the operational demands of artificial recharge systems together with common misunderstandings and a lack of familiarity have so far prevented its wider roll-out[39].

**A Groundwater Assessment Methodology (K5/2048) (2013)**

This research project was funded by the Water Research Commission and was aimed at improving on the original GRA2 methodology. The project ended in 2013 and concentrated specifically on the application of new methods for baseflow analysis and quantification in South Africa – one of the areas in which the original GRA2 dataset was thought to be weak. The K5/2048 deliverables are available from the Water Research Commission. Rather than coming up with a "better" version of the GRA2 database, the project instead looked in more detail at using both chemical and hydrological river

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[38] Artificial recharge is the deliberate transfer of surplus surface water into aquifers for storage, through infiltration basins or injection boreholes. It is also known as managed aquifer recharge.

[39] For example, a proposal and pilot study in 2008 to address high summer water demand in Plettenberg Bay with a cost-effective artificial recharge system using the underlying Cape Supergroup fractured quartzite aquifer to store excess winter surface water was never implemented.

baseflow data to quantify the contribution of groundwater to surface water flows in South Africa – a much debated area which has still not been fully resolved, and one in which this project makes a good contribution. Like most WRC reports, it is available for free download on the WRC website at www.wrc.org.za .

**Water Research Commission Project K5/1763 (2012)**

This WRC project (formally known as "The delineation of high-yielding wellfield areas in Karoo Aquifers as future water supply options to local authorities") focused on the Karoo geological basin and has established an aquifer yield model, a wellfield assessment model, costing algorithms for local authorities, and other practical tools designed to assist the hydrogeologist working at local municipality level (Baker and Dennis, 2012). The software and tools are all available from the Water Research Commission in Pretoria. A GIS type interface allows a user (or planner) to establish a "virtual wellfield" at any chosen location in the Karoo basin and derive information about borehole productivity, depth to groundwater, borehole interference, water quality, the cost of treatment, and other valuable information. The outputs of the project are important planning tools, but were not intended as a substitute for hydrogeological fieldwork. As with all such projects, the outputs and estimates are only as good as the underlying data.

### *3.6.1. Discussion of assessment and planning tools*

In summary, a large range of hydrogeological planning and assessment products and tools is available in South Africa, mainly focused on the assessment of the physical groundwater resource, and on technical matters associated with its management such as establishing protection zones or monitoring of groundwater levels. South Africa has a range of such tools on a par with those available in many other countries. The inherent limits of the available raw groundwater data have arguably now been reached or exceeded. The tools are also evidence of contemporary South African hydrogeological expertise and capacity.

Despite appearances in some cases, the desktop tools available in South Africa described above do not endorse groundwater development without suitable field investigations by qualified hydrogeologists, and they were never intended to replace fieldwork. Such investigations might involve the geophysical siting of boreholes, trial drilling, pumping tests, delineation of protection zones, and other fieldwork. Once established, groundwater schemes need to be monitored and the conceptual model regularly updated, in line with the principle of adaptive management (Seward et al., 2006). JR Vegter (2001:xi) summarised the problem as follows:

> "The yield of a geohydrological unit can definitely not be determined or estimated prior to its development - at best it can only be guessed. It is only through exploratory drilling and testing that the hydraulic structure of a geohydrologic unit and its spatially variable hydraulic parameters may be determined. Even then, because the pattern of the permeable fractures in the hard rock formations (comprising 90% of S.A.'s area) is generally unknown and does not necessarily conform to a simple regular system for which theoretical models have been developed, reliable evaluation of parameters (mostly double-porosity) may be very problematic. Numerical modelling on any such geohydrologic unit requires an inordinate amount of (borehole) data. If, in addition, the wide margin of uncertainty about recharge values is taken into account, prediction of long-term water level response to groundwater abstraction would appear to be highly questionable and a fruitless exercise."

There tends to be an assumption that a group of "implementers" or users of the products or tools will put them to use. In reality many of the tools gather dust as hydrogeological curiosities on the top shelves of municipal officials, decision-makers and other stakeholders. The tools also focus mainly on "technical" or hydrogeological issues, suggesting that this is the primary impediment to better groundwater supplies. In fact, issues of implementation or "roll-out" are very important, as is operation and maintenance (O&M) of groundwater sources. The existence of the tools discussed here, most free of charge, demonstrates that a lack of hydrogeological information is not the main reason for under-use or mismanagement of groundwater in South Africa.

## 3.7. Operation and Maintenance (O&M) of groundwater schemes

This final section of the first part of the literature review covers a neglected aspect of the use of groundwater for domestic water supplies. Operation and Maintenance (O&M) includes all of the tasks needed to keep a groundwater source or wellfield functional. There is a large element of management implied in the concept of O&M, such as using water level measurements to adjust pumping rates in line with adaptive management, but

O&M also implies regular maintenance, re-fuelling, response to breakdowns, and other routine tasks. Rogers et al. (1998) define O&M costs as those costs needed for "running the system", such as electricity, materials, and staff costs, as opposed to the capital costs needed to install or purchase the system.

O&M, in other words, is the practical, routine, applied part of groundwater management – without O&M, the best technical and scientific assessments, plans and installations will fail. O&M is far more important than many realise. A cost-benefit study of groundwater supplies for rural areas in developing countries (Whinnery, 2012) found that almost 40 times more benefit, than cost, is provided when a groundwater supply system is properly constructed, operated and maintained. It was calculated that a 3 to 5 fold increase in net value is realized with the implementation of a suitable operation and maintenance (O&M) program (Whinnery, 2012).

Despite this, little has been written about the subject in South Africa, and O&M guidelines, manuals and similar resources are scarce. There is a draft manual by Taljaard (2008) that was never finalised, and parts of the NORAD toolkit (DWA, 2004b) have O&M instructions. Taljaard (2008:42) writes: "Basic first-line maintenance is an absolute necessity for sustainable operation of any borehole and plant and should be conducted conscientiously." The costs and difficulties of poor O&M are of course amplified if it leads to contamination of the aquifer more generally (e.g. from a leaking diesel tank).

Groundwater O&M manuals and other resources are available in the international literature - e.g. GoI (2013); USEPA (1988); and Schneider (2012) - or from websites such as www.operationandmaintance.net. Organisations such as DWS, the CSIR and the South African Bureau of Standards have specifications for borehole drilling and construction, groundwater monitoring, and other tasks relevant to well-field O&M. As far as is known, there is no standard, agreed upon and widely respected list of O&M tasks for domestic groundwater supplies in South Africa.

Adequate O&M relies on a surprisingly complex set of organisational functions and competencies - for example the right human skills, access to the right repair or lifting equipment, an inventory of spare parts, adequate transport, a mechanism for reporting breakdowns, regular flow of funds, etc (Gibson, pers.comm., 2013). Taljaard (2008:42) states: "There are many factors that determine the quality of O&M. The main ones are quality of staff, access to dedicated O&M funds, and the quality of records and analysis of information". More complex and higher yielding water supply systems (e.g. a dam or a big groundwater wellfield) may have technically more demanding O&M requirements, but may be logistically (or institutionally) simpler (Gibson, 2011). In contrast, single boreholes in a distributed network may only need basic and less frequent attention, but the logistical challenge can be surprisingly high. Part of the problem is that O&M is seen as a municipal responsibility that is at least one degree removed from hydrogeology[40].

The type of mechanical equipment chosen for a groundwater scheme can greatly effect O&M in the long-term. For example, electrical pumps are generally more difficult to repair than diesel-powered mechanical pumps (especially if electronic control systems are incorporated), but tend to break down less often. Electrical pumps are more complex, and few electricians are available to serve remote settlements (Gibson, pers.comm., 2014; Gibson 2010; and Gibson 2011). Diesel-powered boreholes lie at the simpler end of the spectrum of repairability, and can often be repaired by a local mechanic. Thus a "more reliable" technology in the short term can in fact be less reliable long term when the complexity of repairs, availability of trained personnel, and other issues are considered[41].

These considerations contribute to a preference in many areas of South Africa for big regional schemes where bulk water is sourced from large dams and pumped long distance, with centralised management of a complex network of pump stations, valves and reservoirs. Big regional schemes are often considered very reliable, yet detailed assessment by Gibson (2011) in a study of Eastern Cape schemes found no compelling evidence of this[42]. In practice it can be difficult to achieve and sustain hydraulic balancing across widely differing elevations with numerous users; and when the system fails, the impacts are experienced over a wide area. As Figure 3-5 illustrates, big regional schemes may merely substitute a technical complexity challenge for the logistical challenges of small scheme O&M. Neither is simple, neither provides an assured

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[40] There is even less guiding material on the institutional arrangements necessary to implement and sustain O&M and other asset management programmes – in other words, the "political economy" of groundwater management in South Africa.

[41] Development experts working on groundwater schemes elsewhere in Africa have long recognised this, supporting a range of "appropriate technology" solutions that are repairable by local people with limited resources such as the Afridev handpump. Ironically, it is in environments where no state support for O&M is forthcoming such as impoverished parts of rural Africa that O&M requirements may be taken most seriously at the scheme planning stage.

[42] The deterioration in performance (from 20 to 10 ML/day) of the Mmabatho water treatment works at Mahikeng's Setumo Dam between 1997 and 2012 supports this (DWS, 2014b).

reliability advantage, and both require specific sets of institutionalised activities by the organisations responsible for O&M.

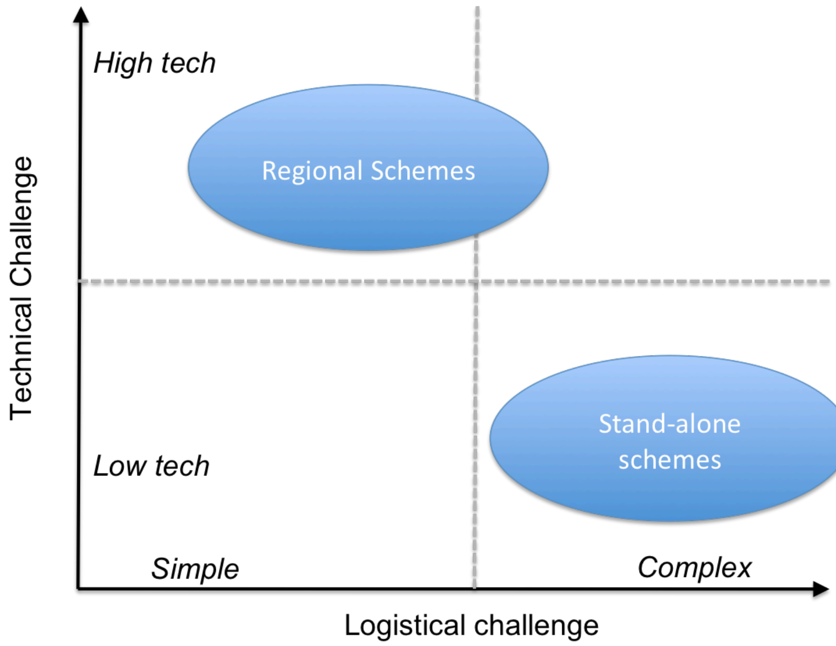


**Figure 3-5 Big regional schemes substitute technical complexity for small schemes' logistical challenges (after Gibson, 2011)**

The applicable local government level water authority or water services provider is usually responsible for O&M. This is often the relevant municipality, but the situation can be more complex, and in many cases different O&M functions may be carried out by different responsible authorities (e.g. a Water Board). Successful O&M of larger groundwater schemes requires close collaboration between different entities or organisations (see Section 3.5). Difficulties with cost-recovery further complicate matters. When funds grow short, routine O&M functions are often cut from budgets. As roles and personnel change the final responsibility for O&M may become difficult to establish. Tasks once considered routine become exceptional. Trained personnel resign. Consultants, engaged to oversee the initial installation of a system, depart. In these circumstances a typical groundwater supply scheme is exposed to a greater risk of failure. Ensuring adequate O&M requires strong overall management, training of operators, and adequate funds (Gibson, pers.comm., 2014). These are linked to management recognition of the need for O&M. The input of hydrogeologists and other specialists is occasionally needed to interpret results and solve problems. It is more difficult to ensure continuity of O&M than it is to carry out the tasks themselves, and it may even be more difficult and expensive to establish systems for O&M than it is to install the infrastructure in the first place.

There is evidence that groundwater schemes have lower up front costs but proportionately higher operational costs (including O&M), compared with surface water schemes (Eales and Cobbing, 2013). Whilst a groundwater scheme might be cheaper overall, its operational (or recurrent) costs may be more difficult to obtain and sustain than the initial capital expenditure. Recurrent costs are also vulnerable to appropriation for other (often temporarily more important) purposes, particularly as it may come to seem that regular O&M money spent on a well-maintained groundwater scheme does not yield any tangible benefits or improvement. These problems seem to affect groundwater supplies in South Africa particularly seriously.

The international literature now acknowledges that adequate operation and maintenance of groundwater supplies is one of the critical factors in success – if not the main factor (Lockwood and Smits, 2011; and Schweitzer and Mihelcic, 2011). This has led to renewed debate about the type of management approach that is best for rural water supply systems in developing countries or areas – for many years community-based management (or village-level operation and maintenance – "VLOM") was advocated, particularly where state organisations were unable or unwilling to operate or manage rural water supplies. There is now some acknowledgement that many communities either cannot (or simply do not) manage rural water supply systems in isolation, but do need support. Lockwood and Smits (2011:12) state that:

> "A tipping point may now have been reached with more and more national governments and development partners beginning to recognise the scale of the problems associated with poor sustainability and the real threat this presents to achieving the WASH Millennium Development Goals."

Or as Carter (2009:2) puts it:

> "Moving from an unimproved to an engineered water supply actually increases dependence on external organisations to provide support. If the support does not follow, then systems fail."

Lockwood and Smits (2011) talk about "professionalising" community water supplies, and outline a "sustainable services at scale" or "Triple-S" approach that aims at better sustainability. However, a lingering conviction that rural water supply schemes should be maintained and operated as much as possible by the local people that they serve remains. This contributes to difficulties with poor O&M, and with the perception of groundwater's unreliability.

A focus on technical hydrogeological tools rather than on protocols for O&M of groundwater sources and their wider institutional setting has cost South Africa dearly. It has contributed to groundwater being perceived as unreliable and second rate, and to a preference for surface water schemes. Whilst ostensibly a "technical" issue, it is clear that O&M is in fact closely linked to funding, personnel, management, planning and many other social institutions in the relevant local-level organisations. The easy part of O&M is how to carry out routine maintenance or fix a breakdown – the hard part is ensuring that the right people with the right tools arrive at the right time to do the job.

## 3.8. Conclusions

Groundwater potential in South Africa does not get the recognition it warrants, particularly in prolific aquifers such as the North West dolomites (Adams et al., 2015). Efforts to implement modern policies such as IWRM and decentralisation have spread groundwater skills thinly and increased the number and complexity of the various organisations that need to cooperate to manage groundwater resources.

Few realise that groundwater in South Africa has been semi-quantified, and is of comparable magnitude to the assured surface water resource. Groundwater cannot of course deliver the same volumes of water at a single location as a large dam, but the distributed nature of groundwater is an advantage in scattered rural settlements. There are many documents, maps and other tools aimed at better groundwater assessment, planning and management in South Africa, suggesting that South Africa does not lack technical information. None of these tools can replace local hydrogeological expertise and fieldwork for final scheme selection and siting. Few of the tools are used today by organisations at local level in South Africa. O&M of groundwater schemes is often neglected for a variety of reasons including budgetary and planning challenges, and this has predictable consequences for scheme reliability and the reputation of groundwater. Operation of groundwater schemes requires adaptive management (Seward et al., 2006), since it is difficult to accurately predict an aquifer's response in advance.

# 4. Groundwater in the North West dolomites

## 4.1. Introduction

This literature review chapter focuses on the North West dolomites, particularly the Grootfontein aquifer supplying part of Mahikeng's water supply. It demonstrates the considerable hydrogeological work completed in the Grootfontein area over the years, and the relatively robust technical understanding of it (Cobbing et al., 2014; CGS, 2008; EMA, 2003). This chapter also expands on the management principles and organisations as they specifically apply to the North West dolomites and to the Grootfontein aquifer. It concludes with sections on the Molopo Eye spring and the Steenkoppies dolomite aquifer, including an overview of past groundwater management at Steenkoppies that is directly relevant to Grootfontein.

The dolomite deposits of the North West Province, known as the North West dolomites, cover about 5 000 km$^2$. They stretch from the Botswana border near Lobatse towards Zeerust and Lichtenburg where they broaden into a west-east trending zone from Mahikeng in the west to beyond Ventersdorp in the east.

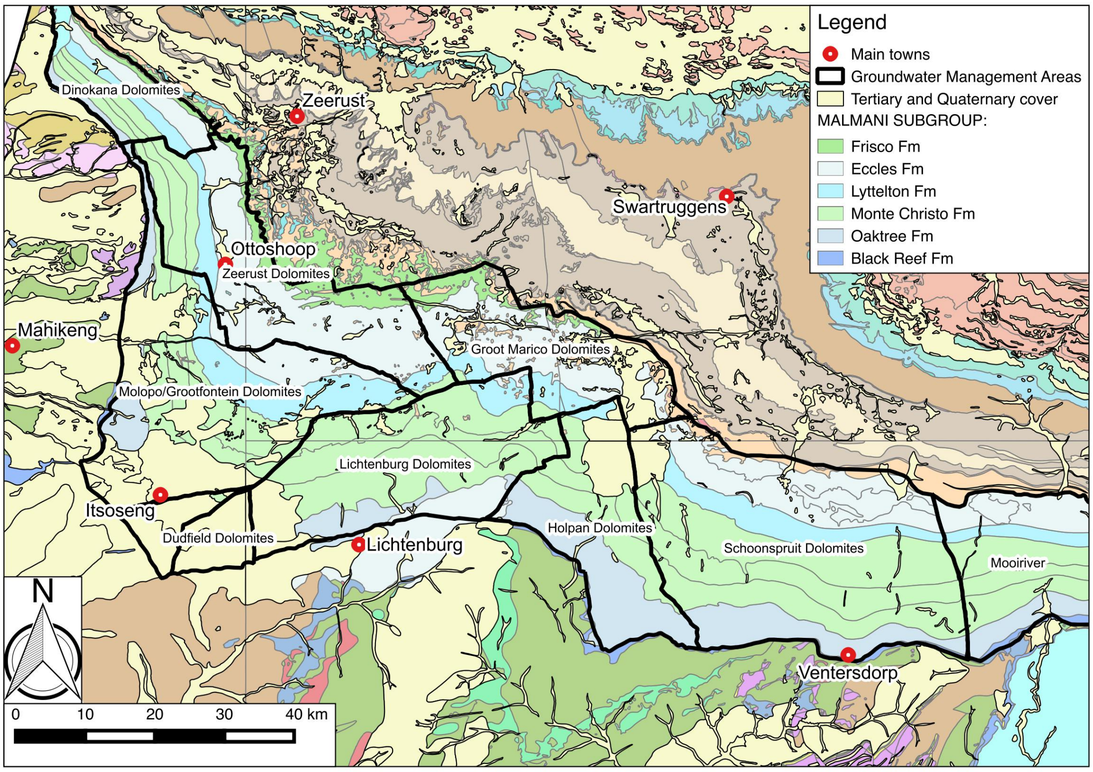


**Figure 4-1 North West dolomite GMAs (boundaries after Holland and Wiegmans, 2009; geology after CGS 1981, 1986, 1991 and 1993)**

## 4.2. Geology and hydrogeology of the North West dolomites

Strictly speaking, "dolomite" is a carbonate mineral ($CaMg(CO_3)_2$), but is usually taken to mean a particular type of limestone rock which contains the mineral dolomite. Dolomites of the Transvaal Supergroup are as much as 2 km thick in places, and form curved outcrops to the east and west of Gauteng Province (Malmani Subgroup of the Chuniespoort Group) as well as a triangular plateau east and south of Kuruman in the North Western Cape Province (Ghaap Group) (Figure 1-1). Formed around 2.7 billion years ago, the dolomites have been tectonically deformed and faulted, and are intruded by igneous dykes and other structures (Johnson et al., 2006). They are thought to have been deposited in shallow marine environments as a chemical precipitate and also in association with algal mats and stromatolites, some of the earliest recorded life on earth (McCarthy and Rubidge, 2005). In outcrop, the North West dolomite is moderately hard, greyish to brown in colour, and often weathers to a surface "elephant skin" texture.

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 allows. Weathering is limited by overburden, and at depth aquifer characteristics are generally poor.

The North West dolomites are divided into formations based partly on the chert content (Table 4-1). They comprise of the Eccles, Lyttelton, Monte Christo and Oaktree Formations, that together comprise the Malmani Subgroup of the Chuniespoort Group (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 Wiegmans, 2009; Meyer, 2012). The Monte Christo Formation has been divided into three sub-formations or members (Table 4-1). The entire sequence dips to the north beneath the Pretoria Group. See Section 4.3.1 for a stratigraphic column and geological map of the Grootfontein study area.

**Table 4-1 Formations of the Malmani Subgroup (after CGS, 1991)**

| Symbol | Formation | Description |
|---|---|---|
| *Vf* | Frisco | Stromatolitic dolomite, chert-poor dolomite, shale |
| *Ve* | Eccles | Interbanded dolomite and chert |
| *Vl* | Lyttleton | Chert-poor dolomite |
| $Vmo_3$ | Monte Christo | Chert-rich dolomite |
| $Vmo_2$ | Monte Christo | Interbanded chert and dolomite |
| $Vmo_1$ | Monte Christo | Oolitic chert and dolomite |
| *Vo* | Oaktree | Chert-poor dolomite |

Unconsolidated deposits overlie the North West dolomites in places, including the following (Stephens and Bredenkamp, 2002):

- Alluvial gravel (and calcrete) in places over 20 m thick
- Alluvium consisting of black organic clay derived from decomposed reed beds near springs and seepage along stream courses
- Residual chert and red soil covering large parts of the area
- Large parts of the area are covered by fertile soils

Dolomite weathers easily in the presence of acidic water. Joints, fractures and other discontinuities or zones of weakness are enlarged by dissolution to form highly permeable conduits, and these together with weathered and leached horizons can transform dolomite into an excellent aquifer. The same mechanisms can lead to serious sub-surface instability. Insoluble material such as silica and metal oxides remain as structurally weak and porous "wad" (from "weathered and altered dolomite"). In some cases, weathered and permeable dolomite areas are classed as "karst" areas, with sinkholes, dolines, caves and other distinctive features present.

### 4.2.1. *Compartmentalisation*

The North West dolomites have been divided into semi-autonomous groundwater units or "compartments" mainly by dolerite dykes, but occasionally also by faults and at contacts with adjacent rocks (RSA, 1977; Vegter, 2001; Stephens and Bredenkamp, 2002; and Holland and Wiegmans, 2009). These compartments are used as the basis for hydrogeological characterisation and groundwater management. Compartment boundaries are rarely completely impermeable however, particularly in the upper weathered sections, and the extent of groundwater movement across compartment boundaries is difficult to quantify. Compartment boundaries are normally marked by a distinct change in water levels, and in some cases force groundwater to the surface as springs, seeps or wetlands. Large springs (e.g. the Molopo Eye or Maloney's Eye), found at geological or compartment boundaries or at topographic lows, are a feature of the North West dolomite aquifers. The water table or piezometric surface within a compartment is relatively flat, reflecting the topography and generally high permeability. Defining compartment boundaries, and assessing groundwater conditions (flow direction, water levels and water quality) within compartments, has been an important task in dolomite hydrogeology in South Africa over the years.

A Council for Geoscience study identified 37 compartments in the North West dolomites, divided into 5 main units (CGS, 2008). Work done by Holland and Wiegmans in 2009 (Holland and Wiegmans, 2009) distinguished between Groundwater Management Areas (GMAs) and Groundwater Management Units (GMUs) in the North West dolomites and elsewhere, as follows:

GMAs generally coincide with surface drainage boundaries (e.g. quaternary catchments). A GMA does not necessarily represent a dolomite compartment or unit, but is a larger unit comprising a number of GMUs and groundwater resource units or GRUs (Holland and Wiegmans, 2009).

A GMU is an area of a catchment that requires consistent management actions to maintain the desired level of use or protection of groundwater. GMUs are based on surface water drainage and hydrogeological considerations, each of which represents a hydrogeologically homogeneous zone wherein boreholes tapping the shallow groundwater system will be, to some degree or other, in hydraulic connection. (Holland and Wiegmans, 2009). The GMU boundaries correspond roughly with the known dolomite compartments.

Holland and Wiegmans (2009) identified 10 GMAs consisting of 33 GMUs, as shown in Figure 4-1 and Figure 4-2. They made these distinctions using previous knowledge and experience, analysis of aeromagnetic data to identify dykes, and analysis of water level changes across proposed compartment boundaries. More work is needed to further refine the number and exact extent of GMUs in the North West dolomites, as well as the "leakiness" of compartment boundaries. There is a potential danger in the simplified conceptual model of a series of autonomous and separate aquifers.

The Grootfontein aquifer or compartment, shown in Figure 4-2, covers an area of approximately 239 $km^2$ (see Section 4.2) and is the main subject of this research.

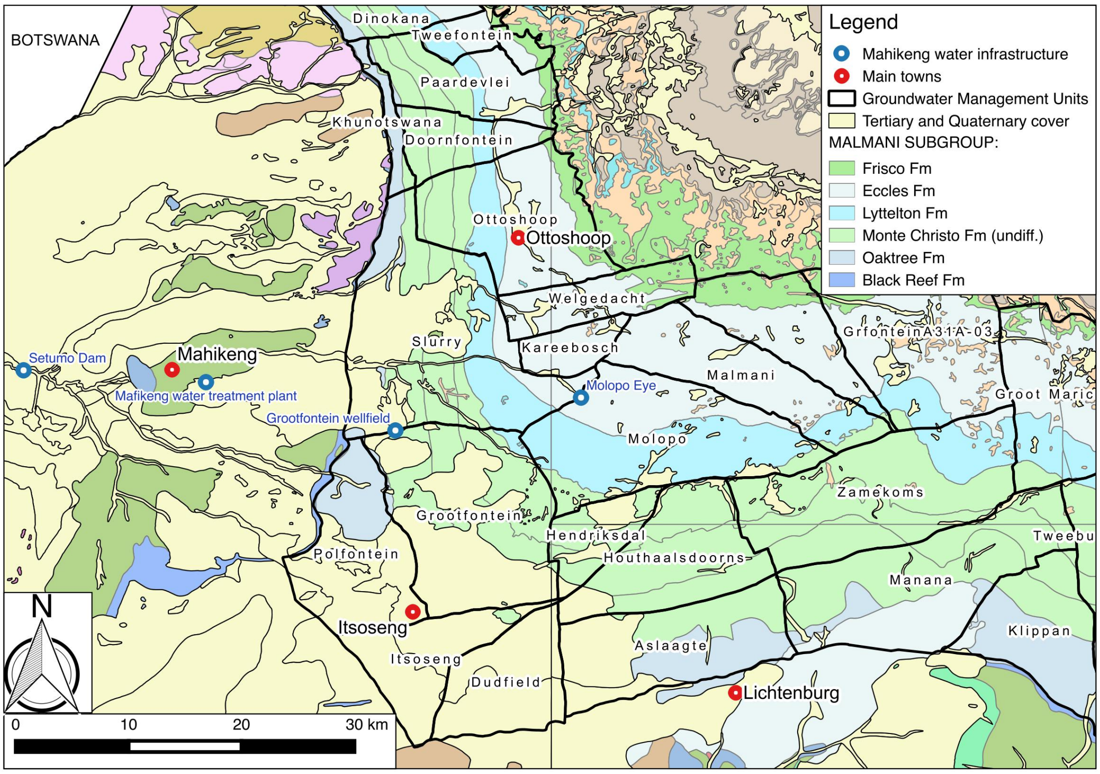


**Figure 4-2 North West dolomite GMUs near Mahikeng (boundaries after Holland and Wiegmans, 2009; geology after CGS 1981, 1986, 1991 and 1993)**

### *4.2.2. Aquifer properties*

Storativities (S) of South African dolomite aquifers generally vary between 1% and 5% (Barnard, 2000), but this property depends greatly on the extent of weathering and dissolution and can be 10% or higher. Transmissivities (T) can be several hundred $m^2$/day or more[43]. Groundwater movement in dolomites can, via permeable conduits, be several metres per day or faster, over distances of kilometres or more (Atkinson and Smith, 1974). Groundwater flow can be unpredictable, due to the discrete networks of channels, fissures and void spaces. Recharge values as high as 14% of annual rainfall have been derived (Barnard, 2000). Stephens and Bredenkamp (2002) estimate recharge in the North West dolomites as about 10% of rainfall (i.e. about 300 $Mm^3$ per year), and the total volume of groundwater stored in the aquifer at about 5 000 $Mm^3$ if an average thickness of 30 m and a storativity of 0.03 (or 3%) are assumed (this is about the same

[43] Storativity is the volume of water released by an aquifer per unit decline in hydraulic head. It is similar to porosity in many aquifers. Transmissivity (T) is the product of the hydraulic conductivity of an aquifer "K" and the aquifer's thickness. Transmissivity is a practical way to compare or assess aquifers. Its units are length$^2$/time, and $m^2$/day is often used.

volume of water as the Gariep Dam when it is full). Table 4-2 below shows typical transmissivity (T) and storativity (S) values for different geological formations within two dolomitic compartments of the North West dolomites (after CGS, 2008).

**Table 4-2 Aquifer Properties (T and S) of the North West dolomites**

| Formation | Grootfontein T value ($m^2/d$) | Grootfontein S value | Zeerust T value ($m^2/d$) | Zeerust S value |
|---|---|---|---|---|
| Oaktree | 35 | 0.025 | 87 | 0.01 |
| Monte Christo | 1200 | 0.08 | 1200 | 0.032 |
| Lyttelton | 1100 | 0.008 | 70 | 0.18 |
| Eccles | 3000 | 0.12 | 3000 | 0.18 |
| Dykes | 400 | 0.11 | 25 | 0.11 |

(After Bredenkamp, 1997; and quoted in CGS, 2008)

### *4.2.3. Vulnerability to pollution*

Although often used in the context of water quality, "vulnerability" can also refer to the quantity of a groundwater resource and the likelihood of this diminishing (e.g. drought vulnerability – see Calow et al., 1997). This section discusses vulnerability to pollution, rather than to over-abstraction. Vulnerability mapping is a way of showing the vulnerability of an aquifer or area to groundwater contamination, and vulnerability maps are generally used as planning tools – they do not usually replace local investigations and assessments. Vulnerability of groundwater to contamination depends on various factors, such as depth to groundwater, nature of the aquifer material, recharge, or soil properties. The National Research Council of the United States has defined groundwater vulnerability to contamination as the likelihood of contaminants reaching a specified position in the groundwater system after introduction at a location above the uppermost aquifer (NRC, 1993). There are various methodologies for assessing vulnerability or constructing vulnerability maps, such as the DRASTIC method (Aller et al., 1985). The methodology chosen depends on the characteristics of the area being considered, as well as the availability of data and the intended application. Vulnerability is often depicted as a relative rather than an absolute characteristic. The NORAD documents (DWA, 2004b) recommend five relative vulnerability classes, from Negligible to Extreme. Vulnerability maps are also usually "intrinsic", which means they focus on the aquifer properties and do not take into account the properties of the contaminant. Strictly speaking vulnerability changes depending on the properties of the contaminant being considered.

The conduits and weathered zones in dolomites can allow pollutants to move quickly and easily in the aquifer, whilst relatively little physical filtering of water occurs. Karst landforms such as sinkholes and dolines together with typically thin soils also allow surface pollutants rapid access to the aquifer. Together, these characteristics can make dolomite aquifers very vulnerable to surface pollution of various types. It is generally easier and cheaper to protect groundwater from pollution than it is to remediate or clean up the pollution once it has occurred (World Bank, 2002).

Aquifer protection can be divided into "resource protection" methods (e.g. mapping the vulnerability of a whole aquifer) and "source protection" methods that protect individual boreholes or springs (e.g. source protection zones). A combination of the two is usually recommended (World Bank, 2002). A standard method that is used world-wide to help protect groundwater quality at source is to establish areas or "protection zones" around groundwater abstraction points (and sometimes well fields and even whole aquifers too) within which polluting activities are controlled (Lawrence et al., 2001). Protection zones can be defined in various ways, ranging from simple circles drawn around boreholes (assuming a homogeneous, isotropic aquifer and no regional groundwater gradient) to complex zones derived using numerical groundwater modeling and taking into account aquifer properties, topography, groundwater flow direction and recharge. They can vary in size from a few tens of metres around a borehole to hundreds of square kilometres protecting an entire recharge area. The final protection zone chosen will depend not only on the physical properties of the aquifer and the presence of potential hazards, but also on the resources available to enforce the protection zones and the existing land area (Lawrence et al., 2001). Beyond fencing off the immediate area around boreholes, protection zoning does not exist in the North West dolomites, even for large domestic supply sources. The low intensity land use activities and the lack of polluting industries compensate for this omission, to some extent[44].

There have been limited attempts to assess the vulnerability of South Africa's dolomite aquifers. Options range from the simple characterisation of all dolomite aquifers as "vulnerable", to the analytical determination of groundwater protection zones, to more sophisticated numerical methods which take more detailed physical characteristics into account. Some combination of these is also possible. Work carried out at the University of Pretoria and applied by DWA has given rise to the "VUKA" vulnerability index

[44] The Groenkloof Nature Reserve at Fountains Valley immediately south of the Pretoria CBD was established in the late nineteenth century partly to protect the Fountains springs, and is probably South Africa's earliest groundwater protection zone.

(Leyland and Witthüser, 2009). A map of the dolomites in the Sudwala / Pilgrim's Rest area showing vulnerability using the VUKA method was later developed (DWA, 2008b). Vulnerability zoning work has also been done for the Pretoria Fountains springs (Sami, 2005). However, the technical work done on delineating protection zones in South Africa is not matched by uptake into policy, and protection zoning remains rudimentary and poorly understood at local level in South Africa. No protection zones have been delineated for the Grootfontein public water supply boreholes.

### *4.2.4. Management aspects and research questions for the North West dolomites*

The Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa" (DWA, 2008a; see Section 3.6) is based on an earlier guideline called "A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa" (DWA, 2006a). This dolomitic guideline describes the groundwater management role-players, discusses public participation, and describes procedures associated with the steps of assessment, planning and management. Resources such as risk management tools, a drilling contract template and pumping-test formats are included. Like the protection zoning resources, this Dolomite Guideline has struggled for traction in policy and implementation.

Arising from this Dolomite Guideline, a study was carried out in 2008 to investigate the future research priorities of the North West dolomites (DWA, 2008b). This study drew on previous work by the Council for Geoscience (CGS, 2008), and included interviews with dolomite groundwater experts conducted in 2008. The following summary of technical and management research questions was compiled as part of this study:

Technical issues in the North West dolomites in need of further work:

- Groundwater compartments need to be better understood and delineated. This work should include the interaction between compartments, water balances within compartments, and the grouping of compartments into Groundwater Management Units (GMUs).
- Once compartments and GMUs are better defined, improved water balances should be done for each.
- Recharge is still not fully understood, but is critical to water balances, and therefore to better management of the aquifer. More accurate rainfall

measurements, as well as measurements of groundwater parameters such as Cl, $HCO_3$, and $^{14}C$, will assist in refining recharge calculations.

- More detailed, local studies are needed in some areas to determine groundwater contours, spring flow variations, etc.
- More information on infrequent or anomalous recharge events (i.e. in particularly wet years) is likely to be needed for more accurate sustainability calculations.

Management issues in the North West dolomites in need of attention:

- Better coordination of research efforts is needed to avoid duplication of effort and possible waste of resources.
- The technical research done so far on the North West dolomites should be combined into a single archive or database.
- Better estimates of current groundwater abstractions, particularly from irrigation boreholes (which are heavy users)[45].
- Management needs to work on extended timescales of several years or longer, to take into account recharge following abnormally high rainfall. Average annual values for rainfall and for recharge can be misleading (e.g. van Wyk, 2010).
- Communicating the current "state of the resource" to groundwater users to facilitate regulation of abstractions.

The technical issues described above in general call for refinements of existing knowledge, and do not in themselves prevent more effective management, nor explain the generally poor management of North West dolomite groundwater to date.

In 2002, a report published by the Water Research Commission (Stephens and Bredenkamp, 2002) provided an overview of the issues related to dolomite groundwater use in the North West Province, as they then were. A comprehensive technical overview is also included, building on previous work by Bredenkamp (Bredenkamp, 1995). The authors recommended that a "dolomite aquifer management committee" be established, with a technical sub-group, covering all of the North West dolomites and working closely with DWS, the relevant CMA, and other organisations (Stephens and Bredenkamp, 2002:49). Issues related to inequitable access to groundwater resources and the representivity of local management structures were highlighted. Gaps in technical or

[45] The Council for Geoscience (CGS, 2008) refers to "a glaring lack of measured abstraction data and records" for the North West dolomites.

hydrogeological knowledge were identified, which "pose constraints to the development of institutional arrangements for the sustainable and equitable management of groundwater" (Stephens and Bredenkamp, 2002:52). These are similar to the technical issues described in the preceding paragraph. These authors further state that "Managers and users simply do not have the information needed to make informed decisions about groundwater, or the ability to develop this information base through monitoring" (Stephens and Bredenkamp, 2002:71). However, Section 4.2 and Chapter 5 of this thesis show that the technical information for the Grootfontein aquifer (and arguably the rest of the North West dolomites too) is adequate for making informed decisions about groundwater, especially if some degree of adaptive management is accepted.

In 2005 a second report was published by the Water Research Commission, building on Stephens and Bredenkamp (2002). This report, "Situational Analysis for the Preparation of Institutional Arrangements for Groundwater Management in the North West Dolomite Water Area" (Stephens et al., 2005), describes the social, ecological and institutional context of the North West dolomites. It also identifies issues affecting water resource management. The report strongly supports decentralisation of water management and IWRM. It aims to identify the resources required to bring the new organisations into being (particularly WUAs). The authors report on field interviews, providing information on proto-WUAs (including the Grootfontein WUA) as these organisations sought official confirmation from the Department of Water Affairs. The report recommends the appointment of an interim groundwater management coordinator, who would ensure that the aquifers are represented in the various tiers of water management organisations. Stephens et al. (2005) place considerable faith in these new structures to overcome existing institutional dynamics (the complexity of which are well described in the report).

The report also predicts some of today's challenges – in their conclusions the authors write: "The DWAF national office is not processing WUA applications fast enough and communication between the Department and applicants has been poor" and: "The local government authorities in the area tend to have a poor service delivery image" (Stephens et al., 2005:37). The report implies that South African water management policies are pioneering or lead the world – the authors write: "There is little substantive experience from anywhere in the world on which to base the proposed structures and guidelines for the management of the North West Dolomite aquifer" (Stephens et al., 2005:17)[46].

Subsequently, Pietersen et al. (2011) present a case study of South African groundwater governance that is part of larger project funded by the World Bank entitled "Too Big to Fail: The paradox of groundwater governance"[47]. Three of the four aquifers examined by Pietersen et al. (2011) are dolomite aquifers. Using an assessment approach prescribed by the World Bank, Pietersen et al. (2011) conclude that technical resources such as maps and data for groundwater governance in the four South African case study aquifers are adequate. However, legal and institutional issues, and cross-sector policy coordination, were found to be less satisfactory. In general, "governance provisions" are rated more satisfactory than "institutional capacity", implying that South Africa struggles particularly to implement policies. Pietersen et al. (2011) recommend the implementation of existing strategies and plans, including the integration of the National Groundwater Strategy (DWS, 2010a) into over-arching policy. They also recommend the "establishment and operationalising" of the CMAs and WUAs (Pietersen et al., 2011:82). However, the report does not identify which organisation should be responsible for this work, or examine in detail why implementation has failed in the past.

The ex-DWS hydrogeologist Paul Seward recently completed a PhD on groundwater governance in South Africa (Seward, 2015). Seward acknowledges that there is no "one size fits all" approach to groundwater governance, and identifies significant failings of groundwater governance in South Africa. Seward describes deficiencies within organisations charged with groundwater governance in South Africa. He identifies in the Department of Water and Sanitation bureaucratic shortcomings similiar to those identified by Von Holdt in a study of the public health sector in South Africa (Von

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46 Stephens et al., (2004) were writing at a time when management of the West Bank aquifer in Israel/Palestine was being studied; numerical modeling work aimed at managing the Cretaceous Chalk dolomite aquifer in the UK was being done; the Water Framework Directive as over-arching EU groundwater management legislation was being debated; issues over the level of community involvement in managing groundwater overdraft in India were being studied; research into the management of the Murray-Darling Basin in Australia was focusing on groundwater; the role of groundwater in drought management in the Horn of Africa was being researched; over-abstraction in the Ogallala Aquifer in the mid-west of the USA was being studied; and similar projects. In the opinion of this researcher, the belief that South African groundwater is unique owes more to isolation under apartheid than to reality.

47 For more information on this project see the World Bank document archive at: http://documents.worldbank.org/curated/en/docsearch/projects/P113191

Holdt, 2010). Lack of trust and social capital are seen as key deficiencies in both studies[48]. Seward recommends a "backcasting" approach for groundwater governance, i.e. a practical strategy linked to a desired outcome. A new "implementation agency" for groundwater governance is also suggested. Seward's thesis overlaps with several of the themes of this current study, including the emphasis on social institutions as key to understanding groundwater governance failures. Seward contends that a pragmatic approach rather than a theoretical or ideological approach would lead to better groundwater management. Seward's findings include the requirement for inputs from an outside agency – implying that external help of this kind might overcome a lack of experience, political will, knowledge, organisational ability, or other deficiencies.

More recently, a two-year WRC project working on water governance of groundwater and surface water resources in South Africa has just been completed (Riemann et al., 2016), using the water supply to Mahikeng as a case study. The main aim of this project was to build a "framework and action plan" for improving groundwater governance in South Africa. In their draft final report, Riemann et al. (2016) endorse IWRM and decentralisation, but identify a bias towards surface water in South African policy and legislation. The authors make use of the "trialogue" approach of Turton et al. (2006), who stress that good relationships (i.e. institutional structures) should exist between the three main "actor clusters", namely science, government and society. This emphasises the relations *between* organisations, rather than the nature of the organisations themselves. The groundwater supply and management situation at Mahikeng is classified by Riemann et al. (2016:76) as "problematic and extremely vulnerable" with a lack of management and technical skills in particular being highlighted. Good governance is seen as a "process of interaction and exchange between stakeholders" that could be facilitated by a special water resource management committee (Riemann et al., 2016:88). In the case of Mahikeng specifically, the authors argue that DWS needs to urgently lead a groundwater governance process since other organisations are under-capacitated, or have not yet formed. This research emphasises the failure of institutions that promote cooperation

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[48] Von Holdt's paper "Nationalism, Bureaucracy and the Developmental State: The South African Case" argues that poor performance of the South African state bureaucracy is linked to six issues: class formation, ambivalence towards skill, the importance of 'face', hierarchy, ambivalence towards authority, and budgetary rituals. He identifies a tension between the desire for an efficient bureaucracy needed to underpin the "developmental state", and the inclination to depart from Western meritocratic "Weberian" models of bureaucratic functioning. Von Holdt argues that the modern South African bureaucracy is ineffective as a result (Von Holdt, 2010).

between major stakeholders, and concludes that this can be remedied by the input of a committee, organisation, or similar support structure, as Seward (2015) also suggests.

In a review of the dolomite aquifers in the Upper Vaal Water Management Area, Pietersen and Lenkoe-Magagula (2013) concluded that less is known about the current chemical and hydraulic state of these aquifers today, compared with the 1970s and 1980s – and the same is probably true for the North West dolomites.

## 4.3. The Grootfontein aquifer or compartment

This literature review now concentrates on the Grootfontein aquifer in more detail. The literature on the hydrogeology and management of the Steenkoppies aquifer is described in Section 4.5, as it can be usefully compared with Grootfontein (see Figure 1-4).

The Grootfontein aquifer or compartment of the North West dolomites (sometimes also known as the Kliplaagte compartment) is located south east of Mahikeng in North West Province. It is one of the best-studied aquifers in South Africa, with a body of scientific research dating back to the 1960s. This is partly because it was the main source of domestic water for the town of Mahikeng until the 1980s, and it was also important for irrigation and other uses. It also had political significance since Grootfontein water supplied Mmabatho, the capital of the former "homeland" of Bophuthatswana and located adjacent to Mahikeng[49] (RSA, 1977).

The Department of Water and Sanitation has carried out the bulk of the hydrogeological research at Grootfontein over the years, and has mostly published this research as internal reports in their "GH" (geohydrology) report series. At least 16 GH reports exclusively or mainly on Grootfontein are available: Bredenkamp, 1964; Temperley, 1965; Gombar, 1974; Vipond, 1979; Cogho, 1982; Cogho and Bredenkamp, 1982; Mulder, 1982; Bredenkamp and van Rensburg, 1983; Taylor, 1983; Bredenkamp, 1984; Bredenkamp, 1985; Bredenkamp, 1986; Bredenkamp and Zwarts, 1987; Bredenkamp, 1990; Janse van Rensburg, 1992; and Dziembowski, 1995. Grootfontein is also discussed in several journals and conference proceedings, with a detailed description found in Van Tonder et al. (1986). Adding to earlier geological work by DWS, the Council for

[49] Today Mmabatho is essentially a suburb of Mahikeng, but is still considered a separate town by some residents in recognition of its history. The situation is similar to that of King William's Town and Bisho in the Eastern Cape Province.

Geoscience, and others, Holland and Wiegmans (2009) delineated the compartment boundaries as part of the Department of Water Affairs' Dolomite Project and produced a series of compartment maps for the North West dolomites. More recent work on aspects of the Grootfontein aquifer, supported through the Water Research Commission, includes that of Cobbing et al. (2013, 2014, 2015); and Riemann et al. (2016).

### *4.3.1. Topography, drainage and geology of the Grootfontein aquifer*

The Grootfontein aquifer is a typical ancient karst landscape with a very flat land surface, sloping gently towards the north-west with a gradient of about 50 m in 16 km (van Tonder et al., 1986). Average annual rainfall is about 560 mm and occurs mainly during thunder storms (Janse van Rensburg, 1992). The Grootfontein aquifer falls entirely within quaternary drainage region D41A. The course of the Dry Molopo River cuts across the far north east corner of the aquifer, and marshland shown on the 1:50 000 scale topographic map of the area associated with this water course indicates that groundwater would once have contributed to the Dry Molopo, along with the flow from the Grootfontein Eye. Both the Dry 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 is shown on the topographic map at Blaauwbank near the centre of the aquifer. No marshy ground exists today due to the drop in the water table. See Figure 4-3 below.

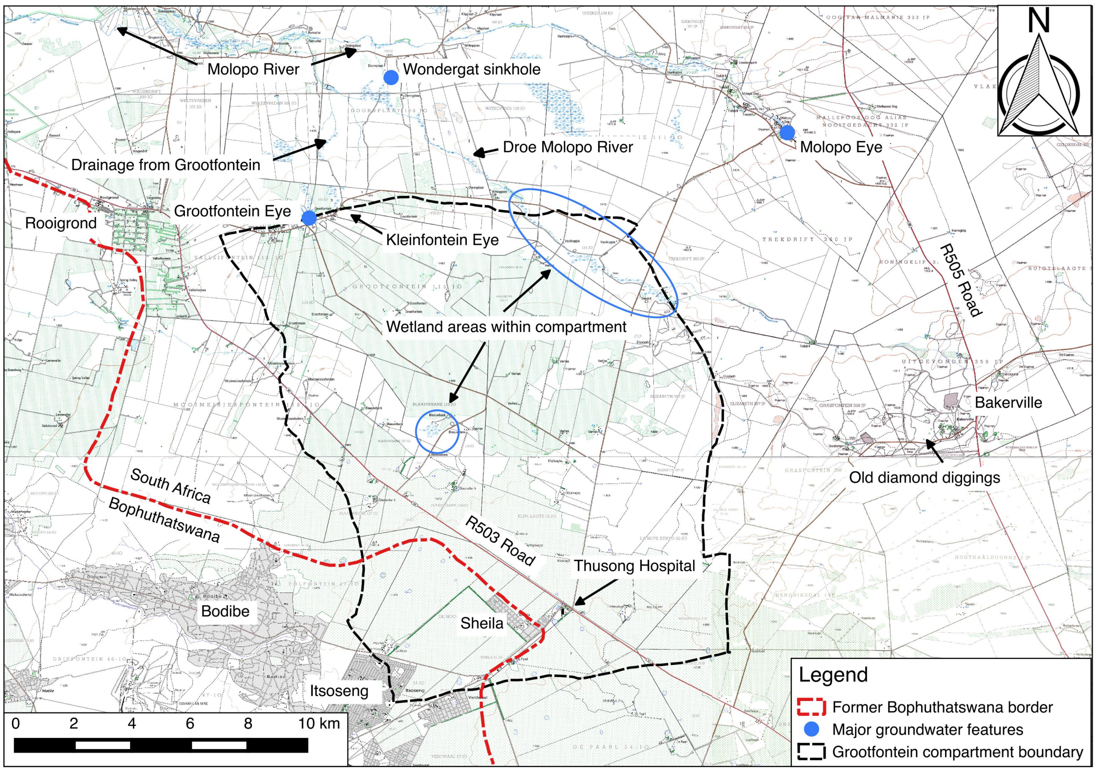


**Figure 4-3 The Grootfontein area when the Grootfontein Eye was still flowing**

The Grootfontein aquifer is underlain at depth by crystalline basement rocks of Archaean age (Janse van Rensburg, 1992; and Johnson et al., 2006). The basement is overlain by quartzites, shales and lavas of the Ventersdorp Supergroup, and these are overlain in turn by sedimentary and carbonate rocks of the Transvaal Supergroup. Figure 4-4 shows the major lithologies in the study area. The Malmani Subgroup of the Chuniespoort Group crops out at surface, and consists of the Black Reef, Oaktree, Monte Christo and Lyttleton Formations in the Grootfontein aquifer study area (CGS, 1991; and see Figure 4-5). The Black Reef and Oaktree Formations outcrop in the western part of the aquifer, whilst the Monte Christo Formation, thickening towards the east, occupies the majority of its area and is the most important water-bearing formation (Janse van Rensburg, 1992; Meyer, 2012). The Lyttleton Formation outcrops in the north-eastern corner of the aquifer and is a poorer aquifer than the Monte Christo Formation because it has little chert (Janse van Rensburg, 1992).

Unconsolidated Quaternary deposits of the Gordonia Formation of the Kalahari Group overlie the dolomites in places, and consist of sands, gravels and alluvium. These are diamondiferous in places (de Wit et al., 2009). Quaternary chert-rich gravels and alluvium make cultivable soil that is irrigable, in contrast to outcropping dolomite devoid of such cover known as “klipveld” and of poor agricultural potential (Bredenkamp, 1964).

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 (±2000 Ma) and the youngest post-dating the Karoo Supergroup (Day, 1981). A radiometric (Ar-Ar) date obtained by Day (1981) for a sample of dyke material near to the Molopo Eye was 1262±8 Ma. Dyke exposure in the study area is poor, and in general they cannot be identified visually in the field. Aerial photography and magnetic surveys are used to identify and map dykes, with drilling to confirm locations.

| Approximate 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** | Dolomite (massive) |
| | | | | **Eccles** | Dolomite, chert |
| | | | | **Lyttleton** | Dolomite, shale, quartzite |
| | | | | **Monte Christo** | Dolomite, chert |
| | | | | **Oaktree** | Dolomite, carbonaceous shale |
| | | | Black Reef | | Quartzite, conglomerate |
| 2700 - 2800 | VENTERSDORP SUPERGROUP | Andesite, quartz porphyry, conglomerate, calcareous shale, quartzite, lava | | | |
| 3090+ | BASEMENT COMPLEX | Granite, gneiss | | | |

**Figure 4-4 Stratigraphic column (not to scale) showing major lithologies in the study area (after Barnard, 2000; Johnson et al., 2006; and Meyer, 2012)**

### *4.3.2. Extent and thickness of the aquifer*

The Grootfontein aquifer or compartment is roughly rectangular in shape, is bounded by low permeability dykes on all sides, and covers an area of about 239 $km^2$ (Figure 4-5). This area was calculated using GIS software using the dyke boundary positions of Holland and Wiegmans (2009), which are recent estimates using both geophysical anomalies and water level changes. Over the years different boundary positions have been inferred by different authors, especially for the southern / south western boundary (for example, Cogho (1982) and Janse van Rensburg (1992) estimated that the Grootfontein aquifer covered about 160 $km^2$ and 169 $km^2$, respectively).

The aquifer thickness is a function of the weathering and karstification that give it its favourable hydraulic properties. Cogho (1982) estimated that the average thickness of the weathered (upper) part the Grootfontein aquifer was 56 m. Van Tonder et al. (1986) provided contours for the top of the unweathered dolomite in the Grootfontein aquifer as part of their numerical model baseline, constructed using 61 borehole logs with weathering information. These contours indicate an aquifer thickness ranging from roughly 40 m in the north west of the Grootfontein aquifer to 60 m in the south east.

### *4.3.3. Grootfontein aquifer boundaries*

The Grootfontein aquifer is bounded or compartmentalised by sub-vertical diabase dykes of varying thicknesses and hydraulic properties (Holland and Wiegmans, 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 hydrogeologic importance (Day, 1981:19). Subsequent studies have estimated aquifer compartment boundaries using dyke thicknesses, pumping tests and changes in groundwater levels.

Figure 4-5 below shows the Grootfontein aquifer with the compartment boundaries as mapped by Holland and Wiegmans (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).

The northern boundary of the Grootfontein aquifer is generally agreed to be the Grootfontein and Trekdrift 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 Trekdrift 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 sediments (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 Wiegmans (2009) placed the southern boundary of the Grootfontein aquifer further 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 show 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 Wiegmans, 2009).

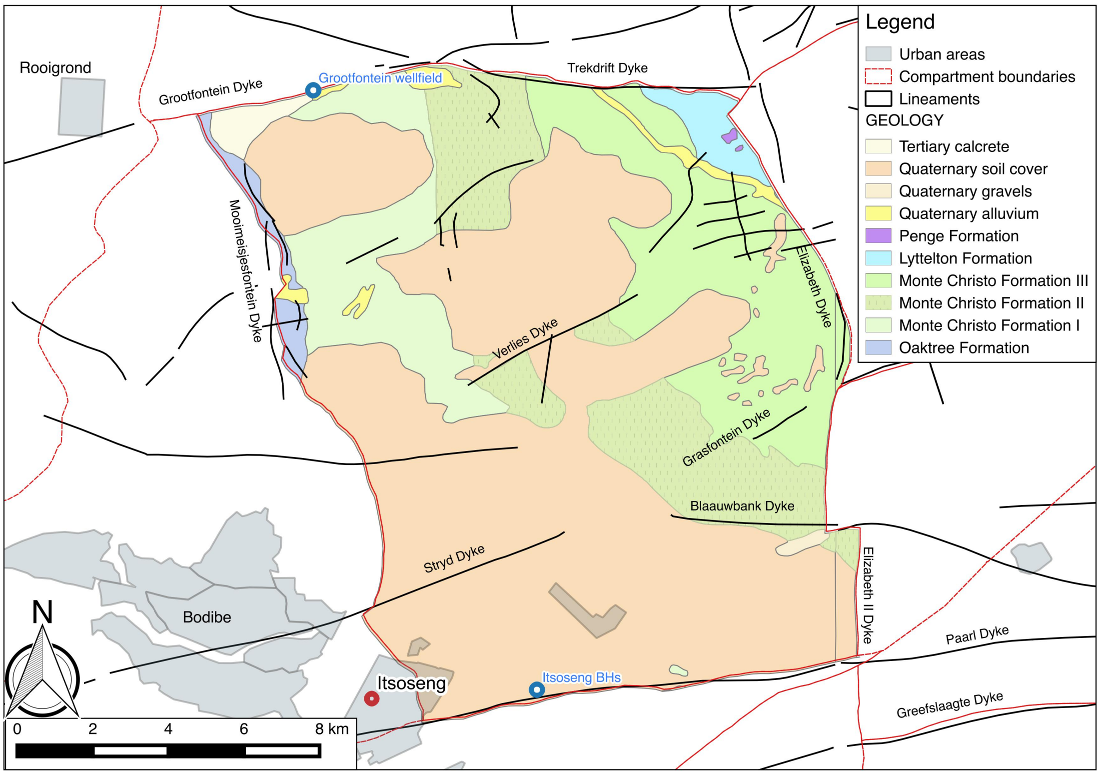


**Figure 4-5 Simplified geology of Grootfontein (after Holland and Wiegmans, 2009; CGS 1981, 1986, 1991 and 1993; and Day, 1981)**

### *4.3.4. Transmissivity and hydraulic conductivity*

Transmissivity (T) values for the Grootfontein aquifer vary considerably, reflecting the heterogeneous nature of the dolomite. T values from pumping tests in the aquifer range from 1 to 23 000 $m^2/d$, and in the vicinity of the Grootfontein Eye or spring from 11 000 to 23 000 $m^2/d$ (van Tonder et al., 1986). The diabase dykes bounding the aquifer have T values of up to 16 $m^2/d$ (van Tonder et al., 1986), although for modeling purposes they are sometimes assumed to be impermeable (e.g. Janse van Rensburg, 1992). T values for the Monte Christo Formation are thought to be higher than those for the Oaktree and Lyttleton Formations – van Tonder et al. (1986) observed that borehole yields in the Monte Christo Formation were generally higher than 15 L/s, and lower than this in the other two dolomite formations. Hydraulic conductivity (K) values used by Cogho and Bredenkamp in their early finite-difference numerical model of the aquifer ranged from very low to more than 900 m/d.

### *4.3.5. Storativity (storage coefficient)*

Storativity values for the dolomite depend on weathering and karstification and can vary greatly across short distances as well as with depth. Storativity is approximately equal to specific yield in unconfined dolomites. Enslin (1967) gives specific yield values for weathered dolomite generally of 18% (i.e. 0.18), but average figures across a compartment or aquifer are likely to be considerably lower (see below) due to variation in degree of weathering. Van Tonder et al. (1986) report average storativity values of 2.8% based on the response of groundwater levels to rainfall and a recharge rate of 8% of rainfall. These authors provide a storativity contour map showing storativity figures varying from about 1% in the south western part of the aquifer to 14% in the north eastern part. Porosity estimates of 2% for the Grootfontein aquifer are given by Mulder (1982) and Cogho (1982), whilst Bredenkamp and van Rensburg (1983) estimate porosity at 2% across the aquifer, except near the spring where it is 4%. Janse van Rensburg (1992) estimates porosity values between 2.15% and 2.45% for the Grootfontein aquifer.

Evaluation of storativity by pumping tests is complicated by the high yields and heterogeneity of the aquifer, and methods to estimate storativity from the response of water levels to rainfall must account for uncertainty related to the different recharge pathways (direct and diffuse), the non-linear relationship between rainfall and recharge, and the complications that arise due to the unknown pumping rates of boreholes across the aquifer. Pumping tests were not carried out as part of this research.

### *4.3.6. Recharge*

Van Tonder et al. (1986) report recharge in the Grootfontein aquifer as 8% of rainfall, based on work done by Bredenkamp for his PhD thesis in 1978 using tritium isotopes. Cogho (1982) specifies recharge values of 4.5% to 8% of rainfall, whilst Bredenkamp and van Rensburg (1983) use 10% of rainfall in calibration of their early finite-difference numerical model of the aquifer. Dziemboswki (1995) estimates recharge at 7% of long-term average rainfall. Janse van Rensburg (1992) uses the following relationship in his study, which requires above average monthly rainfall before any recharge occurs:

**Monthly recharge = 0.1 x (monthly rainfall – 67 mm)**

More recent work by Bredenkamp on relating recharge to spring flows in the North West dolomites (Bredenkamp, 2007; and Bredenkamp et al., 2007) uses $^{3}H$ and $^{14}C$ isotopes to describe a "bimodal recharge" model in which some recharge bypasses the soil zone (via macropores) causing the bicarbonate in the water to derive a different $^{14}C$ signature compared with recharge that infiltrates via the soil. This method relies on an independent estimate of recharge, and Bredenkamp (2007) suggests using the chloride mass-balance method for this. However the chloride mass-balance method suffers from difficulties in incorporating rapid recharge via macropores, from the general lack of data on chloride concentrations in rainfall, and from the non-linear relationship between recharge and the magnitude of individual rainfall events in semi-arid South Africa (including the dolomites). Furthermore, little is known about the effect of lowered water levels due to over-pumping on the rate and mode of recharge. Work by van Wyk (2010), Beekman and Xu (2003) and others has shown that recharge in years of low to average rainfall may be negligible, and that rainfall amounts must cross a "threshold" value before significant recharge takes place – this can happen as little as every decade or so. Thomas et al. (2016) document the importance of precipitation intensity to recharge, and show that episodic recharge comprisese the bulk of groundwater recharge in arid environments, using data from the southwestern United States.

As with storativity, it may be best to recognise a range of recharge results and err on the side of caution when using these to plan abstractions or manage an aquifer - this is in line with the adaptive management method advocated by Seward et al. (2006).

### *4.3.7. Yields*

Groundwater abstractions from the Grootfontein aquifer can be divided into three classes – abstractions from boreholes at the site of the Grootfontein Eye by DWS for water supply to Mahikeng (the Grootfontein wellfield); abstractions by irrigating farmers; and other abstractions such as the Itsoseng boreholes, small businesses, and smallholdings. These are introduced below, and further discussed in the water balance in Section 5.10.

**The Grootfontein boreholes**

Mulder (1982), Cogho (1982) and Bredenkamp (1984) all estimate that the boreholes at the Grootfontein Eye supplying Mahikeng yielded about 15.6 ML/day (about 180 L/s) at that time. Bredenkamp and van Rensburg (1983) record the boreholes as yielding between 15.5 and 24 ML/day (between about 180 and 280 L/s). Van Rensburg (1992) mentions that the permit allocation for the municipal water supply from the Grootfontein boreholes was about 12.4 ML/day (about 143 L/s) at that time.

In 2013 the Grootfontein wellfield was yielding about 8 ML/day (about 93 L/s), but in previous years it yielded as much as 20 ML/day (about 231 L/s), both estimates by staff of Botshelo Water Board interviewed at that time (Cobbing et al., 2013). The drop in yield at the wellfield is due to falling water levels that have rendered some of the boreholes dry and reduced the yields on those that remain in service. There were originally up to nine water supply boreholes drilled at or near the site of the old Grootfontein Eye or spring, but according to DWA (2010b) five of these were no longer operational by 2010. At present (following site visits in 2015) only three of the boreholes operated by DWS near the site of the Grootfontein Eye are operational, the others having gone dry over the last few years. These three boreholes together currently yield about 7.2 ML/day (about 83 L/s), according to the minutes of the Stakeholder Operating Forum meeting held at DWS in Mahikeng on 9 June 2015. Sedibeng Water Board records the daily volumes of water arriving at the Mafikeng Treatment Plant from both the Grootfontein wellfield and from the Molopo Eye. The Grootfontein wellfield data was obtained for 2015 from DWS (see Section 5.8.1).

**Irrigation abstractions**

It is difficult to accurately specify irrigation abstractions from the Grootfontein aquifer. This is because verification and validation of the licensed quantities, and enforcement of these license conditions, has never taken place. A complicating factor is that irrigation water demand is a function not only of crop type and irrigation scheduling, but also of total rainfall and rainfall intensity for any particular year. Writing more than fifty years ago, Bredenkamp (1964) stressed the importance of the Grootfontein area, recommended that it be included in the subterranean water control area then being considered, and stated that no new abstractions for irrigation should be allowed. In the early 1980s Bredenkamp and others used electricity consumption figures from Eskom to estimate irrigation withdrawals from the Grootfontein aquifer (Bredenkamp, 1985). These established that between 1977 and 1985 an average of about 9 $Mm^3$/a (about 24.6 ML/d or about 285 L/s) of groundwater was being abstracted for irrigation, but the totals for individual years varied from about 3.2 $Mm^3$/a to about 10.6 $Mm^3$/a (i.e. from about 8.8 ML/d or 101 L/s to about 29 ML/d or 336 L/s). Mulder (1982) and Cogho (1982) both estimate that about 22 ML/d or 255 L/s of groundwater was being used for irrigation purposes. Bredenkamp and van Rensburg (1983) used a figure for irrigation abstraction of 38.5 ML/d or 446 L/s to calibrate their finite difference model of the Grootfontein aquifer. Van Rensburg (1992) stated that the licensed allocation for irrigation in the Grootfontein aquifer was about 30 ML/d or 349 L/s.

**Other abstractions**

There is little information in the literature regarding other abstractions in the Grootfontein aquifer (i.e. apart from the public water supply abstraction at the site of the old spring, and the irrigation), but most of these are likely to be small abstractions for households or small businesses. The largest of these abstractions are likely to be the boreholes for public water supply at Itsoseng. These plot within the Grootfontein aquifer under the dyke compartment boundaries proposed by Holland and Wiegmans (2009). The operational borehole visited at Itsoseng in May 2015 had a yield marked on its data plate of 0.8 ML/d or 9.5 L/s. Even if this borehole pumps continuously at this rate it seems likely that it and other miscellaneous abstractions together abstract less than about 10% of the supply abstracted at the Grootfontein wellfield for supply to Mahikeng.

### *4.3.8. Flow of the former Grootfontein Eye or spring*

Cogho and Bredenkamp (1982) quote flow records for the Grootfontein Eye from July 1980 to March 1982. For several of the months during this period the eye was dry, but following rainfall in late 1980 and early 1981 flows ranging from 15.8 ML/d in April 1981 to about 4.6 ML/d in October 1981 were recorded. It is thought that October 1981 was the last time the Grootfontein Eye flowed. Vipond (1979) states that the average flow of the Grootfontein Eye in 1979 was 14.4 ML/d or 167 L/s, and that this figure was likely close to the long-term average flow of the eye.

### *4.3.9. Current state of the Grootfontein aquifer*

The Grootfontein aquifer is being over-utilised at present as evidenced by falling groundwater levels, and has been for years – for example more than twenty years ago Janse van Rensburg (1992:22) wrote, "In the case of the Grootfontein Compartment it is clear that the permit allocations to farmers by far exceed the recharge to the aquifer". Water levels near the Grootfontein boreholes were about 28 m below ground level in April 2015, and some of the boreholes used for water supply in the past were dry. An analysis of 35 boreholes in or very near the aquifer with recent water level data from the DWS NGA database shows that 33 of them have water level trends that show a decline over the monitoring period (the average record length for the 35 boreholes is 32 years). The average drop in water level of the 35 boreholes (calculated by subtracting the start water level from the end water level of each borehole's data series) is 12.7 m. This is discussed in Section 5.5, and the hydrographs are shown in Appendix C.

A first-order calculation based on the area of the compartment (239 $km^2$), a storativity of 2% and an average dewatered depth of 12.7 m suggests that around 61 $Mm^3$ of water in excess of recharge volumes has been removed from the aquifer since water levels began to decline in the early 1980s. If this volume of water was entirely available to Mahikeng, then based on the year 2020 projected water demand for Mahikeng (DWA, 2010b) of about 17 $Mm^3/a$, this volume of water would be able to sustain the town for more than three years (e.g. during a severe drought which affected the Molopo Eye flow). A policy of sustainable irrigation abstractions and abstractions from the Grootfontein wellfield and other sources which restored the water levels in the aquifer to the levels last seen in the early 1980s would therefore provide Mahikeng with a valuable "insurance policy" against drought or disruptions to the Molopo Eye source – the town could over-abstract during the drought, using the storativity in the Grootfontein aquifer. Such a policy would have the added benefit of ensuring smaller pumping heads and providing higher certainties of supply for all groundwater users.

This section has described the general hydrogeological data for the Grootfontein aquifer contained in existing literature. The next chapter of this thesis will incorporate new data on some of the parameters to arrive at an independent water balance and conceptual model of the aquifer. Chapter 6 will describe the management conditions at Grootfontein in much more detail, including the various organisations involved.

## 4.4. Summary of Molopo Eye flows

The Molopo Eye spring drains a different dolomite compartment (the Molopo compartment) to the north of Grootfontein (Figure 1-3). Part of the natural flow from the Molopo Eye spring is diverted to the Mafikeng Water Treatment Works for public water supply to Mahikeng and surrounds. According to DWS (2014b) this source began to be used for public water supply in 1985. Following declines in the yield from the Grootfontein boreholes (particularly after 2010), the Molopo Eye is now the most important source of groundwater to the town, supplying about 20 ML/day on average. The volume of water from the eye is regulated by a moveable gate and weir system that divides the flow of water between the pipeline to the treatment works and the natural course of the Molopo River. Data from January and February 2014, seen during an interview with staff members of Sedibeng Water Board in 2015, show that flows from the Molopo Eye arriving at the Mafikeng Water Treatment Works varied over those two months between about 5 ML/day and 25 ML/day. The variation in this public water supply flow is partly a result of the natural flow of the eye, but is also controlled by the weir system. The setting of the weir and the division of water between the public supply and the flow of the river is the subject of some local controversy, according to people interviewed in 2015, with some people living downstream of the eye having the view that too much water was being diverted for public water supply purposes.

DWS maintains two flow-gauging stations at the weir below the Molopo Eye (stations D4H030 and D4H014). Figure 4-6 below shows the variability in flows from the Molopo Eye over time, since records began in the early to mid 1980s. This variability shows a general increase in flow, but this is likely to be related to the increasing appropriation of the Molopo Eye water for municipal supply rather than a natural increase in spring flow.

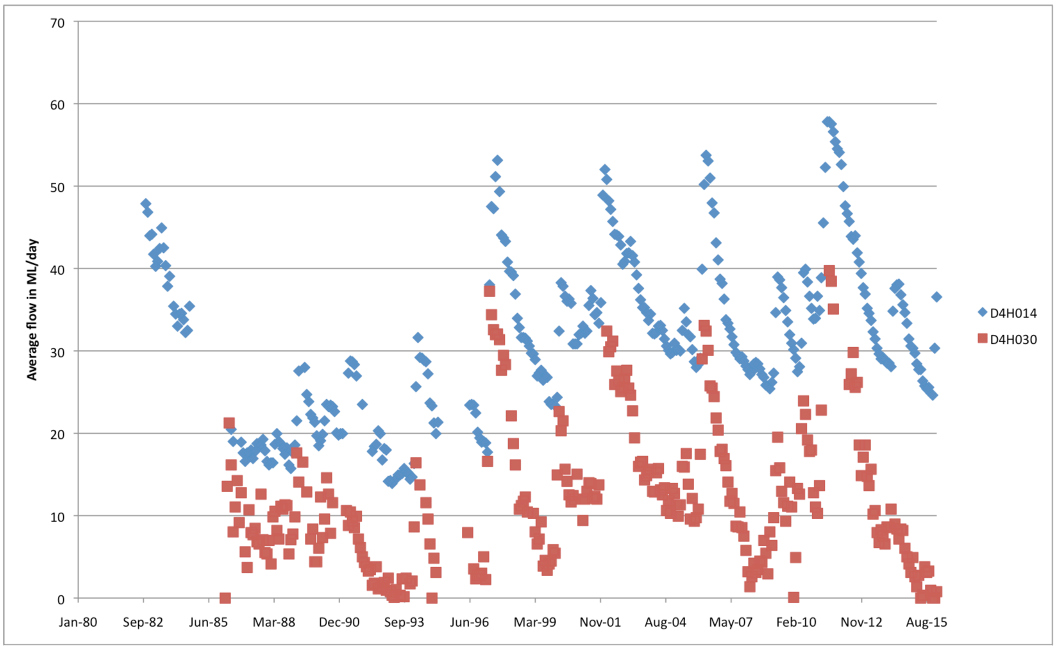


**Figure 4-6 Flows at the Molopo Eye, 1982 to 2015 (data from the DWS NGS)**

Mahikeng is vulnerable to low flows and/or technical problems at the Molopo Eye source. The New Age newspaper illustrated this in January 2016, attributing water shortages in parts of Mahikeng to "technical challenges at Molopo Eye and the breakdown of a borehole in Grootfontein" (New Age, 2016). Droughts in the mid 1980s and early 1990s show that the flows from Molopo Eye can drop below Mahikeng's requirements. DWS (2014b:5) state that after the decline in performance of the Grootfontein boreholes in 2010, the city of Mahikeng was subject to "regular and systemic water shortages", a prime motivation for the repair and upgrade of the Mmabatho Water Treatment Works. Without Grootfontein as a backup source, Mahikeng must depend on the Setumo Dam, which relies partly on return flows.

## 4.5. The Steenkoppies aquifer or compartment

This final section of the literature review describes the Steenkoppies aquifer, a dolomite aquifer or compartment similar in many ways to the Grootfontein aquifer (see Figure 1-4 and Figure 4-7 below). Steenkoppies allows comparisons to be made with Grootfontein which underline and support the conclusions of this research. Groundwater management at Steenkoppies is therefore discussed below, as well as the hydrogeology. No new hydrogeological data was collected at Steenkoppies as part of this research.

The Steenkoppies groundwater compartment or aquifer in the North West dolomites is located west of Krugersdorp near Tarlton, and has a total area of about 311 $km^2$ (Holland, 2009). According to the classification of Holland and Wiegmans (2009) the compartment is a groundwater management area (GMA) and can be further subdivided into three groundwater management units (GMUs): A21F-01, A21F-02 and A21F-03; with areas of 58, 85 and 168 $km^2$, respectively. For the purposes of this research the three GMUs will be collectively referred to as the Steenkoppies compartment or aquifer. A major consolidation of previous work together with considerable new data collection and research took place between 2007 and 2010 as part of the Department of Water Affairs' Dolomite Project. Outputs included a report focusing specifically on the Steenkoppies aquifer by Holland (2009). This work was added to by Meyer (2014) in his study of Groundwater Region 10 (The Karst Belt) for the Water Research Commission. Along with the Grootfontein aquifer, the Steenkoppies aquifer is one of the best studied South African aquifers. A book chapter by Vahrmeijer et al. (2013) summarises both the physical conditions in the aquifer, and the management challenges and drivers of change.

Irrigation from the Steenkoppies aquifer underpins a valuable agricultural industry. (Vahrmeijer et al., 2013). Irrigation supports higher value crops such as export-quality vegetables, mushrooms, nurseries, and cut flowers. Vahrmeijer et al. (2013) state that groundwater from the aquifer supports the largest producers of carrots in Africa, and the largest producers of mushrooms and chrysanthemums in South Africa. The industry employs more than 4 000 people and salaries of more than USD 900 000 are paid monthly. Annual turnover is approximately USD 66 million (Vahrmeijer et al., 2013).

The irrigation requires considerable investments in agricultural infrastructure such as centre-pivots, poly-tunnels, pumps, and reticulation systems, and Vahrmeijer et al. (2013) estimate capital investments of around USD 100 million. When backward and forward economic linkages are included, economic dependence on groundwater is substantial.

Large-scale irrigation began at Steenkoppies in the mid-1970s (Holland, 2009). The natural discharge point of the Steenkoppies aquifer is a large spring known as Maloney's Eye, the source of the Magalies River (see photograph in Appendix F). A low-flow crisis beginning in about 2004 and caused partly by drought led to legal threats and a legal directive from DWS restricting abstractions for irrigation, and initiatives to change the groundwater resource management framework (see Section 4.5.3 below). This included serious efforts to establish a Water User Association (WUA) for the aquifer, a multi-year process which was ultimately unsuccessful in establishing a formal WUA. However, the process gave rise to one of the more sophisticated local groundwater management stakeholder groups in South Africa.

The Steenkoppies aquifer invites comparison with the Grootfontein aquifer, which also supports an irrigated farming industry and also suffers from problems of over-abstraction. However, at Grootfontein progress towards a management organisation has been more modest by comparison, and the stakeholder group is broader, including organisations managing the public water supply abstractions.

### *4.5.1. Topography and drainage of the Steenkoppies aquifer*

The surface topography of the Steenkoppies aquifer is relatively flat, sloping from about 1570 m above sea level in the south to roughly 1500 m above sea level in the north. The aquifer falls within quaternary drainage region A21F. Mean annual precipitation in the area of the aquifer is approximately 670 mm/a. In the southern part of the Steenkoppies aquifer the Blaauwbankspruit (also known as the Upper Rietspruit) carries storm water and surface runoff from the town of Randfontein as well as about 8 ML/day of treated sewage effluent from the Randfontein Sewage Works (Holland, 2009). The Blaauwbankspruit's flow falls to nearly zero by the time it reaches a small dam wall near the town of Tarlton, due to leakage into the aquifer and irrigation withdrawals. Inputs to the Steenkoppies aquifer's groundwater therefore include losses from the Blaauwbankspruit and irrigation returns from water taken from the Blaauwbankspruit.

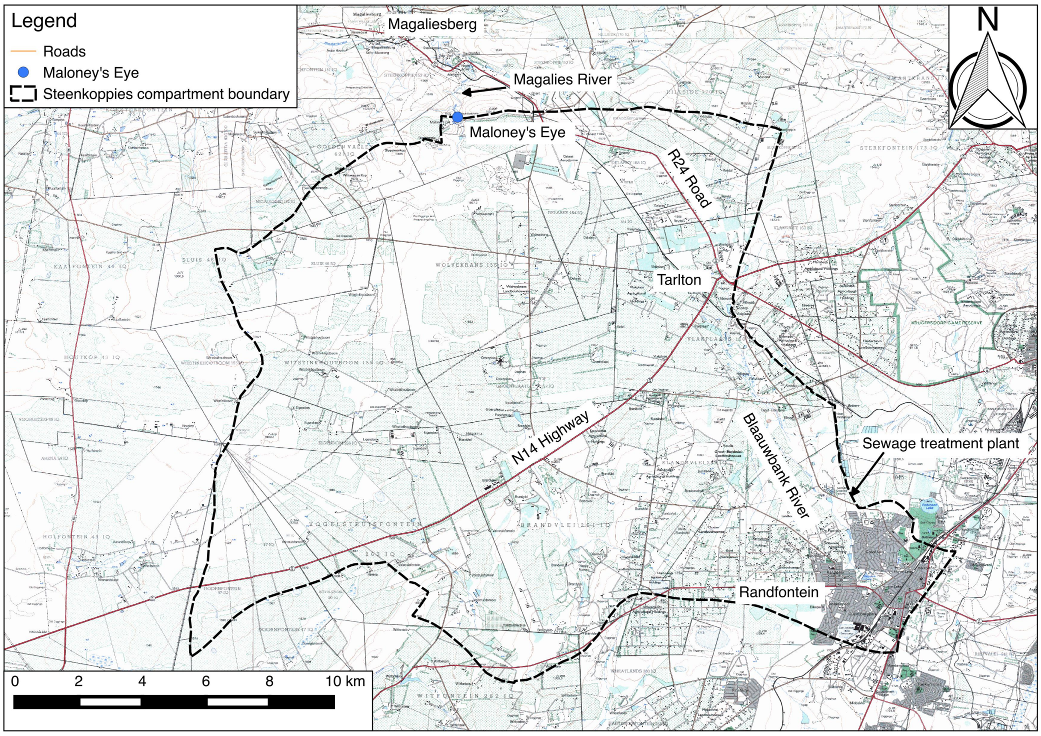


**Figure 4-7 Overview of the Steenkoppies compartment (boundary after Holland and Wiegmans, 2009)**

The natural groundwater drainage point, Maloney's Eye, is made up of nine separate smaller springs grouped together (Holland, 2009). Discharge records for Maloney's Eye date back about 100 years and show a long-term average flow of 0.455 $m^3/s$ (about 39 ML/day or 14.3 $Mm^3/a$), with the flow varying between 0.05 and 1.035 $m^3/s$ (Vahrmeijer et al., 2013). Several consecutive years of above-average rainfall are required to substantially increase flows from the eye (Vahrmeijer et al., 2013). Maloney's Eye is the source of the Magalies River, which supports activities such as small-scale irrigation and gardening, trout fishing and fish farming; and is also vital to the natural ecology.

**Table 4-3 Summary of Maloney's Eye flows (after Holland, 2009)**

| Year* (Record) | Min ($Mm^3/a$)ʸ | Max ($Mm^3/a$) | 10 Percentile ($Mm^3/a$) | 90 Percentile ($Mm^3/a$) | Median ($Mm^3/a$) | Average ($Mm^3/a$) |
|---|---|---|---|---|---|---|
| Pre 1975 | 10.63 | 22.04 | 11.48 | 18.95 | 14.13 | 14.56 |
| Post 1975 | 1.58 | 32.64 | 6.34 | 26.81 | 12.02 | 14.01 |
| Since 1999 | 1.58 | 16.05 | 3.37 | 14.82 | 7.98 | 8.93 |
| 1908-2009 | 1.58 | 32.64 | 9.46 | 20.85 | 13.81 | 14.35 |

*In 2009 it was estimated that Maloney's Eye was flowing at an average of 5.49 $Mm^3/a$ (Holland, 2009).

ʸSpring flows are in $Mm^3/a$, or million cubic metres per year.

### 4.5.2. *Geology and hydrogeology of the Steenkoppies aquifer*

The northern boundary of the Steenkoppies aquifer is formed by quartzites and shales of the Black Reef Formation (the basal formation of the Transvaal Supergroup) which mostly have a low permeability. The aquifer itself consists of N-NW dipping rocks of the Malmani Subgroup, alternating between chert-rich and chert-poor dolomites, which overlie the Black Reef Formation. The Malmani Subgroup is not further divided into its constituent formations on the Council for Geoscience 1:250 000 geology map of the area, and it has not been possible to distinguish between the different dolomite formations. The Rooihoogte and Timeball Hill Formations overlying the dolomites make up the northern boundary of the aquifer, and consist of conglomerates, shales and quartzites of low permeability relative to the dolomite. The eastern boundary is associated with mafic dykes (the Tarlton East and Tarlton West Dykes) and is confirmed by water table elevations and water chemistry (Meyer, 2014). Further work is however needed to confirm the nature of this boundary as a hydraulic barrier. The Wolwekrans and Wolwekrans South Dykes cut across the aquifer trending east-west, but based on groundwater level measurements are not thought to be substantial barriers to groundwater flow (Holland, 2009). The Eigendom Dyke forms the western boundary.

Holland (2009) describes a conceptual hydrogeological model in which groundwater flows towards the north to discharge at the Maloney's Eye spring. The spring is found at the intersection of the Maloney's Eye Dyke and an east-west striking fault zone, juxtaposing rocks of the Malmani Subgroup with low permeability rocks of the overlying formations, forcing groundwater to the surface. The Malmani dolomites making up the aquifer show higher transmissivity areas in the centre of the Steenkoppies aquifer based on gravity survey data and related to karstification (Holland, 2009). Inputs to the aquifer are from natural recharge, effluent discharge from the Randfontein Sewage Works, irrigation return flows, and inputs from the quartizites and shales making up the southern boundary of the aquifer. Recharge estimates for the Steenkoppies aquifer range from about 9% to as much as 21% of mean annual precipitation (Holland, 2009).

Holland (2009) and Vahrmeijer et al. (2013) demonstrate the relationship between the cumulative rainfall departure (CRD) and the Maloney's Eye discharge until about 1987, since when the actual discharge has been lower than the rainfall records would suggest – indicating the effect of external factors such as irrigation abstractions after 1987. Two periods of severe meteorological drought (1990-1992, and 2002-2005) have been followed by consequent periods of hydrological drought (1994-1996, and 2005-2009), worsened by the excessive abstraction of groundwater (Vahrmeijer et al., 2013).

### *4.5.3. Groundwater management at Steenkoppies*

Large-scale irrigation using groundwater from the Steenkoppies aquifer is thought to have begun in the mid-1970s. In 2009 the total area under irrigation was about 2 592 Ha (Tarlton, 2007). In 1997, Barnard estimated that lawful abstraction of groundwater in the Steenkoppies aquifer was about 19 $Mm^3/a$ (Barnard, 1997). Holland (2009) discussed the difficulties in estimating irrigation abstractions in the aquifer without data from the irrigating farmers, and estimated irrigation abstraction at between about 25 and 33 $Mm^3/a$ based on consultants' reports to DWS and his own water balance calculations.

Groundwater abstraction from the Steenkoppies aquifer appears to have grown steadily through the 1980s and 1990s in terms of volume and the number of boreholes, in a similar way to the expansion of irrigation at Grootfontein. Vahrmeijer et al. (2013) estimate that more than 200 boreholes are currently in use for irrigation in the aquifer. In 1994, following low flows in the Magalies River, DWAF (now DWS) forbade abstraction of water from the Magalies River for an interim period, pending review of water allocations from the river. Good rains in 1995-1997 led to this injunction not being pursued and the crisis receded (Vahrmeijer et al., 2013).

In early 2004 shallow boreholes used for household water supply in the Steenkoppies aquifer dried up (Vahrmeijer et al., 2013). In September 2004, a group of concerned water users downstream of the Maloney's Eye formed the Magalies River Crisis Committee (MRCC) to "address the problems associated with the flow of the [Magalies] river and to engage DWAF in seeking a solution to the problem and in following up on the promises that had been made." In December 2004 DWAF issued a series of directives aimed at stopping unlawful water use in the Steenkoppies aquifer. Later it was agreed that so-called "illegal pivots" would be allowed to continue operating as long as they took part in a validation process (Vahrmeijer et al., 2013).

In early 2007 Maloney's Eye reportedly ceased to flow for the first time on record (Holland, 2009). This followed a drought period of several years during which time irrigation abstractions did not decrease (in fact may have increased due to the lower rainfall and drier conditions). In 2007, the MRCC was reconvened and made a submission to the South African Presidency regarding the low flows at Maloney's Eye and the possible impact on the Magalies River, seeking amongst other things a temporary cessation of all groundwater abstractions from the Steenkoppies aquifer to allow the flow at the eye to recover (MRCC, 2007). The submission also raised the risk of sinkholes forming as a consequence of declining water levels in the aquifer. Vahrmeijer et al. (2013) report that the MRCC also initiated a lawsuit against DWAF in March 2007. Essentially, the 2007 submission / lawsuit by the MRCC stated that the primary cause of low flows at Maloney's Eye (and therefore low flow in the Magalies River) was irrigation using groundwater by farmers in the Steenkoppies aquifer, and that such irrigation needed to be drastically reduced.

The 2007 actions by the MRCC led to a response by 21 groundwater users (the "Tarlton farmers") in the Steenkoppies aquifer in the form of a submission to the Director-General of DWAF, dated November 2007 (Tarlton, 2007). The Tarlton farmers disputed that irrigation caused the low flows at Maloney's Eye, although they agreed that water resources in the greater Magalies area were under stress. They stated that "no credible evidence has been put forward to show that the water difficulties in the Tarlton and Magalies River area is attributable to the existing lawful use of water by the Tarlton Farmers" (Tarlton, 2007). The Tarlton farmers consequently disputed the restrictions on groundwater irrigation contained in the DWAF directive of 2004.

The Tarlton farmers commissioned and paid for a groundwater study by the environmental consultancy ERM (Pty) Ltd (ERM, 2007). This ERM study broadly supported the views of the Tarlton farmers. In particular, the ERM report stated that changing rainfall patterns, changing sewage inputs to the aquifer, changing water uses downstream of Maloney's Eye, alien vegetation along the banks of the Magalies, mining activities and other factors were also to blame for the decline in flow at the eye and in the Magalies River (ERM, 2007). The study done by Barnard in 1997 estimated a catchment size (177 $km^2$) and a water balance for the Steenkoppies area (Barnard, 1997). The ERM report stated that the catchment is in fact likely to be considerably larger (about 500 $km^2$) compared with the size estimated by Barnard (1997), based on bicarbonate concentrations in the groundwater. In ERM's view, the catchment area of the Maloney's Eye includes the Magaliesberg Formation quartzites to the north of the eye. The ERM report concludes that better aquifer management was needed, together with a more detailed hydrogeological study. The study by Holland (2009) was partly aimed at resolving these and other discrepancies, in effect answering ERM's recommendation.

In 2008, DWAF published a notice in the Government Gazette of 14 March 2008 restricting the use of irrigation water in the aquifer to certain days and times, dependent on the volume of flow at Maloney's Eye. When flows at the eye were less than 93 L/s, then all abstractions apart from Schedule 1 use would be prohibited[50]. The notice also called for the details of all irrigators to be submitted to DWAF within 21 days of publication of the notice.

In 2007 the Tarlton farmers started negotiations towards establishing a Water User Association (WUA) for the area, with the assistance of the Danish government aid organisation DANIDA. One of the first steps towards the WUA was the formation of the Steenkoppies Aquifer Management Association or SAMA (Vahrmeijer et al., 2013). It was intended that this association would facilitate the later formation of the official WUA. The organisation aimed to further the joint interests of Steenkoppies aquifer groundwater users, and a draft constitution for the WUA was prepared.

The Tarlton farmers have stated that restrictions in irrigation amounts will have serious consequences for their industry, and that even reductions of as little as 10 % of irrigation volumes will need to be phased in slowly (Tarlton, 2007). Vahrmeijer et al. (2013) state that "No restrictions on drilling, size of boreholes and pumps or compulsory measuring of water abstraction or monitoring of groundwater levels are currently enforced" (2013:254), but that a limited number of flow meters have been installed by some irrigators on a voluntary basis as part of a pilot study.

The Steenkoppies Water User Association was never legally constituted, and current DWS policy is likely to phase out WUAs altogether (DWS, 2014a). The irrigating farmers (or at least some irrigating farmers) do however continue to cooperate in certain of the functions that a fully-fledged WUA would carry out. Part of the reason that the crisis receded is that better rainfall returned, following the below-average rainfall that led to the crisis. However, another period of poor recharge has begun following the current (2015/16) drought; and another crisis is likely to commence.

Despite the years of effort that have been put into establishing governance mechanisms to deal with over-abstraction, and the very substantial volumes of hydrogeological

[50] "Schedule 1" use of water, as defined by the National Water Act of 1998, is an entitlement to take water for "reasonable domestic use", including for stock watering or small gardening, from any water resource to which a person has lawful access (RSA, 1998). It is generally considered to be small amounts for non-commercial purposes.

research produced for the Steenkoppies aquifer, the next dry period will probably also be marked by legal challenges and threats – a form of expensive, debilitating and retro-active "management" that increases suspicion and mistrust (e.g. Business Day, 2007). At present droughts have driven advances in groundwater management at Steenkoppies (Vahrmeijer et al., 2013), together with the consequent legal actions. Ideally groundwater governance mechanisms should move from this reactive position to a proactive model that supports the economic and human potential of the area.

## 4.6. Conclusions

The dolomitic groundwater resources close to Mahikeng (the Molopo Eye and the Grootfontein aquifer) are capable of supplying Mahikeng with an adequate supply of cheap water of excellent quality, even taking into account the projected growth in water demand, if they are managed well. Since the Molopo Eye is a spring and is vulnerable to fluctuations in groundwater level (e.g. during a severe drought), the Grootfontein aquifer should be seen as both an auxiliary supply during times of normal rainfall, and as a potential emergency reserve that could supply Mahikeng during a severe drought. Unfortunately the Grootfontein aquifer is poorly managed, as shown by falling water levels (see Section 5.5) and the failure of most of the public water supply boreholes.

The lack of technical knowledge is less harmful to sustainable management than the absence of the groundwater management institutions provided for in policy and legislation. The situation implies significant cost and risk, and harms most stakeholders (see Chapter 6). Businesses and the general public in Mahikeng (as well as in other groundwater-dependent towns with similar problems such as Lichtenburg and Zeerust) must prepare for reduced assurance of water supply, harming economic growth. The limited existing management interventions tend to be driven by crises or legal action.

The self-organising capacity of stakeholders is limited, particularly where officially sanctioned organisations such as CMAs or WUAs do not exist, or where state support is poor. This is shown in the example of the Steenkoppies aquifer, where relatively high levels of self-organisation on the part of irrigating farmers and downstream users of spring water have not led to an organisational framework effective enough to overcome the "crisis-driven" mode of groundwater management. If decentralised groundwater management is to work, it needs institutional support and affirmation from state organisations such as the Department of Water and Sanitation.

# 5. The hydrogeology of the Grootfontein aquifer

## 5.1. Introduction

Chapter 4 provided an overview of previous hydrogeological studies at Grootfontein. Much is known about the hydrogeology of the aquifer as a result of these previous studies. However, it is still sometimes assumed that poor hydrogeological understanding of the Grootfontein aquifer is a major reason for inefficient management. Evidence for this includes recent initiatives to further improve the technical understanding of the aquifer[51], or literature recommendations for more technical work (e.g. Stephens and Bredenkamp, 2002). Past emphasis on hydrogeological work at Grootfontein, compared to work on the social or management aspects, also has an institutional momentum and persists today.

This chapter combines past work on the Grootfontein aquifer with new hydrogeological data collected as part of this research to demonstrate the current hydrogeological understanding. It shows that the Grootfontein aquifer represents a potentially prolific source of very good quality water, and that technical or hydrogeological understanding is sufficient to support better management. It also shows that the groundwater resource is in decline and that this decline could be arrested by the decisions and actions of groundwater users (i.e. the decline is not a natural or inevitable phenomenon).

The various sources of data are presented, and a conceptual hydrogeological model of the Grootfontein aquifer is described (Section 5.9). Conceptual models describe a physical aquifer or groundwater environment, taking into account hydrogeological variables such as recharge, discharge (or abstractions), and groundwater quality. The physical properties of the aquifer are fundamental to a conceptual model, including its dimensions, hydraulic properties, and boundaries. A hydrogeological conceptual model ideally allows uncertainties or probabilities to be assigned to the physical properties, allowing various scenarios to be evaluated.

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[51] For example, DWS is currently working on a hydrogeological project to better understand the Grootfontein aquifer. The study has the working title "Development of aquifer operational and management plans: Grootfontein / Mahikeng case study" but the work done so far concentrates on hydrogeological and not management issues. Three of the interviewees for this research mentioned the need for a further technical study of the Grootfontein and adjacent compartments. DWS hydrogeologists interviewed in Mahikeng wished to focus on the geophysical delineation of the Grootfontein aquifer's dyke boundaries.

A hydrogeological conceptual model is also the basis of a water balance – i.e. a description of the fluxes of water in an aquifer. Ideally, a "three dimensional picture of the saturated zone" should emerge, including a description of the aquifer's geology and weathering, the nature of its water-bearing openings, its natural flow and discharge regime, the behaviour of the aquifer when it is pumped, and a description of its boundaries (Vegter, 2001:52). The conceptual model and water balance provides a scientific foundation for management interventions (see Chapter 6).

## 5.2. Hydrogeological fieldwork and data collection

Two visits were made to the Grootfontein compartment and surrounds in 2013 and six visits between April and September 2015 during which hydrogeological data was collected[52]. These included water level measurements in the vicinity of the Grootfontein Eye, the collection of sixteen water samples for major and minor ion analysis and stable isotope analysis, and data on water supply, land-use and irrigation in the area[53]. This field sampling was aimed at confirming (or refuting) the existing conceptual understanding of the Grootfontein aquifer. Collection of water samples also provided an opportunity to meet farmers and other stakeholders, leading to discussions and in some cases a formal interview (discussed in Chapter 6). Boreholes, irrigation systems, springs and other features in the study area were also visited as part of the sampling activities. Water samples were taken from across the aquifer where possible, but sampling was also affected by the availability of boreholes, permission to sample, time and luck.

Digital data for the Grootfontein compartment from the Department of Water and Sanitation, and from other organisations such as Botshelo and Sedibeng Water Boards, was also obtained during several meetings with these organisations. An inventory of all hydrogeological data collected is shown in Table 5-1 below, with details of the source.

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[52] A total of about 3 weeks of fieldwork were carried out at Grootfontein, including the collection of new hydrogeological data such as water samples, stakeholder interviews and visits to relevant organisations. Stakeholder interviews also took place in other locations (see Table 2.1).

[53] These sixteen samples were not intended to characterise the hydrochemistry of the Grootfontein aquifer on their own, but rather to confirm (or refute) the existing conceptual understanding of the Grootfontein aquifer's basic hydrogeological functioning. This research contends that the existing hydrogeological understanding of Grootfontein is an adequate foundation for more effective management, and does not attempt to describe the hydrogeology of the Grootfontein aquifer in detail, or resolve remaining hydrogeological questions.

## Table 5-1 Inventory of hydrogeological data

| Description | Source | Notes |
|---|---|---|
| Groundwater levels | DWS National Groundwater Archive (NGA) | There are 35 active water level measuring stations in and around the Grootfontein aquifer – this data was imported from NGA as .csv files. |
| Groundwater levels | Own measurements in field (Solinst dipmeter) | Measurements made at three old abstraction boreholes near the Grootfontein Eye site. |
| 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. |
| Molopo Eye flows | Literature review, personal communications, DWS National Groundwater Archive | DWS has monitored the flow of the Molopo Eye since the early 1980s. |
| Grootfontein borehole pumping rates | Literature review, personal communications, DWS pumping data | Estimates from the literature, and from interviews with Sedibeng Water Board and other organisations were used, together with daily data provided by DWS for 2015. |
| Irrigation pumping rates | Literature review, personal communications, estimates derived by private consultants | The private consultancy Schoeman and Vennote currently estimate irrigation volumes at Grootfontein using satellite imagery, and a summary of this data was obtained for use in WRC Project K5/2429. |
| Rainfall data | DWS | This data is currently collected by the South African Weather Service (SAWS) and was provided by SAWS to DWS for the rainfall stations closest to Grootfontein, as part of the DWS Grootfontein investigation. |
| WARMS license data | DWS WARMS database | This data represents licensed amounts. Actual use may be higher or lower. |
| Major and minor ion chemistry | Field samples | Sixteen samples were collected in and around Grootfontein in 2015, and analysed by Waterlab (Pty) Ltd in Pretoria for major elements and minor (trace) ion content. |
| Isotope chemistry | Field samples | Sixteen samples were collected in and around Grootfontein in 2015, and analysed by iThemba LABS in Johannesburg for stable isotopes of hydrogen and oxygen. |
| Aquifer properties data | Literature survey (see Chapter 4) | The GH series of reports published by DWS contain the most hydrogeological information on the Grootfontein aquifer. |
| Dyke boundaries | Literature survey (see Chapter 4) | The dyke boundaries were estimated by Holland and Wiegmans (2009), based on geophysical data and an analysis of water levels in the area. These boundaries were obtained in .shp format for use in this research. |
| Aerial photographs | The Chief Directorate National GeoSpatial Planning, part of the Department of Rural Development and Land Reform (Pretoria) | High resolution colour (RGB) georeferenced and orthorectified aerial photography. |
| Other field observations | Own observations during approximately three weeks of field visits in 2013 and 2015 | Observations made during field work of pumping boreholes, the Grootfontein Eye abstraction area, the Molopo Eye, irrigated areas, dry river beds, land use, the Mafikeng Water Treatment Works, etc. |

## 5.3. Major and trace ion chemistry of Grootfontein groundwater

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-$HCO_3$ water type. DWA (2006c) 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 (DWA, 2006c:31). (A pristine state implies that no anthropogenic impacts are detected.)

Water samples were collected in and around the Grootfontein compartment between April and July 2015 according to Figure 5-1 and Table 5-2. Samples were collected where pumping boreholes were available and permission could be obtained to sample. Sample 5 (Setumo Dam) is not shown on Figure 5-1 as the dam is on the other side of Mahikeng.

**Table 5-2 The Grootfontein sample locations**

| Sample | Description of sample site | Date | Latitude | Longitude |
|---|---|---|---|---|
| 1 | Combined outflow of the 3 DWS public water supply boreholes at Grootfontein | 29-Apr-15 | -25.917167 | 25.860861 |
| 2 | Domestic water supply borehole | 29-Apr-15 | -25.913944 | 25.872389 |
| 3 | Domestic water supply borehole | 29-Apr-15 | -25.915361 | 25.868583 |
| 4 | Public water supply borehole | 29-Apr-15 | -26.076389 | 25.920667 |
| 5 | Setumo Dam sample near dam wall | 13-May-15 | -25.856528 | 25.508611 |
| 6 | Irrigation borehole | 22-Jun-15 | -26.054528 | 25.954889 |
| 7 | Domestic water supply borehole | 23-Jun-15 | -25.915667 | 25.869250 |
| 8 | Irrigation borehole | 23-Jun-15 | -25.925611 | 25.863861 |
| 9 | Irrigation borehole | 23-Jun-15 | -25.925417 | 25.863833 |
| 10 | Irrigation borehole | 23-Jun-15 | -25.934667 | 25.910667 |
| 11 | Molopo Eye taken at eastern end | 23-Jun-15 | -25.887528 | 26.026500 |
| 12 | Domestic water supply borehole | 24-Jun-15 | -26.097167 | 25.984250 |
| 13 | Irrigation borehole | 24-Jun-15 | -26.087361 | 25.973500 |
| 14 | Thusong Hospital borehole | 24-Jun-15 | -26.054389 | 25.949389 |
| 15 | Irrigation borehole | 22-Jul-15 | -26.035611 | 25.952694 |
| 16 | Domestic water supply borehole | 23-Jul-15 | -25.906722 | 25.911583 |

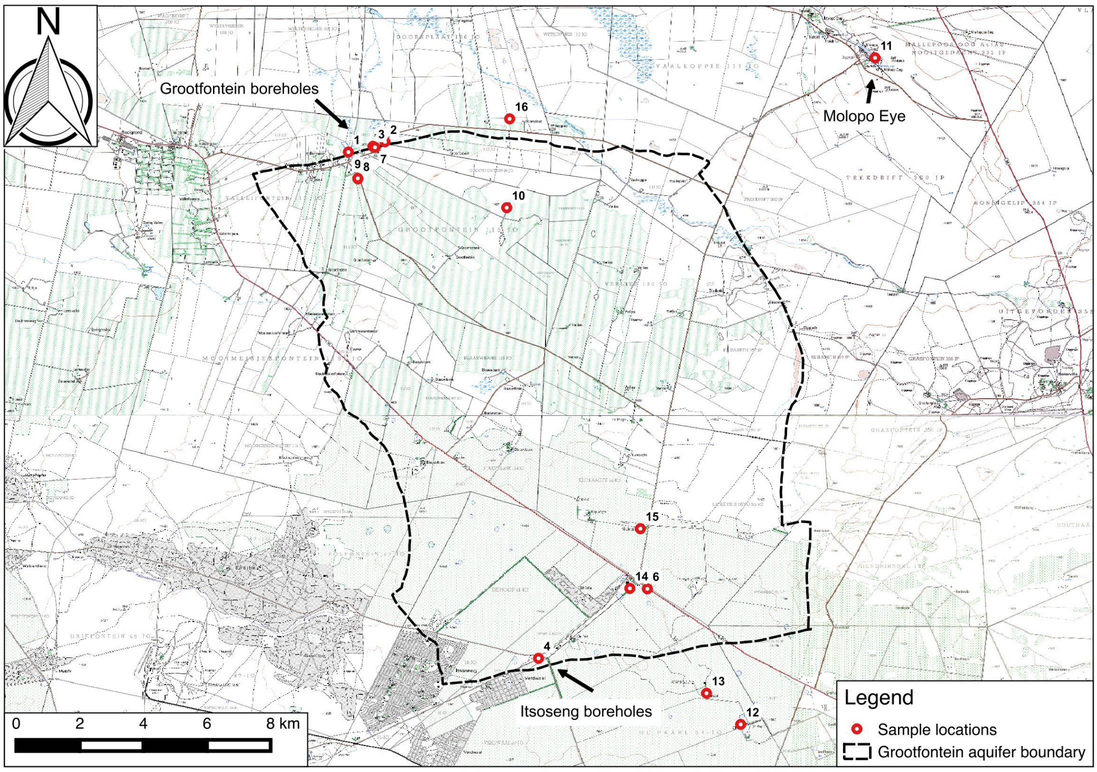


**Figure 5-1 Groundwater quality sample locations (sample 5 not shown)**

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 Waterlab (Pty) Ltd in Pretoria for analysis[54]. Samples were analysed for a suite of major ions, pH, EC and total alkalinity. An ICP scan for minor constituents was also performed. The full Waterlab results are shown in Appendix B, and major ions are plotted as Figure 5-2. Duplicate samples were taken in the same way at each location and submitted to iThemba LABS in Johannesburg for isotope analysis (see Section 5.4).

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 four categories: aesthetic, operational, chronic health and acute health.

[54] Waterlab is a SANAS accredited laboratory according to ISO/IEC 17025:2005 standards. When samples could not be submitted to Waterlab on the day of collection, they were kept refrigerated. All samples were submitted to Waterlab within 48 hours of collection.

The pH values of the samples are in the range that would be expected of 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 has 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 (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. Nitrate can be naturally derived but it is likely that at least some of the nitrate concentration in Grootfontein groundwater is due to anthropogenic contamination, probably a combination of agricultural fertilizers and human or animal excreta. 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 groundwater from the Grootfontein aquifer. 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.

A trilinear plot of the major ion concentrations (Figure 5-2) shows that the samples have a CaMg-$HCO_3$ signature and cluster relatively closely together, apart from the Setumo Dam sample (sample 5). This suggests relatively homogeneous groundwater and an undifferentiated and well-connected aquifer.

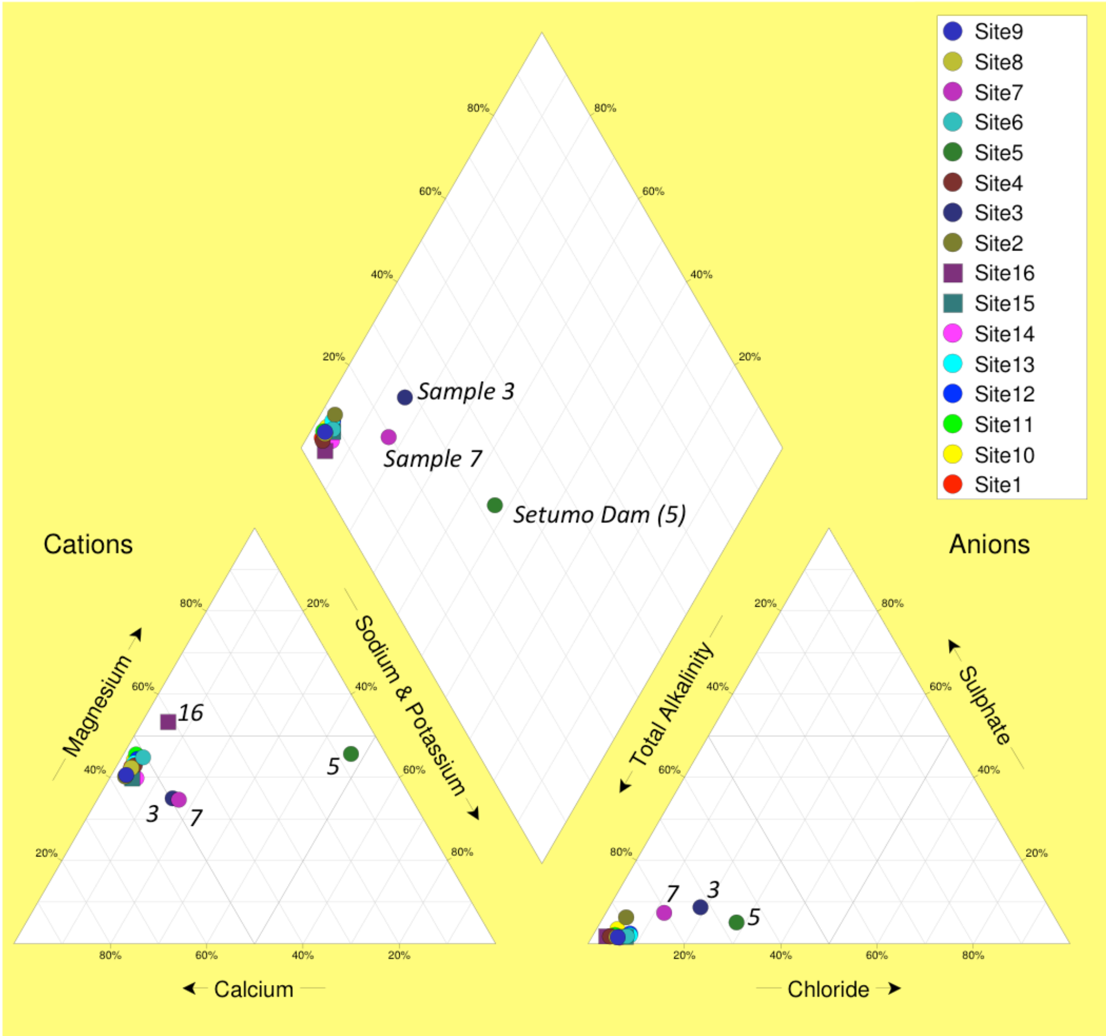


**Figure 5-2 Piper or trilinear plot of the Grootfontein samples**

Of the minor constituents, arsenic concentrations are above the SANS guideline limit for chronic health risk of 0.01 mg/L in 6 samples (samples 5, 6, 7, 8, 9 and 10). Four of these samples had arsenic concentrations just above the limit, but higher concentrations of 0.048 and 0.038 mg/L were measured in samples 6 and 7 respectively. The origin of this arsenic is not known, but may be related to the application of inorganic fertilizers to the soil that leach into groundwater (MDH, 1999). Groundwater sampling by the CSIR in the North West dolomites has also shown elevated As levels however (Talma, 2010), suggesting instead that a natural source may be present[55]. Selenium levels are elevated

[55] Local reducing environments due to decomposing reed beds or other organic material, for example, may cause reductive dissolution of naturally occurring As into groundwaters. In Bangladesh, where the guideline As concentration for drinking water is 0.05 mg/l, reductive dissolution of As can lead to concentrations of As in groundwater two orders of magnitude higher than found at Grootfontein (Ravenscroft et al., 2005).

above the SANS guideline limit for chronic health risk in samples 2, 3, 6 and 7. Three of these concentrations are close to the detection limit (0.01 mg/L) but sample 6 has a Se concentration of 0.039 mg/L. This also corresponds with the highest arsenic concentration. These selenium concentrations may also be related to fertilizer leaching.

Laboratory results for the other minor constituents do not exceed the SANS guideline values, apart from concentrations of iron (samples 6 and 7) and manganese (sample 2) that exceed the guideline for aesthetic limits.

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 Grootfontein groundwater is currently pumped into municipal supply at Mahikeng at the Mafikeng Water Treatment Plant with only precautionary chlorination carried out as water treatment. Sand filters are installed at the treatment plant but these are considered unnecessary by Sedibeng Water Board and are bypassed. Note that sample 1, the sample from the combined public water supply boreholes, has all dissolved constituents that were measured falling within the applicable guidelines[56].

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 2014b:5).

## 5.4. Isotope analysis

Water samples for stable isotope analysis were duplicates of those collected for major and minor ion analysis (Table 5-2) – i.e. were collected under the same conditions, in matching containers and at the same time. The samples were submitted to iThemba Laboratories in Gauteng in two batches for D/H ($^{2}H/^{1}H$), $^{18}O/^{16}O$ and $^{3}H$ analysis. The first batch (samples 1 to 5) was submitted on 29 May 2015 and the second batch

56 Sample 1 was not analysed for all possible contaminants of drinking water and its analysis for this research should not be taken as evidence on its own that the Grootfontein water is safe to drink or passes applicable standards for drinking water.

(samples 6 to 16) was submitted on 25 August 2015. The main purpose of the isotope sampling was to attempt to confirm the relatively recent recharge expected for groundwater at Grootfontein as introduced in Section 4.3 and described in more detail in Section 5.7 below. The Grootfontein aquifer is thought to receive contemporary recharge, rather than containing mainly older or fossil groundwater that would imply a finite and fundamentally unsustainable resource. Since Grootfontein is a single dolomite compartment, reasonably homogeneous groundwater samples are expected.

Using the isotope ratios of the samples to confirm the conceptual understanding of the Grootfontein aquifer is not regarded as definitive, and the isotope results are therefore combined with other sources of evidence (e.g. abstraction rates and water balance calculations) to support the conceptual model described in Section 5.9 below. This is because stable isotope ratios of groundwater depend partly on flow and mixing in the aquifer, the mode of recharge (e.g. proportion of rapid bypass flow), evaporation in the soil zone and from the surface, seasonality of recharge, and other (uncertain) factors (Scanlon et al., 2006). The long-term mean stable isotope composition of rainfall in South Africa, particularly in inland areas, differs from that of the groundwater at any particular location (Talma and van Wyk, 2013)[57]. In their assessment of recharge studies and techniques in southern Africa, Xu and Beekman (2003:3) endorse methods of recharge estimation in semi-arid areas based on the relationships between rainfall, abstraction and water level fluctuations.

A description of the method of isotope analysis is contained in the reports produced by iThemba laboratories, included as Appendix E. According to these reports, the stable isotope analyses for all sample data could be well reproduced within the expected analytical error limits. Each sample was analysed for $^{2}H/^{1}H$ and $^{18}O/^{16}O$ as two aliquots, with the final sample result being the average of the two. The analytical precision is estimated at 0.2‰ for $^{18}O/^{16}O$ and 0.8‰ for $^{2}H/^{1}H$, and the analytical precision for $^{3}H$ is shown in Table 5-3 below. The individual aliquot results are shown in Appendix E. Table 5-3 summarises the isotope sample results, including the difference between the two aliquots for each sample:

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[57] The use of $^{14}C$ isotopes as a method to determine the age of the groundwater at Grootfontein was not carried out due to uncertainties in applying $^{14}C$ results to recharge in the North West dolomites (Talma, pers. comm., 2015; Bredenkamp et al., 2007; and see Section 4.3.6). The large sample volumes and specialised sampling procedures required would also have reduced time available for field interviews and other data collection methods.

**Table 5-3 Stable isotope results for the Grootfontein samples**

| Sample No | Deuterium | | Oxygen-18 | | Tritium ($^3H$) | |
|---|---|---|---|---|---|---|
| | ∂D‰ SMOW | Diff.# | $\partial^{18}O$‰ SMOW | Diff.# | TU | ± |
| 1 | -24.5 | 0.1 | -4.33 | 0.13 | 1.2 | ±0.3 |
| 2 | -25.7 | 0.5 | -4.18 | 0.11 | 0.9 | ±0.3 |
| 3 | -24.6 | 0.7 | -3.87 | 0.06 | 0.3 | ±0.2 |
| 4 | -26.3 | 0.7 | -4.48 | 0.06 | 1.0 | ±0.3 |
| 5* | +20.3 | 0.5 | +4.75 | 0.13 | 2.3 | ±0.3 |
| 6 | -24.6 | 1.0 | -4.46 | 0.13 | 0.9 | ±0.3 |
| 7 | -24.2 | 0.4 | -4.26 | 0.06 | 0.4 | ±0.2 |
| 8 | -24.7 | 0.7 | -4.39 | 0.10 | 1.0 | ±0.3 |
| 9 | -24.0 | 0.2 | -4.53 | 0.12 | 1.6 | ±0.3 |
| 10 | -25.6 | 0.3 | -4.40 | 0.03 | 1.1 | ±0.3 |
| 11 | -29.4 | 0.5 | -4.94 | 0.03 | 0.3 | ±0.2 |
| 12 | -26.6 | 0.2 | -4.81 | 0.05 | 1.7 | ±0.3 |
| 13 | -25.4 | 0.1 | -4.41 | 0.06 | 1.1 | ±0.3 |
| 14 | -25.0 | 0.5 | -4.37 | 0.03 | 0.7 | ±0.2 |
| 15 | -26.6 | 0.7 | -4.50 | 0.05 | 0.5 | ±0.2 |
| 16 | -24.1 | 0.6 | -4.55 | 0.07 | 0.3 | ±0.2 |

*Sample 5 represents evaporated and polluted surface water from the Setumo Dam.
#Diff. = difference between the two aliquot analyses for each sample.

The linear relationship between hydrogen and oxygen isotope ratios in most terrestrial waters, known as the global meteoric water line, is expressed as follows (Craig, 1961):

$$\partial D = 8\partial^{18}O + 10‰$$

The sample results for $^2H$ and $^{18}O$ have been plotted in Figure 5-3 below. The global meteoric water line is shown on the plot, along with the Excel best fit line for the sample data. The Setumo Dam sample (sample 5) has been excluded from the plot. The similarity or clustering of the stable isotope results and their proximity to the global meteoric water line supports the conceptual idea that the Grootfontein aquifer is a single unit with groundwater reflecting relatively recent water that has not been subjected to extensive evaporation or pollution, or to mixing with connate waters with different isotopic signatures. The stable isotope results from within the Grootfontein compartment boundaries are also similar to samples taken outside of the boundaries (e.g. at the Wondergat and the Molopo Eye). The major ion results support this conclusion.

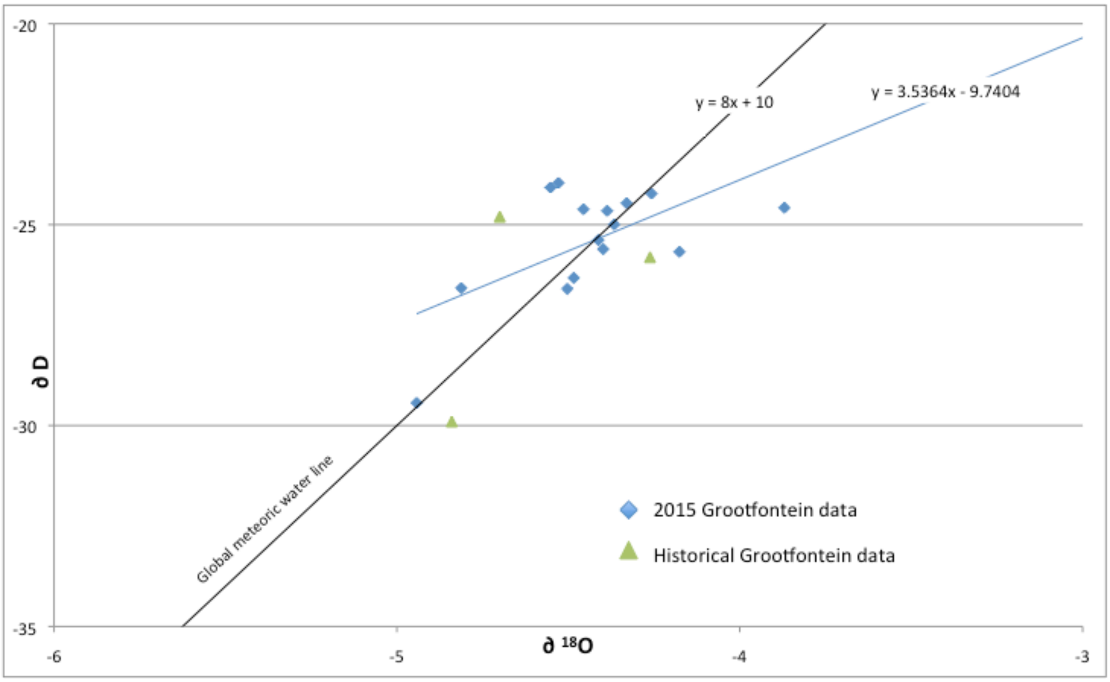


**Figure 5-3 Stable isotope results for the Grootfontein samples**

A collaborative programme of isotope sampling from springs in the dolomites between Pretoria and Kuruman was conducted by DWS/DWAF and the CSIR between 1969 and 2007 (Talma, 2010). Isotope sampling included $^{3}H$, $^{2}H$, $^{18}O$, $^{13}C$, $^{14}C$, as well as CFCs and $SF_6$ in the later years. This sampling included three samples from a borehole at Grootfontein close to the site of the Grootfontein Eye, taken between 1997 and 2007 and analysed for $^{2}H/^{1}H$ and $^{18}O/^{16}O$ (see Table 5-4 below). These results are also plotted on Figure 5-3 above ("Historical Grootfontein data"). These isotope ratios are similar to those obtained from the 2015 samples for this research, but display a wider variation in isotope composition, which may be related to the different years of sampling. The fact that samples taken from the same borehole in different years appear to show more variation in stable isotope content than samples taken from different boreholes over the same three-month period suggests that variation in stable isotope ratios in Grootfontein groundwater owes more to variations in inter-annual rainfall and recharge characteristics than it does to heterogeneity in the aquifer itself. Although all three historical samples were taken at the same time of year, the differences between them appear to support the idea of sporadic or episodic recharge, rather than the regular seasonal recharge expected in more temperate areas.

**Table 5-4 Historical isotope results for Grootfontein (after Talma, 2010)**

| Date borehole sampled | Deuterium | Oxygen-18 | Tritium | |
|---|---|---|---|---|
| | ∂D‰ SMOW | ∂18O‰ SMOW | TU | ± |
| Oct 1997 | -29.9 | -4.84 | 1.9 | 0.2 |
| Oct 1999 | -24.8 | -4.70 | n/a | n/a |
| Nov 2007 | -25.8 | -4.26 | 0.4 | 0.2 |

Talma (2010) and Talma (pers. comm., 2015) state that whilst $^{3}H$ (tritium) concentrations in rainfall before the "atom bomb spike"[58] in the early 1960s were less than 1 TU, modern tritium in rainfall is between 2 and 3 TU. The range of results for $^{3}H$ obtained from the samples (from 0.3 to 1.7 TU) suggest that some mixing of older pre-bomb water with more modern water is occurring in the Grootfontein aquifer. This may point to stratification in the aquifer, or to more complex flow paths in the weathered dolomite than are usually assumed. Low TU values such as these have been seen in other North West dolomite springs but are generally not confirmed by $^{14}C$ results for the same waters, presenting something of a puzzle (Talma, 2010; and Talma, pers. comm., 2015). Unfortunately the construction details and pump depths of the boreholes sampled in 2015 at Grootfontein were mostly not available, making it difficult to confirm whether the range in $^{3}H$ values is related to the depth from which groundwater is abstracted. The $^{3}H$ results obtained by Talma (2010) for the Grootfontein aquifer (Table 5-4) between 1997 and 2007 are similar to those obtained in 2015. If a substantial proportion of the water abstracted from the Grootfontein aquifer is indeed pre-1960 in age, this may mean that long term estimates of sustainability for the aquifer should be lowered.

The Grootfontein sample stable isotope ratios can be compared with groundwaters from the Western Cape Province. Harris et al. (1999) collected samples from two aquifers near Cape Town, the Culemborg-Black River (CBR) Aquifer and the Cape Flats Aquifer, as well as from natural springs in and around Cape Town[59]. Diamond and Harris (2000)

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[58] Natural tritium in atmospheric water is cosmogenic, but above-ground testing of nuclear weapons in the 1950s increased concentrations of atmospheric tritium. Above-ground testing was banned in 1963, leading to a steady decline in tritium concentrations (tritium has a half-life of about 12.3 years). Measurements therefore show a peak or "spike" in atmospheric tritium corresponding with 1963/64 (Bradbury, 1991).

[59] The samples plotted on Figure 5-4 include 8 samples from the Culemborg-Black River Aquifer, 12 samples from the Cape Flats Aquifer, and 8 samples from spring waters in Cape Town. All of these samples were collected in April 1997 by Harris et al. (1999). The 12 thermal spring results plotted on Figure 5-4 are the means of several sampling runs conducted in 1995 and 1997 by Diamond and Harris (2000).

reported on stable isotope analyses of 12 thermal springs in the Western Cape, mostly issuing from quartzites of the Table Mountain Group. These four groups of samples are shown on Figure 5-4 below, together with the Grootfontein samples.

Compared with the other sample groups, the Grootfontein samples cluster together, close to the global meteoric water line. Diamond and Harris (2000) attribute the depletion in ∂D and $\partial^{18}O$ of the thermal spring samples to the altitude and continental effects (i.e. waters become increasingly depleted in heavier isotopes with increasing altitude and increasing distance from the coast). This depletion of the thermal spring samples may also be influenced by ancient meteoric water with a different isotopic composition to modern meteoric water. It is likely that the isotopic depletion of the Grootfontein samples, relative to the Cape Town groundwater samples, is at least partly due to altitude and continental effects too. These effects may also explain the divergence of the Grootfontein samples' best fit line and the global meteoric water line (Figure 5-3). These observations are consistent with the conceptual model of the Grootfontein aquifer as having homogeneous groundwater with a stable isotopic composition close to that of modern meteoric water.

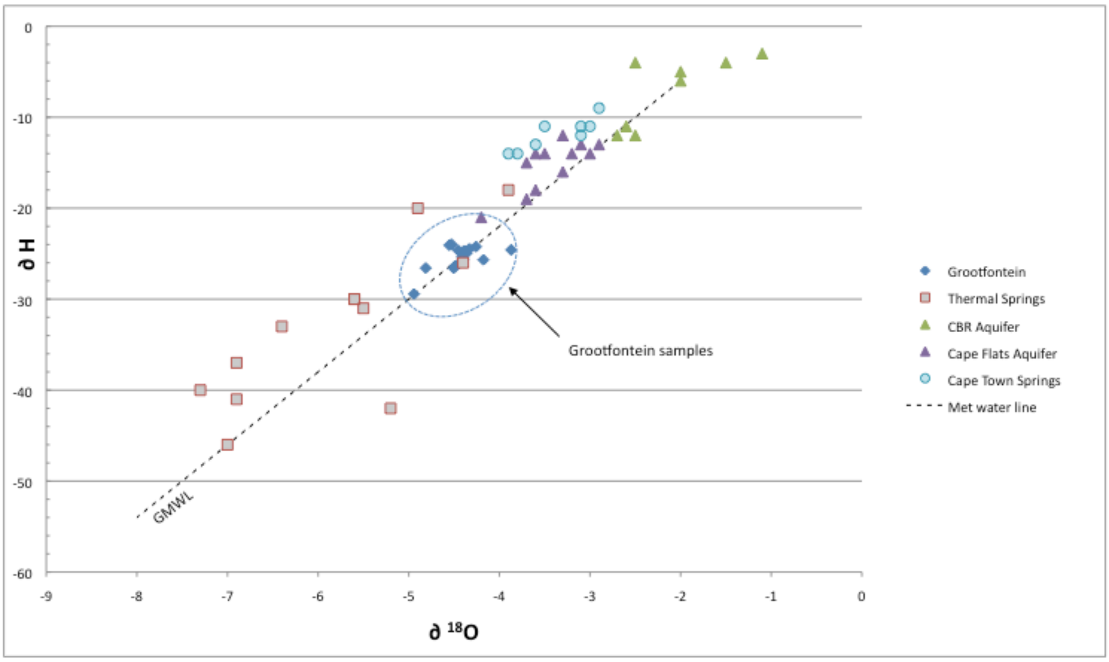


**Figure 5-4 Comparison of Grootfontein with the Western Cape samples of Harris et al. (1999), and Diamond and Harris (2000)**

## 5.5. Groundwater levels

Water levels were measured near to the DWS public abstraction boreholes at the Grootfontein Eye site on the 29th April 2015 as shown in Table 5-5. These measurements confirm ongoing measurements made by DWS nearby (at e.g. D4N0854).

**Table 5-5 Water levels measured near the Grootfontein Eye**

| Borehole | Water level (mbgl)* | Latitude | Longitude |
|---|---|---|---|
| D4N0855 | 28.17 | -25.917250 | 25.860750 |
| D4N0852 | 27.88 | -25.918917 | 25.861250 |
| D4N0075 | 27.45 | -25.918528 | 25.862444 |

*mbgl = static water level in metres below ground level

DWS collects groundwater level information in South Africa as part of its ongoing monitoring duties. This data is entered into the HYDSTRA database, from where a selection is exported to the on-line National Groundwater Archive (NGA) where it is available to the public. This NGA data was accessed for this research.

Data obtained in June 2015 from the NGA indicates that North West Province has 129 active groundwater level monitoring stations across the province[60]. Most of these stations are monitored manually (i.e. using a hand-held dipmeter) and all except two are monitored quarterly. The longest time record for any station in North West Province is about 58 years (station C2N1107, record from 1936 to 1993). Station D4N0017 in the Grootfontein aquifer is in theory the longest active station (1964 to present) but data for this station is derived from the period 1964 to 1975 only, with the exception of a single reading taken in 2011. This station has not been included in this water levels assessment. The next longest record lengths are around 38 or 39 years old, representing stations that started recording in the 1970s. A few of these are found close to or in the Grootfontein compartment (e.g. D4N0113, D4N0117, D4N0120 and D4N0128). The mean station record length in North West Province is 21.4 years. 39 of the 129 stations (30%) have data series lengths less than ten years. 49 of the 129 stations (38%) have data series

[60] An active groundwater monitoring station is one where groundwater level data is still being collected, or has stopped for a temporary reason such as a bee infestation.

lengths of more than 30 years[61]. Figure 5-5 below shows a histogram of the record lengths, sorted from shortest to longest.

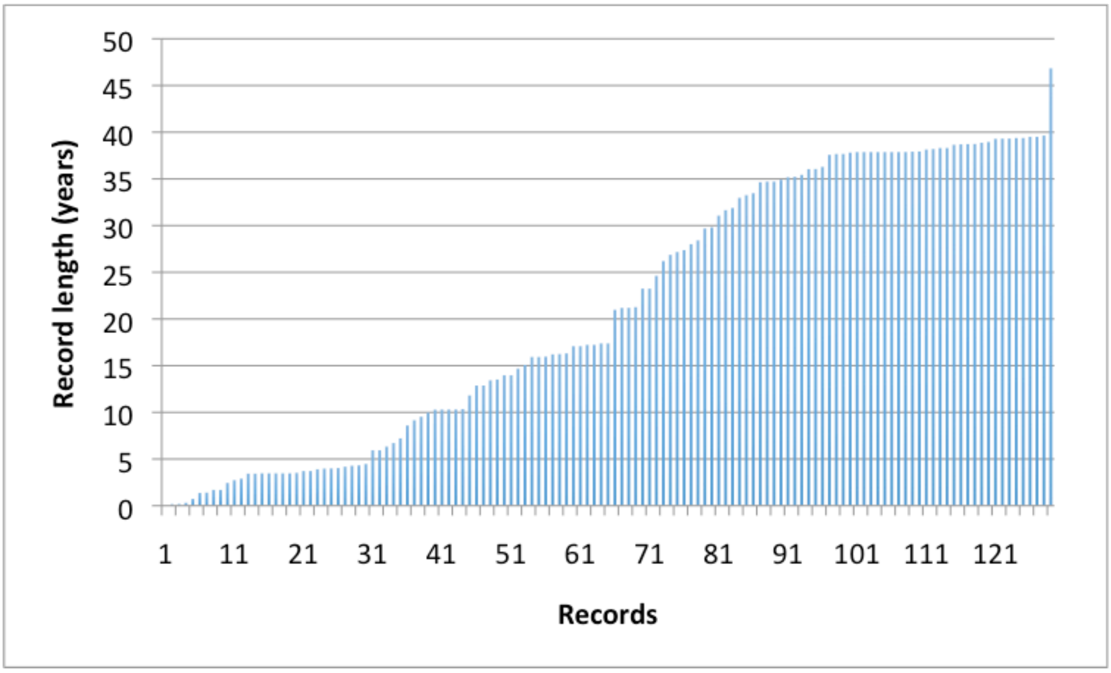


**Figure 5-5 Histogram showing groundwater level record lengths for the 129 active North West Province groundwater-level monitoring stations, including station D4N0017 (data from DWS NGS)**

A subset of 34 groundwater-level monitoring stations was identified for the Grootfontein aquifer. The hydrographs for all 34 stations are shown in Appendix C. They are also summarised in Table 5-6 below, and their locations are shown in Figure 5-6. 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 last 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 (excluding D4N0017 due to poor data, see above). Irrigation is known to have started before the 1960s in the Grootfontein compartment and surrounds (Temperley, 1965; and interviews with local farmers) but apart from estimates of the flow of the Grootfontein Eye, records showing groundwater levels in the Grootfontein area before the early 1970s are not available.

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[61] Water level records at the collapsed sinkhole known as the Wondergat, a few kilometres to the north of the Grootfontein aquifer in a different dolomite compartment, are said to be available for many decades but it proved impossible to obtain this data for this research.

Of the 34 borehole water level records, all but 2 show a declining water level on average over the record length. These 2 are both outside of the Grootfontein compartment (D4N0833 and D4N0830). To calculate a rough net change in water level for each borehole over its monitored period, the mean of the first readings corresponding to a continuous monitoring period of reasonable length (assumed to be at least 6 months, and 12 months where possible) was compared to the mean for the last such period:

**(Mean of last continuous 6-12 month period) - (mean of first continuous 6-12 month record period) = average decline per monitoring borehole.**

This is more reliable that simply comparing the first and last readings for each record, since it partially compensates for annual fluctuation, as well as for outliers. The average decline in water level for all 34 records calculated this way was 12.0 m. (If the first reading is simply subtracted from the last reading for each record, the average is 13.5 m.) Figure 5-8 illustrates this method, using the hydrograph from D4N0111.

This method ignores the different record lengths - an average decline per year of record might be more useful. This was calculated to be about 0.4 m per year for all records.

Inter-annual fluctuations are more difficult to compensate for, but an attempt was made by fitting a best-fit straight line through the data for each record in MS Excel and comparing the gradients of the lines (with all water level measurements in metres below datum and time measurements in days, gradients are independent of record length.) 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 in the compartment, was calculated (see Figure 5-8 for an example). This is equivalent to 4.1 m per decade for all records, or 4.6 m per decade for those records within the compartment boundaries, which corresponds reasonably well with the first method described above. These are of course averages of the average gradients for the records – 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, as well as the local effects of large-scale abstractions in parts of the aquifer.

Hydrographs for 6 of the 21 monitoring boreholes located within the Grootfontein compartment are shown in Figure 5-7 to illustrate the general decline in groundwater levels since the mid-1970s. These hydrographs are for boreholes located in different parts of the compartment, and showing a range of rates of decline (Figure 5-9). All of the hydrographs are included as Appendix C.

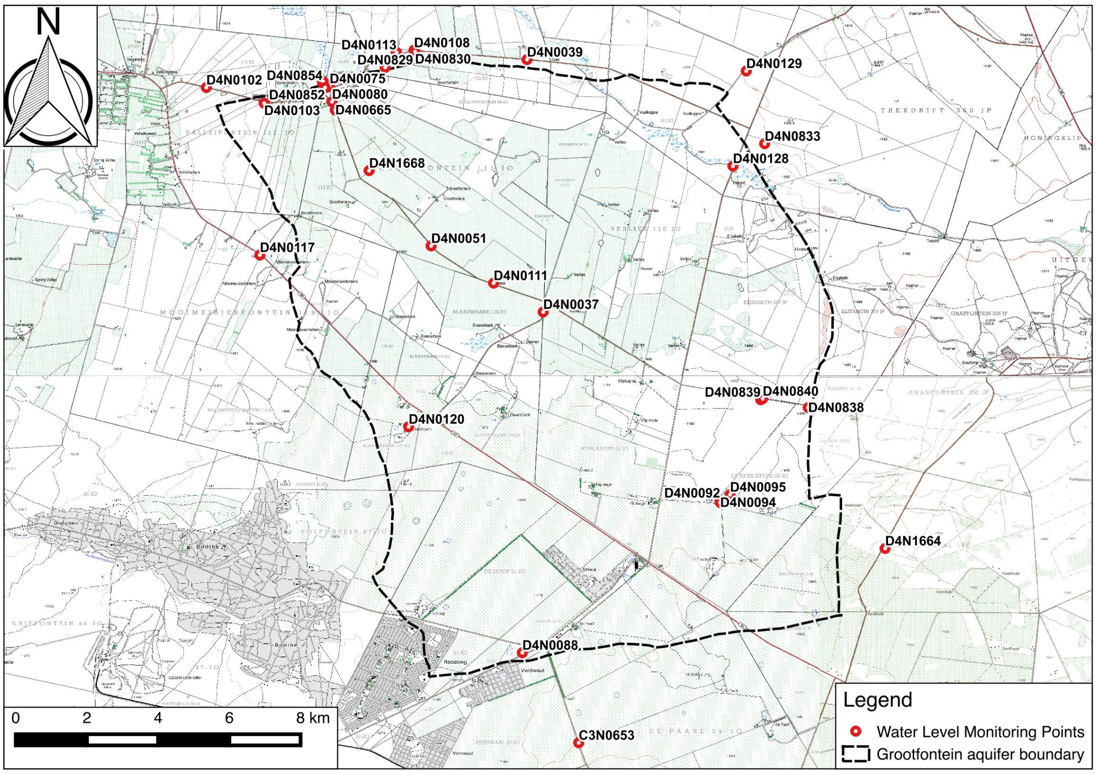


**Figure 5-6 Locations of water level monitoring stations at Grootfontein (data from DWS NGA)**

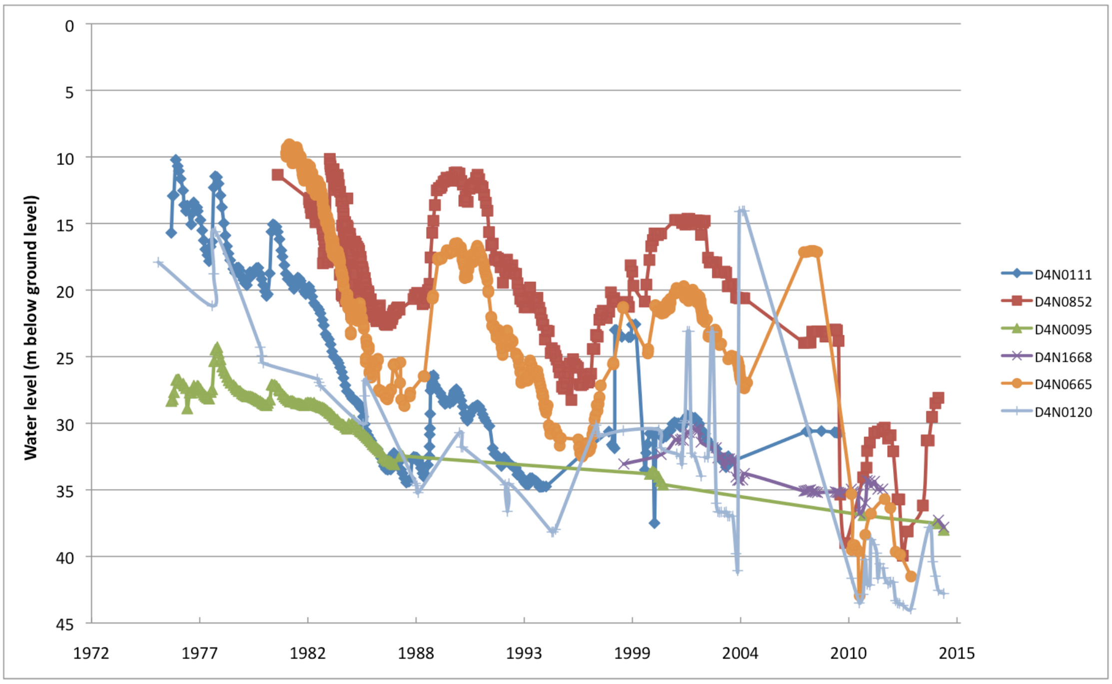


**Figure 5-7 Hydrographs of six monitoring stations from across the Grootfontein aquifer (data from DWS NGA)**

## Table 5-6 Summary of water level changes at Grootfontein

| Borehole | Start date | Start wl | End date | End wl | Years | Trend | Total | TrendGrad | Annualdrop |
|---|---|---|---|---|---|---|---|---|---|
| D4N0103 | 10-Feb-72 | 5.42 | 17-Feb-15 | 27.27 | 43.05 | decline | 21.85 | 0.002 | 0.56 |
| D4N0037 | 10-Aug-73 | 20.62 | 23-Feb-12 | 28.85 | 38.56 | decline | 8.23 | 0.0018 | 0.21 |
| D4N0051 | 5-Apr-74 | 17.1 | 23-Nov-09 | 32.76 | 35.66 | decline | 15.66 | 0.0016 | 0.42 |
| D4N0080 | 8-Oct-74 | 6.99 | 23-Dec-08 | 26.9 | 34.23 | decline | 19.91 | 0.0023 | 0.59 |
| D4N0088 | 8-Oct-74 | 11.37 | 18-Sep-07 | 36.8 | 32.97 | decline | 25.43 | 0.0023 | 0.81 |
| D4N0092 | 15-Jan-75 | 29.22 | 24-Apr-13 | 36.67 | 38.30 | decline | 7.45 | 0.0009 | 0.28 |
| D4N0094 | 15-Jan-75 | 21.24 | 15-Dec-04 | 33.21 | 29.94 | decline | 11.97 | 0.001 | 0.48 |
| D4N0117 | 20-May-75 | 0.93 | 19-Feb-15 | 6.58 | 39.78 | decline | 5.65 | 0.0002 | 0.09 |
| D4N0120 | 20-May-75 | 17.91 | 19-Feb-15 | 42.79 | 39.78 | decline | 24.88 | 0.0012 | 0.55 |
| D4N0102 | 7-Jul-75 | 5.39 | 11-Nov-14 | 11.23 | 39.38 | decline | 5.84 | 0.0002 | 0.11 |
| D4N0108 | 9-Jul-75 | 12.35 | 17-Feb-15 | 13.84 | 39.64 | decline | 1.49 | 0.0001 | 0.01 |
| D4N0128 | 11-Aug-75 | 1.82 | 17-Feb-15 | 12.98 | 39.55 | decline | 11.16 | 0.001 | 0.28 |
| D4N0095 | 15-Jan-76 | 28.33 | 19-Feb-15 | 38.01 | 39.12 | decline | 9.68 | 0.0009 | 0.17 |
| D4N0111 | 15-Jan-76 | 15.7 | 10-Nov-09 | 30.75 | 33.84 | decline | 15.05 | 0.0016 | 0.53 |
| D4N0039 | 10-Sep-76 | 3.39 | 17-Feb-15 | 14.3 | 38.46 | decline | 10.91 | 0.0005 | 0.26 |
| D4N0113 | 15-Dec-76 | 5.8 | 17-Feb-15 | 22.87 | 38.20 | decline | 17.07 | 0.0008 | 0.37 |
| D4N0129 | 20-Jan-77 | 8.94 | 22-Jun-10 | 8.96 | 33.44 | decline | 0.02 | 0.0001 | 0.07 |
| D4N0075 | 30-Aug-79 | 3.6 | 17-Feb-15 | 27.91 | 35.49 | decline | 24.31 | 0.0021 | 0.67 |
| D4N0852 | 4-Jun-81 | 11.34 | 11-Nov-14 | 28.09 | 33.46 | decline | 16.75 | 0.001 | 0.48 |
| D4N0665 | 10-Nov-81 | 9.7 | 25-Jun-13 | 41.51 | 31.64 | decline | 31.81 | 0.0013 | 0.87 |
| D4N0697 | 3-Jan-83 | 5.21 | 23-Feb-09 | 28.97 | 26.16 | decline | 23.76 | 0.0014 | 0.64 |
| D4N0850 | 3-Jan-83 | 5.78 | 23-Feb-09 | 28.4 | 26.16 | decline | 22.62 | 0.0009 | 0.62 |
| D4N0851 | 3-Jan-83 | 5.43 | 23-Feb-09 | 27.74 | 26.16 | decline | 22.31 | 0.0011 | 0.67 |
| D4N0854 | 3-Jan-83 | 2.73 | 6-Jun-12 | 25.89 | 29.44 | decline | 23.16 | 0.0013 | 0.63 |
| D4N0855 | 3-Jan-83 | 9.25 | 17-Feb-15 | 28.37 | 32.15 | decline | 19.12 | 0.0015 | 0.56 |
| D4N0840 | 4-Oct-83 | 23.64 | 7-Dec-09 | 30.785 | 26.19 | decline | 7.145 | 0.0004 | 0.11 |
| D4N0833 | 26-Oct-83 | 8.5 | 15-Jul-04 | 8.85 | 20.73 | **rise** | 0.35 | -0.0002 | -0.02 |
| D4N0829 | 28-Oct-83 | 13.1 | 17-Feb-15 | 24.36 | 31.33 | decline | 11.26 | 0.0011 | 0.25 |
| D4N0830 | 19-Jan-84 | 17.16 | 11-Nov-14 | 24.3 | 30.83 | **rise** | 7.14 | -0.0003 | 0.02 |
| D4N0838 | 15-Sep-86 | 28.05 | 7-Dec-09 | 31.82 | 23.24 | decline | 3.77 | 0.0002 | 0.01 |
| D4N0839 | 15-Sep-86 | 28.88 | 7-Dec-09 | 32.65 | 23.24 | decline | 3.77 | 0.0003 | 0.11 |
| D4N1664 | 31-Oct-97 | 28.83 | 3-Mar-15 | 47.6 | 17.35 | decline | 18.77 | 0.0034 | 1.26 |
| D4N1668 | 10-Dec-98 | 33.06 | 19-Feb-15 | 37.81 | 16.21 | decline | 4.75 | 0.0012 | 0.22 |
| C3N0653 | 9-Nov-10 | 28.31 | 18-Feb-15 | 32.46 | 4.28 | decline | 4.15 | 0.0033 | 0.80 |

*Start / End wl: First water level recorded / last water level recorded*
*Trend: calculated from Excel best fit line through the data.*
*Trend grad = gradient.*
*Rise = rising water level, decline = declining water level*
*Total: total change in water level over length of record*
*Annual drop: Average annual change (drop) in water level over length of record*

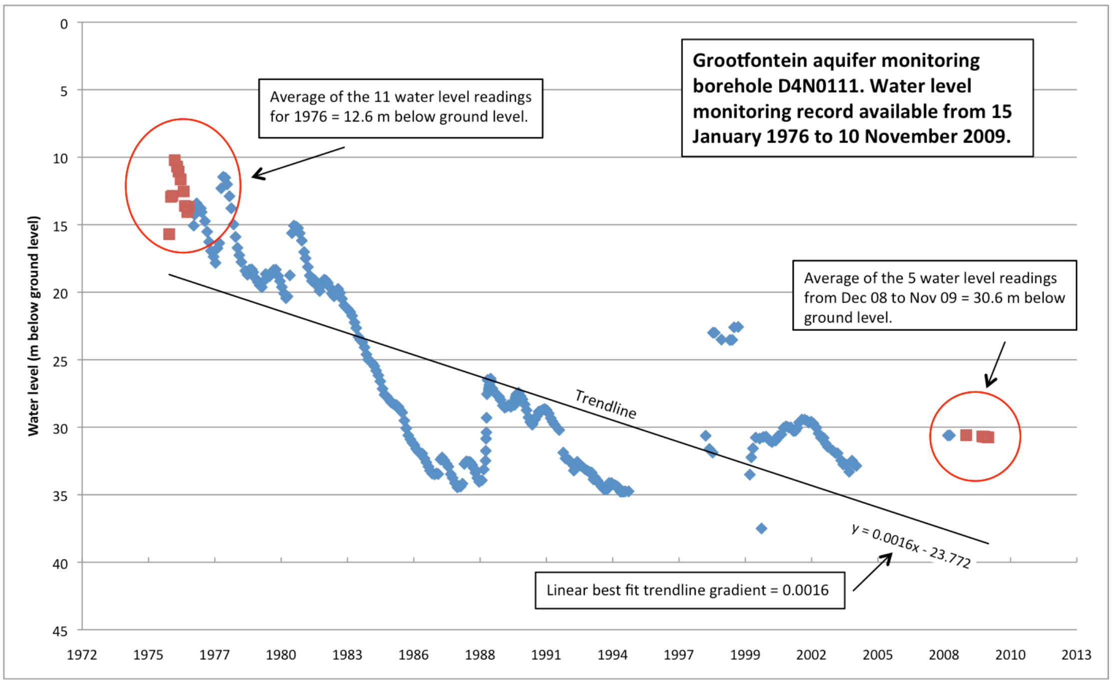


**Figure 5-8 Example of water level calculation using the data for D4N0111 (data from DWS NGS)**

If the average thickness of the Grootfontein aquifer is taken as 50 m (literature estimates varied between about 40 m and 60 m – see Chapter 4) and a (conservative) specific yield of 2% is assumed, then a very rough estimate of its total storage would be (area x thickness x specific yield) = (239 x $10^6$ $m^2$ x 50 m x 0.02) = 239 $Mm^3$. This is more than ten times the capacity of the Setumo Dam, which is roughly 20 $Mm^3$. The specific yield figure of 2% is conservative and some authors (e.g. DWS, 2006) put porosity in the more weathered upper parts of the aquifer at 10% or higher, implying much higher storage in the Grootfontein aquifer.

Based on these assumptions, an average one-meter drop in groundwater level across the Grootfontein aquifer would correspond with a volume of groundwater of approximately 4.8 $Mm^3$. The average observed fall in groundwater levels across the compartment discussed above of about 0.4 m per year corresponds to a volume of groundwater of roughly 1.9 $Mm^3$, or a deficit of about 60 L/s, pumping continuously, between recharge and abstractions across the compartment. However, specific yield decreases with depth - the upper parts of the aquifer yield the most groundwater per unit drop in water table.

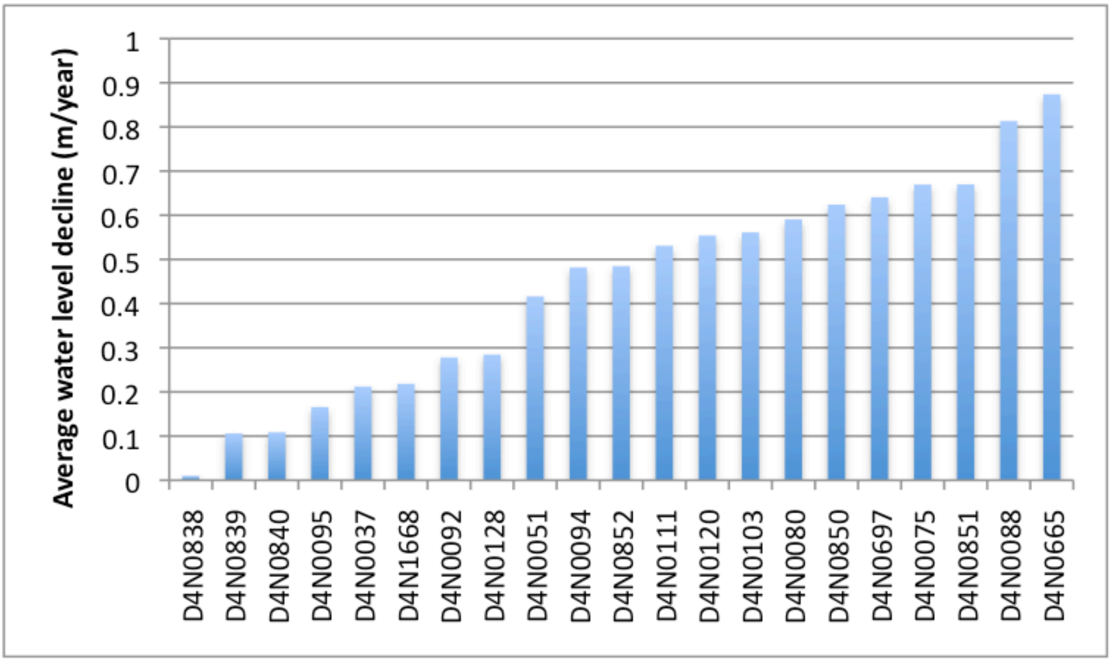


**Figure 5-9 Histogram showing average water level decline for the 21 groundwater monitoring stations across the Grootfontein aquifer (data from DWS NGA)**

There is considerable heterogeneity in water level changes across the Grootfontein aquifer, as expected in a karst aquifer with differences in transmissivity of several orders of magnitude over short distances, as well as large abstractions in certain places (Figure 5-9). The seven monitoring boreholes closest to the Grootfontein Eye (D4N0075, D4N0080, D4N0665, D4N0697, D4N0850, D4N0851 and D4N0852) have average falls in water level of between 0.48 and 0.87 m/year. This is expected since large groundwater abstractions occur nearby. However, large average falls in water level are also found elsewhere at Grootfontein, such as at D4N0088 in the south (average fall of 0.8 m/year) and D4N0120 near the centre (average fall of 0.6 m/year). Boreholes outside of the compartment boundaries generally have lower average falls in water level. However, the largest average fall in water level (D4N1664, with an average annual fall of 1.3 m) is found outside the Grootfontein boundary[62].

The compartment boundaries are likely to be leaky in places, particularly in the upper more weathered parts, and are in any case indistinctly defined in the south. Nevertheless, water levels appear to vary more outside of the compartment, including the only two boreholes assessed where average annual water level changes were positive (i.e. water

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62 Station D4N1664 is about 1 km north of an area of extensive irrigation using dolomite groundwater, outside of the south-eastern boundary of the Grootfontein compartment.

levels were rising on average over the record lengths). Accurate estimates of the volumes of water leaking across the compartment boundaries would require further data (e.g. on aquifer properties closer to the boundaries, more detailed water level observations, or tracer tests). Such leakage would of course respond to changes in the relative difference in water levels on either side of a boundary.

The water level observations described above strengthen the assumption of a compartmentalized dolomite aquifer with heterogeneous physical properties, which is also heavily affected by pumping from high-yielding irrigation boreholes. Average groundwater levels in the Grootfontein aquifer have declined by about 0.4 m per year (Figure 5-9), indicating a decreasing volume of groundwater in storage and in turn implying over-abstraction and a failure of management.

## 5.6. Rainfall

Six rainfall monitoring stations were identified close to the Grootfontein aquifer and rainfall data was obtained up to the end of 2014 (Table 5-7, Table 5-8 and Figure 5-10 below). A seventh nearby station, Lichtenburg Plaasverlies, had poor data and a short record and was discarded.

**Table 5-7 Rainfall stations near Grootfontein**

| Station Name | Latitude | Longitude | Start | End | Altitude |
|---|---|---|---|---|---|
| Lichtenburg Dorp | -26.1440 | 26.1600 | Nov 1983 | Dec 2014 | 1489 m |
| Lichtenburg TNK | -26.1550 | 26.1540 | Jan 1974 | Dec 2014 | 1481 m |
| Lichtenburg Manana | -26.1130 | 26.2480 | Jan 1974 | Dec 2014 | 1447 m |
| Lichtenburg Silverton | -26.3370 | 25.6720 | Jan 1974 | Dec 2014 | 1382 m |
| Mafikeng Game Reserve | -25.8620 | 25.6950 | Mar 2006 | Dec 2014 | 1321 m |
| Mafikeng WO | -25.8030 | 25.5420 | May 1984 | Dec 2014 | 1281 m |

The rainfall data charts showing monthly and annual rainfall for each of the six stations are shown in Appendix D. Rainfall data for each station is recorded daily. However, the raw rainfall data for stations Lichtenburg TNK, Lichtenburg Manana and Mafikeng WO has gaps in several places, either due to the data not being collected at all on a particular day, or the data for several days being aggregated together. Since this study uses only monthly and annual rainfall data, data for several days aggregated together does not affect the final monthly records. Where whole months of data were not recorded (this mainly occurred at the Lichtenburg TNK rainfall station, for unknown reasons) the average for that particular month from the rest of that rainfall record was used to patch the data. A statistical summary of the rainfall data is shown in Table 5-8 below:

**Table 5-8 Statistics for rainfall stations near Grootfontein**

| | Lichtenburg Dorp | Lichtenburg TNK | Lichtenburg Silverton | Lichtenburg Manana | Mafikeng WO | Mafikeng Gme Res |
|---|---|---|---|---|---|---|
| **Maximum** | 874.1 | 918.6 | 809.7 | 885.2 | 873.8 | 727.6 |
| **Minimum** | 237.7 | 231.4 | 144.3 | 301.0 | 312.5 | 337.4 |
| **Mean** | 577.1 | 599.2 | 476.3 | 625.2 | 533.4 | 536.9 |
| **Std Dev.** | 166.7 | 150.5 | 139.2 | 148.6 | 140.7 | 160.8 |

The average annual rainfall varies between 479.3 mm/a for Lichtenburg Silverton (lower in altitude and about 50 km further west than the other Lichtenburg sites) and 625.2 mm/a for Lichtenburg Manana (Table 5-8 above). The average annual rainfall calculated across all of the rainfall stations is 558 mm/a. Long-term trends for all of the sites except Lichtenburg Dorp show a small average long-term decline in annual rainfall, calculated using a best-fit line for the total length of each record (this does not necessarily imply a reduction in recharge – see Section 5.7).

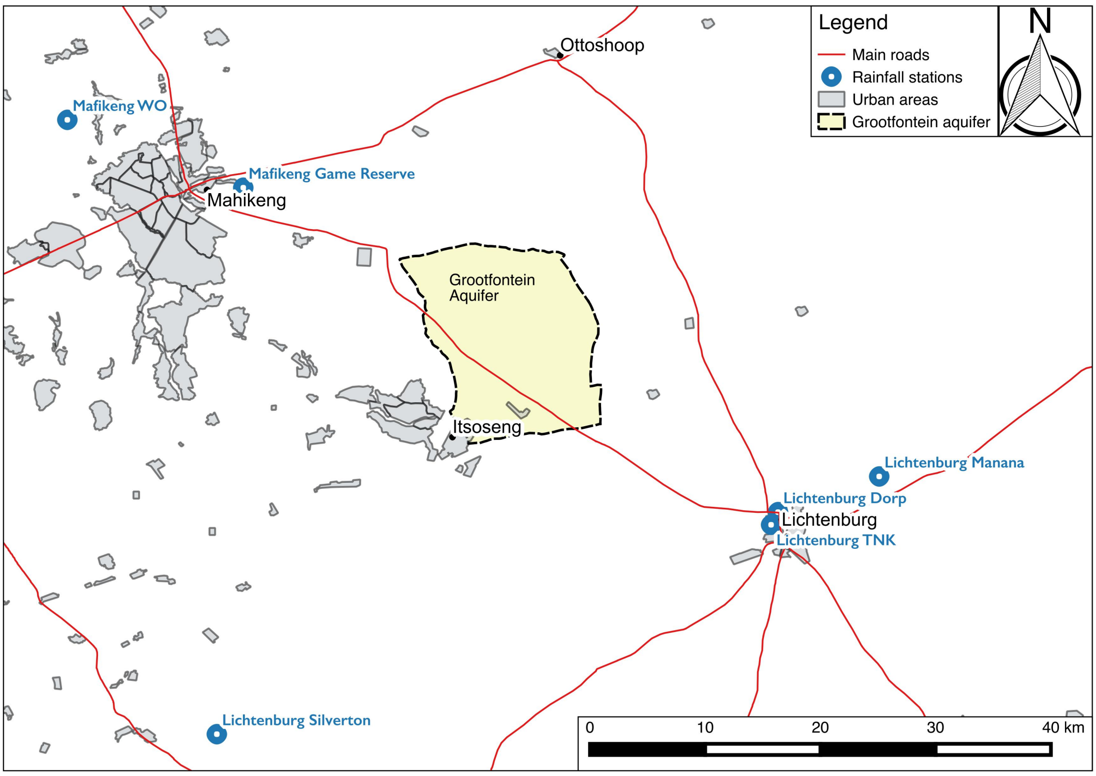


**Figure 5-10 Locations of rainfall stations near Grootfontein**

## 5.7. Recharge

Estimates of effective recharge at Grootfontein using existing data and assuming reasonable parameters have been made. The cumulative rainfall departure method[63] is sometimes used to estimate recharge, but in the case of Grootfontein it would be complicated by the lack of a representative water level series for the aquifer (both before and after abstractions began), and that fact that irrigation withdrawals are not uniform but also respond to the rainfall for any given year. For any given drop in groundwater level, it would be difficult to distinguish between the effects of reduced recharge and increased irrigation withdrawals. A mass balance approach is more useful in this case, but requires estimates of contemporary irrigation withdrawals as well as pumping volumes from the Grootfontein boreholes (see Section 5.7.1 below).

Recharge is also a function of rainfall intensity, or the extent to which rainfall exceeds a particular threshold (Vegter, 2001; Van Wyk, 2010; Xu and Beekman, 2003; DWS, 2006a). Janse van Rensburg (1992) used the following relationship to depict this threshold effect at Grootfontein:

**Monthly recharge = 0.1 x (monthly rainfall – 67 mm)**

Van Wyk (pers. comm.) states that significant recharge to dolomite aquifers in North West Province only occurs every several years or so, following unusually high rainfall events, and that the period between such events is becoming longer due to climate change. Examination of the groundwater hydrographs from the Grootfontein aquifer support this view, with large recoveries in groundwater level only appearing to occur every decade or so (e.g. the late 1980s, late 1990s, and around 2009/10 – see Appendix C). This suggests that recharge may be related more to the occurrence of unusually high rainfall events rather than long-term rainfall averages, and these phenomena may not be correlated – in other words, slightly lower long-term average rainfall may not imply lower recharge, if rainfall events become more intense with climate change.

If a simple linear relationship between total annual rainfall and recharge is used (e.g. 4.5% to 10%, see Section 4.2), then recharge can simply be calculated as the average

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[63] The cumulative rainfall departure method examines the temporal correlation of rainfall with groundwater levels or spring flows, allowing the effect of changes to a system (e.g. growing abstractions) to be discerned (Holland, 2009). It can however be statistically misleading (Weber and Stuart, 2004) and like all methods for estimating recharge has advantages and drawbacks.

annual rainfall multiplied by the recharge factor and the area of aquifer. A minimum recharge figure using this method, assuming average rainfall of 558 mm/a, an aquifer area of 160 $km^2$ and a recharge figure of 4.5% of annual rainfall gives a total recharge volume of 4 017 600 $m^3$/a or about 11 ML/day. If the currently accepted aquifer area of 239 $km^2$ is used, then this minimum recharge figure becomes 6 001 290 $m^3$/a or about 16.4 ML/day. Similarly, a maximum recharge figure based on the same rainfall, an aquifer area of 239 $km^2$ and a recharge figure of 10% gives a total recharge volume of 13 336 200 $m^3$/a or about 36.5 ML/day.

Applying Janse van Rensburg's (1992) method described above to the Lichtenburg Manana rainfall record (the closest rainfall station with a 41 year record to the Grootfontein aquifer) corresponds to an average linear recharge of 3.2% of the Lichtenburg Manana annual mean rainfall figure of 625.2 mm/a. Using an aquifer area of 239 $km^2$, this equates to about 4 781 530 $m^3$/a or about 13.1 ML/day. Whilst this method does take into account the concept of a minimum recharge threshold it is still relatively crude, and does not for example take rainfall intensity at timescales of less than a month into account, although this may in fact be critical (Van Wyk, 2010).

### *5.7.1. A mass balance approach to recharge*

A mass balance approach is difficult to apply in today's conditions of data scarcity, but under "pristine" aquifer conditions with no borehole abstractions, the natural recharge would be 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 simple mass balance can be expressed as follows:

**Recharge = Grootfontein flow + other spring flows + ET ± ΔS**

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 evaporation 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 prior to the start of borehole abstractions are not available. As discussed in Chapter 4, Vipond (1979) reported that the average flow of the Grootfontein Eye at the time of his investigation was 14.4 ML/day or 167 L/s, and that he thought that this figure was likely close to the long-term average flow of the eye. One farmer interviewed in August 2015 stated that the Grootfontein Eye, before it dried up in 1981, was considerably larger than the Molopo Eye (which currently flows at between about 5 and 25 ML/day). Flow records for the Grootfontein Eye were kept while it flowed – interviewees report that the Eye was gauged, and the V-notch gauging weir at the site of the nearby dry Kleinfontein was observed to be still in place in the winter of 2015. One of the earliest technical reports to mention the Grootfontein Eye, by Temperley (1965), reports that:

> "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" (Temperley, 1965:2).

This implies that the gauging of the Grootfontein Eye began in the late 1950s. Assuming that Temperley (1965) meant imperial gallons, 1500 gallons per minute is about 9.8 ML/day or 114 L/s. 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, and possibly as much as 20 ML/day. The flow of the Kleinfontein and other springs and seeps along the northern boundary of the aquifer also need 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 interviews 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, and possibly as much as 25 ML/day.

### *5.7.2. Other recharge considerations*

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 when considering 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 reduced since the water table is considerably lower today.

Irrigation return flows are another complicating issue when assessing contemporary recharge. This refers to the proportion of irrigation water that bypasses the root zone of crops and reaches the water table. It can effectively be added to the figure for recharge in terms of volume, although its impact in terms of quality can be less benign. A detailed study by Colorado State University in 2012 of the state of Colorado's Lower Arkansas River Valley was carried out over four years, and used in-situ measurements of return flows and runoff. The study found that on sprinkler irrigated fields (such as those found at Grootfontein), deep percolation of irrigated water was negligible (Gates et al., 2012). However, the authors found that these fields were typically under-irrigated – which may not be the case at Grootfontein, where return flows might not be negligible. On the other hand, farmers would typically try to irrigate as efficiently as possible to save on pumping costs, and for the purposes of this study it will be assumed that irrigation return flows are indeed negligible. In other words, irrigation water is lost to the system once it is pumped out of the aquifer.

The drying of the wetland areas that are shown on the 1:50 000 topographic maps of the area (see Figure 4-3) has reduced this source of natural discharge from the aquifer to zero – today no standing water occurs in the Grootfontein aquifer area. There are two main areas of wetland within the compartment boundaries shown on the 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. With the cessation of the spring flows and the fact that the hydraulic gradient across the aquifer boundaries is probably towards the aquifer, discharges from the aquifer today are most likely limited to the combined borehole abstractions plus the reduced figure for evapotranspiration.

An estimate of the former wetland areas shown on topographic maps using the area measurement tool in QGIS software gives an area of about 1.2 $km^2$ for the Droë Molopo wetland and 0.22 $km^2$ for the Blaauwbank wetland. Assuming potential evaporation of 1500 mm/a and standing water all year round, this implies that these areas together might have discharged as much as 2 130 000 $m^3/a$ or about 5.8 ML/day to evaporation.

The most important control over recharge today may be the degree to which rainfall in any month exceeds the long-term average, as well as the intensity and total volume of individual rainfall events. Work has been done on this topic (Van Wyk, 2010), and hydrographs do show large recoveries in water level following anomalously high rainfall events, but these effects at Grootfontein are still not fully understood.

### *5.7.3. Recharge summary*

It is difficult to accurately estimate recharge to the Grootfontein aquifer today. Chemical methods such as the chloride mass balance approach and isotope approaches (see Chapter 4) are flawed by a lack of detailed understanding of the physical mechanisms of recharge (e.g. relative contributions of bypass flow and piston flow) and the lack of data on rainfall chloride and isotope composition, as well as geochemical interactions in the sub-surface and the complications of irrigation return flows. Linear estimates of recharge as a percentage of rainfall ignore the evidence for recharge thresholds and the need to take rainfall intensity and prior soil moisture conditions into account. A water mass balance approach requires better estimates of abstraction quantities, as well as ways of estimating today's evapotranspiration. Estimates of recharge under "pristine" conditions, already based on several assumptions, rely on uncertain data for the Grootfontein Eye flows prior to the start of abstractions.

Nevertheless, all of these methods provide a defensible upper and a lower limit to contemporary recharge and therefore a starting point for groundwater management. The minimum average recharge figure for the Grootfontein aquifer is probably about 13 ML/day (about 4.7 $Mm^3/a$), 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 $Mm^3/a$) 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 $Mm^3/a$) seems too high when considering likely discharges under "pristine" conditions. Recharge figures corresponding to averages above 30 ML/day (about 11 $Mm^3/a$) may however be possible today due to the effects of induced recharge[64].

The study by DWS done in 2006 (DWA, 2006c) reports recharge figures for the Grootfontein compartment of 15.8 ML/day (5.8 $Mm^3/a$) in a normal year, and 11.2 ML/day (4.1 $Mm^3/a$) in a drought year, based on the GRA2 data (see Section 3.6). The Grootfontein aquifer boundaries used by the DWS (2006c) report are not the same as those used in this study, and there are limitations inherent in using the GRA2 data, but these recharge values do correspond roughly to the values derived using the mass balance approach described in Section 5.7.1 above.

## 5.8. Abstractions

There are two main categories of borehole abstractions from Grootfontein: the cluster of boreholes around the site of the Grootfontein Eye operated by DWS on behalf of Ngaka Modiri Molema District Municipality, and the boreholes used by farmers for irrigation across the compartment. Boreholes with smaller yields also exist in the compartment (see Section 5.8.3) but these are thought to represent only relatively minor abstractions.

### *5.8.1. The Grootfontein boreholes*

In 2015 only three of the DWS boreholes at the Grootfontein Eye site were still operating, known as Grootfontein A, B and C. The other boreholes originally drilled for water supply around the eye have gone out of service due to the falling water table – the pumps have been removed from these boreholes and they are useful for measuring water levels. According to DWS (2014b) the yield of the DWS boreholes at Grootfontein "collapsed" to about one third of their previous yield in about 2010. In 2013 staff at Botshelo Water Board interviewed at that time said that the three Grootfontein boreholes together yielded about 8 ML/day (about 93 L/s) on average. In mid-2015, staff members at Sedibeng Water Board (the organisation which replaced Botshelo Water Board in early 2015, see Chapter 6) stated that the three boreholes yielded an average of about 7.5 ML/day (about 87 L/s) during January and February 2014 (a period for which data had been plotted and was made available during the interview). The minutes of the

[64] Induced recharge is a mechanism whereby pumping from boreholes lowers groundwater levels, and potentially induces flow from surface water bodies such as rivers or wetlands, or increases flow through aquifer boundaries such as dykes.

Stakeholder Operating Forum meeting held at DWS in Mahikeng on 9 July 2015 state that the three boreholes together yielded 7.2 ML/day (about 83 L/s) at that time. An ex-DWS employee interviewed in June 2015 stated that the Grootfontein boreholes were "giving about, safely, five, six, megaliters per day".

Each of the three Grootfontein boreholes is equipped with a flow meter, and these are read and recorded daily by DWS staff members. This daily data was obtained from DWS for the whole of 2015 for these three meters, and has been summarised in Table 5-9 and Figure 5-11 below, showing the monthly totals. Grootfontein A yields only about 3% of the combined yield of the Grootfontein boreholes, with Grootfontein B and C contributing about 44% and 53% of the total, respectively. The data shows that the average daily flow rate from all three boreholes combined in 2015 was 8.7 ML/day (about 101 L/s) with a maximum abstraction of 13.04 ML/day (about 151 L/s) in July 2015 and a minimum abstraction of 4.8 ML/day (about 56 L/s) in November 2015 (see Figure 5-11). The pumping regime depends on electricity (for example there was a two-day power failure in November 2015, and consequently no pumping) and mechanical reliability, but the reasons for the variation between monthly abstraction totals are not known. It was not possible to obtain the meter readings for raw water from the combined Grootfontein site arriving at the Mafikeng Water Treatment Works operated by Sedibeng Water Board, which would corroborate the DWS data and allow leakage from the pipeline between Grootfontein and the Treatment Works to be estimated.

**Table 5-9 Summarised flow readings for Grootfontein A, B and C (ML/month)**

| **2015** | **Grootfontein A** | **Grootfontein B** | **Grootfontein C** |
|---|---|---|---|
| January | 9.3 | 162.5 | 181.8 |
| February | 8.3 | 125.2 | 142.9 |
| March | 10.1 | 108.7 | 174.3 |
| April | 8.3 | 98.5 | 156.3 |
| May | 8.6 | 96.8 | 136.7 |
| June | 8.3 | 113.1 | 129.2 |
| July | 9.2 | 191.6 | 203.6 |
| August | 8.1 | 125.6 | 166.9 |
| September | 8.2 | 87.6 | 99.1 |
| October | 8.2 | 95.9 | 119.2 |
| November | 10.5 | 74.2 | 59.7 |
| December | 9.5 | 105.9 | 118.2 |
| **MEAN** | **8.9** | **115.5** | **140.7** |

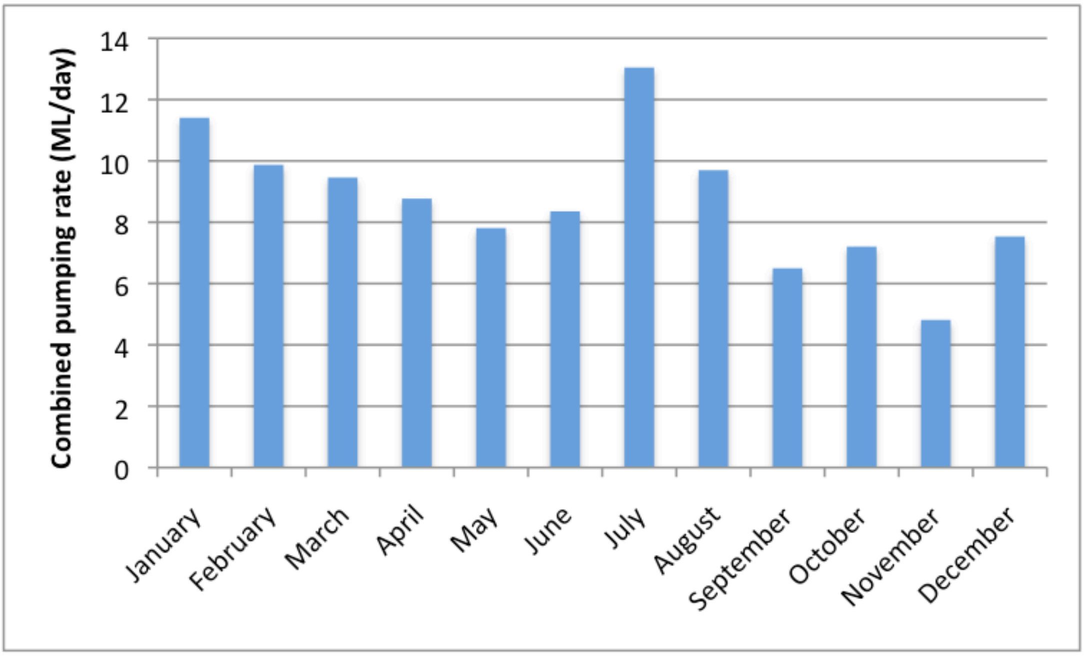


**Figure 5-11 Mean daily flow of Grootfontein A, B and C boreholes in 2015 combined (flow in ML/day)**

These abstraction figures for the three Grootfontein boreholes agree reasonably well with the figures obtained during interviews in 2015. For water balance and analysis purposes, an average abstraction figure of between 7 and 9 ML/day seems a defensible assumption for the three Grootfontein boreholes.

### *5.8.2. Irrigation abstractions*

As discussed in Chapter 4, Van Rensburg (1992) reported the total license allocation for irrigation in the Grootfontein Compartment as about 30 ML/d (or 349 L/s). There was however a rush to formalise licensing in the years immediately before and after the National Water Act was passed in 1998, and this appears to have added to the number of licensed boreholes in the North West dolomites.

There are currently two possible sources of irrigation abstraction data for the North West dolomites: (1) the WARMS database maintained by DWS, which records the licensed amounts that farmers may abstract, and (2) the actual volumes abstracted calculated by the independent consulting company Schoeman and Vennote, under contract to DWS. Actual abstractions may differ substantially from the WARMS figures since licenses are currently not enforced.

The DWS WARMS data shows that 58 water use licenses plot within the Grootfontein compartment boundaries. All are listed as for "agriculture: irrigation", apart from one listed for "mining", one listed for "agriculture: watering livestock" and one (the Itsoseng boreholes) listed for "water supply service"[65]. The "mining" license[66] is only for 300 $m^3/a$. The Itsoseng boreholes are licensed for 4 ML/day (about 46 L/s). The combined agricultural WARMS licenses falling within the Grootfontein aquifer or compartment area amount to about 60.5 ML/day. This figure would represent a theoretical legal maximum that could be abstracted for irrigation from the Grootfontein aquifer under current DWS policy. However, several interviewees stated that illegal irrigation abstraction was occurring and that licensed quantities were sometimes ignored.

A summary of the most recent data from Schoeman and Vennote, provided by them as part of WRC project K5/2429 in December 2015 and discussed in Eales (2015), states that present agricultural groundwater use in the Grootfontein compartment is 37.26 ML/day, irrigating a total area of 2050.7 Ha (or 20.5 $km^2$). This estimate relies on satellite imagery, and knowledge of crop types and irrigation requirements. It is likely to be the best estimate of current groundwater irrigation abstraction at Grootfontein.

DWS is, however, using the Schoeman and Vennote data as the basis for further "V&V" (verification and validation) of license quantities, and not relying on the data as it stands. One interviewee (an ex-DWS employee with knowledge of the issue) stated that estimates of irrigation volumes using satellite imagery was not accurate, because it did not take into account the weather and prevailing soil moisture at any particular time – i.e. a crop may be irrigated with more or less water than its theoretical average amount depending on how hot or dry it is. This interviewee stated that a more accurate way was to either meter the boreholes themselves or use electricity consumption as a proxy for water pumped[67]. Both DWS and Schoeman and Vennote are aware of the drawbacks of

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65 The WARMS license data has not been shown on a map to help preserve the confidentiality of license holders. These license volumes in any case need to be verified and validated by DWS for the Grootfontein area and may not accurately reflect current abstractions.

66 As far as is known, no mining takes place in the Grootfontein aquifer or compartment today. This license may have been obtained at a time when mining was being contemplated, perhaps to exploit local diamondiferous gravels.

67 The use of electricity consumption data to estimate abstractions is an intriguing possibility, with one interviewee saying in 2015 that ESKOM might release this data subject to official request from a government department. Estimates of irrigation abstractions using electricity consumption were made at Grootfontein in the 1980s (e.g. Bredenkamp, 1985) and some experts

using satellite imagery in this way, and neither organisation intends the information to be used without further verification. The Schoeman and Vennote figure of 37.26 ML/day is therefore the best available estimate, but potential errors are difficult to quantify.

### *5.8.3. Other abstractions at Grootfontein*

As mentioned in Section 4.3.7, the Itsoseng boreholes near the southern boundary of the Grootfontein compartment are probably the largest "other" abstraction from the aquifer (i.e. apart from the Grootfontein boreholes and the irrigation abstractions). According to the DWS WARMS data, the Itsoseng boreholes are licensed for up to 4 ML/day (about 46 L/s). A visit to Itsoseng in May 2015 established that the boreholes do not pump continuously, but only when needed to replenish the large concrete reservoir at the site. The borehole sampled had a pumping rate of 0.8 ML/day (9.5 L/s) marked on it. It seems likely that the 4 ML/day figure represents a maximum value for the abstractions from Itsoseng, and that the real abstraction rate may be as little as half of this.

Other groundwater users abstracting from the Grootfontein aquifer are thought to use groundwater for domestic use, stock-watering and other small-scale uses only. All of these other abstractions therefore probably make up a maximum of about 10% of the groundwater abstractions from the Grootfontein aquifer.

## 5.9. Conceptual model of the Grootfontein aquifer

The data described in this chapter combined with literature data allows a conceptual hydrogeological model of the Grootfontein aquifer to be described (Figure 5-12). In summary, the Grootfontein aquifer can be thought of as a semi-rectangular secondary aquifer developed in the upper weathered zone of Malmani Sub-group dolomites. Low permeability igneous dykes form its boundaries, with permeability being higher in the upper few metres where the dykes are weathered. Regional groundwater flow is from the south to the north, following the topography. The highly heterogeneous nature of the dolomite weathering and karstification can result in aquifer properties changing by several orders of magnitude over a few tens of metres or less. It is likely that linear karstified flow zones of relatively high permeability and porosity have developed,

---

urge further use of this method (e.g. Stephens and Bredenkamp, 2002). It has been assumed that there are intractable problems in obtaining or using ESKOM data, otherwise DWS would already have done it and would not be relying on satellite proxy estimates.

contrasting with areas of lower weathering where porosity and permeability are functions of fracture networks where proportionately less karst dissolution has taken place. Early water boreholes in the Grootfontein aquifer were often unsuccessful, with developers preferring the shallow alluvial gravel deposits with a higher chance of a good yield (Temperley, 1965)[68].

Under pre-development conditions ("pristine conditions"), the Grootfontein aquifer would have received groundwater via natural recharge, and discharged this groundwater as evapotranspiration, evaporation from wetlands, and discharges from springs on its northern boundary. The largest of these springs was the Grootfontein Eye. Smaller springs included the Kleinfontein Eye about 800 m east of the Grootfontein Eye. These springs were the origins of marshy areas and perennial drainages that were tributaries of the Molopo River, such as the Droë Molopo River (Figure 4-3). Groundwater quality was excellent, and water from the Grootfontein Eye, via an open channel, was used for public supply in Mahikeng with only precautionary chlorination needed.

Following the drilling of irrigation boreholes in the Grootfontein aquifer from the 1960s onwards, the flow of the Grootfontein Eye began to decline. Public water supply boreholes were drilled around the spring in the late 1970s and early 1980s, to increase the yield from Grootfontein. In 1981 the spring flow stopped, and none of the springs along the northern boundary of the compartment have flowed since. With time, these public water supply boreholes began to fail as the water levels dropped. Their collective yield saw a steep decline in 2010 (DWS, 2014b), and only three now function. Today, irrigation boreholes remove most groundwater from the aquifer, with the public water supply boreholes and other abstractions pumping smaller quantities (see Section 5.8).

[68] Alex du Toit described difficulties with dolomite boreholes in his "Geology of South Africa": "Excepting for such solution channels following joints and bedding planes the rock itself is compact and impervious, wherefore the dolomite is one of the most unsatisfactory formations for water boring." (du Toit, 1939:113). Persistence and modern borehole siting techniques have reversed this view of the dolomites (Vegter, 2001).

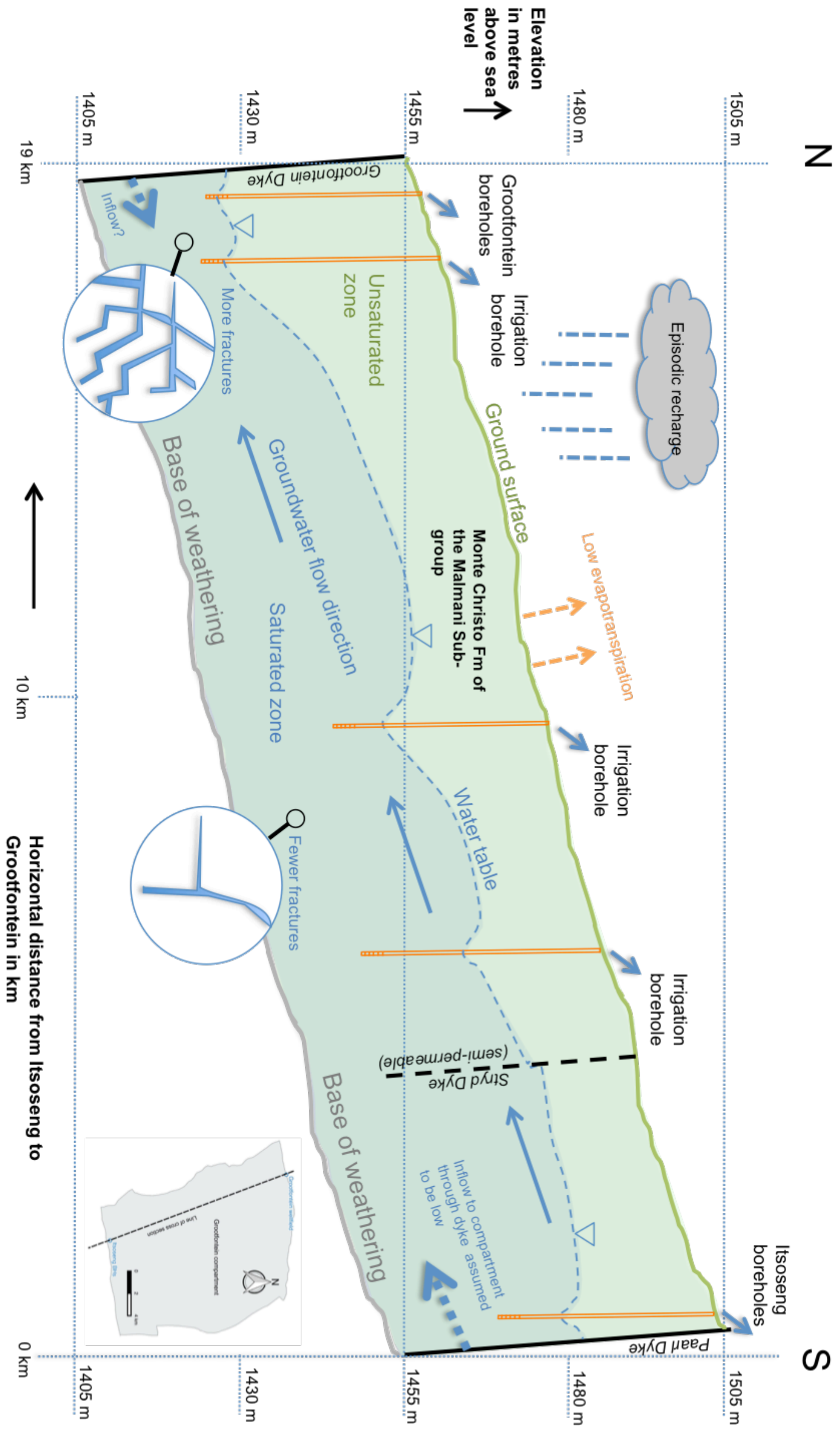


Figure 5-12 Conceptual cross-section of the Grootfontein aquifer

## 5.10. A water balance for Grootfontein

The basic water balance for the Grootfontein aquifer can be written as follows:

**Inflows - Outflows ± ΔS = 0**

If irrigation return flows and the sum of flows through the boundaries of the compartment are assumed to be zero , then inflows will equal recharge. A recharge figure of between 13 ML/day and 30 ML/day (about 4.7 to 11 $Mm^3/a$) seems most likely (discussed in Section 5.7).

It is assumed that contemporary evapotranspiration is zero due to the deep water table, net flow across compartment boundaries is zero, and all spring flows have ceased. Therefore outflows from the Grootfontein compartment are equal to the sum of all borehole abstractions. These abstractions can be divided into the irrigation boreholes, the DWS boreholes at Grootfontein, and other miscellaneous boreholes (including Itsoseng). These figure calculated by Schoeman and Vennote of 37.26 ML/day (about 13.6 $Mm^3/a$) is the best estimate for the irrigation boreholes. The average flow from the three DWS boreholes in 2015 was 8.7 ML/day (about 3.2 $Mm^3/a$). The miscellaneous boreholes likely have abstractions of between 2 and 4 ML/day (0.7 to 1.5 $Mm^3/a$).

The long-term change in storage (ΔS) at Grootfontein can be estimated by assessing water level changes, as described in Section 5.5. An average water level change for all boreholes of 0.4 m per year was calculated. Assuming an aquifer area of 239 $km^2$, zero net flow across compartment boundaries, and a specific yield of 2%, this equals approximately 5.2 ML/day (1.9 $Mm^3/a$). If the higher estimate of specific yield of 10% provided by DWA (2006c) is used this figure becomes a maximum of 26 ML/day (9.5 $Mm^3/a$). Specific yields in the upper part of the aquifer greatly depend on the nature and extent of weathering and karstification, and are likely to decline with depth. Therefore considerable uncertainty regarding this figure exists. The DWS study done in 2006 (DWA, 2006c) supports the general conclusion that abstractions exceed recharge at Grootfontein.

The combined groundwater abstractions from Grootfontein are therefore approximately 48 to 50 ML/day (about 17.5 to 18.3 $Mm^3/a$). Even with a relatively high value for change in storage (e.g. 20 ML/day, or 7.3 $Mm^3/a$) this implies recharge towards the higher end of what is expected (e.g. about 30 ML/day, or 11 $Mm^3/a$). Further complicating the picture is the combination of leakage into the aquifer through the aquifer boundaries, possible induced recharge caused by falling water tables, and irrigation return flows. Table 5-10 summarises the water balance:

**Table 5-10 Summary of Grootfontein aquifer water balance**

| INFLOWS | Estimate | Notes |
|---|---|---|
| Recharge | Between 13 ML/day and 30 ML/day | These figures are based on spring discharges and evapotranspiration. |
| Return Flows | Assumed to be zero under current conditions | May be a locally significant source of recharge. |
| Inflows across boundaries | Assumed to be zero under current conditions | May be significant particularly where water levels have dropped. |

| OUTFLOWS | Estimate | Notes |
|---|---|---|
| Irrigation boreholes | 37.26 ML/day, may be higher | DWS WARMS data implies amount may be higher. |
| Evapotranspiration | Assumed to be zero under current conditions | Low water tables have eradicated wetland areas, springs and seeps. |
| DWS boreholes | 8.7 ML/day | Based on DWS 2015 data, likely to have been higher a few years ago. |
| Other boreholes | Between 2 ML/day and 4 ML/day | Mostly Itsoseng boreholes for public supply since other abstractions small. |

| Δ STORAGE | Estimate | Notes |
|---|---|---|
| Falling groundwater levels | Between 5.2 ML/day and 26 ML/day | 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. |

## 5.11. Conclusions

The natural quality of Grootfontein's groundwater is good and it can be used for public water supply with basic treatment. However, Section 5.5 has shown that the volume of the groundwater resource at Grootfontein is diminishing, with average annual declines in water level of about 0.4 m across the aquifer. This decline in caused by pumping more water from the aquifer than can be replenished by natural recharge. The biggest groundwater users are the irrigators, with estimated abstractions of about 37 ML/day (about 13.5 $Mm^3/a$). The public water supply boreholes operated by the Department of Water and Sanitation yield about 9 ML/day (3.3 $Mm^3/a$) on average. Other abstractions may remove another 2 to 4 ML/day (0.7 to 1.5 $Mm^3/a$). Recharge is between about 13 and 30 ML/day (4.7 and 11 $Mm^3/a$), on average.

A recharge rate for a "pristine" aquifer can be estimated from historical measurements of springs and other discharges, but the total volumes that can be withdrawn under contemporary conditions are harder to estimate. This is because effects such as induced recharge and leakage across compartment boundaries may become increasingly important as water levels in the aquifer drop due to over-abstraction. There is also the question of the flow of the Grootfontein Eye – if groundwater levels recovered and the eye starting flowing again, how much of a reduction in the natural flow of the eye would be acceptable? It is likely that a long-term average sustainable volume of about 13 to 30 ML/day (4.7 to 11 $Mm^3/a$), based on the recharge estimates, could be abstracted without implying a long-term decline in groundwater levels. However this is subject to various caveats (see Kalf and Woolley, 2005; Vegter, 2001; and Chapter 4) and an adaptive management approach would be preferred (see below).

If a dynamic balance in the groundwater levels at Grootfontein is to be reached, then abstractions from the aquifer would need to drop by at least 5.2 ML/day or 1.9 $Mm^3/a$ (the minimum figure implied by a long-term average falling water table of 0.4 m/a and a conservative specific yield of only 2%). Ultimately an adaptive management approach (Seward et al., 2006) would be best, in which the effects of changes to abstractions were monitored, and used to update the conceptual model of the aquifer and the management interventions.

More sophisticated adaptive management would take a multi-year view of the aquifer, accepting deficits in dry years in the expectation of replenishment in years of higher recharge. Maintaining the water table at a relatively shallow depth (or better still, allowing the Grootfontein Eye to flow again) would minimise pumping costs and also hold a large volume of groundwater in storage for emergency public water supply use.

Whilst much hydrogeological work has been done at Grootfontein, there are still issues of hydrogeological uncertainty and opportunities for further hydrogeological research. These include better knowledge of the abstraction volumes, and of the recharge characteristics, volumes and relationship to rainfall. The physical characteristics of the aquifer, whilst broadly understood, also require further refinement. In particular, how leaky are the dyke boundaries to the Grootfontein compartment, and how do their properties change with depth? What is the relationship between macro-structures in the dolomites such as weathered channels, and groundwater flow? The isotope ($^{3}H$) results suggest that older groundwater might be mixing with more recently recharged groundwater in places. How is this related to age stratification of groundwater in the aquifer, and how might this change with time? With respect to water quality, what are the controls on natural groundwater quality variation across the aquifer? How is groundwater quality being affected by activities such as fertilizer application and pollution?

These possible areas for future research in general represent refinements of existing hydrogeological knowledge rather than new areas of enquiry. They are unlikely to substantially change the conceptual understanding of the Grootfontein aquifer, required for adaptive management to begin. Indeed, answers to some or all of these questions would emerge with a better groundwater management program and associated monitoring. Remaining hydrogeological uncertainty should not postpone better management at Grootfontein – the groundwater deficit is increasing every year.

If the reasons for the collective failure to manage the Grootfontein aquifer sustainably cannot be traced to a deficiency in hydrogeological understanding, then the answer to the question "What is necessary for successful management of the Grootfontein aquifer?" must lie, at least partly, elsewhere. As hypothesised, an understanding of both the hydrogeology of the aquifer and its institutional setting is required. An effective management approach would likely need the cooperation and agreement of all stakeholders, convened in a suitable forum, adequately funded, with appropriate sanctions for non-participation (or "free-riding"), and suitable gauging and monitoring equipment or access to this data. These institutional aspects are discussed in Chapter 6.

# 6. The institutions of the Grootfontein aquifer

## 6.1. Introduction

The primary research question of this study is "What is necessary for successful management of the Grootfontein aquifer?" The primary hypothesis is that an integrated understanding of the technical or hydrogeological aspects of the aquifer as well as the social or institutional aspects of the aquifer is required. These cannot be treated separately or in succession, since changes in one lead to changes in the other in a feedback system, and the word "integrated" emphasises this characteristic. The relative emphasis or weight given to each can also change, since at different times aspects of one or the other can determine the outcomes of management efforts.

The Grootfontein aquifer is in fact a complex hydro-social system that responds not only to physical changes (such as recharge or abstractions), but also to institutional changes such as shifts in official policy, organisational alignment, crop and electricity prices, changes in social configurations, and so on. These institutional changes can have a more profound effect on the physical state of the aquifer than "natural" changes such as droughts or high rainfall events. Profound physical changes driven by human behaviour have characterised Grootfontein since the 1970s, if not earlier.

Chapter 5 discussed the technical / hydrogeological characteristics of Grootfontein and included a conceptual model and water balance that provide the envelope of hydrogeological possibilities in which aquifer management activities may theoretically be effective or may gain traction. Management cannot aim to abstract more water than the aquifer can physically yield (as is the case now), or try to abstract groundwater of a different quality to that available. Management must be based on the physical reality, and must defer to it.

It is tempting therefore to consider the physical aquifer as the underpinning or determining feature of the hydro-social system, upon which all management and policy must be based, and therefore as the most important feature of the system and the starting point for management. The tendency is to start with the question "what are the physical limits of this aquifer and what can be sustainably abstracted?" rather than "what sort of outcomes might be expected from this hydro-social system, given the existing institutional framework as well as the institutional framework that may arise once groundwater exploitation starts?" In the opinion of this researcher, it is unwise to consider the physical aquifer first, and then the likely institutional framework, since the institutional framework dominates the final outcomes, as will be shown in this chapter.

This chapter uses the results of the fieldwork conducted between 2013 and 2015, particularly interviews and participant-observation, to describe the different interest groups, organisations or stakeholders that control or influence the management of groundwater at Grootfontein. Ostrom (2005) calls these stakeholders "participants" in her work on management of common pool resources. The Department of Water and Sanitation (DWS) is a participant, for example, and irrigating farmers are another[69]. The participants are described in Section 6.2. The "resource attributes" of the Grootfontein aquifer are then discussed in Section 6.3. Section 6.4 discusses the institutionally-determined interactions between participants, using Ostrom's "appropriator attributes" categories (Ostrom, 2005). The use of Ostrom's categories provides a framework for the range of interactions that were observed, and simplifies the thorny question of how to order these. Thereafter, the current management situation at Grootfontein is described based on the analysis of the participants and their interactions. Chapter 6 ends with conclusions that discuss possible outcomes, based on this analysis.

In Chapter 6 it is necessary to move away from the focus on the physical space occupied by the Grootfontein aquifer and concentrate on the groups (participants) who influence its hydrogeology by having a stake in the abstraction of groundwater via sets of policies, rules, social norms, behaviours and other institutions. This is because participants are not all found in a single physical space (farmers, for example, are mainly located at the aquifer, but other participants are located in Mahikeng, Pretoria or elsewhere) and are best thought of as occupying a metaphysical "action arena" (Ostrom, 2005). This action arena, with its participants and their numerous interactions, is the institutional "layer" or component of the Grootfontein hydro-social system. Ostrom's (2005) descriptions of "participants" exercising options within a institution-defined metaphysical "action-

[69] The classification of individuals with an interest in Grootfontein into participant groups is potentially controversial. The approach used here relies on existing formal organisational affiliations (e.g. a government department, a water board, or a municipality) as far as possible. As will be discussed, differences of opinion and outlook exist within participant groups as well as between them, contributing to the complexity of the situation.

arena", together with the "appropriator attributes" of these participants and the "resource attributes" of the aquifer, is used as a general guide for Chapter 6.

The choices and motivations of participants are important, but this is sometimes not recognised. As discussed in Chapter 3, the law (e.g. the National Water Act of 1998) is often seen as a rigid framework for water management. When combined with the scientific understanding of the physical limits of the hydrogeological system, the law determines a range of outcomes that are all designed to optimize use of the resource. By this rationale, illegal groundwater abstractions and other activities with negative consequences are simply breaches of the law, solvable by better law enforcement. Enforcement of the law, however, depends on the socio-institutional context – most stakeholders need to broadly agree with the law otherwise they will find ways around it or challenge it directly in court (both occur in the North West dolomites). Legal action is in fact a sign of the failure of other management efforts and is expensive in money, time and in the social capital that successful natural resource management requires[70].

A distinction has been drawn in the groundwater management literature between "hard" or more authoritarian legal regimes, such as China, and more democratic or "soft" dispensations, such as India (Mukherji and Shah, 2005). This is similar to the distinction that Shah draws between the current democratic and "populist" Indian state and the previous authoritarian colonial state in south Asia (Shah, 2009). It is more difficult to enforce laws and policy in "soft" or "populist" situations since citizens have more ways to challenge the state's authority, and more dialogue and cooperation is normally required to achieve the same changes in behavior or water use. Although this takes more time and effort, it is arguably more consultative, democratic and respectful of individual rights. On the other hand, "hard" or more coercive legal administrations may be able to gain more with the same time and energy, with more desirable long-term outcomes for a wider range of people. Seen in this way South Africa can be located more on the consultative or "soft" side of the spectrum, and enforcing environmental laws and policy in reality requires cooperation from stakeholders. This cooperation is a bundled set of social institutions, the outcome of complex histories and linkages, and is in constant flux in response to changing circumstances. Concentrating on "what should be" in legal terms

[70] In the Steenkoppies aquifer interaction with the state during the ultimately unsuccessful attempt to establish a water user association (WUA) was characterised as communication "by court order" by one intereviewee, and seen by all parties as undesirable.

rather than "what is" in reality, is of limited use in the quest for better groundwater management. Nearly two decades after the passing of the National Water Act, groundwater management in aquifers such as Grootfontein is unsatisfactory (Pietersen et al., 2011), and groundwater remains underused in South Africa (see Chapter 3).

## 6.2. The Grootfontein participants

Chapter 5 showed that the answer to the implied sub-question "Is there enough technical data to start making management decisions at Grootfontein?" is "yes". Furthermore, South African water laws and policies together form an official mandate and set of sanctions for misuse. They are endorsed by the democratic state, and are given partial expression in an interlinked set of official organisations and institutions (discussed in Section 3.5). This in turn implies that there is also sufficient legal mandate to act.

However, better groundwater management at Grootfontein also depends on the nature of and interactions between individuals and organisations (i.e. stakeholders, interest groups or "participants") through whom legally mandated implementation of governance and management must take place. These participants were introduced in Section 1.3. Their nature, viewpoints and key interactions are the subject of this chapter. Important sub-questions relating to these institutional issues include the following:

- Is there sufficient knowledge or data on the institutional conditions pertaining to the Grootfontein hydro-social system in order to make management decisions?
- Of the participants in the hydro-social system, who should initiate or lead the management actions, and what might the first steps be?
- What sort of forum for interaction between participants is necessary, and which participants should attend?
- What are the key institutional hurdles or barriers to progress, and what can be done about them?
- Can these conditions conceivably be met – in other words, is it likely that progress can be made in managing the Grootfontein groundwater, given the existing institutional framework?

Figure 6-1 shows the participants at Grootfontein plotted on a chart with estimated level or sphere of government on the vertical axis and direct influence on abstractions at Grootfontein on the horizontal axis. WUAs and CMAs do not yet exist and are shown as dashed circles. Figure 6-2 shows the relevant municipal boundaries in the study area.

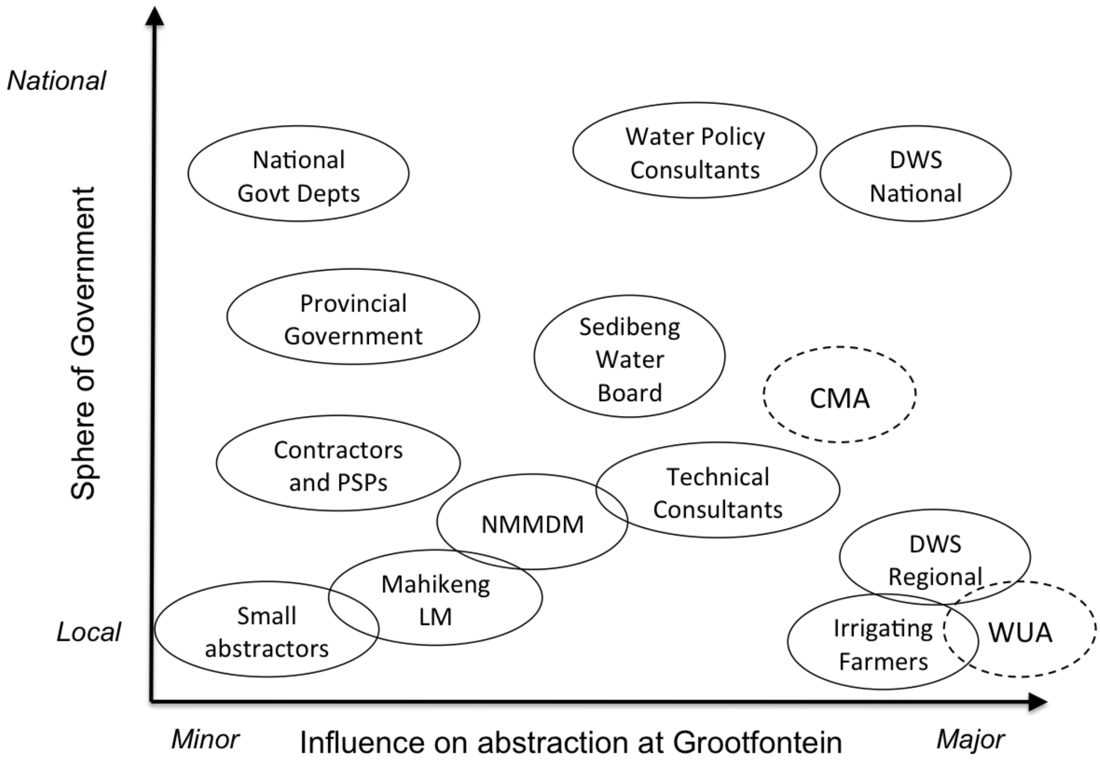


**Figure 6-1 Sphere and influence of Grootfontein participants**

The participants described above and shown in Figure 6-1 are discussed in turn, in the following sections.

### *6.2.1. Ngaka Modiri Molema District Municipality*

Ngaka Modiri Molema District Municipality (NMMDM) is one of four district municipalities in North West Province. It has a population of about 842 000 people (NMMDM, 2015). NMMDM is a Water Services Authority (see Section 3.5) with responsibility for providing domestic water supplies in the area of its jurisdiction, including to the town of Mahikeng and peri-urban areas. It has at least two office complexes in Mahikeng. Poor financial management led to NMMDM being placed under provincial administration in 2014, accompanied by picketing and lock-out of some municipal employees. Internal issues such as high turnover rates of senior municipal staff and lack of continuity generally (e.g. the current municipal manager is acting in the post) characterise NMMDM. These internal challenges have made it hard for NMMDM to meet its external commitments in terms of supplying water to residents of the DM, although it rates this as a top municipal priority (NMMDM, 2015). Water supply challenges include sustaining supplies in rural and peri-urban areas, and maintaining supply networks and associated cost recovery in the town of Mahikeng itself. Scattered, remote villages, arid conditions, illegal connections and poor electricity supplies make this task difficult, and the most recent annual report has the following sentence under the subsection Achievements: "There are no achievements in the 14/15 FY in terms of provision of basic delivery to our communities due to non-payments to service providers which led to incomplete projects" (NMMDM, 2015:13). Apart from the contribution of the Setumo Dam to the water supply of Mahikeng, all of the water supplies across the DM are derived from groundwater, either from the major dolomite sources (Molopo Eye and Grootfontein) or from a large number of mostly low-yielding boreholes outside of the dolomite outcrop spread across the peri-urban and rural areas (NMMDM, 2014). About 75% of households in the DM have water supplies to RDP standard (NMMDM, 2015).

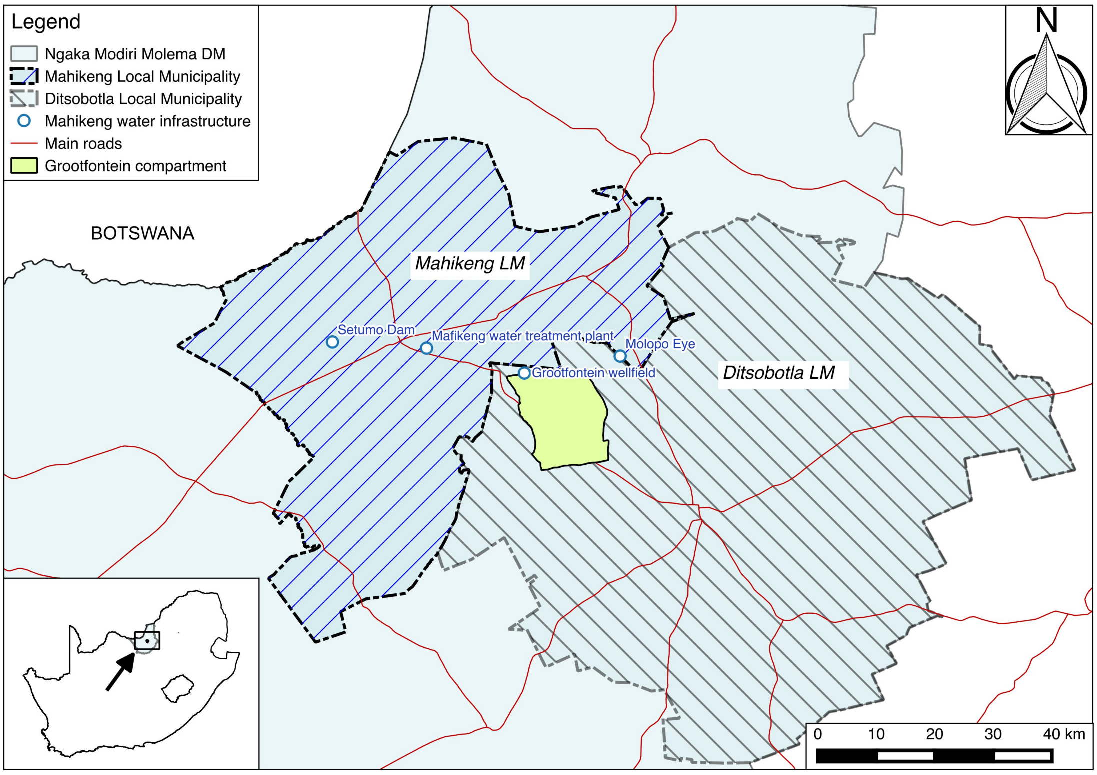


**Figure 6-2 Municipal boundaries in the study area**

NMMDM currently relies on Sedibeng Water Board for water supplies and associated systems operation and maintenance in Mahikeng and also in some of the rural areas. Service level agreements with local municipalities are also in place for other rural areas (NMMDM, 2014). NMMDM staff members include an experienced bulk water and sanitation manager. NMMDM also employs a full-time hydrogeologist, making it one of the few DMs in South Africa to do so. The DM has assets including heavy earth-moving equipment and water tankers, but its abilities to carry out operation and maintenance of water infrastructure have been constrained by operational budget problems and other issues. Internal processes at the municipality such as convoluted chains of command and accountability, and lack of access to operational budgets, constrain operational abilities – for example it proved impossible to obtain a formal recorded interview with a key staff member since the necessary permission from the municipal manager could not be obtained. The last annual report states that only 3 of the 26 posts at the most senior level in water services in the DM were filled, implying a vacancy rate at this level of 81% (NMMDM, 2015). However the main constraint is likely to be availability of funding for all of the posts that appear on the municipal organogram.

In general NMMDM is an organisation in serious crisis, with many important responsibilities that it is currently unable to fulfill. Disagreements have characterised its relationship with the Department of Water and Sanitation in the last few years (see Section 6.3.4). Technical staff members with responsibilities for water supply and sanitation work under difficult organisational conditions with uncertainties related to budget and mandate, and even straightforward tasks related to hydrogeology and groundwater supplies, such as making field visits, are constrained by lack of transport and poor support from line managers.

### *6.2.2. Mahikeng Local Municipality*

Mahikeng Local Municipality (MLM) is not a Water Services Authority and is not legally responsible for domestic water supply services. Nevertheless it is involved with water supply infrastructure and billing in Mahikeng as a water services provider[71]. According to the most recent available annual report for the LM (MLM, 2013) it purchases water from the Water Board and distributes it to households and businesses within its area of jurisdiction. Incorrect accounting for water and sanitation infrastructure assets in the 2012/2013 financial year was given as one of the reasons for the audit disclaimer received by the LM for that year (MLM, 2013). The current arrangements between Mahikeng LM, NMMDM and Sedibeng Water Board in terms of supplying water to residents of Mahikeng, maintaining the infrastructure, and apportionment of the revenue

[71] The Grootfontein aquifer itself falls within the boundaries of the neighbouring LM, Ditsobotla Local Municipality – see Figure 6.2.

appear to be in transition, with responsibility for urban supplies, metering and billing being transferred to Sedibeng from the LM. However it is likely that water charges to domestic consumers will remain a source of income for MLM. In January 2016 MLM posted notice of water restrictions in Mahikeng on its website saying that water reservoir levels had dropped to below 30% and also that volumes from the Grootfontein boreholes had declined, indicating that they are still involved to some extent with urban water supplies. According to one interviewee in mid-2015, the Premier of North West Province had instructed those local municipalities who were not yet water service authorities to apply for water service authority status, and the outcome of this process is not yet known. If MLM were to become as WSA, then this would involve a considerable transfer of legal responsibility from NMMDM to MLM.

MLM used to operate the two wastewater treatment plants in Mahikeng, but these operations were plagued by problems and were the primary reason for the eutrophic status of the Setumo Dam. Sedibeng Water Board is assisting with their operations, but according to one interviewee in mid-2015 the quality of the wastewater effluent was still very poor – "worse than 2010" (State sector employee, July 2015). No employees of the LM were interviewed for this research. Like Ngaka Modiri Molema District Municipality, Mahikeng Local Municipality struggles with its basic functions, and this is reflected in its poor financial state.

### *6.2.3. Sedibeng Water Board*

Sedibeng Water Board took over the responsibilities of the former Botshelo Water Board in late 2014 / early 2015, in line with the national process expanding the mandate of large water boards in South Africa and following the financial collapse of Botshelo Water. Botshelo Water arose out of the former Bophuthatswana Water Services Authority. The takeover by Sedibeng included taking over the former Botshelo offices and other Botshelo assets such as vehicles, and transferring former Botshelo staff to Sedibeng. Botshelo Water Board had been unable to operate effectively for a variety of reasons, amongst the most important of which was a serious financial crisis due to non-payment by NMMDM, which in turn was related to disputes between the LM, the DM and the former Water Board – the NMMDM 2014/15 annual report refers to "poor operational relations" between the DM and Botshelo Water, resulting in the "high rate of outstanding payments" (NMMDM, 2015:28). Part of the new arrangement with Sedibeng Water involves the Municipal Infrastructure Grants (MIGs) to NMMDM being reduced and funds being paid directly to Sedibeng Water Board by the National Treasury (NMMDM, 2015). The incorporation of Botshelo Water was not seamless, with alignment of employees' terms and conditions and the issue of debt owed to Botshelo by municipalities both mentioned in Sedibeng's most recent annual report as vexing issues (Sedibeng, 2015).

Sedibeng Water Board is the Water Services Provider contracted to supply water in Mahikeng and in parts of the rest of NMMDM. It is a relatively large Water Board with 713 employees (including the former Botshelo staff) and operations in Free State, Northern Cape and North West Provinces. Sedibeng has taken over the operations of the former Pelladrift and Namakwa Water Boards, as well as Botshelo Water Board. It had revenues of R958 million and net profit of R191 million in the 2014/15 financial year and has received unqualified financial audits since 2002 (Sedibeng, 2015). As a statutory Water Board, the government of South Africa through the Minister of Water and Sanitation is the sole shareholder. Its head office and SANAS-accredited laboratory is at Balkfontein near Bothaville in the Free State and it has several satellite offices across its area of operations.

Sedibeng Water now manages, operates and maintains the Mafikeng Water Treatment Works that chlorinates groundwater arriving from the two dolomite sources, and pumps this groundwater to the bulk water reservoirs supplying Mahikeng (this is the single largest source of bulk water in Sedibeng's North West Province operational area). Sedibeng Water also has responsibility for various other technical, operational and engineering tasks including overseeing the refurbishment, operation and expansion of the Mmabatho Water Treatment Works at the Setumo Dam, maintaining and expanding the water reticulation network in Mahikeng including the bulk water storage reservoirs, combating leaks, operating the 4 ML/day Itsoseng groundwater supply scheme, upgrading meters, and supplying water to 82 villages in the NMMDM area (Sedibeng, 2015). Sedibeng Water is also rolling out new services in certain of the peri-urban and rural areas. For example in July 2015 Sedibeng Water issued tenders for contractors to site, drill and equip boreholes for four clusters of villages in the NMMDM area.

Sedibeng Water Board is not responsible for the actual abstractions at Grootfontein, the diversion at Molopo Eye, or for any of the other operations and infrastructure upstream of the Mafikeng Water Treatment Works. These are the responsibility of the Department of Water and Sanitation. Sedibeng are however responsible for the Mafikeng Water

Treatment Works and the downstream infrastructure, and they consequently have a major stake in the dolomite groundwater. However, with all of the other responsibilities which Sedibeng Water Board assumed by taking over the operations of the former Botshelo Water Board, the sustainability of the dolomite groundwater sources did not seem to be a key concern of the water board employees and former employees interviewed in 2015, as it is seen as falling outside of their sphere of influence. Commenting on this issue, one Sedibeng employee stated:

> "DWS and the farmers are fighting, but the fight is theirs." (Source: Sedibeng Water Board employee, June 2015).

The Sedibeng Water Board annual report notes the fluctuations in yield from the dolomite sources and states only that DWS is funding a project to address the issue, without providing any details of this project (Sedibeng, 2015). Considerable funding and energy is being put into the upgrade of the Mmabatho Water Treatment Works and associated works, and Sedibeng staff members and sub-contractors are enthusiastic about the improved performance of this facility and its implications for water supply assurance in Mahikeng. In general, Sedibeng Water Board is a large, efficient organisation that is seen by many stakeholders including the Department of Water and Sanitation as the answer to many of the problems that municipalities in North West Province have experienced in operating and maintaining water supply and water treatment systems.

### *6.2.4. Department of Water and Sanitation*

The Department of Water and Sanitation (DWS) is the legal custodian of all water in South Africa, as described in Section 3.5. The head or national office is located in Pretoria, and DWS is divided into operational regions corresponding to each of the nine provinces. Functions such as policy and regulation, infrastructure and corporate services cross-cut the regions and these divisions are based mainly in Pretoria. The collection of groundwater data (e.g. groundwater levels and water quality samples), and regulation of groundwater abstractions, is the responsibility of the applicable region, supported by head office. Each regional office may have more than one physical location – for example, the North West Province Region of DWS has offices at Hartbeespoort and a main office in Mahikeng. There is also a small satellite office at the Grootfontein Eye site, and a gatekeeper to prevent unauthorized access to the boreholes.

The DWS North West Region has several groundwater specialists[72] on its staff, but until early 2015 there was a shortage of Mahikeng-based hydrogeologists. In line with the wider South African programme of technical cooperation with Cuba, two Cuban hydrogeologists were deployed to the DWS office in Mahikeng, beginning in about February 2015. These Cuban hydrogeologists are currently (early 2016) the only qualified DWS hydrogeologists based permanently in Mahikeng. Groundwater level measurements and groundwater sample collection are done by staff members based mainly in the Hartbeespoort office, whilst a technician in the Mahikeng office collates flow measurements from the Grootfontein boreholes. The groundwater level measurements, and the results of groundwater quality samples, are submitted by the regional office staff to the applicable directorate in head office, who check them and enter them (or a summary of them) into the publicly-accessible National Groundwater Archive (NGA).

The DWS site at the Grootfontein Eye includes at least ten boreholes, of which only three were operational in the winter of 2015 due to falling groundwater levels. From a hydrogeological point of view the Grootfontein site is poorly managed, with no source protection zones around the abstracting boreholes, and cattle grazing within two or three metres of the concrete structures built around two of the abstracting boreholes. At least one of the former abstraction boreholes is not securely closed (there is a poorly fitting metal plate secured with wire), representing a potential direct contaminant pathway bypassing the unsaturated zone. Protection zones, pollution control and securing open boreholes are basic hydrogeological requirements at any groundwater abstraction site for public water supply, particularly in karst areas. Their omission suggests operational problems at DWS. DWS hydrogeologists visit the site regularly, even when not based permanently in Mahikeng, implying problems with internal procedures or chains of command and accountability, rather than a lack of skilled staff. The Grootfontein borehole flow data was also difficult to obtain for this research, and key hydrogeological personnel in DWS did not have access to it – further suggesting internal communication or "silo" problems at DWS regional level (in the end, Grootfontein borehole flow data for 2015 was obtained). One private-sector consultant based in Mahikeng commented:

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72 A groundwater specialist at DWS might not necessarily have a post-graduate degree in hydrogeology, but would have specialist training, and responsibility for aspects of groundwater work in his or her formal job description. The qualifications necessary to be a "hydrogeologist" in South Africa are still debated. Most agree that formal university training in hydrogeology is required, whilst some specify an MSc in hydrogeology as a minimum.

> "The problem with Water Affairs is that the guys who operate Grootfontein barely even talk to the Regional Office." (Source: Consultant, May 2015).

Records of groundwater abstraction licensed volumes are held in the WARMS database held by DWS, maintained at head office. There is an ongoing process of verification and validation ("V&V") of licensed quantities, since many of the original groundwater abstraction licenses were granted before the National Water Act and were transferred to "new order" licenses after 1998 with the same volumes. This process is the responsibility of the Gauteng Regional Office, based in Pretoria, rather than the North West Regional Office. A private consulting company, Schoeman and Vennote, has been assisting DWS for several years with annual estimates of irrigation volumes used by farmers, based on satellite imagery and knowledge of crop types. "Water theft" by irrigators exceeding licensed volumes in many parts of the country is a recognised problem, but to date no concrete action has been taken in the Grootfontein area. This has greatly contributed to a breakdown in trust between DWS and other participants (discussed in Section 6.3.4).

DWS is presently undergoing organisational restructuring. The process of establishing the nineteen Catchment Management Agencies (CMAs) was put on hold in early 2007 since up to that date only two of the nineteen had been formed. An "Institutional Reform and Realignment" process delivered the formal approval of nine consolidated CMAs in March 2012, and they were gazetted for establishment in May 2014. The transfer of powers, functions and staff to the new CMAs is an issue that is taking much time and energy within DWS, hampered partly by negotiations over staff terms and conditions in the proto-CMAs as well as the final division of responsibilities. This process has the unintended side effect of delaying and complicating decisions regarding water resource management, since this will be a key function of the CMAs. Since there are nine regional offices and there will be nine CMAs, the outcome of the process may be that DWS staff performing regional water management will be moved to the CMA, whilst strategic national planning and data management staff will remain in DWS. This may imply jurisdictional conflict and complicate intra-organisational collaboration. As mentioned in Section 3.5.1, the consolidation of powers into nine CMAs implies partial re-centralisation of water management powers.

There is also an ongoing process to disband all existing Water User Associations (WUAs) and transfer their functions and powers to the CMAs (DWS, 2014a). The length of time it took to approve WUAs in North West Province – or rather to elect not to approve WUAs – has contributed to a stalemate in the Grootfontein area (see Section 6.4) and the amount of work and time it will take to empower or enable the CMAs to take over WUA functions will be very considerable.

DWS is an organisation that is unable to deliver some of its most important functions in North West Province such as enforcing licensed abstraction quantities in the Grootfontein aquifer, or facilitating processes (such as forming water user associations or other forums) to carry out this task on its behalf. Routine tasks including protecting the abstraction site at the Grootfontein Eye, or making data available centrally, are faltering. At the same time, DWS's professed commitment to these efforts and organisations discourages other institutional forms that might perform the functions instead.

DWS appears to suffer from many of the maladies identified by Von Holdt (2010) including ambivalence towards technical skills, undue deference towards authority, and a focus on process rather than on outcomes. Seward (2015) confirms these observations[73]. These problems are rooted in the management and culture of DWS, and do not reflect on the skills and experience of the many DWS staff who assisted with this research.

### 6.2.5. *Advisors / consultants to formal structures*

A number of private-sector consultant engineers, technicians and hydrogeologists work or have worked on the water supplies to Mahikeng, or on the hydrogeology of the Grootfontein aquifer. Some of these consultants are independent, whilst engineering and environmental companies of varying size employ others. Some are physically based in Mahikeng, others reside in Gauteng or elsewhere. Many are ex-employees of the Department of Water and Sanitation (normally in its earlier incarnations as the Department of Water Affairs and Forestry or the Department of Water Affairs). Consultants share several attributes – they tend to have considerable experience as well as advanced formal technical qualifications, and tend to be strongly biased towards "technical" science and engineering problems. They represent the bulk of the technical institutional memory in the Mahikeng area. They sell their time (either as freelancers or

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[73] In his PhD thesis Seward (2015) describes a "rigid, autocratic, centralised style of management" at DWS that is "reluctant to even devolve quite minor functional duties and responsibilities from a national head office to regional branch offices". He describes an organisation bereft of skills, somewhere between "dysfunctional or severely incapacitated".

through a private company) to the state sector, usually either to DWS or to one of the municipalities, and therefore tend to be present intermittently – i.e. during a contract period, or for a contracted task only. Their stake in long-term outcomes can therefore be limited, and as a result there may even be unintended incentives to concentrate on short-term processes at the expense of resolving longer-term challenges.

Consultants frequently carry out routine technical tasks for the state sector (usually for DWS or for one of the municipalities) such as refurbishing wastewater treatment plants, determining sustainable abstraction amounts, siting boreholes, verifying real rates of groundwater abstraction, or installing monitoring equipment. Consultants are also often used in more abstract ways such as determining hydrological research priorities, optimizing hydrological data collection, mentoring technical staff, or providing regional overviews of resource availability. The extent to which consultants are employed is a perennial issue within DWS and the municipalities, with various initiatives over the years aimed at reducing spend on consultants. However, not only do consultants have skills or experience which those in the state sector may lack, they also fulfill a more abstract role as "impartial experts" and are sometimes favoured by DWS and other public-sector organisations as a means of breaking intra-departmental logjams, resolving internal power struggles or initiating unpopular but necessary courses of action. In Mahikeng, consultants have the longest institutional memories of any of the participant groups – several are semi-retired and have decades of experience working for one or more of the state-sector organisations. One younger consultant based in Mahikeng, speaking about an older colleague, said:

> "…in his brain he's got every borehole and every water pipe from – what can I say? – from Christiana to Kuruman. And I've sat in meetings that consultants tell him they can't find boreholes and he'll tell you to ride down that road to that tree and look behind the tree and there's the borehole. That type of thing. So he's very clued up." (Source: private sector consultant, June 2013).

Consultants are consequently very influential, albeit usually within a relatively narrow technical specialty or contracted ambit. It is consultants who initiate many ideas and courses of action, and are often at the root of the commonly agreed range of technical possibilities or options[74]. Consultants also tend to consider themselves above the day-to-day cut and thrust of state sector intra-departmental politics and this longer-term view has made them a useful source of information for this research. Like any specialist community, however, some consultants may be prone to path dependency or "groupthink" in terms of favoured technical choices and strategies. Some consultants also feel that they are the "wrong" race and gender demographic to progress as formal employees within the state sector.

There is a wider group of outside specialist consultants and experts who concentrate on policy and organisational issues, rather than on hydrogeological, engineering or technical issues. Some of these specialists are funded or employed by international aid agencies or multilateral development organisations, which have collectively had a profound impact on South African water law and policy (see Section 3.3)[75]. This group of policy consultants are not directly involved with water supply to Mahikeng - most have no experience of it - and are at least one level removed in terms of Ostrom's concept of nested institutions (Ostrom, 2005). They are not considered to be participants in the Grootfontein hydro-social system for the purposes of this research, but their deep influence long-term and over-arching authority do form part of the background to the problem. Limited interaction between this group and the technical consultants described above can lead to misunderstandings.

### *6.2.6. Irrigating farmers*

The Grootfontein aquifer is a rural area with good soils for growing a variety of crops. Irrigation is the largest user of groundwater from the aquifer (see Section 5.8) and the commercial farmers who abstract this water are therefore important participants in the Grootfontein hydro-social system. The farmers have been grouped as a single entity, implying similar outlooks, motivations and attitudes towards the other participants.

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74 It is an impression of this researcher that private-sector consultants are helping to drive the refurbishment of the Setumo Dam's Mmabatho Water Treatment Works. This does not imply impropriety – consultants who specialise in surface water or engineering projects are likely to lean towards these solutions when their opinions are solicited, just as hydrogeologists might favour a groundwater project, in a demonstration of institutionalised subconscious preference.

75 There are currently plans for a team from the Organisation for Economic Cooperation and Development (OECD) to be contracted to provide specialist advice to the Department of Water and Sanitation regarding new water policies in South Africa. This illustrates a South African tendency to see "high-level" policy formulation as a solution to water challenges, and a willingness to look outside of South Africa for these solutions.

However there are key differences between sub-groups of farmers that are relevant to groundwater management, and this should be remembered even when they are conceptually grouped as a single "participant". The area of the Grootfontein aquifer can be divided into a large number of farms and farm portions, and individual farmers or companies might own several of these, either contiguous or not[76]. Some farmers also manage land for other farmers, including making choices about crop types and irrigation scheduling. These management arrangements may be informal and based on family ties, or formally contracted. It can be difficult to distinguish between who owns farmland, who actually farms it, and who makes the decisions regarding crop types and irrigation scheduling. Furthermore, groundwater pumped from one farm subdivision may be irrigating an adjacent piece of land (although of course drawing from the same aquifer).

Some key differences between irrigating farmers at Grootfontein are discussed below in the following broad categories: differences in size and scale of investment; racial designation; reliance on irrigation and diversification of income; and relations between sub-groups.

Relying on rain-fed (dry land) farming is not considered viable at Grootfontein, since the risk of drought is too high. Growing crops needs irrigation, otherwise other options such as stock rearing need to be considered. Irrigation infrastructure is expensive, with a single large centre pivot and centrifugal pump costing close to a million rand in 2015 (Eales, 2015). Electricity bills to run the pumps can amount to tens of thousands of rands per month. To irrigate profitably, a certain minimum capital investment is needed, but operations can differ quite markedly after that threshold has been reached. Some may farm with several large centre pivots, others with only one or two small ones. Additional equipment such as packing sheds, tractors, grain storage facilities or poly-tunnels are also significant investments. A farmer's level of investment naturally contributes to the long-term view taken regarding the viability of the farming enterprise, and by association the sustainability of the groundwater resource. The significant capital investments required also make it more difficult for new or emerging farmers to begin farming profitably. There is a view amongst many farmers that in today's farming environment, large size

[76] Farm portions at Grootfontein managed as single entities vary in size from less than 14 Ha to more than 350 Ha. Economically, the size of the area under irrigation is important, rather than the total farm size. A single small centre pivot irrigation system at Grootfontein has a radius of about 80 m (irrigated area of about 2 Ha), whilst large centre pivots have radii of more than 400 m (area under irrigation of more than 50 Ha).

and consolidation are key – exemplified in one farmer interviewee's comment of "Go big or go home" (Eales, 2015).

A common distinction in South Africa is between "commercial farmers" (usually white) and "emerging farmers" (almost always black). This is considered to be a fundamental basis for land reform in South Africa, with the implication being that a transition needs to be made from white commercial farmers to black emerging farmers. In time, some emerging farmers will themselves become commercial farmers, and commercial farming areas will start to reflect the racial makeup of the country. Land reform is an important national priority and is regularly referred to in national political debate (e.g. Daily Maverick, 2016a and 2016b). In Grootfontein, most of the commercial farmers with large-scale irrigation operations are white, but there are a smaller number who are black. Black commercial irrigating farmers range from managing sophisticated operations comparable to white commercial farmers (in at least one case) to less well developed operations relying on loans or other forms of state support. Not surprisingly, black and white commercial farmers have similar practical concerns (crop prices, Eskom, drought) but it was interesting to find that both groups also share a certain skepticism towards the state and its ability to assist generally, or manage the groundwater resource more specifically. The land reform process in South Africa since 1995 has been slow and difficult (e.g. Cousins, 2016; De Villiers, 2003) and this is a source of frustration to both black and white farmers. According to at least two interviewees in or near Grootfontein, white farmland that had been sold to black farmers under state-led programmes was being leased back to the original white farmers who continued to farm it as before, paying a rent to the new owners. Another interviewee maintained that a former white-owned commercial irrigation farm was no longer being irrigated by its new owners but was functioning as a series of sub-divisions with diverse and off-farm sources of income, presumably with considerably less groundwater abstraction. One farmer held the view that the farm that the state had bought from him was purchased mainly for the housing on the farm – this farmer paid a rent to the new owners and continued to farm as before:

> "And I know why they came to me, they were looking for housing infrastructure. But, I've been paid, and I'm still farming there, it's now about nine years later." (Source: farmer, August 2015).

In the view of this researcher, based on field interviews and observations, the issue of race at Grootfontein is complex – and given South Africa's history it is central to identity. Farmers at Grootfontein do share commercial and occupational concerns and some may be inclined to group primarily around income, farming type or other activities under certain circumstances and at certain times. Nevertheless, race is generally a major barrier to cooperation and collaboration, and misunderstandings based on invalid or partially valid assumptions between different racial designations are common and contribute to problems. Race and language are closely related, with most white farmers speaking Afrikaans as a mother tongue, whilst black farmers speak mostly Setswana. Nearly all speak English however, and English seems to the language of most meetings in which state organisations, farmers and others might interact.

Not one of the farmers interviewed in the Grootfontein area relied solely on irrigated agriculture as their only source of income. Several of the more wealthy white farmers have sophisticated, commercially diversified farming operations which include stock raising, intensive poultry operations or grain processing, and who practice some irrigation but derive only a minor part of their income from irrigated crops. The larger commercial farmers, black and white, also frequently have some form of off-farm income such as a job in town (or a member of the household with a job in town), small businesses, and other sources. Many farmers see this as necessary for economic survival in the present, as well as insurance against future crop price fluctuations, electricity availability, and of course water availability.

A key issue is the added income that increased irrigation provides to farming households – in at least two cases, water-intensive dry-season (winter) irrigation of maize was seen as providing only a relatively small increase in farm income. Crop choice, too, has a big impact on water use but not always a corresponding change in household income. This issue – that it is possible in many cases to reduce groundwater abstraction without severely harming farm income, may be key to future negotiations over water use. When other variables such as crop prices, land tenure, other potential irrigation methods, irrigation scheduling, and electricity prices are taken into account, it can be seen that correlating groundwater volumes abstracted with farm livelihoods is too simplistic.

The commercial farmers at Grootfontein do not all know each other, and there is no single farmers' association, union or other forum that all farmers appear to participate in. Ownership of some of the farms, particularly those close to the Grootfontein Eye, can be traced back for at least two generations and kinship ties between adjacent farmers are a determining issue in relations between the farmers in this sub-area. Kinship facilitates equipment loans, technical advice, shared harvesting arrangements, the potential ad-hoc consolidation of land into larger and more economically viable units, and other economically beneficial strategies, that would be more difficult otherwise. In other cases, white commercial farmers with similar sized economic operations situated within the Grootfontein aquifer have relatively little contact. Formal farmers' associations such as Agri North West or the Transvaal Agricultural Union appear to link individual farmers over much larger areas and not all farmers are active members. In at least one case, disillusionment with a local farmers' association and its ability to engage with local government structures led to a farmer not wishing to participate in its activities[77]. Some farmers have part time or even full time jobs in either Lichtenburg or Mafikeng and these activities and relationships may be more important than relations with neighbouring farmers – in some cases, farming may effectively be a weekend pursuit.

In other cases institutional norms developed during the apartheid regime, such as loans from the Land Bank or support provided by agricultural boards, may persist even though the original organisational and legal forms have disappeared. One example of this is the old rule of thumb that no more than 9% of farmland could be irrigated, developed during the days of the subterranean water control areas with hydrogeological advice at that time, now superseded. Several farmers referred to this in interviews, and still consider it a basis for sustainable water use.

After the end of apartheid, with new laws governing farm workers' rights, many black farm workers lost their jobs on commercial farms around Mahikeng and consequently also their right to live on those farms – effectively leading to mass evictions of farm labourers (Eales, 2015). Some of these former workers have settled around the edges of the Grootfontein irrigated farming area in communities such as Rooigrond where municipal services are poor and disputes continue regarding the permanence or otherwise of the settlement (Rooigrond, 2011). Some of these evicted workers aspire to become farmers themselves but have neither the land nor the capital to do so. There have also been numerous requests to connect the Rooigrond community to the Grootfontein boreholes, specifically the pipeline supplying the Rooigrond prison

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[77] Stephens and Bredenkamp (2002) also report that some irrigating farmers in the North West dolomites were unwilling to participate in water management initiatives such as discussions towards forming WUAs.

(Rooigrond, 2011). Rooigrond is a constituency that adds to pressure for land reform and a change to groundwater use in the area. See Figure 6-3 below.

### *6.2.7. Other Grootfontein groundwater users*

An important distinction to make is between commercial irrigating farmers, who own nearly all of the land area overlying the Grootfontein aquifer and abstract most of its groundwater, and a smaller group of part-time farmers, smallholders, government organisations and other residents who use Grootfontein groundwater for domestic supplies or other smaller uses only. This distinction is based partly along racial lines, but not always. In the south western portion of the Grootfontein aquifer the communities of Sheila and Itsoseng are home to hundreds of households (these were part of the former Bophuthatswana "homeland" during apartheid, see Figure 4-3). Individual groundwater abstractions here are thought to be small, and the communities are mainly supplied with water from the Itsoseng boreholes in the south-western corner of the Grootfontein compartment, managed by Sedibeng Water Board (Sedibeng, 2015). The nearby Thusong Community Hospital has at least one borehole of its own drawing water from the Grootfontein aquifer, but the volumes abstracted are not known and the hospital may derive some or most of its water from the Itsoseng public water supply boreholes too. Closer to Mahikeng, the community at Rooigrond and the adjacent prison are outside of the aquifer boundaries, but the prison does have a water supply that is taken directly from the pipeline between the Grootfontein boreholes and the Mafikeng Water Treatment Works, and it is possible that Rooigrond community or nearby communities such as Dihatshwane (between Rooigrond and Mahikeng) also benefit from the Grootfontein source. See Figure 6-3 below.

There are a few small businesses such as scrap yards and guest-houses along the R503 between Mahikeng and Lichtenburg who probably use groundwater as a domestic water source (there is no other source of water, apart from rainwater collection). The amounts abstracted are likely to be small.

All of these other users would fall under Ngaka Modiri Molema District Municipality as the Water Services Provider, but in terms of the National Water Act they or their representatives would have an interest in a water user association or other organisation managing the Grootfontein groundwater resource, making them potential participants in the hydro-social system especially if the groundwater resource became unreliable.

The small volumes of groundwater used by these other users, compared to the irrigating farmers, should not hide the fact that thousands of people depend on this water for domestic supply and for small business use. The abstractions by the Department of Water Affairs at Grootfontein should be seen in the same terms – smaller than the irrigating farmers' abstractions, but helping to underpin the water supply to thousands of people with all the social, economic and livelihood implications that this implies.

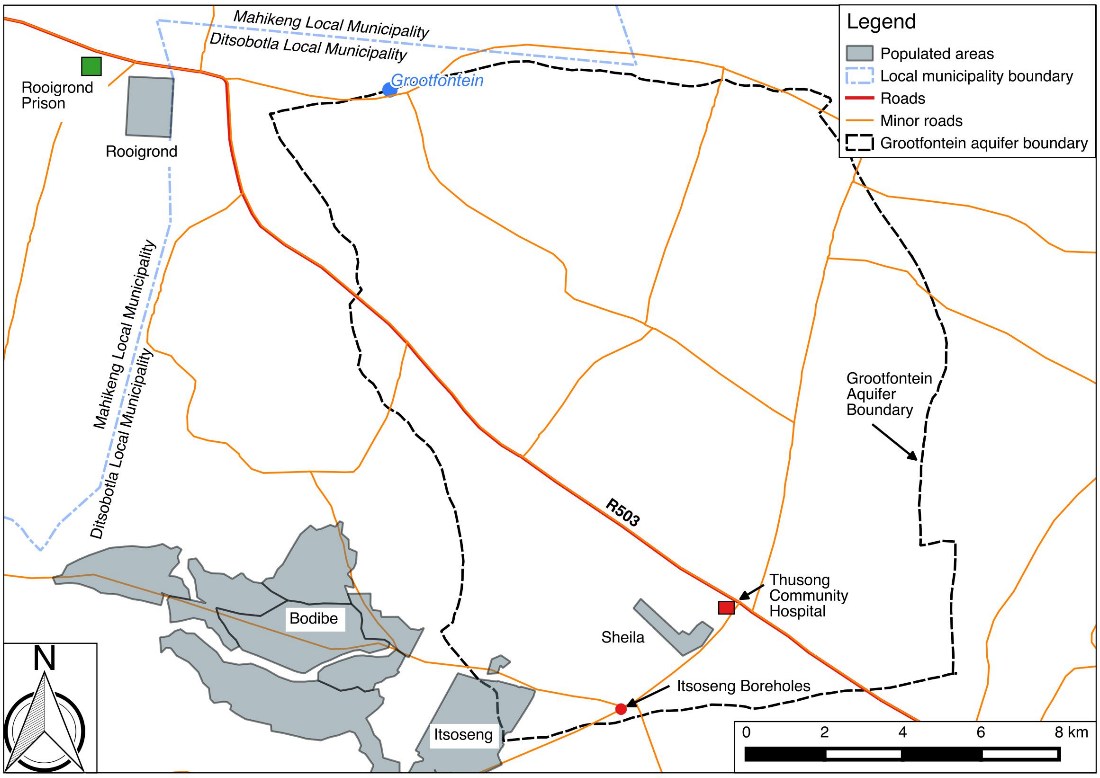


**Figure 6-3 Populated areas and municipal boundaries near the Grootfontein aquifer**

## 6.3. Analysis of resource attributes

As described in Section 3.4, Ostrom (2005) distinguishes between "resource attributes" and "appropriator attributes" of a common pool resource. The resource attributes refer to the physical characteristics of the common pool resource itself, whilst the appropriator attributes refer to the individuals and organisations using or appropriating the resource. This section assesses the resource attributes of Grootfontein, whilst Section 6.4 discusses the appropriator attributes.

According to Ostrom (2005), four attributes of a common pool resource such as groundwater are required to "enhance the likelihood of appropriators organising themselves to try to avoid the social losses associated with open access or rules that are not yet working well" (Ostrom, 2005:244). Ostrom argues that these attributes represent substantial agreement amongst scholars in this field. Ostrom defines these "resource attributes" as follows (Ostrom, 2005):

1. Feasible Improvement. Resource conditions are not at a point of deterioration such that it is useless to organise or so underutilised that little advantage results from organising.
2. Indicators. Reliable and valid indicators of the condition of the resource system are frequently available at a relatively low cost.
3. Predictability. The flow of resource units is relatively predictable.
4. Spatial Extent. The resource system is sufficiently small, given the transportation and communication technology in use, that appropriators can develop accurate knowledge of external boundaries and internal micro-environments.

Despite remaining hydrogeological uncertainty at Grootfontein, discussed in Chapter 5, the Grootfontein aquifer nevertheless possesses all of these resource attributes:

1. The resource is still being utilised for irrigation and for public water supply (albeit at lower pumping rates for public water supply) and has clearly not deteriorated to the extent that organisation or management is pointless (Attribute 1). As a groundwater resource with modern recharge, the Grootfontein aquifer is moreover capable of recovery to former water levels, and no interviewee expressed doubts about this during this research.
2. With respect to indicators (Attribute 2), the data on water levels across the aquifer discussed above is freely available from DWS, and can be downloaded from the NGA website as shown in Section 5.5. Pumping rate data is harder to access, but reasonable estimates can be made. Aquifer parameters such as recharge can also be estimated, despite inherent uncertainty. If water levels across the aquifer are taken as a proxy indicator of the state of the aquifer, incorporating or lumping together pumping rates, recharge values, leakage, and other issues, then the overall "health" of the aquifer can be assessed, as demonstrated in Chapter 5.
3. Groundwater levels at Grootfontein do respond to periods of high rainfall (Attribute 3 or predictability) as well as to excessive pumping, and all users of the groundwater interviewed during this research were aware of this. Predictability is complicated by the multi-year recharge cycles and also by widespread

misconceptions about the scale of abstractions. For example, some of the irrigation abstractors stated that the public water supply abstractions at Grootfontein were the largest single use of groundwater in the compartment.

4. There is broad agreement on the spatial extent (Attribute 4) of the Grootfontein aquifer, and it is certainly small enough to be assessed using what Ostrom (2005) describes as contemporary "transportation and communication technology". In fact, a striking characteristic of the Grootfontein aquifer is the high level of technical knowledge and data availability, compared with other South African aquifers (Vegter, 2001; and see Chapters 4 and 5).

## 6.4. Analyis of appropriator attributes

Section 6.2 describes the various stakeholder groups or participants with an interest in the groundwater at Grootfontein (Ostrom, 2005; and Figure 6-1). The interactions between the participants are based on a complex variety of formal and informal institutions, ranging from formal laws and official meetings, to intra-organisational interactions between colleagues in the same organisation, through to informal interactions between friends and family members. As mentioned, institutions based on former policies and laws, such as those of the subterranean groundwater control areas, may persist even though their formal structure or basis has now disappeared[78].

As discussed previously, Ostrom's (2005) "appropriator attributes" are a useful way of ordering and interpreting this institutional landscape as it applies to common-pool governance. The field data (primarily derived from the interviews, observation and participant-observation) will be described and discussed using this framework. There are other ways of ordering and interpreting such qualitative field data (such as pattern matching, analysis with specialist software, or the tagging used in Grounded Theory) but Ostrom's framework has the advantages of being widely known and understood in water and other natural resource management studies where some level of self-regulation or informal consensus-building over a common-pool resource must occur. As Ostrom

[78] The Polish journalist Ryszard Kapuscinski (1932-2007), who wrote on post-colonial Africa, once noted: "Although a system may cease to exist in the legal sense or as a structure of power, its values (or anti-values), its philosophy, its teachings remain in us. They rule our thinking, our conduct, our attitude to others. The situation is a demonic paradox: we have toppled the system but we still carry its genes."

acknowledges, her framework is itself a summary built on a considerable and contemporary scholarly consensus:

> "Scholars familiar with the results of field research do substantially agree on a set of variables that enhance the likelihood of appropriators organizing themselves to try to avoid the social losses associated with open access or rules that are not yet working well" (Ostrom, 2005:244).

Whilst the Grootfontein case does not require complete self-government by participants, the National Water Act and other South African policy and legislation aims for a substantial component of self-regulation by local participants through devolving powers within the wider legal framework. This is a component of the decentralisation or subsidiarity ideology discussed in Section 3.3. Valuable natural resources are rarely self-governed by immediate participants, without an over-arching legal or administrative framework.

It could be asked whether all of the participants can be regarded as "appropriators" for the purposes of this discussion[79] – after all, most of them are not actually abstracting groundwater themselves (abstractors are mostly irrigating farmers, and the Department of Water and Sanitation). However, it is argued that even non-abstracting participants have a direct stake in the abstractions, and also have some ability to control the scale of the abstractions. For example, Ngaka Modiri Molema District Municipality are not themselves operating submersible pumps in the Grootfontein aquifer, but they are the Water Services Authority in the area with a direct interest in the water and the ability to change those abstractions (by favouring other sources – such as a larger supply from the Setumo Dam – or by more efficient use of the Grootfontein water by curbing losses). Similarly, Sedibeng Water Board could influence the rate of abstractions at Grootfontein by DWS if it chose to do so – motivated perhaps by anxiety over the long-term sustainability of the resource. On the other hand, DWS is not abstracting groundwater for its own purposes, but is doing so on behalf of the residents of Mahikeng via the local municipality and various intermediate organisations. Similarly, there are farmers abstracting groundwater who may be doing so on behalf of neighbouring farmers, or

[79] Ostrom (2005) distinguishes between participants and appropriators in an action situation. Appropriators are a sub-set of participants able to remove or use part of a common-pool resource.

even for absent landowners. The irrigating farmers are in any case not concerned with the organisational distinctions between the various state-affiliated participants, many considering them as more or less a single unit (the "state" or government) for the purposes of groundwater regulation and abstraction. For many irrigating farmers, the "state" is a more coherent and collaborative body than other experience suggests. The issue may ultimately become one of scale – where does one draw the boundary of the Grootfontein hydro-social system? As Ostrom writes about the attribute variables: "Many of these variables are affected by the larger regime in which a resource and its appropriators are embedded" (Ostrom, 2005:245). Ultimately the participants are defined by their agency – do they have some measure of control over the Grootfontein resource, and some stake in the local outcomes?

The six appropriator attributes advanced by Ostrom are as follows (Ostrom, 2005:244):

1. **Salience**: Appropriators depend on the resource system for a major portion of their livelihood or the achievement of important social or religious values.
2. **Common understanding**: Appropriators have a shared image of how the resource system operates and how their actions affect each other and the resource system.
3. **Low discount rate**: Appropriators use a sufficiently low discount rate in relation to future benefits to be achieved from the resource.
4. **Trust and reciprocity**: Appropriators trust one another to keep promises and relate to one another with reciprocity
5. **Autonomy**: Appropriators are able to determine access and harvesting rules without external authorities countermanding them.
6. **Prior organisational experience and local leadership**: Appropriators have learned at least minimal skills of organisation and leadership through participation in other local associations or learning about ways that neighbouring groups have organised.

Issues identified during this research did appear to group themselves under these attribute headings in the early stages of analysis. The structure that they impose also helps to reduce bias and other consequences of being both a researcher and a participant in the hydro-social system. However, drawbacks to using Ostrom's appropriator attribute framework exist. Equivalence may be implied between the attributes by listing them in this way – i.e. it might appear that they are all equally important (Ostrom does not say that they are equivalent, however). In fact, the scale or impact of one attribute might be pivotal to management outcomes, whilst another might be of relatively minor importance. Similarly, one attribute might be easy to establish (e.g. a common understanding), and durable once established, another might be much harder to nurture (e.g. trust and reciprocity).

Attributes are also sensitive to degree in a non-linear way – for example, some trust and reciprocity may be all that is needed to establish a management process (which would then in turn support further trust and reciprocity), but a lack of this attribute might prohibit any cooperation between participants, independent of the other attributes. Attributes might also interact in complex and unexpected ways, with both positive and negative outcomes possible. Small changes may lead to "cascades of failure" in a complex system, as Ostrom (2005) acknowledges[80]. The appropriator attributes may also blind researchers to other important issues that are not specifically mentioned.

The appropriator attributes may also imply equivalence in power, stake, dependence, or authority between the participants, but this is rarely the case. Equivalence between participants is a goal of South African water law and policy, with its emphasis on participation and consultation. The real power in any action arena may of course be much less democratically and clearly distributed.

Any system of ordering institutions has drawbacks – arguably inevitable for nested sets of institutions that interact in complex ways. The Ostrom framework is respected, and also appears to lend itself well to the Grootfontein case study. Therefore the appropriator attributes as advanced by Ostrom and applied to the Grootfontein situation are discussed below.

### *6.4.1. Salience*

The Grootfontein Eye used to be the main water supply for Mahikeng, and according to one of the local farmers there was originally a mechanical device with which water

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80 The book "Normal Accidents" describes non-linearity and unanticipated consequences in "tightly coupled" complex systems where technology and people interact (Perrow, 1999). The book focuses on nuclear safety - it was first published in 1984 following the Three Mile Island nuclear plant accident, and not long before the Chernobyl disaster in 1986 which bore out much of Perrow's analysis. Helbing's (2013:55) analysis of risk in interdependent, globalised systems acknowledges that "interaction rules or institutional settings" in social systems are a component in the stability or otherwise of complex interconnected systems, and should be understood.

flowing from the eye was divided "equally" between local irrigating farmers and the town (Vipond (1979) wrote that in the late 1970s Mahikeng had rights to ¾ of the eye's flow, plus abstraction from two adjacent boreholes drilled in 1966, but the actual division is not known). With increasing demand from Mahikeng, and particularly with the decline in volumes from the Grootfontein Eye and later from the boreholes around the Eye, Mahikeng has come to depend more and more on the Molopo Eye. Today the Grootfontein boreholes supply about 20% of Mahikeng's supply, possibly less. There is wide agreement that without the Molopo Eye, the water supply to Mahikeng would be in serious jeopardy – one interviewee said:

> "…actually Molopo if it's dry then the town would be closed, honestly the town would be closed" (source: municipal employee, July 2015).

However, as the supply from Grootfontein has declined, some participants perceive its importance to be lessening, and feel that as long as Molopo Eye continues to flow, Grootfontein may even be unnecessary. Talking of the need to blend the water coming from the Setumo Dam with better quality groundwater, one state sector employee said:

> "We've got another, er, bulk coming from Molopo. So Molopo would be utilised for blending. But we can rest the Grootfontein." (Source: municipal employee, July 2015).

Private consultants interviewed in Mahikeng placed great importance on the refurbishment of the Mmabatho Water Treatment Works at the Setumo Dam. Whilst they did not specifically say that this makes the Grootfontein sources less important, the implication was that the improved source of water from the dam reduced the dependence on the groundwater sources, particularly Grootfontein. The substantial funding being allocated to this project suggests that DWS is also betting on the Setumo Dam resource. One retired consultant with long experience in the town commented in July 2015 that whilst Mahikeng could do without Grootfontein now, it would need the source in the long term. This same informant felt that the Molopo Eye was susceptible to low or zero flows during times of severe drought (stating that a change of "two standard deviations of the average flow rate" would be enough to dry up the Molopo Eye). It is also widely recognised that the main source of raw water flowing into the Setumo Dam is from wastewater discharges and leaks, which originate with the two groundwater sources. In summary, technical staff and representatives of the abstractions done on behalf of Mahikeng consider Molopo Eye and the Setumo Dam as the major water sources for the town, and not Grootfontein. No informant mentioned the potential of a recovered or "full" Grootfontein aquifer as an emergency source during a drought. Thus the salience of Grootfontein for the town is not increasing, and may even be declining.

The irrigating farmers close to the Grootfontein Eye site know that without the groundwater they will not be able to continue farming in the same way. One interviewee said:

> "Look um you can't do anything in the farm, in irrigated land, without groundwater, you know. Um as much as you know, drylands farming is way, way too much of a risk…" (Source: farmer, June 2015).

At the same time, the farmers are well aware of the decline in groundwater levels since the early 1980s, particularly as this has caused some boreholes to go dry, and increased pumping costs in others. Some irrigating farmers have drilled new boreholes or deepened others, chasing the water table downwards, in order to sustain similar rates of groundwater abstraction. Some farmers believe that the town of Mahikeng is taking most of the water (and more than it is entitled to take) and that the town will simply abstract anything the farmers do not take. As one private consultant put it:

> "… the arguments from the farmers in the Grootvlei is that Mafikeng has increased their abstraction without consulting them and that's why it seems to me they are now a bit *hardegat* [stubborn] and say well ok if Mafikeng can pump two point five the amount which they originally were authorized – we can also do that." (Source: private sector consultant, June 2015).

The majority of the irrigating farmers who were interviewed valued the sustainability of the groundwater resource, but felt that there was not much that they alone could do to control it. Most of the irrigating farmers therefore had a "plan B" of some sort, for a time when the groundwater resource would be finished. These strategies included plans to diversify away from irrigated farming into other activities that used less water such as stock rearing, and even plans to sell their farms if buyers at the right price could be found. One interviewee discussed in some detail options for moving his operations to a neighbouring country.

The sustainability of the groundwater source was not the only issue, or even the main issue, causing several irrigating farmers in the Grootfontein area to consider diversifying, moving farms, giving up farming altogether or otherwise reducing their dependence on the Grootfontein groundwater. Fluctuating commodity prices, rising input costs, anxieties over the land reform process, perceptions of increases in crime, a general perception of a state that is hostile to commercial farmers, perceived corruption and the breakdown of official processes, and other factors combine with water insecurity to drive a generally pessimistic outlook regarding commercial irrigated farming in the minds of several interviewees in and around Grootfontein. As one farmer noted:

> "The political atmosphere now I think is the most worrying thing. I'm saying, and it's my own personal view, that we standing on the cliff. And I'm not, I'm not quite sure if there's, I dunno if we are able to turn the ship around, it's becoming very late" (source: farmer, May 2015).

When asked about long-term planning, a respondent answered:

> "Ja but people do not think like that anymore, they've got only some sort of a short-term goal, and say listen, while it's possible let me make, let me make a living, let me make money while I can, and I'll deal with the consequences later. Of course it's foolish, but that's unfortunately how many people are thinking." (Source: farmer, May 2015).

Another farmer said that he was encouraging his son to gain tertiary qualifications, and be independent of the family farm. In summary, irrigating farmers know that they are dependent on groundwater, are pessimistic about the water resource's long-term sustainability and about the outlook for commercial farming more generally, and are exploring ways to reduce their dependence on groundwater and in some cases on farming altogether[81]. An interesting issue is the extent to which more than one farmer stated that they could considerably reduce irrigation without dramatically impacting profits by changing crops, giving up winter irrigation, or scheduling irrigation differently. (Discussed in Section 6.5.2).

Immediate or short-term dependence on Grootfontein groundwater may therefore be in decline as Mahikeng invests in treating surface water and farmers either look to diversify,

[81] In many ways a classic "Tragedy of the Commons" situation (Hardin, 1968).

or increasingly accept what some see as an inevitable decline in groundwater reliability. At the same time, the actual importance of Grootfontein groundwater remains high since it represents a significant (if generally unacknowledged) potential emergency resource for Mahikeng, and it probably also underpins farming activities and commercial farmland prices more than many realise. The salience of groundwater is therefore an issue with a counter-intuitive component – as demand has grown and the resource has diminished, the short-term and perceived salience of the resource has actually declined as a result of strategies employed by abstractors to reduce dependence on the resource. It is only when the resource has disappeared for practical purposes, or is only intermittently available, that a sharp rise in salience can be expected, as abstractors come to realise the true significance of its absence.

### *6.4.2. Common understanding*

A key problem in the Grootfontein aquifer and in the North West dolomites generally is the general sense that it is a resource in decline, and that is somehow finite. In other words, the groundwater is a resource that will inevitably run out sooner or later, and the aquifer is more like a mine than a dam. This informs many users in their outlooks and strategies for the future. This collective understanding has several causes. Numerous springs or "eyes" in the North West dolomites have diminished or failed in the last few decades, driven either by increased abstractions (e.g. the Grootfontein Eye, the Malmani Eye, the Polfontein Eye at Itsoseng, the wetlands around Lichtenburg and the Lichtenburg Eye, the eye at Ventersdorp, or Maloney's Eye at Steenkoppies) or by dewatering following mining (e.g. the Bank and Oberholzer dolomite compartments closer to Johannesburg and their associated springs – see Vegter, 2001). It seems clear to many that dolomite groundwater resources are finite and liable to "dry up". An early report by the then Department of Water Affairs (Vegter, 1960) on the diminishing yield of the Lichtenburg Eye supplying water to the town of Lichtenburg – caused mainly by industrial (cement plant) abstractions nearby - recommended the drilling of boreholes around the eye to increase yields to the town. No mention was made of the possibility that abstractions could be brought back into balance, or of the desirability of doing so – this being before today's discourse of sustainability. Mining activities at the time were drying up natural groundwater discharge across the West Rand in a deliberate state-sanctioned process (Vegter, 2001; Adler et al., 2007). Actions taken at this time in Lichtenburg, and the example set by the report (Mr Vegter went on to head the

Geohydrology Directorate at DWS) have contributed to the decisions to drill boreholes at other dolomite eyes where yields were falling such as at Grootfontein[82]. At the time of writing some participants believe that Ngaka Modiri Molema District Municipality is exploring for additional groundwater resources around the town of Ottoshoop:

> "And now Mafikeng started focusing their eyes on this water now. They trying with very clever things, buying specific portions of land, and making a lot of, um, huge promises, they trying to get their hands on these waters now, these waters surrounding Ottoshoop." (Source: farmer, May 2015).

No confirmation of this was obtained from DWS. The general perception is that each dolomite source will eventually be exhausted, and that new ones need to be found. Few people outside of professional groundwater or environmental circles argue for actions to bring abstractions into some kind of dynamic balance with groundwater resources, and perhaps even partially restore the flows of some of the old dolomite eyes and vleilands or wetlands.

This perception – that the groundwater resource is in gradual, inevitable decline – is bolstered by the intractable problems, clear to most participants, in reversing the declines by controlling abstractions in the North West dolomites. It is underpinned by the residual understanding (no longer the legal reality) that groundwater is the property of the landowner and is consequently difficult to manage collectively. The view coincides with a wider national perception of groundwater as mysterious and unreliable, and can be contrasted with the general public understanding that a dam or surface water resource can remain viable indefinitely if discharges equal inflows in the long term. The Grootfontein aquifer, as with many other aquifers, is not seen in the same way as a dam, and is not thought of as having the same potential. Some farmers still speak of underground rivers or "arteries" (*aare*) that bring groundwater from distant places, and

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[82] There have been attempts to drill boreholes in the compartment to the north of Grootfontein where the Molopo Eye is located, but these were apparently unsuccessful. Talma (2010) describes reductions in the flow of the Kuruman Eye due to drilling upgradient of the spring for water supply purposes. Enslin (1967) recommended that boreholes replace dolomite springs, to save on evapotranspiration. Drilling close to dolomite springs to increase abstractions despite knowing that this will reduce or stop the spring flow is nothing unusual in South Africa.

water diviners are still employed to site boreholes[83]. This perception is reinforced by the heterogenous nature of the dolomite aquifer properties, where transmissivities and borehole yields may vary dramatically over a few metres or less.

Another key issue in terms of a common understanding of the resource is the ongoing dispute over abstraction quantities. The municipalities, Sedibeng Water Board and DWS all maintain that the irrigating farmers are taking most of the abstracted water from the Grootfontein aquifer, and that this quantity exceeds their licensed amounts. Some of the irrigating farmers feel the opposite, i.e. that the municipality is taking most of the water. (Although several farmers acknowledged that other farmers were taking more than their licensed quantities). One interviewee commented:

> "We know, the studies has been done, what percentage of extraction can be maintained for this water compartment. And as far as I know, and you can look at the aerial photographs and things from the sixties, seventies and now, this area is so tightly controlled that you cannot go outside the line. So we're inside, in terms of Grootfontein water compartment, we're in line. Nothing has been extended here, nothing. The only transgression here is at the spring itself, where they've killed the spring. So from our side as far as I know there's not much, alright? Why should we, the next phase now, and that's what your question is relating to, why should we now reduce below what we're entitled to and below what we know is sustainable if the public sector is destroying the infrastructure? And it's a simple thing, the public sector, the municipality, should stick to the regulation, and we'll stick to the regulation." (Source: farmer, May 2015).

Perceptions are also common amongst farmers that the municipality is wasting the water that is abstracted from the dolomite:

> "…and then the other problem is that I've seen reservoirs in Mafikeng where around the reservoirs the guys are even fishing in that water, so

83 Vegter (2001) quotes a paper by Alex du Toit written in 1923 in which du Toit dismisses water divining and writes "The supernatural has always made a strong appeal to mankind and the idea of divining has become so firmly established that it is doubtful whether any facts to the contrary would weigh much with the majority of persons". Much the same can be said today, nearly a hundred years later.

> long it's been there, you know, so where it's just leaking, it was even in the papers at that time when we had that meeting…. Ja so that's sort of, and then I think they can only account for something like forty or sixty percent of the water that they using…" (Source: farmer, July 2015).

Another farmer complained of "water running down the road" in Mahikeng. One retired consultant living in Mahikeng told of a leaking municipal pipeline near his residence, and estimated the flow as more than "a tap running continuously" (source: consultant, July 2015). This informant stated that he reported the leak many times but in his opinion "poor supply chain management" meant that the necessary spare was not in stock at the municipality. When eventually repaired, the consultant estimated that the value of the lost water was more than ten times the eventual cost of the repair. In mid 2015 an informant at the district municipality, asked about leakage, stated: "I would believe forty to forty five percent is being wasted" (source: municipal employee, July 2015). However, this might combine actual leakage with unbilled and otherwise unaccounted for water in the municipal system. Unaccounted for water (due mainly to leaks and to water theft) commonly exceeds 30% in many South African municipalities, and also in many systems world-wide. Thus leakage in Mahikeng, whilst concerning, is not radically out of proportion to other towns in South Africa. The larger problem may be that the municipality is perceived by some as not addressing the problem, an impression confirmed by the municipality's financial and operational difficulties[84].

Finally, there are still scientific disagreements regarding the groundwater resource at Grootfontein (see Chapter 5). Whilst these are mainly relatively minor (e.g. leakiness of the dyke boundaries, precise nature of episodic recharge, etc) they contribute to perceptions of uncertainty around the Grootfontein aquifer. This is embodied in the local municipality stating on its website that "a study" is being carried out by DWS to determine reasons for erratic abstraction quantities at Grootfontein. There is a common view that a complete and thorough hydrogeological study still needs to be done. Talking of the dolomites in the wider area (i.e. not just Grootfontein), one consultant said:

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[84] During the course of fieldwork for this thesis in 2015 in Mahikeng, strikes, budget problems and protests had led to piles of rubbish burning alongside suburban streets, numerous pot holes, street light failures and power cuts, giving the city a dismal and run-down air. Under these circumstances cynicism regarding municipal capacity thrives, and this may well have influenced the responses of some interviewees.

> "Jude ja look what we did, we started in back in 2001 we said to the Department you need to do proper assessment of the dolomites, because the dolomites is the biggest source of water in the region, for this Ngaka Modiri Molema District Municipality. Er and we actually started it and, and then they sort of ran out of money and interest and everything so it never became… So two years ago we motivated, we requested a cost from [an environmental consulting company] … we said we wanted to know how much water there is, where it is, and at the end of the day we wanted a set of, of, to do with water, we wanted to be told where, a set of wellfields are to, to supply each municipality. And Water Affairs has sort of been nibbling at this thing - cos it's not big money, their price was about six million, cos it's pretty academic exercise, but they getting more and more keen and the District Municipality was one of their problems, they've been now sort of reconfigured, they've got a new municipal manager and so on… So I'm hoping that we can try and get that study going. (Source: consultant, May 2015).

An ex-DWS employee said that:

> "…we started to investigate the, in compartments near Lichtenburg, and then, then it was stopped. So it was an incomplete study and I always said to them we need a complete study so that we know the interaction between the compartments and there must be a model so that you know um… first very important you must know how much is abstracted every year, and you must know the rainfall. And you must have the levels. Then you can see the, the, you know how the different compartments, how much is abstracted percentage-wise etcetera, whether it's over-abstracted, the level is lower. Because what they say there's a, what is the word? The water flow from one compartment to another, but much more at a high water levels, when it's coming, water levels is coming lower it's more sort of a compartment… So all that information should have been gathered over many years so that they can have a picture, but it was never done. But they want to do it now I understand." (Source: former DWS employee, June 2015).

All of these issues together mean that a common understanding of the Grootfontein aquifer (and other groundwater resources in the North West dolomites) does not exist – or where it does exist (e.g. in the widely held perception that the aquifer is in inevitable decline) – it may be flawed. Given the complexity of groundwater resource delineation at a variety of scales, complete agreement will remain elusive, but at Grootfontein the two main classes of users do not even agree on a simplified model that includes the extent of the resource, its potential, and the current scale of abstractions. There is still less agreement on the range of management options for the aquifer.

### *6.4.3. Low Discount Rate*

The third of Ostrom's appropriator attributes, the discount rate that participants apply to the resource, refers to the future value that participants place on the resource and how it compares to the value today. A low discount rate means that participants value the future resource nearly as highly as they value it today. A low discount rate is desirable because it would be an incentive to conserve or protect the resource, since the resource is accorded a relatively high future value. However, as described above, many participants in the Grootfontein hydro-social system doubt the long-term viability of the resource. This is partly due to the widely acknowledged over-abstraction that is taking place, and also to the view that the groundwater resource is inherently less sustainable than a surface water dam and will eventually fail no matter what is done. Furthermore, recent attention and funding has been focused on the upgrade to the Mmabatho water treatment works at the Setumo Dam, inadvertently lessening the importance of the over-abstraction problem at Grootfontein. As mentioned, one informant (a retired consultant) did state that, whilst Grootfontein is not an essential resource now (i.e. in 2015/16), it will become one in the future. No other informant took the view that Grootfontein was a potentially long-term strategic resource for Mahikeng.

As described, many irrigating farmers are considering or implementing strategies to reduce dependence on Grootfontein groundwater, either out of a conviction that the groundwater will inevitably run out, or out of concern for a wider range of issues related to the viability of commercial farming in the area. As one farmer put it, referring to Grootfontein groundwater:

> "You know, if you know something is gonna be destroyed, and I can give you examples of such guys, ride the horse while it's there. Alright? If we run out of water, so be it." (Source: farmer, May 2015).

There is a fairly common idea that if the groundwater supplies to Mahikeng (and other groundwater dependent towns in North West Province) fail, then a pipeline from the Vaal River system could be constructed to replace it. This is part of a wider national discourse of surface water pipelines replacing apparently unreliable groundwater resources, such as has happened at Colesberg or at Delmas. One consultant interviewed for this research stated:

> "Well I mentioned to [a former DWS employee] a long time ago - fifteen years ago - when I was also - and [an environmental consultancy] was looking at doing a similar project there what we did in the far West Rand - is that groundwater management thing - and er I've told [former DWS employee] that the best thing in that whole Zeerust [*inaudible*] is to get a pipeline in from the Vaal River. Their eyes went like that and say well it's too expensive and I told them the system is not going to last - you are over-pumping, there's a stock in groundwater because the area is influenced by climate variability - not like the old days where you get your recharge every year." (Source: Consultant, June 2015).

Asked about future water resources for Mahikeng, and whether these would be groundwater, a municipal employee said:

> "If there is adequate one yes, but if not we can go to Vaal system, Vaal River system." (Source: municipal employee, July 2015).

The pipeline idea may not in fact be feasible – one retired DWS staff member, a qualified engineer with long experience in North West Province, estimated that the costs would be prohibitive to build the pipeline, and that Vaal River water would be approximately twenty to thirty rand per kilolitre compared with three rand per kilolitre for local (and better quality) groundwater. Reallocating water from the Vaal catchment would also mean revoking irrigation licenses, since Vaal water is already fully allocated – effectively transferring the problem of license rationalization and enforcement from the Grootfontein aquifer to the Vaal catchment.

All of these issues together combine to mean that the Grootfontein groundwater has a relatively high discount rate applied to it by most participants, lowering the incentive to manage or conserve the resource. The problem may also compound itself – as the resource diminishes, participants work to make themselves less dependent on it in the future (whether this is the municipality upgrading its surface water supplies, or farmers looking to diversify) and the discount rate grows higher still.

### *6.4.4. Trust and Reciprocity*

Trust and reciprocity, the fourth of Ostrom's appropriator attributes, is generally at low levels in and around Grootfontein. The issue has several important strands or causes, which together have the dominant influence on the current difficulties with groundwater management at Grootfontein and collectively present a major obstacle to its resolution. These strands will be discussed in turn, and then summarised at the end of this section.

Trust and reciprocity are abstract concepts that are difficult to gauge objectively. The approach taken here will be to provide evidence from the interviews (direct quotes and also general issues of agreement) as well as to discuss observable outcomes and situations (e.g. formal meetings) that suggest trust and reciprocity, or its absence.

The first issue identified with respect to trust and reciprocity are the generally poor relationships between the major organisations, and also in some cases within organisations. For example, the breakdown in the relationship between Botshelo Water Board, the Department of Water and Sanitation, and the District Municipality contributed to the financial crisis at Botshelo and its subsequent dissolution. In the years leading up to Botshelo's demise, maintenance of vital infrastructure was neglected which contributed to the leakage / lack of maintenance. Water meters that would have helped the local municipalities collect revenue stopped functioning, contributing in turn to the inability to pay Botshelo. Interviewed in 2013, one consultant based in Mahikeng stated that the single thing that would most help in the resolution of Mahikeng's water challenges would be for all stakeholders to sit down together at a common meeting. In 2015 a consultant stated:

> "Well they went through a very bad stage of a lot of conflict with the municipalities, and Ngaka and you know, I remember one meeting in 2013 when [name withheld] stood up and called the local Water Affairs office director, you know, a monkey. He said don't you even come into my office here and talk this nonsense… Ja, so given the sort of silo mentalities of the various departments and municipalities are doing their own thing. And you can see why Water Affairs then said well we're not going to give you any more money. OK now cos it's

being done through Sedibeng Water … the NMM seem to be more inclined to cooperate with Water Affairs and say ok use your own information we'll just cooperate, I'm hoping this will improve now." (Source: consultant, May 2015).

A retired Water Affairs employee described the relationship between DWS and NMMDM thus:

> "Ngaka Modiri and us was in a big, big, big, big fight, until the management or the board or the council, and the top management, was dissolved by the Minister of, of Local Government. They were fired, all of them, new councilors were there, um, were elected, and up til now there's only administrators for more than a year now, about one year. An administrator. Because they have, *ag* how, they have mismanaged funds to the tune of one billion, if not more." (Source: DWS former employee, June 2015).

When asked about improving collaboration between the various stakeholders, a current DWS employee stated:

> "But you know to some extent the farmers may be easier because my personal view is that the municipalities don't really have the skills or the knowledge to make good decisions." (Source: DWS employee, May 2015).

For their part the commercial farmers tend to have a low opinion of the ability of DWS or anybody else to assist them, or to resolve the over-abstraction issue at Grootfontein. One farmer commented:

> "Jude it's straightforward, the administrative burden is such that you cannot keep up with everything, keeping up with lobbying via the farmers' association, keeping up talking to Eskom about this and that, talking about water, and nothing comes of anything. Meetings are a futile exercise." (Source: farmer, May 2015).

Another farmer stated:

> "It doesn't even help mentioning [water problems in Mahikeng] to [DWS employee seen as responsible], he's not doing anything, nothing, nothing at all." (Source: farmer, May 2015).

Meetings that are convened by DWS confirm the generally poor relations between participants at Grootfontein. For example, this researcher attended a meeting of the Mahikeng Stakeholder Operating Forum (SOF) meeting on 9 June 2015 hosted by DWS at their offices in Mahikeng. The main reason for the meeting was to review the viability of the water sources to Mahikeng, including operating rules for the Setumo Dam and the performance of the dolomite sources. Despite being an important annual meeting, the only stakeholder to attend apart from DWS were two representatives from NMMDM. No farmers' representative (the major abstractors at Grootfontein) attended, and no LM or Sedibeng Water Board representatives (responsible for effluent quality of wastewater entering the Setumo Dam and for repairing leaks in Mahikeng) attended. No representatives from the cement factories abstracting groundwater from the dolomites (these abstractions are from nearby compartments, not from the Grootfontein aquifer itself) attended either.

The third meeting of the Molopo Catchment Management Forum (CMF), also convened by DWS in Mahikeng and designed to bring together all stakeholders in the catchment on the issue of water resource management, was held on 24 July 2015. This meeting attracted a broader participation than the SOF meeting, with Sedibeng Water Board, NMMDM and cement industry representatives, but no farmers attended and nor did anyone from any of the relevant local municipalities. Asked whether he was going to attend this meeting a few days before it happened, one farmer replied:

> "No, definitely not… As I said we attended the first meeting, but it was a complete waste." (Source: farmer, July 2015).

One of the cement industry representatives at the Catchment Management Forum said afterwards that they attended mainly because it was a condition of their groundwater abstraction license. Asked if it was easy to get all stakeholders around the table, a DWS employee with partial responsibility for convening the CMF meeting replied:

> "Ah, you know, it's not easy, it's not easy because some of these people they might have interest on water resource management but remember to actually travel from where you are to get there may be, to the centre point where we actually have our meeting it's actually difficult also because of er money and everything, you understand? …Other people, they get the emails, they don't respond and everything, and those are, in most cases we find that they are actually

key people within that Molopo Catchment Management Forum, you understand." (Source: DWS employee, July 2015).

Low levels of trust and reciprocity between the major participants are not only reported by the participants themselves, or manifest themselves in the non-attendances at meetings, but can also be discerned from the general lack of a jointly held conceptual idea of the Grootfontein aquifer (discussed in Section 6.3.2). The falling water levels at Grootfontein are both a result of, and a reason for, low levels of trust and reciprocity. Meetings that are convened by DWS such as the SOF and the Molopo CMF give a superficial impression of wide consultation and participation, but are in fact held in low regard by many of the most important participants in the Grootfontein hydro-social system, some of whom do not attend at all.

The second major issue with respect to the levels of trust and reciprocity, related to this issue of meetings and forums, is the failure of the Grootfontein Water User Association (WUA) process. As described in Section 3.5, WUAs were envisaged in the National Water Act as a key instrument in local consensus building around, and control of, water resources in South Africa, with an additional primary aim of social transformation. The WUA process has now been halted and DWS has a new vision for the local and inclusive management of water resources (DWS, 2014a). However the slow death of the WUA process in the years since the passing of the National Water Act has contributed to both the poor state of many dolomite aquifers and also to the low levels of trust and reciprocity between major users (mainly irrigating farmers) and regulators (i.e. DWS). In the years immediately following the National Water Act there was momentum to establish WUAs, and especially to convert former Irrigation Boards into WUAs. A group of farmers in the Grootfontein area collaborated to form a WUA, but the process was ultimately not approved by the Department of Water Affairs and Forestry (as it then was). One farmer who was involved at the time explained it as follows:

> "Everything was done, the consultant, which has been, which worked on it, was [name withheld], everything was done, the constitution was finished, it was presented to the Minister - Kader Asmal at that time - and that's where everything stopped." (Source: Farmer, July 2015).

When asked what the reason for this was, this farmer said:

"No I don't know what the reason was, everything was submitted to him, everything was done, we only needed his signature, and that's where everything stopped." (Source: Farmer, July 2015).

Since that time, abstractions from the Grootfontein aquifer have proceeded effectively without any local organisation or control beyond what the major abstractors (the irrigating farmers, and DWS/the municipality) each decide.

Formal reasons for the rejection of the proposed Grootfontein WUA by DWS are not available, but experiences with three other WUAs in the North West dolomites suggest that DWS was not satisfied with the composition of the proposed WUA in terms of participation by historically disadvantaged individuals and by women, and considered the proposed WUA to be an organisation that would entrench patterns of apartheid inequality and water use. One retired DWS employee, when asked why the Grootfontein WUA had not been approved, said the following:

"You see in fact Water Affairs, Water and Sanitation now, they, they are very prescriptive in the establishment of a water user association. There must be, if, un, if possible a majority of, um black people, and now they are not users except now through the municipality…" (Source: former DWS employee, June 2015).

Farmers in the Lichtenburg area to the south of Grootfontein reached an advanced stage in their efforts to form a WUA, including a constitution, a management committee and a set of meetings with Water Affairs and other stakeholders[85]. Commenting on the eventual rejection of this WUA application by DWS, a farmer stated:

"Look it was never approved. We were at a very advanced stage with the, with that application, to register. At that stage I knew of several areas that were busy with water user associations and I don't know of one of them that was successful. I heard later that Komatipoort did register, and, so we were far advanced, I mean we were in the last stages of such an association, our constitution was drawn up, the members were involved, we had all the people who were supposed to be there, and then the application was, submitted to the Department

[85] Minutes of meetings and the draft constitution of the Lichtenburg proto-WUA document a fairly lengthy and painstaking process, but do not provide formal reasons for its demise.

> of Water Affairs, the only feedback that we've ever got was that we didn't have a woman on the users' association." (Source: Farmer, August 2015).

A prolonged effort to form a Water User Association in the Groot Marico area reportedly went through four different applications beginning in the late 1990s, with each application rejected by DWS for a different reason. A farmer in that area commented:

> So they contracted [name withheld] to come and train us, to make sure we'd, we were going to become a water users association, and this is for the fourth time, ok, and once again all these feasibility studies, and, and they asked for the previous studies because they didn't want to do all the work again, and it got to the point of being ready and the Minister said, and this was under Minister Edna Molewa, she said no more water users associations would be approved. (Source: farmer, May 2015).

Perhaps the most concerted effort to form a groundwater-based water user association in the North West dolomites was led by a consortium of farmers with extensive irrigation activities in the Steenkoppies groundwater compartment near Krugersdorp. The agricultural activities in this area are very valuable (see Section 4.5 for more information). Declines in groundwater availability from the late 1990s resulted in threats of legal action, and subsequent scientific studies showed that over-abstraction was partly to blame (Pietersen et al., 2011). Concern for the long-term security of groundwater irrigation and around potential legal battles with downstream users encouraged the Steenkoppies irrigating farmers to work towards forming a WUA. In October 2010, DWA rejected the Steenkoppies WUA application on the grounds that previously disadvantaged groups and women were not adequately represented on the proposed WUA (Rossouw, 2016). An amended constitution for a Steenkoppies WUA was again rejected (in 2015) on the grounds that a moratorium was being imposed on new WUA applications. Steenkoppies farmers today collectively manage their own irrigation volumes in an informal "proto-WUA" grouping – an uncommon outcome in South Africa and one that may be driven by the particularly large investments in agricultural equipment at Steenkoppies. Steenkoppies is an aquifer where valuable farming activities and good hydrogeological knowledge coincide with a relatively homogeneous group of groundwater users (irrigating farmers) who place an unusually low future discount value on the groundwater resource. If these users could not get a WUA established then it implies that the task will be even harder elsewhere.

A common feature of the eventual rejection of these WUAs across the North West dolomites by DWS was that the farmers involved perceived that little or no feedback was given to them regarding the reasons for the rejections, and that little guidance was provided about how to rectify the rejected applications. Many of the white commercial farmers also consider the WUA process to be inherently political, with an element of removing control of water resources from them and placing it in the hands of a broader coalition of other stakeholders including emerging farmers– as is indeed largely the case. The failed attempts to form WUAs in the North West dolomites, including the Grootfontein aquifer, has contributed to a lack of trust between the farmers and DWS, as well as encouraging farmers to essentially determine their own abstractions – in rare cases (such as Steenkoppies) the conditions are such that farmers keep their abstractions in check, whilst in other areas (e.g. Grootfontein) a *de facto* anarchy, or tragedy of the commons, prevails. Having experienced the failure of the early WUA efforts, many farmers are reluctant to invest energy in contemporary forums such as the Molopo Catchment Forum. As mentioned, frustration or lack of connection with DWS is not confined to white commercial farmers, but was also found when interviewing black "emerging" farmers, one of whom said:

> "…because everyone is just doing their own thing hoping that Water Affairs does not come and catch them out…" (Source: farmer, June 2015).

Another black farmer in the Grootfontein area said that he had never had a meeting with DWS or a visit from DWS, and that the only place that he heard about water conservation was from his radio. His neighbour, a white farmer, asked whether anyone had come to talk to him about water forums, said:

> "There was a lady from the government about two or three years ago and she was, she had a few plans but er I saw her once and never again, so…" (Source: farmer, July 2015).

A third issue affecting trust and reciprocity, specifically between farmers and the state in general, is the issue of land claims (see Section 6.2.6). Many of the white farmers see this as a process imposed by a largely hostile state. One farmer near Lichtenburg commented:

> "Land claims, ja, the so-called land claims. They had thirty-six thousand land claims that they were trying to handle and they haven't finished them yet and now they've opened the process again and [name withheld] the other day said they received fifty-nine thousand and something already, and they can claim up to 2018, so there's no way that anybody in his right mind is going to say listen I'm going to invest a lot of money now and my farm, well I presume that every white piece of land will be claimed in the next five years. So I think over and above the whole water situation, I think the restitution issue is going to be a … for food security is going to be very bad." (Source: farmer, May 2015).

This same interviewee later said:

> "It's a political focus against farmers, against especially the white farmers there. It's a political game." (Source: farmer, May 2015).

Frustration with the land claims and land reallocation process was not confined to white farmers. Talking about "Land Affairs" (likely the Ministry of Rural Development and Land Reform as it is now known), one black farmer commented:

> "Aaah those guys are messing up, I mean honestly, yesterday I was fighting with [name withheld]… Ja, um, you guys want to fund us, hooray great, but you know there's a programme that we're under, there's issues here, it does not make sense that we don't resolve these issues, we jump onto another programme and say ah that one did not work let's just you know, let's just go into another one and another one and another one and… Oh ja so it's like guinea pigs and stuff…" (Source: farmer, June 2015).

Whilst the land claims issue, like other macro issues such as crop prices, electricity availability and price, labour laws, or import duties on farming equipment, is not directly related to the abstraction of groundwater at Grootfontein, it does form part of the wider institutional framework at Grootfontein and other parts of the North West dolomites, and affects trust and reciprocity between the state and irrigating farmers. This in turn affects the discount rate that farmers place on the groundwater resource and a desire amongst some to irrigate today in case there is no water tomorrow (described above). Not all participants distinguish clearly between different government departments (e.g.

DWS and the Ministry of Rural Development and Land Reform) or even between organs of the various spheres of government (e.g. between the provincial government and a district municipality). The perceived sins of one become the sins of all of the others. The land claims issue illustrates the potential linkages between issues that might appear unrelated at first. Solving a problem of groundwater over-abstraction requires parallel problems to be addressed in a holistic way.

A final issue that is part of the trust and reciprocity attribute is the issue of intra-organisational cooperation – in other words, the level of cooperation between individuals and departments in the same organisation. This is more difficult to assess than trust and reciprocity between organisations, since intra-organisational relationships are institutions determined within that particular organisation and not obvious or accessible to an outside observer. Again, trust in interviewee statements can be combined with observations of outcomes where possible. The general impression of this researcher is that levels of trust and reciprocity in the relevant state organisations (DWS and the municipalities) are low. Some staff members are willing to speak about this directly. For example, speaking about difficulties with convening the Molopo CMF, a DWS staff member said:

> "… I'm not blaming any organisation, within the Water Affairs, Water and Sanitation, we also have a problem because that is why in most cases we allow that the chairperson [of the CMF] should be somebody from outside. But when we start the forum, we make sure that we are the chairperson, but once the chairperson, once the forum is sustainable, we make sure that we take that chairperson and give it to somebody who's actually independent. Because for me, I know that Water and Sanitation might have problems, and to actually go and tell my colleague and say we need you in this forum, it's, you know, sometimes it's also difficult and everything, ja." (Source: DWS employee, July 2015).

As discussed in section 6.2.4, poor coordination between DWS offices and departments has contributed to the poor hydrogeological housekeeping at the Grootfontein Eye abstraction site (e.g. enforcing protection zones). The organisation is also currently preoccupied with its division into DWS proper and the CMAs, and the final responsibilities of each still need to be ironed out. The location of the CMA office to which some staff in the DWS North West Regional office expect to be assigned was not yet decided when field interviews were conducted in 2015 – Bela Bela or Polokwane were the two options – and this has practical implications for staff members. Asked if the transition was likely to be easy, a DWS staff member commented:

> "Um it's not simple, because now they are still um maybe um dealing with the draft transfer agreement, ja so there are still sort of uncertainties in terms of where um whether these people will want to go there and everything, but hopefully if they clarify all these things um the senior managers, and then everything will be on…" (Source: DWS employee, July 2015).

None of the DWS hydrogeologists working at National Office or the North West Regional office had easy access to the abstraction data from the Grootfontein boreholes, confirming intra-organisational issues between DWS departments.

Cooperation within the district municipality (NMMDM) also seemed poor, with operational staff and the project management unit (PMU) disagreeing on some water issues. As already mentioned, a key employee of the district municipality (NMMDM) was not prepared to speak to this researcher without written permission from the municipal manager. More than one municipal staff member with responsibility for water infrastructure said that the democratic processes in South African local government meant that senior municipal staff members focused on short-term "quick wins" which could be presented either to the electorate or to other government departments such as Treasury, and that this was detrimental to a long-term strategy for groundwater[86].

Perhaps the best evidence for poor or erratic intra-organisational collaboration is the fact that none of the organisational participants at Grootfontein have a clear plan to address the over-abstraction problem. All of them have an interest in a positive outcome for the aquifer, and at least two (the Department of Water and Sanitation, and NMMDM as the Water Services Authority) are legally mandated to address the issue. Pressed on the question of the "way forward" for Grootfontein and whether it was a lost cause, one DWS staff member said:

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[86] This is similar to some of Von Holdt's conclusions regarding current bureaucratic processes in South Africa (Von Holdt, 2010).

> "…I wouldn't say that it's something that is too far to worry about, but it's more of an issue of, if you focus on the water users in that particular area and get them to, to understand the importance of managing the resource, because at the end of the day they need it, whether it's for the municipality or whether it's for the farmers it's important for them to understand it. So, maybe perhaps through the water users or maybe a bit of a education in terms of the way groundwater is functioning may be key, because in the water user association you discuss a lot of things but at the end of the day you need to bring that technical aspect of understanding what does it mean when there is a decline in the water levels and the overall impact, looking into all the other things, whether it's drought, whether it's climate change that most of us do not understand. But the key thing for me is to, for them to understand that. But if, they say from a practical example it would be that to start working on getting the actual abstractions in the particular area, if you can get that and then from there you start working on it, verifying it, and validating to say who is using what, and if there is a need to then, the monitoring that we have in that particular area, to extend it, so that it covers all the areas, or maybe perhaps to, to impose some restrictions. Restrictions might work also." (Source: DWS staff member, July 2015).

#### *6.4.5. Autonomy*

The fifth of Ostrom's appropriator attributes is autonomy, which Ostrom defines as "Appropriators are able to determine access and harvesting rules without external authorities countermanding them" (Ostrom, 2005:245). At first glance the Grootfontein appears to meet this criterion, since nobody is currently instructing either the irrigating farmers or DWS to modify their abstractions. Indeed, this has been identified as part of the problem so far – in the absence of the imposition of external authority, only internally-developed or endogenous rules developed by appropriators themselves would be able to change the abstractions. At present, both parties appear to be able to do as they please, limited only by their pumping equipment and the yields of their boreholes.

However, despite this appearance, the participants at Grootfontein are not fully autonomous users of the resource. The irrigating farmers know that they are over-abstracting groundwater, but feel that if they do not do this, then the municipal abstractions will take whatever water is saved (discussed above). An ex-DWS employee summed it up by saying:

> You see, um the problem is that the farmers, amongst themselves, they know there is illegal abstraction, they know that, and the farmers that have legal rights they are not very happy because they know the source is limited. And you know the fact that it was an eye and now the water is abstracted forty metres below ground level give you an indication how much is a over-utilisation of the source." (Source: ex-DWS employee, June 2015).

The irrigating farmers do not consider themselves to be sole users with autonomy over the resource, since DWS is abstracting unknown (to them) volumes. The farmers rationalise their over-abstraction by arguing that they have no control over the DWS abstractions, and must make hay while the sun shines (or "ride the horse while it's there", as one farmer put it). In any case, the irrigating farmers cannot be considered as a homogeneous group within which the potential to limit abstractions might spontaneously arise, since issues of race, kinship, varying degrees of reliance on irrigation, and disputes over licensed quantities, amongst other issues, intrude.

DWS, for its part, is abstracting groundwater on behalf of the water services authority (NMMDM), with whom it has a rocky relationship including over issues of payments and funding (see above). DWS feels bound to abstract groundwater on behalf of NMMDM, and whilst it could theoretically refuse to continue, this might lead to higher level problems with NMMDM and the provincial government, who would reasonably enough demand to know why commercial irrigating farmers appeared to be taking the lion's share of the resource. Reducing the DWS abstractions would then require a similar gesture from the irrigating farmers (to show that they were not being favoured over the municipal supply) as well as good communications and cooperation with both applicable municipalities. For reasons discussed above, neither would be easy.

Whilst superficially appearing to be autonomous therefore, both the irrigating farmers and DWS are in reality locked into a path-dependent course of action that has the exhaustion of the resource as its most likely outcome. Neither party is prepared to unilaterally reduce abstractions, and the lack of trust and reciprocity between the two (discussed above) makes a jointly negotiated solution more difficult. The failed attempts to form WUAs and the lack of a replacement local organisation with similar powers contributes to this. The longer the situation persists and the lower the water levels get, the less the chance of a positive outcome.

### *6.4.6. Prior organisational experience and local leadership*

The last of Ostrom's appropriator attributes calls for appropriators who have "at least minimal skills of organisation and leadership through participation in other local organisations or learning about ways that neighbouring groups have organised." (Ostrom, 2005: 245). All of the participants in the Grootfontein hydro-social system, with the exception of marginalized small water users such as the Rooigrond community (adjacent to the Grootfontein aquifer), have organisational experience and resources that are greater than most developing country / poorly-resourced contexts. However, as with the autonomy attribute discussed above, this experience and organisational potential may not be the advantage that it first appears.

Prior organisational structures and institutions (e.g. the government water control areas and the irrigation volumes set in those days, the view that dolomite groundwater resources are finite, the technical and surface-water emphasis of many experienced consultants, etc) interfere with the formation of new organisational structures. New structures require considerable inputs of time, energy and "social capital" before they become self-sustaining and completely replace older modes of behaviour. Furthermore, it is precisely the potentially powerful organisational attributes of the two major appropriators (the irrigating farmers and DWS / the municipality) that makes them circle each other warily, each cognizant of the potential of the other to impose burdensome legal and administrative costs (discussed later in this chapter).

## 6.5. Analysis

Section 6.4 has discussed the attributes of appropriators at Grootfontein. The participants in the Grootfontein hydro-social system appear to have few or none of the features that would "enhance the likelihood of appropriators organizing themselves to try to avoid the social losses associated with open access or rules that are not yet working well." (Ostrom, 2005: 244). The current situation at Grootfontein empirically confirms this finding - falling groundwater levels threaten the sustainability of the water supply to Mahikeng as well as continued irrigation. Most interviewees acknowledged the undesirability of the current situation, yet each was acting logically with the information and choices available to him or her.

The current state of the Grootfontein hydro-social system can be described as a sub-optimal equilibrium, in which none of the participants are likely to make any changes to their behaviour that might precipitate a significant change to another state[87]. These equilibria are known as Nash equilibria, a term used originally in game theory to describe a stable situation in which each participant or "player", acting alone and having information about the strategies of the other players, sees no advantage in changing their behavior or strategy even though the situation is clearly sub-optimal as a whole (Nash, 1950; Nasar, 1998). Each player in a Nash equilibrium is acting logically given the available information. This is despite the fact that the situation as a whole, or in its entirety, is clearly not in the long-term interests of any of the players[88]. For such an equilibrium to change, one or more of the players needs to change their behaviour or "make a move" that will precipitate changes in the behaviour of the other players and lead to a new equilibrium forming. The stability of this (sub-optimal) Nash equilibrium at Grootfontein, despite warnings of hydrogeological problems, growing expense and calls for change, is shown by the fact that nothing substantial has changed in management terms at Grootfontein for more than a quarter century – i.e. since the groundwater levels first started to drop severely in the early 1980s.

For the irrigating farmers to unilaterally change their groundwater abstraction behaviour – i.e. reduce their pumping rates – would lead to a loss of income, whilst the water saved, in their view, would simply be abstracted by DWS and the municipality. More than one irrigating farmer said that they needed to take the water while it was available, or "ride the horse while it's there". For an irrigating farmer, voluntarily reducing groundwater abstractions is simply to forgo one's share of the Grootfontein groundwater that is left. In fact, as the "race to the pumps" intensifies with falling water levels, the logical option is to abstract still greater amounts with increasingly lower marginal returns on the

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[87] This refers to the Grootfontein hydro-social system as a whole, in the last few decades and in the forseeable future. It does not mean that the groundwater or the natural environment is in equilibrium, nor should the word "equilibrium" imply a natural or desirable state.

[88] Sylvia Nasar's award-winning biography of Nash states: "… Nash equilibria – defined as each player's following his best strategy assuming that the other players will follow their best strategy – aren't necessarily the best solution from the vantage point of the group of players" (Nasar, 1998:118). Nasar notes that this undermines Adam Smith's famous "Invisible Hand" metaphor, since individuals pursuing their private interests do not necessarily promote the best interests of the collective (Nasar, 1998:119).

irrigation water (a classic tragedy of the commons situation).

The other option open to the farmers is to individually or collectively petition either the municipality or DWS (some farmers do not draw a clear distinction between the two, and assume that they are working closely together) to both reduce abstractions for the town of Mahikeng, and also to enforce some kind of aquifer-wide abstraction limits for all players. However, farmers have reported that they have tried to engage with DWS or with the municipality without success[89]. The major organisations representing commercial farmers feel that the state is opposed to them, and will act against their interests. The withdrawal of support for WUAs and the lack of viable alternatives closed off a possible channel for engagement. As described above, the current forums or meetings (the SOF and the CMF) are seen as talking shops where little of importance gets decided. Many irrigating farmers view engagement with the state (DWS or the municipalities) as time-consuming, expensive and fruitless.

Similarly, and in the short to medium term at least, DWS acts logically in continuing to abstract at Grootfontein while it can, whilst relying more and more on the Molopo Eye source. Abstracting from Grootfontein is a continuation of existing practice and procedures, and does not impose an obvious short-term cost. In contrast, changing the situation has potential dangers (e.g. what if it harms the water supply to Mahikeng? What if farmers don't hold up their end of the bargain?). Taking action, unless sanctioned by very senior DWS staff, transfers the problem from one borne by the whole organisation to one that is vested in a particular individual (or small group) - exposing that individual to potential sanction (see below). For DWS to tackle the declining groundwater levels at Grootfontein (i.e. to make the first move to break the prevailing Nash equilibrium) two possible courses of action present themselves – described here as a "soft" or negotiated option and a "hard" or legal option (see Section 6.1).

The negotiated or soft option would be to engage with the Grootfontein irrigating farmers in an effective forum with the aim of persuading the farmers to reduce their abstractions significantly, perhaps by pointing out that it is in no-one's interests to continue in the current mode, and sharing what is known about groundwater abstraction volumes. This option might require DWS to offer to reduce their abstractions supplying the Mafikeng Water Treatment Plant in a reciprocal way. DWS would also need to make

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[89] DWS and the municipalities appear similarly frustrated with the irrigating farmers.

their abstraction volumes available to the general public, or at least to the irrigating farmers, to prove that they are doing what they say. As discussed above, DWS has not done this to date and the abstraction data is not easily available, even to DWS hydrogeologists. DWS would also need some way of verifying that the farmers were also reducing their abstractions pro-rata, either by analysing satellite data (not very accurate), verifying the electricity consumption of each irrigator (more accurate, but requiring much groundwork) or by installing flow meters on irrigating boreholes (most accurate, but expensive and requiring substantial cooperation of the farmers).

This "soft" option would also need to overcome years of mistrust between the two main participants, including the fallout from the non-approval of the WUAs and the lack of trust and reciprocity between the mainly white farmers and the mainly black DWS. A successful soft option would require an individual or group at DWS with considerable resources of time, energy and funds, and the trust and firm backing of very senior staff. There would be no guarantee of success, and few obvious incentives to take on the challenge. Other individuals within DWS or other government departments might oppose such negotiations, perhaps arguing that negotiating with illegal abstractors was inappropriate, or that the Catchment Management Forums (CMFs) should tackle the problem. At the same time, the incentives not to "rock the boat" would remain very high. Currently, there is no such individual or group of individuals at DWS in a position to initiate this kind of strategy. Over the years DWS employees with responsibility for enforcing abstraction licenses have been unsuccessful in this task, and more than one interviewee commented on the reluctance of these employees to engage with the issue:

> "No [name withheld] is just part of the problem, I must be honest, [name withheld], [name withheld], they just part of the problem. [Name withheld] is somebody who we reported a lot of irregularities to, and he's the one that should be handling this, irrigation water use, um, damaging *vleilands* and all these things, and nothing happens. It doesn't even help mentioning it to [name withheld], he's not doing anything, nothing, nothing at all…he doesn't want to make waves now, he just wants to try to live it out. But [name withheld] is, is worthless in this whole process. " (Source: farmer, May 2015).

Another interviewee stated:

> And so what the hell is the use of the association? Like I asked you yesterday, we, in an open meeting with [DWS staff member, name and position withheld] giving you an undertaking that from our side as farmers we'll restrict use and stick to the law, with an undertaking from their side that he would reign in the municipality so that they stick to the law as well. Because it's a quid pro quo… And I asked you yesterday could you find any evidence of any reprimand, any letter, going from the Province, from Water Affairs, towards the municipality, to say guys fix up your infrastructure, stop wasting water, before we, we keep on destroying the primary sources? And that's the short of it all. What the hell do you have an association for? And you go through huge sub-committee meetings, building up to a structure, a whole pyramid you know, getting up with reasonable suggestions, and which may either just be ignored or accepted and nothing comes of it." (Source: farmer, May 2015).

Another stated:

> "No there's no will, there's no will, the one or two [DWS] guys there who has done the work at this stage I don't think they wanna get involved in something, they just wanna protect their pension, that's the way I see it, go with the flow and protect your pension. That's it." (Source: farmer, July 2015).

Another difficulty with a "soft" negotiated option would be the requirement to involve the other participant organisations. Whilst not themselves directly abstracting groundwater from Grootfontein, the district and local municipalities, Sedibeng Water Board, or the miscellaneous smaller stakeholders would need to be consulted and might well raise objections to any process or final settlement (see Section 3.5 for a discussion of rising complexities of multi-participant processes). Even if all parties agreed on the best way to resolve the over-abstraction problem at Grootfontein, broader participation would slow down the process – particularly if substantial disagreement over technical or hydrogeological factors such as aquifer boundary locations arose[90].

If the soft option of negotiation and mutual reduction of abstractions seems lengthy, difficult, expensive, and fraught with problems of agency, responsibility and the risk of failure, then the "hard" or legal option begins to look more attractive. This option would simply involve verifying existing irrigation abstractions against licensed quantities held in DWA's WARMS database, and sanctioning farmers found to be in breach of their license conditions. It would require a means of verifying abstraction quantities (discussed above), after which the whole problem could be left to law enforcement. Irrigating farmers would at the very least be forced to the negotiating table, and it might even be possible to require them to monitor their own abstractions accurately and submit this data regularly to DWS. If, after taking this "hard" course of action, irrigation abstractions were still deemed too high to allow aquifer recovery, licensed quantities could be reduced in a new round of legal enforcement, based on sound hydrogeological advice.

Like the soft option, this "hard" option would require a champion or driving force within DWS, which has inherent problems as discussed above. The main problem with the hard option, however, is that the farmers would oppose DWS on legal grounds. DWS would need to address the thorny issue of "old-order rights", or the recognition of groundwater abstraction rights existing before the 1998 National Water Act. DWS is unwilling to take on the risk of being challenged in court on the technical verification of licensed irrigation quantities, or on the legality of rescinding old-order rights leading to potential loss of livelihood for irrigating farmers (Rossouw, 2016). Interviewees commented on the risks to DWS of embarking on unsuccessful legal action:

> "Ja it would be easy if you confront the guy and say but your water use unauthorised please stop, and they do stop… But most of them turn to legal aid and it turns into legal battles, which can last for years… I mean I have a couple of - on the verification we did - we have a couple of them that declared disputes. Now the first thing we must do is to train the legal advisors - the attorneys and advocates - this is the prescripts of the Act… But we must work within that. Because they

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[90] At Steenkoppies, disagreements over the size and technical functioning of the groundwater compartment was a feature of the wider dispute between competing water users in that aquifer and has complicated its resolution – see Section 4.5.3.

> don't understand the Water legislation in the first instance." (Source: DWS employee, May 2015).

Another DWS employee stated:

> "That's the worst case scenario where then they will go to court and all those things. So now then it means that you need to follow all the due processes to make sure that all the ticks are done. Because remember if, if it happens that the Department loses that case it sets a precedent, so we don't want that." (Source: DWS employee, July 2015).

Whilst the "hard" legal option seems attractive, it is unlikely given the current makeup of DWS and their (reasonable) aversion to legal action[91]. Many believe that Mahikeng can do without Grootfontein and rely instead on the Molopo Eye and on the upgraded Mmabatho Treatment Works at the Setumo Dam, and this also makes the hard legal option seem unnecessary – why risk losing in court, when there are alternative water sources? Addressing Grootfontein problems with legal action is simply not worth the risk of failure. It is also contrary to the principles of IWRM and the spirit of the National Water Act, in which mutual participation and negotiation are favoured over "top-down" unilateral action of this nature, and might be opposed internally at DWS for these reasons. Thus the sub-optimal Nash equilibrium at Grootfontein continues.

## 6.6. Possible outcomes at Grootfontein

If the Grootfontein hydro-social system is in a state of sub-optimal equilibrium, and under current institutional circumstances this equilibrium is stable, what might precipitate a change in the management of the Grootfontein aquifer? Whilst the social system might be in equilibrium, the groundwater levels are falling and the physical hydrogeology may initiate an "end-game". The Grootfontein hydro-social system is socially stable but hydrogeologically unstable - surely this will force better groundwater management?

Unfortunately, it is most likely that the DWS abstractions at Grootfontein will fail before the irrigation abstractions fail. This is because the farmers can deepen their boreholes or drill new boreholes more easily than DWS, and collectively have a much wider area of land to choose from. Some farmers have already deepened boreholes. Already, in 2015,

[91] Van Koppen and Schreiner (2014b) also mention the reluctance of the Department of Water and Sanitation to undertake legal action.

one farmer stated that when he ran his irrigation boreholes he thought that this reduced the pumping rates of the DWS boreholes. DWS would be more likely to abandon the Grootfontein site altogether, or substantially reduce their abstractions, and rely on other sources (Molopo Eye, the Setumo Dam, the rumoured groundwater explorations further afield, and possibly even a Vaal pipeline). The DWS boreholes have already been in decline for several years, with just three remaining and yields dropping, without DWS taking substantial action. As discussed, there is also a persistent collective belief that major dolomite groundwater sources are inherently finite - DWS concentrates on new sources, rather than managing existing dolomite groundwater sources.

This scenario would leave the farmers as the sole major groundwater abstractors of Grootfontein groundwater, a situation which ironically might usher in a new era of improved groundwater management because the irrigators, as a smaller and relatively more homogeneous group internally possessing more of Ostrom's appropriator attributes, might be in a position to reach an informal internal settlement similar to the Steenkoppies farmers. However, this new era would always be subject to the "threat" of DWS returning to claim its water as groundwater levels recovered, and the irrigating farmers, aware of this possibility, might continue to over-pump. Agricultural investments at Grootfontein are, after all, not as large as those at Steenkoppies, and the discount rate at Grootfontein is relatively high. Furthermore, irrigating farmers at Grootfontein are not as homogeneous a group as is often assumed, nor do they have a track record of successful groundwater management in the 1980s and early 1990s when they had closer ties with state organisations. Failure of the remaining DWS boreholes at Grootfontein is unlikely therefore to effect the required management change.

A more daunting scenario, possibly triggering the "hard" option discussed above, would be a prolonged drought and the consequent failure or partial failure of the Molopo Eye groundwater source. A prolonged failure of Molopo Eye could in turn lead to problems with the Setumo Dam source, as runoff and leakage to the dam dwindled and the lack of a clean groundwater source of water to dilute the poor-quality dam water intensified water treatment challenges[92]. As discussed, a pipeline from the Vaal River system is

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92 Evidence from elsewhere in South Africa shows that such a "tipping point" could occur quite rapidly – water service authorities are not structurally configured to deal with long-term low-amplitude risks to primary raw water sources. For example, despite forewarning the town of Sedgefield completely ran out of water during the drought of 2009 when the level of the Karatara River dropped below the town's intake pipe. The crisis involved tankering water from elsewhere,

unlikely, and in any case would take too long to build. Under these circumstances, anger at the loss of the Grootfontein public supply sources and the potentially huge storage in the Grootfontein aquifer (see Section 5.5) might trigger action to forcibly reduce irrigation abstractions. But this would not solve the drought-induced crisis for Mahikeng, as of course the Grootfontein aquifer would require considerable time and above-average rainfall to recover to useful levels – and time and rainfall would likely restore the Molopo Eye and the Setumo Dam's functioning too.

In a drought crisis, DWS or Mahikeng would need emergency sources of water that could be brought on-stream much more rapidly. The obvious sources would be another dolomite groundwater source (perhaps near Ottoshoop, or near the Wondergat), or closer to home by simply drilling boreholes around the Molopo Eye. Drilling at Molopo Eye could potentially yield a large source of high-quality groundwater that could be brought into production very quickly via the existing pipeline to the Mafikeng Water Treatment Plant. Those living near the Molopo Eye and the environmental lobby would oppose the drilling, but it would be difficult to stop if there was a water crisis in Mahikeng, the capital of the North West Province. Drilling around existing dolomite eyes or springs has already taken place at Lichtenburg, Grootfontein, Itsoseng, Dinokana and other locations nearby – leading to steadily declining water tables and the drying of the eyes / springs. A failure of the Molopo Eye during drought might renew focus on Grootfontein, but this is likely to be temporary since the Grootfontein aquifer cannot provide an immediate source of water in its current state. A harassed DWS, seeking rapid and effective solutions to a crisis, might instead concentrate on other potential water sources and leave Grootfontein alone. Drilling around the Molopo Eye in response to drought might only push the unsustainable management of Mahikeng's groundwater a few kilometres to the north and a couple of decades into the future.

#### *6.6.1. The most probable outcome*

In the medium term (say the next ten years) it is unlikely that the Grootfontein aquifer will recover. It is in the immediate interests of both groupings of major abstractors (the irrigating farmers, and DWS / the municipality) to continue pumping as usual, and the undesirable Nash equilibrium will persist. This deprives Mahikeng of the emergency

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followed by the installation of an expensive desalination plant on the beach. Cheaper groundwater-based solutions proposed at the time were passed over.

backup source of good quality water that a "full" Grootfontein aquifer represents. In turn, it also threatens nearby groundwater sources such as the groundwater compartments around the Molopo Eye or the Wondergat, obvious targets for groundwater exploration if Molopo Eye fails. Apart from the environmental disbenefits of over-abstracting one groundwater source after another, this "business as usual" scenario has several other implications, as follows:

Firstly, towns need to be able to guarantee domestic water supplies of acceptable quality and cost in order to improve the livelihoods of residents. Rollout of domestic water connections in greater Mahikeng (e.g. at Rooigrond), as well as economic investment and growth, require reliable municipal bulk water supplies. Uncertainty and risk of water supply failure is priced into the economic activities and strategies of individuals and businesses in Mahikeng, increasing overhead costs and harming economic activity and confidence[93]. Secondly, there is a reputational and political risk to DWS and to the district municipality (as the water service authority) if problems with water supplies in Mahikeng arise. Thirdly, trust and reciprocity (sometimes known as "social capital"), already lacking in the Grootfontein hydro-social system, will further erode. Fourthly, the financial cost of an emergency augmentation of Mahikeng's water supply would be considerable, even without including a pipeline to a more distant source. Finally, problems with Mahikeng's water supply would be widely seen as a failure of groundwater, reinforcing in the public mind the idea that groundwater is inherently limited and unreliable, and presenting surface water as superior. This in turn would contribute to the sub-optimal use of South Africa's groundwater resources more generally (DWS, 2010a), with all of the inefficiency and expense that this implies.

### *6.6.2. The best-case scenario*

The best-case scenario would of course be a reduction in groundwater abstraction from the Grootfontein aquifer leading to a recovery of groundwater levels to near-surface, perhaps even a revival of the Grootfontein Eye. The lower abstraction volumes would be partly offset by lower pumping costs (through lower pumping rates and reduced

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93 O&M related difficulties with the municipal water supply to the city of Grahamstown in the Eastern Cape over the last few years have disrupted activities at Rhodes University and led to speculation about relocating the town's National Arts Festival (Dispatch, 2016; and Lankester, 2016). Better-off citizens, organisations and businesses insulate themselves against water supply uncertainty with on-site water storage and small reverse-osmosis systems.

pumping heads), and the considerable prize of a large emergency source of good quality water that could be temporarily over-abstracted if other sources failed. The other negative implications or disbenefits of the "business as usual" scenario discussed above would also be removed.

This best-case scenario would of course require one of the major abstractors to initiate substantial change in order to break the prevailing sub-optimal Nash equilibrium. That party is unlikely to be the irrigating farmers, for reasons discussed above, and would therefore have to be DWS / the municipality who "make the first move" (they are also arguably legally obliged to do so as custodians of the resource). Since legal action or the "hard" option has hidden costs, risks and difficulties, some variation of the "soft" option discussed above would be best (and more aligned with current legislation and policy).

An effective forum involving senior DWS staff members would need to be convened to provide the basis for discussions[94]. The starting point of the discussions would need to be agreement that it is in no-one's interest for the current over-abstraction to continue, and that mutual reductions in abstraction are needed. An agreed conceptual hydrogeological model would be required, along with transparent, verifiable estimates of current abstraction volumes by all parties. The current official WARMS license allocations would need to be presented and discussed, and the issue of illegal abstraction dealt with. The illegal abstractions are a potentially messy issue (as discussed) involving "free riders", and present a considerable challenge. The issue of assessing abstraction volumes would also need agreement – are satellites to be relied on, or are more direct means such as meters needed? A roadmap towards progress would need to be agreed, and the success (or otherwise) of early "milestones" being reached would be critical to the viability of the plan.

This "best-case" scenario seems unlikely, but there are nevertheless several things that are in its favour. The first of these is that all participants interviewed said that they would be prepared to discuss a collective "way forward". The situation has not yet been reached where participants are not prepared to speak to each other, or have such mutually negative views that basic interactions are jeopardised. The second silver lining is that many irrigating farmers need a solution to the problem more than DWS / the

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94 A complicating factor would be that DWS senior management has a high turnover, with some key senior staff acting in their posts. This makes continuity more difficult, particularly where long-term plans for groundwater may be involved.

municipality does, in the short run in any case, and this gives DWS a potential negotiating advantage. DWS / the municipality can do without Grootfontein for the time being, even though this undoubtedly imposes long-term costs and risks. The farmers find falling groundwater levels expensive, and must consider diversifying their activities and incomes away from irrigation. Lack of assured irrigation potential also impacts land values. Many farmers would also prefer to obey the law regarding groundwater abstractions – not only out of a general desire to abide by the law, but also because they know that this shepherds the resource, and also because abstraction restrictions were first imposed in the area decades ago (under the subterranean water control areas) and are already an existing (if not always respected) social institution. As one farmer put it:

> "The reason I stay legal is because I was on the water agri-committee of AgriSA for all those years and I realized that, sometime, look the gears of the government turn, but really slowly, and under the black government unbelievably slowly, but they turn. One day there'll be a follow-up. One day these guys [illegal irrigators] will be trapped, I'm sure of that. I just hope it's before the water's totally exploited and nothing's left." (Source: farmer, August 2015).

Talking about an area of groundwater irrigation near Lichtenburg (i.e. not Grootfontein), where DWS had apparently clamped down on illegal groundwater abstractions, one Grootfontein farmer commented:

> "And Water Affairs has gone out and it's taken away their water licenses and reduced them, and some of those areas were closed up, some of those guys stopped irrigating on… and they pulled back to what they're entitled to. Which is not only good for the public sector, it's good for all of us." (Source: farmer, May 2015).

Another positive factor in favour of a "best-case" outcome is the issue of financial returns to irrigation groundwater withdrawals. This factor can be divided into two sub-issues. The first sub-issue is that choice of crop type plays a major part in the volume of irrigation water required. At present few farmers appear to choose crops specifically because they use less water – in fact quite the opposite – some farmers grow relatively thirsty crops such as maize, wheat or cotton because they are convenient and easily sold. It is likely that relatively small incentives would be needed to persuade farmers to consider shifting to crops requiring less water for a similar return. Talking of the common choice to grow maize in the winter dry season, when it requires irrigation, one experienced former DWS employee commented:

> "It [maize] is a very low value crop, now if you use expensive electricity, and the water should be also expensive. Then it will become a no-no. You will not irrigate it… So all I can see that they, can produce, they should produce there is something like pecan nuts that is a high protein crop using very little water, and this time of the year the tree is resting." (Source: former DWS employee, June 2015).

The second sub-issue is that there are diminishing marginal returns to groundwater irrigation at Grootfontein. In other words, the extra income generated by additional irrigation falls significantly and the incentives to use groundwater beyond a certain level therefore diminish. One farmer commented that growing winter (i.e. dry season) maize was hardly worth the time, work and extra expenditure on electricity:

> "The winter irrigation nowadays, if you look at the cost of electricity, the cost of the water, the cost of the, the upward produce, the prices of those primary products that we produce, it doesn't always make sense, economical sense, that we keep on producing a winter crop as well. And it's never gonna be absolute that you can do this, but out of a practical perspective let us go in, see what measures in technology we can take, and see if we cannot produce one or two tonnes of maize or whatever produce you do in summer time more, by limiting your winter extraction, so that if your net effect in the end is the same, why have all the wear and tear on your equipment, the wear and tear on your pivots, the practical wastage of water almost, alright, if we could have applied it better, reduction of risk." (Source: farmer, May 2015).

Another Grootfontein farmer explained it thus:

> "What we do now, say you should fertilise to harvest say twelve tons of mielies and irrigate, but I plant, I fertilise for seven tons, and I irrigate only when I need to, when I see it starting to get dry, and I do a lot better, um, with that method, than a guy who irrigates full-on. Look, if I fertilise for seven tons, I can easily harvest nine tons, it happened again this year, but a guy who fertilizes for twelve tons

struggles to get fourteen tons, you know you struggle to, at a certain stage you get a plateau…" (Source: farmer, July 2015).

These two sub-issues, taken together, illustrate that increasing irrigation does not necessarily increase farm incomes beyond a certain point. Rising electricity prices cause marginal returns to irrigation to fall further. Combined with a focus on switching to less water intensive crop types, and the possibility of more efficient irrigation systems or at least more efficient irrigation scheduling, this implies an opportunity to significantly reduce irrigation volumes without greatly impacting the livelihoods of commercial farmers. More efficient irrigation methods such as drip irrigation are not currently found at Grootfontein, and it is also quite common to see irrigation taking place around mid-day when evaporation is highest.

Whilst a business-as-usual scenario is therefore most likely, it is nevertheless possible that certain extrinsic factors supporting irrigation control could be harnessed to assist in a "soft" solution to the Grootfontein over-abstraction problem. Any such settlement, particularly if it resulted in clear and visible recovery of the Grootfontein aquifer (the best proof of this would be a flowing Grootfontein Eye), could of course be used as a model for similar situations elsewhere in South Africa, and the skills and experience gained would most likely make future problems successively easier to solve. As discussed, a host of other positive spin-offs or externalities would also be created in the process.

## 6.7. Implications for the Mahikeng area

The Grootfontein aquifer is not being managed sustainably, as groundwater levels have fallen and boreholes have failed. This has impacted the environment – for example the flow of the Grootfontein Eye and the flow in the Droë Molopo River have both ceased, and wetlands at Grootfontein have dried up. The increasing use of Molopo Eye water by Mahikeng has reduced flows in the Molopo River and associated environmental functioning. The problem also impacts the groundwater users. There are immediate disbenefits to groundwater users associated with the lower availability of groundwater. These include the costs of diversifying away from groundwater at Grootfontein by irrigating farmers and by DWS, as well as the potentially very high cost of losing the Grootfontein aquifer as a potential emergency water source or as "drought insurance".

Less tangible disbenefits include a deteriorating relationship between the commercial agriculture sector and state organs such as the Department of Water and Sanitation, as well as tensions between organs of state in the different spheres of government. Concerns over reduced assurance of municipal water supplies may also deter commercial investments in Mahikeng and surrounds, or at least cause this uncertainty to be priced into these activities. A less-certain municipal water supply and the general sense that environmental issues are being neglected also have a corrosive effect on society more broadly, contributing to pessimism, finger-pointing, anger and cynicism. The collective failure to manage the Grootfontein aquifer has implications that are far wider than the local impact on a few farmers or on a municipal groundwater source that is considered superfluous. Just as a successful management outcome at Grootfontein would ease the management task in similar situations elsewhere by providing an example and a template, so the failure to manage groundwater at Grootfontein makes successful groundwater management elsewhere less likely. After all, Grootfontein is an aquifer with comprehensive data holdings, proximity to a major town with a DWS regional office, obvious long-term importance to municipal water supply, generally excellent water quality, and participants who say they are willing to cooperate. If management cannot succeed at Grootfontein, the outlook for more complex environments is bleak.

The Grootfontein story of poor management has sobering implications for water and environmental management in South Africa more generally. Groundwater management is considered to be in a poor state country-wide (Pietersen et al., 2011; Knuppe, 2011) with much potential for high-value municipal use of groundwater neglected. By default, the use of high quality groundwater for relatively low value applications (such as irrigating maize) is likely to continue. Surface water is considered to be a superior source of municipal water by many elected officials and decision-makers, but its costs will rise as demand grows and prices of inputs such as electricity and treatment costs get higher. This in turn feeds into a growing discourse of water scarcity in South Africa, and a mounting voice for a water allocation reform (WAR) lobby who consider the problem to be mainly one of allocation under zero-sum conditions. Considerable resources of (badly utilised or poorly managed) groundwater in fact exist, and the challenge is mainly one of management. Concerns about the assurance of water supply in South Africa are growing, and are beginning to impose similar costs to those seen in Mahikeng, only country-wide (de Villiers and de Wit, 2010).

Old management structures governing groundwater abstraction such as irrigation boards and subterranean water control areas fell under the old (1956) Water Act (see Section 3.5). These structures were ineffective in managing groundwater sustainably – as shown in the declining groundwater levels at Grootfontein after the early 1980s. The old water laws were also a component of the apartheid regime that deliberately benefited a small minority at the expense of the majority, and were unsustainable in this sense too. The National Water Act of 1998 sought to rectify both the environmental and the social ills of the old apartheid systems, and in doing so contribute to a wider process of national reform, growth and opportunity for all. Failure to manage important hydraulic assets such as the Grootfontein aquifer contributes, by default, to a partial continuation of old and unfair patterns of water allocation, with all of the implied knock-on effects. Old structures have been removed (*de jure* if not *de facto*), but new and better structures resist implementation. The costs of this, both immediately and tangibly to the participants in the Grootfontein hydro-social system, and externalised more widely to the country as a whole, are very considerable.

## 6.8. Conclusions

Social and institutional factors have a very considerable influence on the piezometric levels of the Grootfontein aquifer. The hydrogeology is important, but the institutions in play may ultimately determine outcomes. These institutions also interact with each other, and with aspects of the hydrogeology, leading to a complex and interdependent situation. For this reason the aquifer has been characterised as a "hydro-social system". Over the years little time and effort has been directed at the social components of the Grootfontein aquifer. In contrast there is a high level of understanding of the physical characteristics of the Grootfontein aquifer, and large investments have been made in understanding it hydrogeologically. This contradiction may be related to a tendency to separate disciplines, particularly those either side of the watershed dividing the sciences and the social sciences. Disciplines follow their own paths, with a tendency towards internal debate or refinement rather than "interdisciplinary" engagement[95]. A causal or fundamental effect of hydrogeological (and other scientific) facts on policy and outcomes is also sometimes assumed - when scientific recommendations do not become policy a "communication problem" is often inferred. The literature is full of appeals for hydrogeologists to learn to "communicate better" (e.g. Jarvis, 2008). Policy is in fact driven by institutional interactions, both within and between organisations. Objective

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[95] Or even in the worst cases what Schwartz (2013) describes as "zombie science"; scientific work that is timid and only a minor refinement of work that has already been done.

scientific fact is only one input into this complex process, particularly in an environment of ambivalence towards skills (Von Holdt, 2010).

The answer to the main research question of this study, "What is necessary for successful management of the Grootfontein aquifer?", therefore begins to crystallise around a collection of institutions and institution-determined interactions between participants. The basic conditions would be the general recognition that there is a problem with the Grootfontein aquifer, acknowledgement that it is both a valuable and a sustainable resource, basic agreement regarding the "way forward" (i.e. abstractions need to be reduced), the participation of all relevant participants in a forum designed and empowered to address the problem, and the legal backing or mandate to make and implement the necessary decisions as well as to deal with defectors and free-riders (Ostrom's "holdouts"). On the face of it, these conditions are not onerous. In practice, however, when the participants are examined using Ostrom's appropriator attributes, it becomes clear that these conditions are unlikely to be met without some kind of external event or force to break the current undesirable and sub-optimal equilibrium. Even a drought crisis is unlikely to do this, although it may temporarily focus attention and energy on Grootfontein.

# 7. Discussion and conclusions

As described, the participants in the Grootfontein hydro-social system have not formed an effective forum or group to begin collective action towards addressing the over-abstraction problem. This is due to problems of commitment, coordination and cooperation within participant groups, as well as between participant groups, in a complex set of institutional interactions leading to poor management outcomes. A major contributing factor is the failure to approve, re-constitute or replace the Water User Associations in the area. It is these social interactions or institutions, rather than any hydrogeological factor, that appear to be the over-riding reason for the declining groundwater levels at Grootfontein.

## 7.1. Discussion of the sub-questions

The primary research question of this study is "What is necessary for successful management of the Grootfontein aquifer?" This research question is underpinned by a series of sub-questions (introduced in Section 6.2) that contextualise and assist in answering the research question. The sub-questions relating to the main research question are as follows:

- Is there sufficient technical or hydrogeological data to start making management decisions at Grootfontein?
- Is there sufficient knowledge or data on the institutional conditions pertaining to the Grootfontein hydro-social system in order to make management decisions?
- Of the participants in the hydro-social system, who should initiate or lead the management actions, and what might the first steps be?
- What sort of forum for interaction between participants is necessary, and which participants should attend?
- What are the key institutional hurdles or barriers to progress, and what can be done about them?
- Can these conditions conceivably be met – in other words, is it likely that progress can be made in managing the Grootfontein groundwater, given the existing institutional framework?

This research suggests answers to these sub-questions. The answer to the first sub-question is "yes". Technical and hydrogeological knowledge of Grootfontein is a sufficient basis for management, as described in Section 5.11. Furthermore, South African water laws and policies provide an official mandate and set of sanctions for misuse, based on a scientific understanding of the water resource.

The answer to the second sub-question, regarding adequate knowledge of the institutional conditions at Grootfontein, is "no". As discussed, many of the irrigating farmers do not distinguish between DWS and the two municipalities, seeing them as closely related or even as the same entity. The municipalities focus on shorter-term issues of functioning and survival, and DWS has internal problems of agency, accountability and poor communication. Sedibeng Water Board has been newly appointed (although they employ experienced staff from the previous water board) and are working mainly to upgrade existing services such as the Mmabatho Water Treatment Plant at the Setumo Dam. Each participant has knowledge of a small piece of the institutional jigsaw, but this knowledge is not coordinated, mitigating against resolution of institutional problems.

The third sub-question, relating to which participant should lead a new management effort, was discussed in Section 6.6.2 – it should be the Department of Water and Sanitation. DWS is legally obliged and empowered to act to rectify the Grootfontein situation. DWS has advantages over the other major abstractor-participant (the irrigating farmers) such as possessing estimates of their abstraction data (the farmers do not know what DWS is abstracting). DWS also needs the Grootfontein water less (in the short term) than the farmers do, incentivising the farmers to cooperate to reach a "deal", and giving DWS a stronger bargaining hand. DWS is also able to officially constitute and fund a forum for discussion, and can persuade or compel other participants to attend a forum (e.g. the municipalities or other government departments). Finally, DWS has the threat of legal action and expropriation (even if they are averse to using it)[96].

The fourth sub-question relates to the forum for discussion that is required. The Water User Associations (WUAs) were initially envisaged in this role, but were never constituted or adequately replaced. The meetings that are currently held in Mahikeng (the Stakeholder Operating Forum and the Molopo Catchment Forum) are poorly attended (i.e. key participants do not attend these meetings – see Section 6.4.4) and are perceived by the farmers (in particular) as ineffective. Some DWS staff members look forward to

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[96] This argument does not absolve the irrigators and other participants of responsibility for the situation.

the Catchment Management Agencies (CMAs) and see these as the correct organisations for local water management, further undermining existing efforts. Any successful forum would need all participants to attend, and crucially would need to have the power to make real changes to avoid being considered a "talking shop", whilst real power lay elsewhere. Reductions in abstractions would likely be an iterative process between the major abstractors, requiring abstraction data from both sides - the forum would need to be able to obtain this data. Finally, the forum would need to have the ability to penalize defectors and "free riders" who might otherwise stall the process – implying a legal mandate.

The fifth sub-question refers to the main institutional barriers to progress. Participants currently do not cooperate or share data. For example, there is suspicion between some farmers related to perceived illegal abstractions. Data on abstractions at Grootfontein, whilst collected by DWS, is not easily available within DWS. Different departments within the district municipality do not collaborate closely – some may not cooperate at all. There is no clear view on the successor to the WUAs, beyond that the CMAs will now be responsible for the local issues WUAs were mandated to address. Furthermore there is no single dominant definition of the problem at Grootfontein, or even a common understanding of the importance and potential of the aquifer. Consultants have different views on priority water supply issues, with some favouring surface water whilst others call for new groundwater studies. Many participants consider the dolomite groundwater resources to be inevitably in decline, linked in some cases to a hazy idea of groundwater occurrence and flow. Some farmers have a bleak view of the future of commercial irrigated agriculture, for various reasons, and place a high discount rate on future groundwater supplies. There are also serious problems with lack of trust and communication between participants. In the absence of a clear definition of the problem, and a "roadmap" towards its resolution, it is difficult to establish the terms on which an agreement could be reached. Reaching wider agreement on basic hydrogeological functioning, and the envelope of possibilities for action, would be an important first step for the kind of forum discussed above.

The final sub-question, related to the likely future outcomes, is discussed in Section 6.6.1. It seems most likely that the current (undesirable) Nash equilibrium will persist, in the absence of the resources (authority, time, energy, collaboration and commitment) that one participant (most likely DWS) will need to break it.

## 7.2. The main hypothesis and sub-hypotheses

The previous section discussed the sub-questions as they relate to the main research question. The answers that were advanced for the sub-questions support the view that the Grootfontein aquifer is best understood as a "hydro-social system" at Nash equilibrium (see Section 6.5), rather than as a physical aquifer, or as a series of policy choices. Social institutions rather than physical constraints may predominantly control groundwater conditions such as water levels, although the physical hydrogeology of Grootfontein does of course constitute an "envelope" of management possibilities. The likely long-term sustainable yield of the aquifer is between 13 and 30 ML/day (about 4.7 and 11 $Mm^3/a$), and this cannot be changed (see Section 5.10).

To study the hydrogeology of Grootfontein on its own, particularly with respect to practical issues such as sustainable yields and maintenance of good water quality, is to implicitly assume that the hydrogeological findings will sooner or later inform management policy. The alternative is to argue that such scientific research should be done without explicit regard for social outcomes, an argument that many research-funding organisations in South Africa reject[97]. The disconnect between the hydrogeological understanding and consequent management recommendations at Grootfontein, and the actual observed situation, problematises the basic rationale for hydrogeological research. Yet, some hydrogeological researchers still consider the *application* of technical research – its traction or incorporation into policy – to be a matter outside of their expertise and holding little interest.

The links between evidence-based scientific research and public policy cannot be taken for granted[98] and hydrogeologists require skills in institutional analysis (which includes the study of policy). The alternative is that the institutional context is determined without hydrogeologists clearly understanding its dynamics, and research recommendations failing or prospering due to poorly understood forces. Hydrogeologists have to take a place in discussing institutional analysis and policy, alongside other technical disciplines

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97 The Water Research Commission, for example, requires applicants for funding to explicitly demonstrate the social value and capacity building impact of proposed hydrological research.

98 The ideal of widely-accepted, politically neutral scientific findings that are linked to policy may even be in decline – complex environmental debates spark demands for better "proof" or more "balance", especially where established or commerical interests are at stake (Oreskes, 2004).

such as economics, law[99], and public health, which already incorporate institutional understanding and know that the "technical" is inseparable from its institutional context.

Many hydrogeological reports still carry recommendations starting with the phrase "The municipality should…" or "The Department of Water Affairs must…" without at the same time demonstrating a supporting institutional understanding or commenting on the likelihood of such recommendations gaining traction. In the worst cases, some hydrogeological research in South Africa might as well not have been done for all the impact it has had on the environment, on water supply security, or on the livelihoods of South Africans. This is not only demoralising, it potentially threatens the "social license" to conduct further research. The need to understand and more closely integrate the technical and the institutional has never been higher.

A set of sub-hypotheses, expanding on the primary hypothesis, includes the assertion that the technical and institutional contexts are not well integrated in contemporary research. It is rare to find a high-quality hydrogeological study as an integral part of a social or institutional study, or vice versa. A second sub-hypothesis is that technical and institutional issues influence each other, often in non-linear ways and over a variety of space- and time-scales. For example, modes of groundwater abstraction rooted in established land-use practices have clearly led to falling water levels at Grootfontein, which in turn influence the institutional strategies of participants such as diversifying away from irrigation on the part of farmers, or upgrading the Mmabatho Water Treatment Works at the Setumo Dam on the part of the state organisations. A third sub-hypothesis is that actual outcomes can be unpredictable or counter-intuitive, since they are the product of the complex hydro-social system. This is shown in the stalemate or Nash equilibrium at Grootfontein, in which the logical mode of action of each group of participants is to act against the collective or common long-run good. Decisions made half a century ago, such as drilling boreholes around the Lichtenburg Eye (Vegter, 1960)

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[99] For example, the legal profession recognises the fragile relationship between "technical" legal matters and wider society. As Chief Justice of the United States Warren E Burger noted in an address to the American Bar Association in 1970: "A sense of confidence in the courts is essential to maintain the fabric of ordered liberty for a free people and three things could destroy that confidence and do incalculable damage to society: that people come to believe that inefficiency and delay will drain even a just judgment of its value; that people who have long been exploited in the smaller transactions of daily life come to believe that courts cannot vindicate their legal rights from fraud and over-reaching; that people come to believe the law – in the larger sense – cannot fulfill its primary function to protect them and their families in their homes, at their work, and on the public streets."

to increase Lichtenburg's groundwater supply, have contributed to a collective understanding of dolomite groundwater resources as essentially finite. Their potential for long-term, reliable public water supplies in South Africa remains largely unknown.

## 7.3. Discussion of alternative hypotheses

The primary hypothesis of this thesis is that the Grootfontein aquifer is a hydro-social system and and understanding of both the technical and institutional aspects of the situation is required for progress in resolving problems. These aspects interact in complex ways, and have unexpected outcomes. However, this is not a widely held view in the Grootfontein area, even if it has been recognised by other researchers in South Africa (e.g. by Knuppe, 2011). Three alternative hypotheses are described below.

- The most common, if not often explicitly articulated, alternative hypothesis explaining Grootfontein's management problems is that not enough is known about the Grootfontein aquifer hydrogeologically, and that in any case it is (like all groundwater resources) unsuitable for domestic supply. This hypothesis can be called the "technical hypothesis". In this view, further hydrogeological studies are needed to underpin better management, and management problems essentially turn on points of hydrogeological understanding. This hypothesis has echoes in the various calls for better technical knowledge of the dolomites, and is implicitly supported by ongoing hydrogeological research.
- A second alternative hypothesis is that the state organisations collectively do not have the skills or "capacity" to tackle the over-abstraction problems at Grootfontein, particularly when one considers resistance from irrigating farmers and other legacy problems. State organisations such as DWS or the municipalities are in any case preoccupied with short-term issues and do not have the staff or structures to worry about long-term groundwater sustainability. This hypothesis can be called the "lack of capacity hypothesis", and essentially locates the state and its component organisations such as DWS at the centre of groundwater management, whilst partly absolving it of procedural failings by highlighting shortages of staff, funding, and other concrete essentials. A cruder variation of this hypothesis paints state organisations as essentially self-serving bureaucracies with little inclination or incentive to carry out legally mandated tasks. Advocates of this hypothesis tend to call for capacity building, training, better accountability systems, or for other changes to existing state organisations. This hypothesis, and

variations on it, is often the basis of interventions by international organisations and experts. It is also, as part of the "discourse of shortage", commonly articulated by state organisations in South Africa themselves.

- A third alternative hypothesis is that the optimum organisational and legal structure for effectively managing groundwater is lacking, and that a new organisation or group of organisations is needed to bring participants together, backed by good technical advice. This hypothesis is supported by the lack of the WUAs, and effective successor organisations. It can be called the "structure hypothesis". In this view, changes to the organisational structures, relationships and attributes in and around Mahikeng (such as the formation of new CMAs) are the key to positive change in the groundwater management. Proponents of this hypothesis discuss better structures, or seek an elusive perfect organisational formula for water management. DWS may be leaning more towards this hypothesis in its future plans for water governance in South Africa, involving disbanding the WUAs and fast-tracking the new CMAs (DWS, 2014a).

Whilst each of these hypotheses has merits, none of them on its own can explain the situation at Grootfontein. With respect to the "technical hypothesis", this research has discussed the large body of hydrogeological knowledge for Grootfontein, and argued that outstanding technical issues need not defer management, particularly adaptive management. Indeed, the process of adaptive management itself will help to answer outstanding technical questions, such as the exact response of water levels to abstraction and rainfall. The technical hypothesis is rooted in the historical notion of water management as essentially a series of technical challenges (the "hydraulic mission"), with the less tangible issues of implementation, equity, or sustainability seen as incidental or "political". South African hydrogeology, with its strong historical focus on mathematical models, is particularly susceptible.

It is true that "capacity" in state organisations is lacking in some respects, but the relatively modest amounts of funding, coordination and technical knowledge needed to begin adaptive management at Grootfontein suggest that something else is contributing to the stasis. DWS now has hydrogeologists at its offices in Hartbeespoort, Mahikeng and Pretoria. Funding and official sanction is available for local water management stakeholder meetings such as the Molopo Catchment Forum. If there is a capacity deficit in DWS and other state organisations then it is less about material issues such as staff, budgets and equipment, and more about internal procedures and chains of accountability of the sort discussed by Von Holdt (2010). Being more ephemeral or intangible in nature, as well as controversial, these deficits are much harder to fix, and less convenient to discuss, compared with more concrete issues. The ephemeral issues in any case tend to produce down-stream deficits in concrete fundamentals such as equipment, staffing levels or transport, and the latter is partly a symptom of the former. It is also worth remembering that many of the issues discussed by Von Holdt (2010) were not present to the same extent in the pre-1995 Department of Water Affairs, which still made little progress on groundwater management[100].

The "structure hypothesis" has the advantage of being difficult to disprove – after all, until all possible organisational combinations have been tried, or every new management theory implemented, how can it be shown they will not work? This is one of the factors behind the longevity of panaceas such as IWRM. However, as this thesis has shown, the relationships between organisations (or participants) are at least as important as the nature of the participants themselves. Any new organisation that might emerge (such as the new CMAs) will still face the existing institutional challenges and stumbling blocks, as well as adding to the overall complexity of the situation. The organisational reshuffles that have taken place in the South African water management landscape since the 1980s, with little improvement in groundwater management, further challenge the "structure hypothesis".

None of the three alternative hypotheses discussed above can completely explain the lack of groundwater management progress at Grootfontein. Yet they persist in various forms, partly because they are easier to summarise and are more palatable than the hypothesis advanced here. Each also benefits from established interests and other institutional underpinnings. At their worst, these alternative hypotheses falsely promise a quick solution, and distract from the messy, complex and incremental task of groundwater governance in the dolomites.

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[100] This does not imply that the pre-1995 Department was better than its current incarnation – quite the opposite – with lower requirements for inclusivity, a narrower remit, experienced scientists, in-house drilling teams, and many social institutions shared with irrigating farmers, the pre-1995 Department's record on sustainably managing groundwater in the North West dolomites was still poor – groundwater levels fell and license conditions were not enforced.

## 7.4. The research question revisited

The discussion above leads back to the main research question, which is: "What is necessary for the successful management of the Grootfontein aquifer?". The short answer to the research question is that a management strategy is required that takes both the institutional context and the hydrogeology into account and is able to overcome the sub-optimal equilibrium that prevails. But what would such a management strategy look like in more detail? Ostrom's (2005) "appropriator attributes" are absent at Grootfontein, and it is not surprising that management is poor as a result.

A forum bringing together all of the major participants at Grootfontein would increase a collective appreciation of *salience*, or the common understanding of the extent to which appropriators depend on the Grootfontein groundwater resource. Linked to this is the second of Ostrom's appropriator attributes, a *common understanding* amongst participants of the nature and limits of the resource. At present most participants understand Grootfontein groundwater poorly, particularly in terms of its potential, despite the decades of hydrogeological research and consequent knowledge. The fifth of Ostrom's appropriator attributes is *autonomy*, or the degree to which "appropriators are able to determine access and harvesting rules without external authorities countermanding them" (Ostrom, 2005:244). An appropriator's forum, if it could reach abstraction agreements, would counter the "tragedy of the commons" idea that water saved by one appropriator would simply be abstracted by the other. Achieving this attribute would greatly assist in decreasing the *discount rate* that appropriators apply to Grootfontein groundwater, or in other words it would increase the future value placed on the groundwater as assurance that the resource would remain predictable and sustainable grew. A *low discount rate* is the third of Ostrom's appropriator attributes, and together with the other attributes discussed would improve the fourth attribute, *trust and reciprocity*.

Such a collective forum was envisaged in the National Water Act of 1998 when it specified the organisations known as Water User Associations (WUAs). Established at local level and by law including all stakeholders, WUAs would theoretically be in a strong position to use local knowledge of water resources for better management. As discussed, the Department of Water and Sanitation (DWS) decided relatively soon after the National Water Act that WUAs were inappropriate since they would likely entrench social and racial hierarchies established during apartheid[101]. In withdrawing its support for WUAs, DWS effectively placed the potential social outcomes ahead of the local management of water since inadequate provision was made for local water management in the absence of WUAs. This decision is defensible on the grounds that redressing apartheid inequality and ensuring economic growth and opportunity are arguably the surest ways to long-term environmental sustainability, and trump short-term local water management.

It is not the opposition to WUAs in itself, but the length of time it has taken to put forward a credible alternative that is less easy to defend[102]. It has been at least fifteen years since DWS withdrew support for the North West dolomite WUAs then being proposed. During this time groundwater conditions at Grootfontein and elsewhere have steadily worsened, and attributes such as trust and reciprocity have eroded. Withholding policy regarding organisational forms for local groundwater management in the North West dolomites has allowed a series of undesirable sub-optimal equilibria, based partly on old institutional forms such as the "right" to abstract groundwater on private property, to take root. In the case of Grootfontein the lack of clear and detailed policy on official organisational forms for local groundwater governance has bolstered less desirable unofficial forms – fair policy delayed is fair policy denied.

However, clear policy does not imply automatic implementation. After all, the licensing and protection measures afforded to the Grootfontein aquifer in the 1970s and 1980s as part of a subterranean water control area under the old Water Act of 1956 did not lead to its sustainable management, indeed arguably presided over the steepest observed declines in groundwater levels. The new National Water Act of 1998 was intended to remedy many of the shortcomings inherent in the old Water Act of 1956, but the two Acts may ironically be linked by a faith that their prescriptions will automatically be fulfilled. The difficulty lies in implementation - there is a danger in confusing policy with its implementation, and in seeing the primary task as one of policy debate and formulation.

Any organisational form designed to tackle the groundwater management problem at Grootfontein would need to take the current institutional landscape into account (not an

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101 This was never clearly articulated to the proto-WUAs and other stakeholders, according to numerous interviewees, leading to much speculation and uncertainty, and stoking cynicism.

102 A credible alternative to WUAs has arguably still not been advanced by DWS.

idealised version of it) and tackle problems in a pragmatic way, emphasising outcomes rather than process. A lot of work stands between good policy and its intended outcomes. A Grootfontein water users' forum or group, designed to tackle the prevailing sub-optimal equilibrium, requires the commitment of both major groups of groundwater abstractors, the irrigating farmers and the Department of Water and Sanitation. There are tremendous institutional hurdles to overcome, as the Grootfontein participants do not appear to share any of Ostrom's appropriator attributes. These attributes were arguably never there originally, but the years of indecision have entrenched regressive institutional norms that make the task harder.

Much recent thinking on water management endorses local self-governance, rooted partly in an optimistic view of the natural capacity of humans to self-organise when long-term cooperation is in our self-interest. This perspective undervalues the deeper institutional forms, ultimately presided over by the state, that help to underpin social cohesion in the developed world. Ironically, it is also rooted in the more pessimistic view that state hierarchies are inherently flawed and automatically encourage "rent-seeking" and other inefficiencies. In this view, "small government", appropriately decentralised, is the medicine for the illness of corrupt, unresponsive and expensive state bureaucracies and the associated high transaction costs. These two perspectives, one from the left and the other from the right, greatly broaden the congregation of the decentralisation church and widen its appeal.

Since DWS has not been able to act to control groundwater over-abstraction at Grootfontein so far, and, bolstered by the decentralisation advocates in water management literature, it may seem that some variety of "hands off", collaborative, local and spontaneous organisational form at Grootfontein should be encouraged. This is not so – the outcomes of such local self-organisation at Grootfontein are likely to lead to the dominance of the powerful over the weak, similar to the situation today. There has to be an organisation, mandated by law, that has the power to break out of stable but sub-optimal equilibria, that can call on impartial, high-quality scientific expertise, and that can act against free-riders. The only possible organisation in South Africa that can do this is the Department of Water and Sanitation or its mandates.

A decision is needed on where DWA's power over Grootfontein will be vested, whether this is via a Catchment Management Agency, a special groundwater division, or a modified version of a Water User Association. DWS can then begin the difficult and lengthy task of implementing the "soft option" of negotiating with and encouraging all participants to do what is already in their best interest. There is no simple recipe for this, and any strategy would need to be flexible and guided by the observed outcomes, in much the same way that adaptive management is recommended as a technical management strategy for groundwater.

## 7.5. The Steenkoppies aquifer as corroborating evidence

The example of the Steenkoppies dolomite compartment or aquifer (described in Section 4.5) supports the analysis of Grootfontein as a hydro-social system, and the main hypothesis that better management needs an understanding of both the technical and the institutional issues. Steenkoppies has many parallels with Grootfontein - it is also a well defined dolomite compartment, heavily utilised for irrigation, and naturally draining at a prominent spring. It is also well understood hydrogeologically (e.g. Holland, 2009), and has experienced substantial overabstraction and consequent management and legal crises. Within the boundaries of Steenkoppies there is only one major group of groundwater abstractors, the irrigating farmers, since no large public water supply sources are located there. Other users include those dependent on the Magalies River, and nearby families and communities who depend on irrigated agriculture.

The similarities between Steenkoppies and Grootfontein suggest that the situation at Grootfontein is not unique or anomalous, but may be representative of conditions elsewhere. The fact that Steenkoppies is also relatively well understood hydrogeologically further undermines the "technical hypothesis" described above – clearly, technical or hydrogeological knowledge on its own is insufficient to trigger good groundwater management. Technical issues have, however, been used in the back and forth disputes between the different parties at Steenkoppies (see Section 4.5.3), and can serve to distract or derail management efforts.

At Steenkoppies a relatively homogeneous and adequately funded group of groundwater users (led by the Steenkoppies irrigating farmers) endeavoured to form a WUA, with additional support from the Danish government, but were ultimately unsuccessful. The informal management cooperation between some Steenkoppies groundwater users today is not able to fully resolve the crisis, and farmers remain concerned about drought. These things suggest the need for overall support and leadership from DWS, and undermine the notion that some form of spontaneous and effective self-governance will arise if participants are sufficiently motivated. The Steenkoppies participants have not been able to pro-actively manage groundwater overdraft on their own, despite the large investments at stake, the good technical knowledge, and adequate funding and support.

During previous low-flow crises at Steenkoppies, DWS issued legal directives to irrigating farmers, and downstream users of the Magalies River also threatened legal action. These legal moves were resisted by irrigating farmers, who engaged lawyers of their own. One informant characterised communication between parties at Steenkoppies at the time as happening "by court order" only. The legal action at Steenkoppies did not improve groundwater governance outcomes, suggesting that such "hard state" actions are not the answer, and justifying DWS' inclination to avoid legal challenges. The willingness of DWS to issue legal directives between 2004 and 2009 was not matched by support for WUAs or other "soft state" solutions to the problem at the time. DWS' reluctance to back the Steenkoppies WUA was and is a policy issue, rather than a matter of "capacity", challenging the "lack of capacity hypothesis" described above.

Informants at Steenkoppies described difficulties in obtaining the involvement or cooperation of the relevant district and local municipalities in the attempts to form a WUA, before these attempts were abandoned. This suggests that effective management is as much about cooperation between existing organisations as it as about defining an ideal constellation of organisations. This undermines the "structure hypothesis" and suggests that a short cut to better groundwater management by way of new high-level policy is an illusion.

The Steenkoppies aquifer is in many ways a shadow of the Grootfontein aquifer, reproducing many of its characteristics despite an arguably more homogeneous group of groundwater users. It suggests that the management problems at Grootfontein are not aberrations or unlikely coincidence, but are representative of South African groundwater management. The management failures at Steenkoppies, despite its resources and shared social institutions, underscore the magnitude of the challenge at Grootfontein.

## 7.6. Ways forward at Grootfontein

A Grootfontein local water user's forum is unlikely to arise spontaneously without the support of DWS, and if it does, it will be unlikely to provide for the progressive social outcomes (e.g. more equitable access to the groundwater resource) as well as the hydrological outcomes that the National Water Act of 1998 prescribes. In the absence of such an organisation, driven partly by DWS' decision not to support the WUAs and the lack of a clear alternative policy, a sub-optimal (and undesirable) equilibrium has established itself at Grootfontein. This equilibrium deprives both irrigating farmers and the city of Mahikeng of a reliable, cheap and sustainable resource of high quality water. In the semi-arid North West Province, lower assurances of water supply for both urban areas and farming areas carry large hidden and externalised costs. Businesses build lower assurances of water supply into their cost models, with an inevitable impact on their economic contribution. Anxiety over municipal and industrial water supplies also contributes to a general and corrosive pessimism, antithetical to the confidence and sense of collective endeavour that development plans for the region require.

DWS is an organisation facing internal and organisational challenges. Changes of leadership, structure, name and policy are not unusual - the organisation is currently in the process of formulating major new policies as well as supporting the transition of staff and resources to new organisations, the enlarged CMAs (DWS, 2014a). Although many DWS staff members are capable professionals, the organisation suffers from many of the ailments identified by Von Holdt (2010). These are notoriously tough to cure. Given the challenges, it is unlikely that DWS will be able to carry out the difficult task of convening a Grootfontein water users forum and using that platform to reverse the hydrogeological problems at Grootfontein in the short or medium term.

The forum that DWS has already convened to deal with the kind of collective action problems involving multiple stakeholders found at Grootfontein, the Molopo Catchment Forum, has neither the support of DWS senior staff nor that of important local stakeholders[103] and is consequently ineffective. It may even discourage other organisational initiatives, since its presence superficially suggests that the problem is already being tackled. A deeper issue may be the emphasis that DWS still puts on high-level policy and planning, arguably to the neglect of implementation[104].

Grootfontein is only one of many water governance challenges facing DWS. The difficulty of reconciling day-to-day management of scarce water resources at a variety of

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103 The impression of this researcher was that the Molopo Catchment Forum was an organisation aimed at surface appearances or processes rather than at outcomes or achievements.

104 The old Department of Water Affairs and Forestry of the 1970s and 1980s was also unable to tackle the Grootfontein over-abstraction, suggesting that sets of shared institutions and beliefs regarding the fundamental unsustainability or unreliability of groundwater persist.

scales with the imperative for social justice and transformation is substantial. DWS must also rely on local proxies, particularly the municipalities, to carry out much of the actual implementation (since water is constitutionally the responsibility of the local sphere of government). Adding the organisational challenges, leadership changes and policy uncertainty into the mix, it begins to seem as if DWS has a nearly impossible task of reconciling the current state of national water management with the vision of the National Water Act.

There are indications that DWS is looking for ways to break cleanly with the past failures to implement the organisational structures, including CMAs and WUAs, specified by the Act (DWS, 2014a). The new emphasis is on nine consolidated CMAs covering larger areas than previously, to which control over some local structures - including those WUAs that already exist – will be transferred. There also appears to be a growing conviction within DWS that fast-track reallocation of water resources is required, and that water allocation reform (deliberately abbreviated to WAR) will be the sword that cuts the Gordian Knot of contemporary water management problems. This view sees the continued disproportionate use of South Africa's water resources by white South Africans as the fundamental problem (van Koppen and Schreiner, 2014a). The WAR discourse presents the issue as essentially one of zero-sum allocation, rather than a more nuanced set of issues consequent on management or governance failure. WAR is also difficult to wage – even if the required "hard state" approach was desirable, it would require efficient verification and validation of license quantities, for example, which DWS and its predecessors have been unable to achieve since the 1960s, greatly contributing to today's problems at Grootfontein. It also reinforces the idea that absolute shortage – of water, rainfall, funding, skills or "capacity" – is at the heart of the current predicament (the "discourse of shortage"). Such zero-sum thinking and the increasing emphasis on race is amenable to easy political and popular summary. It is also contrary to the more complex institutional structures, underpinned by "soft" state intervention, that have the best chance of success.

DWS is required to work closely with the Water Service Provider, Ngaka Modiri Molema District Municipality, as well as local municipalities in the greater Mahikeng region. These municipalities are currently in financial difficulties and have many internal challenges, making them problematic partners. Indeed, it is DWS' desire to regain control of some water functions from municipalities that is partly behind some of the suggested legal and policy changes regarding water such as the merging of the Water Services Act and the

National Water Act (DWS, 2014a). DWS and the municipalities around Mahikeng have not collaborated closely in the recent past, confirmed by several interviewees.

The outlook for Grootfontein therefore remains bleak. It is likely that the groundwater overdraft will continue, and that Mahikeng will use proportionately less and less groundwater from its remaining boreholes at the old Grootfontein Eye site. The Setumo Dam with its refurbished and upgraded water treatment plant and increasing allocations from the Molopo Eye spring will compensate, together with professional attention to leaks and failing infrastructure by the newly appointed Sedibeng Water Board. Uneasy about the Grootfontein groundwater (amongst other issues), irrigating farmers will seek to further diversify.

At least two interviewees, one working at the district municipality and the other a retired consultant, mentioned the possibility of the purchase of Grootfontein irrigation farms by the state for the purposes of taking over the groundwater abstractions. The farms could then be re-sold, or leased, for strictly non-irrigated farming purposes. In many ways a sensible idea, it is unpalatable since the state would effectively be paying for a resource to which it already has the legal right to a more equitable share. It would probably also set an unwanted legal precedent. New farmers would also have to be prevented from abstracting groundwater for irrigation, a potential return to the initial administration and management problem. As one senior manager at the former Botshelo Water Board reportedly said of such a plan, "We are not in the business of buying farms."

There are also some reasons for optimism. Most of the interviewees expressed a willingness to cooperate, despite the years of uncertainty and the erosion of trust and reciprocity contingent partly on the WUAs debacle. As discussed in Section 6.6.2, irrigating farmers could scale back groundwater abstractions significantly without large impacts on income, by changing crop types and irrigation practices[105]. The large amount of hydrogeological work that has been done on Grootfontein, and the continuing technical interest in the aquifer, provide a sound basis for adaptive management. Its location close to the provincial capital of Mahikeng suggests a profile for the Grootfontein aquifer that other dolomite compartments with overdraft problems lack. Grootfontein groundwater quality remains good and there are no polluting industries

[105] There would need to be mechanisms to incentivise farmers to do this, most likely as part of a larger solution to the problem and involving other stakeholders and dealing with other matters at the same time. It would not be a simple matter.

nearby. The major users of groundwater, the irrigating farmers, are more dependent on it in the short term than Mahikeng, since they have no other sources of water – placing DWS as the coordinating state body in a stronger negotiating position. The newly appointed regional water utility, Sedibeng Water Board, has a strong track record and considerable experience. DWS has experienced hydrogeologists in both their Mahikeng and Hartbeespoort offices, and Ngaka Modiri Molema District Municipality also employs a hydrogeologist.

## 7.7. Implications for environmental stewardship in South Africa

In Mahikeng low-value crops such as maize are being grown with high quality water, whilst increasing quantities of expensively recycled sewage are being drunk. At the same time, confidence in technical solutions underpinned by surface water resources leads to millions spent on upgrading surface water treatment at the Setumo Dam, and to serious talk about pipelines from the Vaal River catchment. This way of thinking, often disparagingly referred to as the "hydraulic mission" in water management literature (e.g. Allan, 2003), is in turn institutionally underpinned by South Africa's engineering achievements in inter-basin water transfers and large dams, including Gauteng Province's reliance on water brought from Lesotho (van Vuuren, 2012). These engineering feats are themselves necessitated by South Africa's variable and low rainfall and consequently "flashy" rivers that require huge investments in surface water storage and inter-basin transfer. Thus one element of the hydrological environment influences the collective set of institutions, which in turn sways the common response to another element of the hydrological environment – the dolomite aquifers.

The case study of the Grootfontein aquifer has many parallels with other environmental and resource stewardship challenges in South Africa. It is not poor scientific understanding of the problem that prevents better management, but a more complicated mixture of issues requiring an approach that crosses disciplinary boundaries. Grootfontein was chosen as a case study partly because it appears to have many of the characteristics necessary for successful management: a lot is known about the aquifer hydrogeologically, it is obviously important, there are considerable state resources available, and participants agree that better management is necessary. Yet water levels at Grootfontein inexorably decline, with many inherent and externalised negative impacts.

This research has shown that the root cause of the management problem at Grootfontein probably lies in the institutional domain, as explained in Chapter 6 using Ostrom's attribute framework (Ostrom, 2005). A hydrogeological understanding is also necessary, as described in Chapter 5. The hydrogeology provides the fundamental range of possibilities for sustainable abstraction, and a process of hydrogeological adaptive management would need to underpin an effective stakeholder's forum. Participants should all share the same hydrogeological conceptual model, in other words, and the hydrogeology or technical aspects should not be seen as necessarily subordinate to or dependent on the institutional domain.

There is nevertheless a tendency to see the problem in a simplified way, or represent it as a binary or zero-sum issue. This may even contribute to the difficulties – since at Grootfontein many irrigating farmers see the state as the main problem, and vice versa. Solutions suggested by a simplified view of the problem also tend to be more radical, such as removing some participants' access to water, or other forceful initiatives[106].

Complex environmental problems and resource allocation issues tend to be associated with numerous levels of institutional interactions between stakeholders or "participants", as well as having scientifically or technically challenging attributes (de Wit and Booth, 2016). The key may be to emphasise "win-win" outcomes where possible, and to focus on the obstacles to these. Many modes of behaviour and underlying assumptions are institutionally determined and reinforced – for example the idea that South African dolomite groundwater is unsustainable. A similar amount of work should go into describing the institutional environment as is normally put into scientific efforts to understand the physical environment, if seriously complex problems are to be addressed. The institutional model should be as clearly defined as the scientific model.

None of the above is unique to South Africa, although the Grootfontein case study has many uniquely South African institutional and geological characteristics. Prominent global complex, multi-disciplinary environmental and resource-allocation problems such as climate change, food allocation, desertification, migration, pollution and public health

[106] A parallel can be drawn with the "back to basics" strategy to deal with violent crime a few years ago in South Africa, and the notorious comments by a senior politician that police should "shoot to kill" (Independent, 2008).

provision[107] have no easy answers. Views deeply rooted in an institutional context often determine the response – what is considered normal? What is good? Who is to blame? Which hierarchy of values prevails? What should be prioritised? There is a danger in ignoring this context, particularly when participants claim to be non-ideological "practical men" who seek only what is "best". The many science-led achievements of the twentieth century have helped to foster a comfortable position in the social hierarchy for scientists in many countries, with policy traction or outcomes often presumed[108]. Skepticism or appreciation of nuance in a particular specialist research field may contrast with a less critical awareness of the wider institutional context.

Global problems today demand answers that seem scientifically manageable but are challenging to implement (de Wit and Booth, 2016). At the same time, policy appears to respond increasingly to short-term political imperatives, or aligns itself with a blinkered economic world-view which, expressed crudely, holds that what is best collectively will automatically emerge as long as "free enterprise" is unleashed. Scientists are increasingly called to account for, and to financially value, scientific research[109]. Potential allies in the humanities, mindful of debates around post-modernism, discourse theory and questions of identity, mistrust those claiming an absolute "truth", as some scientists do. Some in the green movement link "science" (more accurately scientific materialism) to contemporary environmental and economic woes (e.g. Swilling and Annecke, 2012). Others see scientists as simply dogmatic, biased or out-of-touch[110].

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107 Difficulties with the eradication of the last pockets of the polio virus in Nigeria and Afghanistan by blanket vaccination are an example – the science is established, but the implementation in an environment of suspicion and misinformation is much more difficult. This is not confined to poor rural areas either - similar difficulties have been experienced in trying to ensure adequate vaccination against measles in wealthy urban parts of the USA and UK.

108 Hodgson (2013:220) writes convincingly about the "institutionalisation of science" leading to "epistemic communities" and "machineries of knowing", with unprecedented impacts on life expectancy and other indicators in the modern world. This relies on what Hodgson calls "specific institutional props" such as property rights, patent laws, a polycentric political system, relative university autonomy, and so on. The point is that science, and translation of scientific outcomes into policy, is a socially mediated system rather than something absolute or inevitable.

109 Evidence for this includes the widespread use of timesheets in scientific research organisations, the need to measure the "impact" of research and other key performance indicators, or the fact that formerly public-domain scientific work such as rainfall data collection have been privatised in South Africa.

110 The BSE / variant CJD crisis of the late 1990s in the United Kingdom showed poor communication by scientists and government officials, contributing to public mistrust at the time (OST, 2004). Writing in the Guardian newspaper in 2013 about the controversial use of

Demand for water in Mahikeng is projected to increase to more than 50 ML/day (about 18.3 $Mm^3/a$) by 2030. There are water quality problems in the peri-urban villages surrounding Mahikeng (particularly anthropogenic nitrate contamination) as well as persistent O&M challenges, and Sedibeng Water Board may well respond by extending Mahikeng's urban reticulation system to these areas, further increasing demand. The Grootfontein groundwater issue may in the end boil down to an economic choice – either invest in managing the aquifer, or pay considerably more for poorer quality water from other sources such as the Setumo Dam or a pipeline from elsewhere. The potential of the Grootfontein groundwater, as well as the complex institutional challenges of management, should be acknowledged. Choosing poorer-quality dam or Vaal River water instead of nearby groundwater hinges on institutional or management challenges, not deficiencies in the groundwater resource nor in hydrogeological understanding.

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neonicotinoid pesticides in Europe, George Monbiot accused British government science advisors of "acting like industrial lobbyists" in support of "political agendas" (Guardian, 2013).

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# 9. Appendices

## 9.1. Appendix A: Letter to interviewees

**Jude Cobbing**
593 Reitz Street, Sunnyside, Pretoria, South Africa
083 612 0413
jcobbing@gmail.com

June 2015

Dear Sir or Madam:

I am writing to request your assistance with my PhD research, which I am currently undertaking at the Nelson Mandela Metropolitan University in Port Elizabeth. My thesis is provisionally titled Groundwater management in South Africa: linking the physical resource to social, institutional and planning requirements. I would be very grateful if you could make yourself available for ***an interview of approximately 30 minutes at a time and place convenient to you***.

Our discussion will be completely confidential, but with your permission, I would like to record the interview. This is in order to satisfy the examination requirements for my study. These recordings will be kept for a period of up to two years in a secure location, and as soon as the Nelson Mandela Metropolitan University is satisfied that the research process complies with their validity requirements, they will be destroyed. In addition, your name and any other personal identifying information will not appear in any part of the text of my PhD research. With your consent, I would however like to include your name in a list of interviewees, which will form one of the Annexures. Maintaining confidentiality of your answers is central to the ethical standards against which the University will evaluate my research.

I am also working on a Water Research Commission project entitled The Path to Successful Water User Associations in the NW Dolomites (Project K5/2429). The research manager at the Water Research Commission is Eiman Karar. Ms Karar can be contacted at eimank@wrc.org.za

Please contact me by email at jcobbing@gmail.com or by cell phone at 083 612 0413 if you have any further questions. My PhD supervisor, Professor Maarten de Wit can also be contacted directly at Maarten.deWit@nmmu.ac.za should you wish to confirm these conditions and arrangements with him.

Thank you in advance for your support for my research, and I very much look forward to hearing from you with respect to your availability for a meeting.

Yours sincerely,

Jude Cobbing

## 9.2. Appendix B: Chemical analysis results

## Appendix B: Chemical analysis results for 16 Grootfontein samples (major and minor ions)

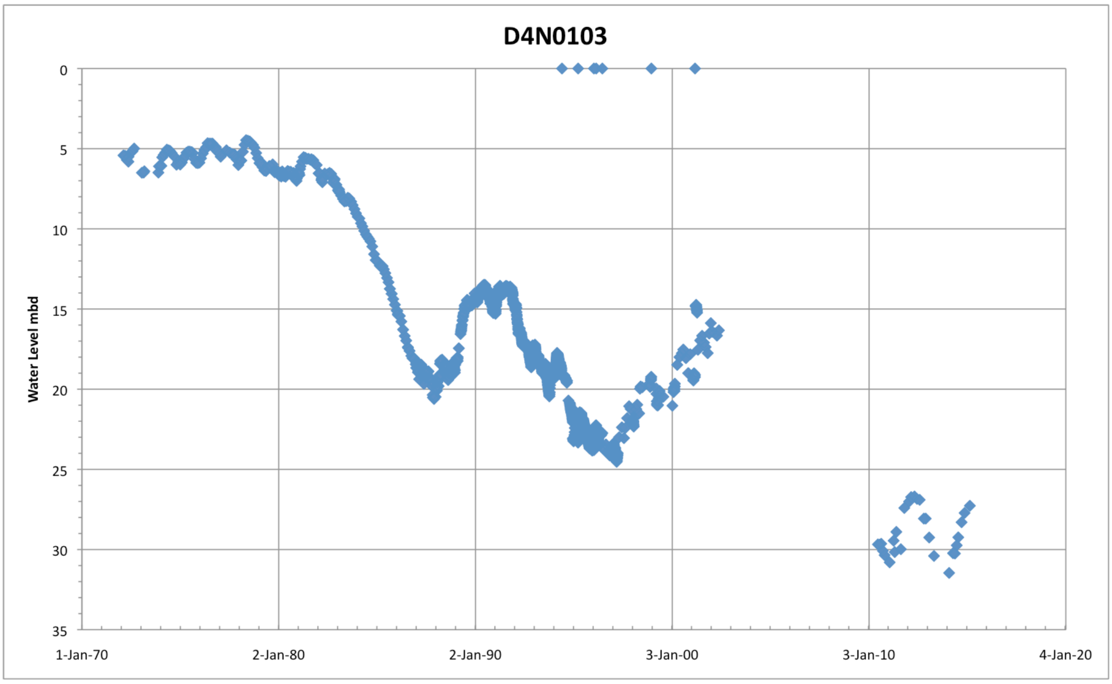
| SAMPLE | SANS Limit | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH value at 25°C | 5 - 9.7 | 7.5 | 7.5 | 7.3 | 7.6 | 9.2 | 7.6 | 7.5 | 7.6 | 7.4 | 7.5 | 8 | 7.8 | 7.5 | 7.4 | 7.9 | 7.9 |
| EC (mS/m at 25°C) | 170 | 60.3 | 78.9 | 100 | 56.6 | 84.3 | 53.5 | 98.2 | 58.8 | 60.4 | 58.7 | 40.2 | 50 | 63.2 | 58.9 | 50.9 | 56.8 |
| Tot. Alkalinity as $CaCO_3$ | | 280 | 368 | 328 | 288 | 312 | 268 | 384 | 308 | 316 | 328 | 232 | 236 | 280 | 336 | 280 | 332 |
| Chloride as Cl | 300 | 8 | 14 | 61 | 8 | 94 | 15 | 41 | 12 | 13 | 11 | 8 | 14 | 17 | 15 | 15 | 7 |
| Sulphate as $SO_4$ | 500 | <5 | 25 | 38 | <5 | 23 | <5 | 34 | <5 | 5 | 12 | <5 | 6 | 6 | <5 | <5 | 6 |
| Fluoride as F | 1.5 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 | <0.2 |
| Nitrate as N | 11 | 6.6 | <0.2 | 17 | 5.3 | <0.2 | 6.9 | 17 | 7 | 7.2 | 2.1 | 0.9 | 9.4 | 19 | 4.5 | 7.9 | 2 |
| % Bal. | | 98 | 99.1 | 99 | 98.5 | 90.3 | 97.1 | 95 | 95.1 | 95.1 | 91.6 | 95 | 93.4 | 94 | 94.6 | 95.5 | 96.3 |
| Ag | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Al | 0.300 | <0.100 | <0.100 | <0.100 | <0.100 | <0.100 | <0.100 | 0.115 | 0.101 | 0.104 | 0.101 | <0.100 | <0.100 | 0.100 | 0.104 | <0.100 | <0.100 |
| As | 0.010 | <0.010 | <0.010 | <0.010 | <0.010 | 0.016 | 0.048 | 0.038 | 0.013 | 0.012 | 0.012 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Au | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| B | | <0.010 | 0.010 | 0.029 | 0.013 | 0.051 | 0.012 | 0.028 | 0.012 | 0.012 | <0.010 | <0.010 | 0.011 | 0.025 | 0.016 | <0.010 | 0.011 |
| Ba | | 0.051 | 0.416 | 0.137 | 0.043 | 0.041 | 0.052 | 0.125 | 0.049 | 0.049 | <0.010 | <0.010 | 0.032 | 0.042 | 0.083 | 0.097 | <0.010 |
| Be | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Bi | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ca | | 66 | 92 | 100 | 66 | 11 | 52 | 94 | 69 | 74 | 64 | 45 | 53 | 70 | 72 | 66 | 55 |
| Cd | 0.003 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ce | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Co | 0.500 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Cr | 0.050 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Cs | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Cu | 2.000 | <0.010 | <0.010 | <0.010 | 0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Dy | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Er | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Eu | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Fe | 0.3 / 2 | <0.025 | <0.025 | <0.025 | <0.025 | <0.025 | 0.449 | 0.387 | 0.271 | 0.280 | 0.268 | 0.181 | 0.208 | 0.276 | 0.270 | <0.025 | <0.025 |
| Ga | | 0.011 | 0.086 | 0.028 | <0.010 | 0.011 | <0.010 | 0.012 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | 0.018 | <0.010 |
| Gd | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ge | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Hf | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Hg | 0.006 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ho | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| In | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ir | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| K | | <1.0 | <1.0 | 37.1 | 1.0 | 12.1 | 1.1 | 40.2 | <1.0 | <1.0 | <1.0 | <1.0 | 1.0 | 1.1 | 1.6 | 1.5 | <1.0 |
| La | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Li | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Lu | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Mg | | 31 | 40 | 43 | 32 | 42 | 28 | 41 | 32 | 32 | 32 | 24 | 27 | 35 | 32 | 29 | 43 |
| Mn | 0.1 / 0.5 | <0.025 | 0.431 | <0.025 | <0.025 | <0.025 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.025 | <0.025 |
| Mo | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Na | 200 | 4 | 5 | 14 | 5 | 74 | 5 | 14 | 4 | 4 | 3 | 2 | 3 | 4 | 7 | 5 | 7 |
| Nb | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Nd | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ni | 0.070 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Os | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |

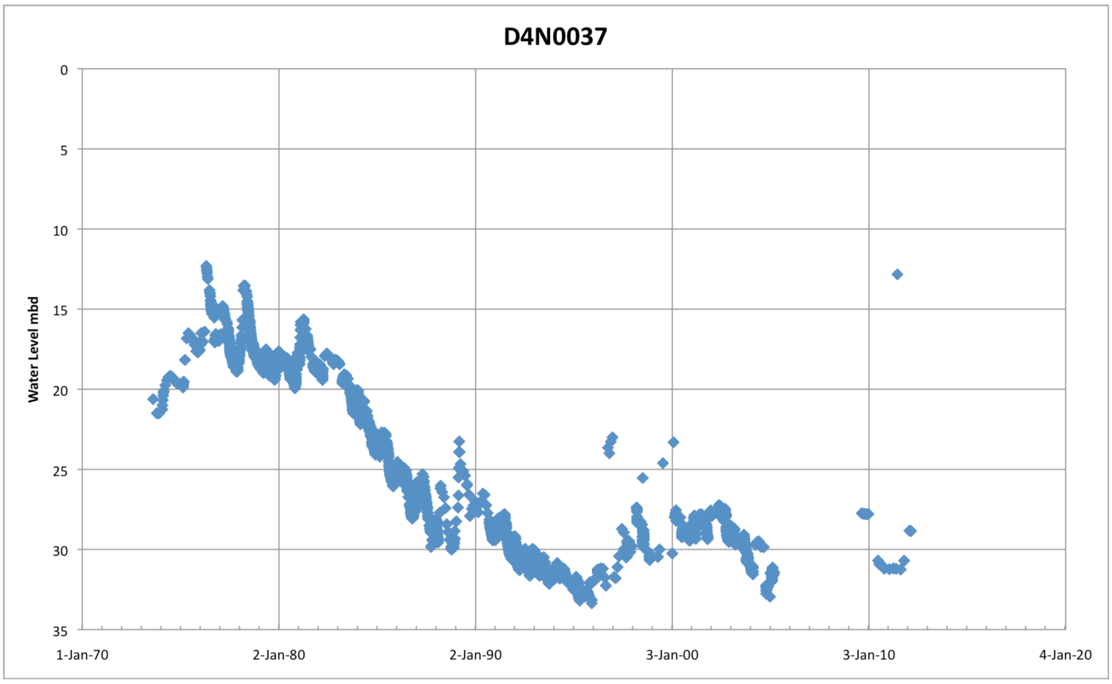
| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P | | 0.047 | <0.010 | 0.015 | 0.022 | 0.034 | 0.023 | 0.028 | <0.010 | <0.010 | <0.010 | <0.010 | 0.013 | <0.010 | 0.011 | <0.010 | <0.010 |
| Pb | 0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Pd | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Pt | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Rb | | <0.010 | <0.010 | 0.013 | <0.010 | <0.010 | <0.010 | 0.015 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Rh | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ru | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Sb | 0.020 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Sc | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Se | 0.010 | <0.010 | 0.011 | 0.015 | <0.010 | <0.010 | 0.039 | 0.017 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | 0.032 | <0.010 | <0.010 |
| Si | | 10.0 | 10.7 | 10.3 | 10.1 | 1.7 | 10.5 | 10.7 | 11.4 | 11.2 | 8.4 | 6.1 | 10.5 | 11.5 | 13.0 | 12.4 | 9.4 |
| Sm | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Sn | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Sr | | 0.036 | 0.060 | 0.050 | 0.037 | 0.033 | 0.044 | 0.052 | 0.038 | 0.039 | 0.031 | 0.020 | 0.036 | 0.039 | 0.055 | 0.046 | 0.064 |
| Ta | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Tb | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Te | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Th | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Ti | | 0.073 | 0.101 | 0.095 | 0.067 | 0.013 | 0.087 | 0.145 | 0.105 | 0.106 | 0.102 | 0.067 | 0.080 | 0.101 | 0.106 | 0.087 | 0.074 |
| Tl | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Tm | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| U | 0.015 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| V | 0.200 | <0.010 | <0.010 | <0.010 | <0.010 | 0.019 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| W | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Y | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Yb | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |
| Zn | 5.000 | <0.010 | 0.013 | 0.052 | 0.014 | <0.010 | 0.107 | 0.022 | 0.021 | 0.126 | 0.016 | 0.027 | 0.021 | 0.075 | 0.026 | <0.010 | <0.010 |
| Zr | | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 | <0.010 |

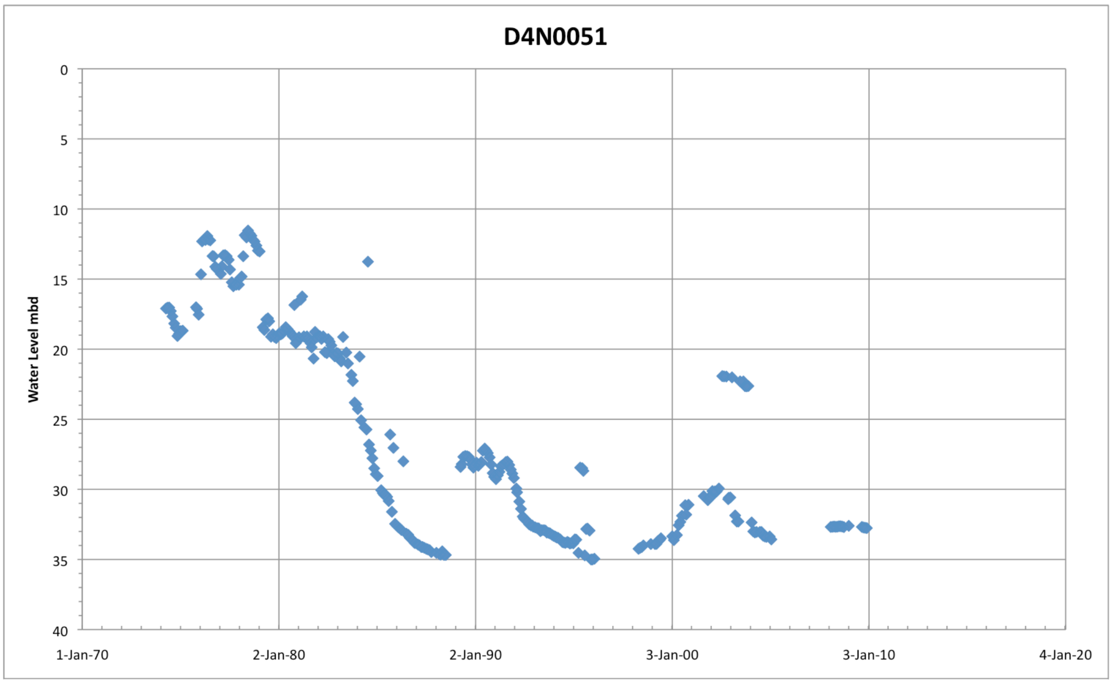
(All results in mg/L unless otherwise stated)

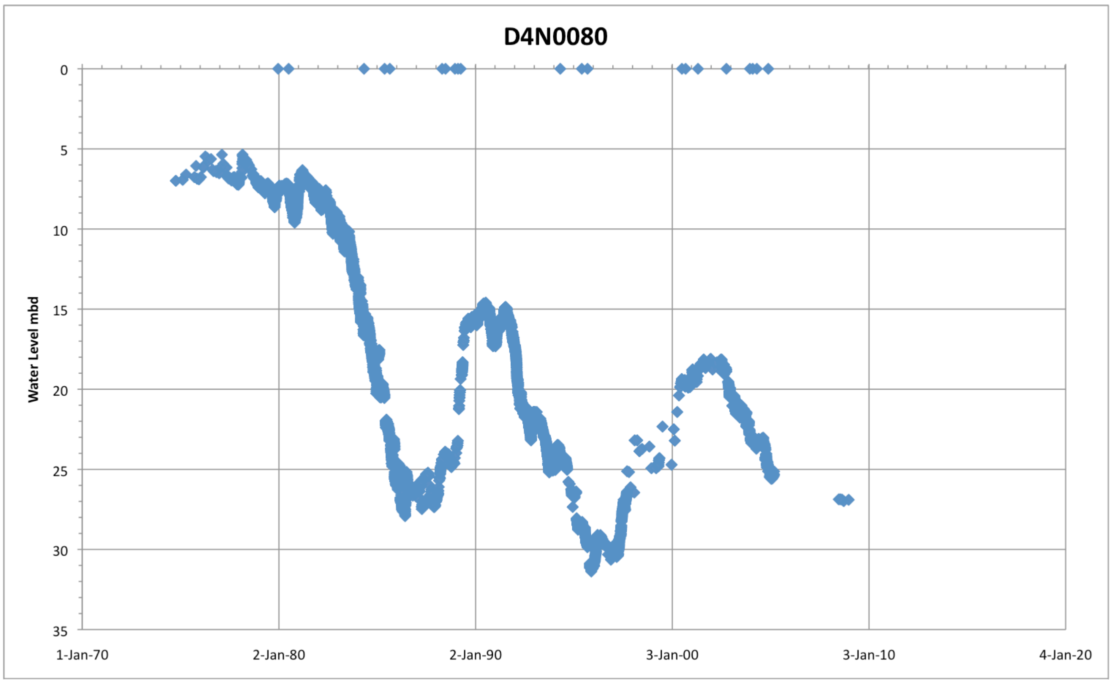
SANS Limit: Limits as provided in SANS 241-1 (2011). Health-based and aesthetic exceedances are shaded yellow and green respectively.

## 9.3. Appendix C: Water level charts


D4N0103
Water Level mbd
0
5
10
15
20
25
30
35
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0037
Water Level mbd
0
5
10
15
20
25
30
35
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0051
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0080
Water Level mbd
0
5
10
15
20
25
30
35
1-Jan-70
2-Jan-80
2-Jan-90
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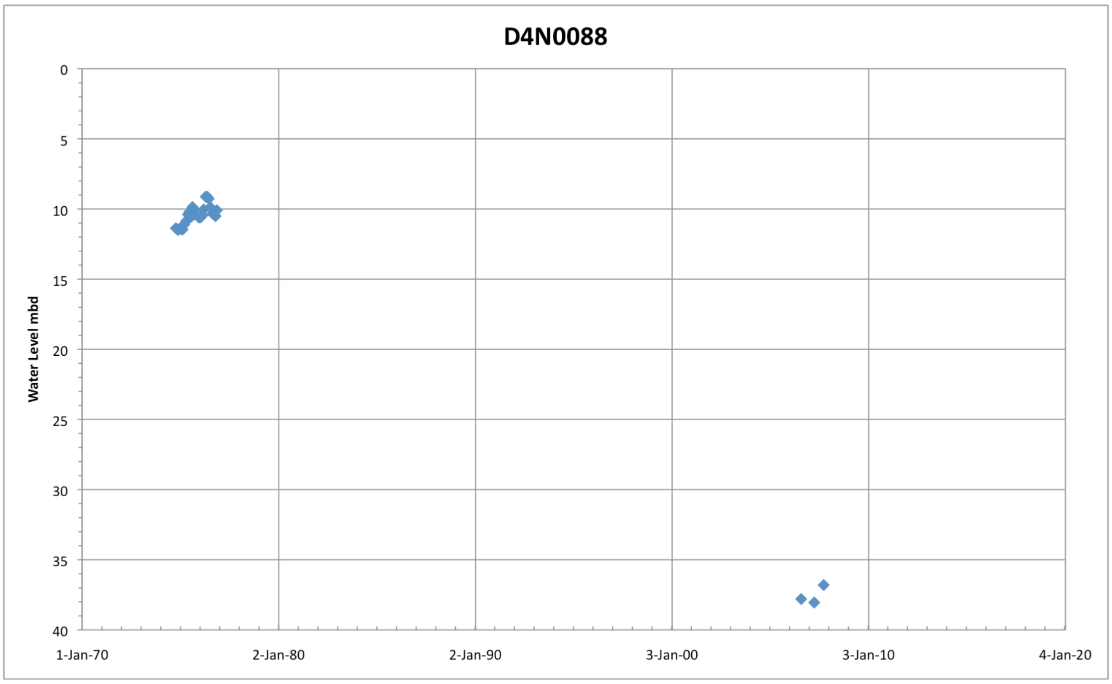
3-Jan-10
4-Jan-20


D4N0088
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-70
2-Jan-80
2-Jan-90
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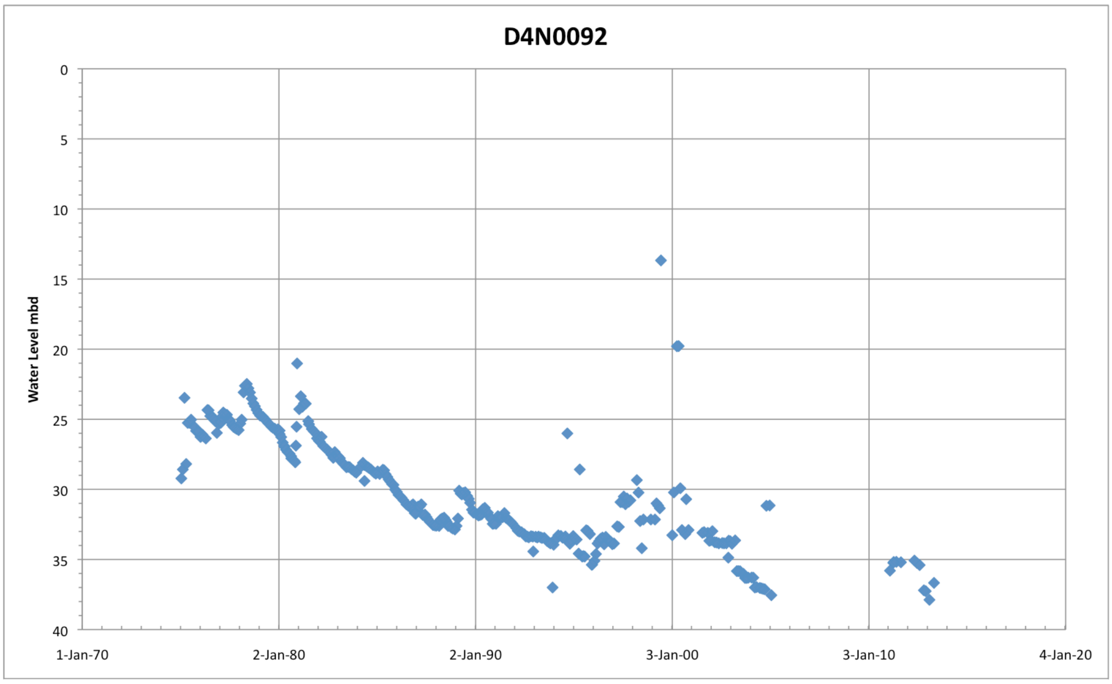
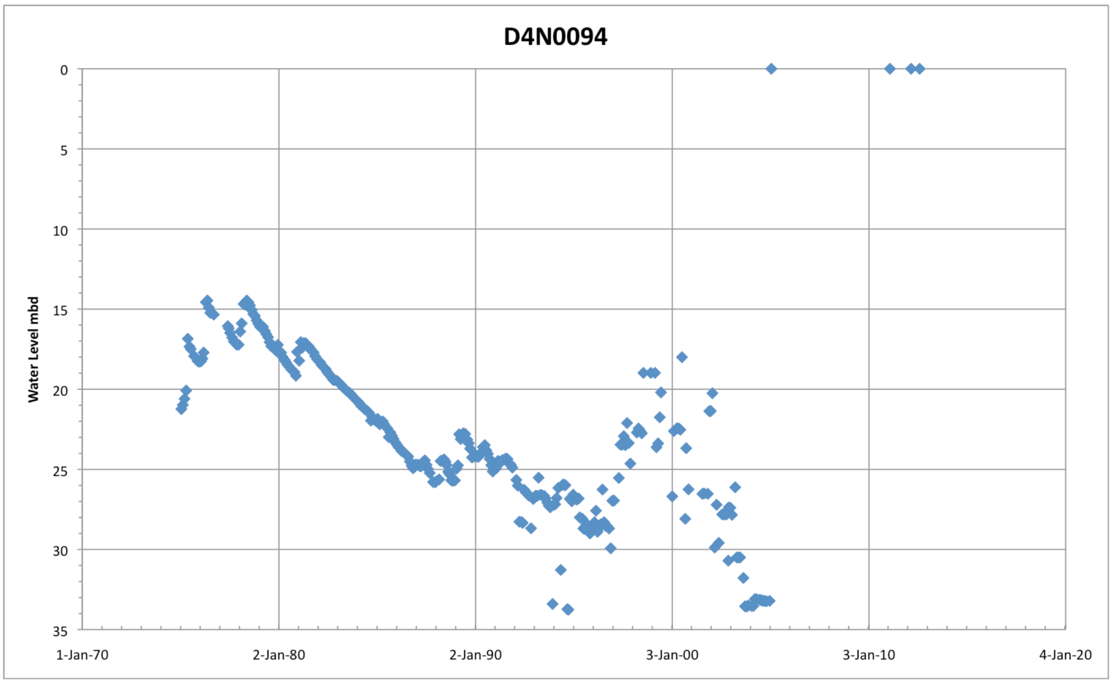
3-Jan-10
4-Jan-20


D4N0092
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0094
Water Level mbd
0
5
10
15
20
25
30
35
1-Jan-70
2-Jan-80
2-Jan-90
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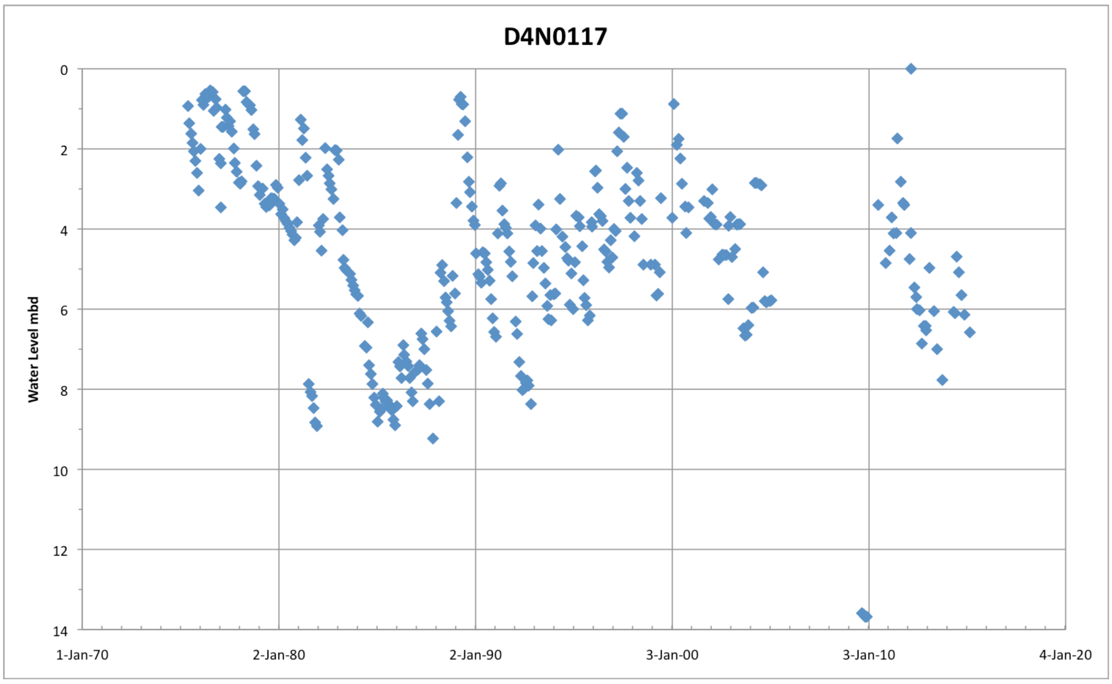
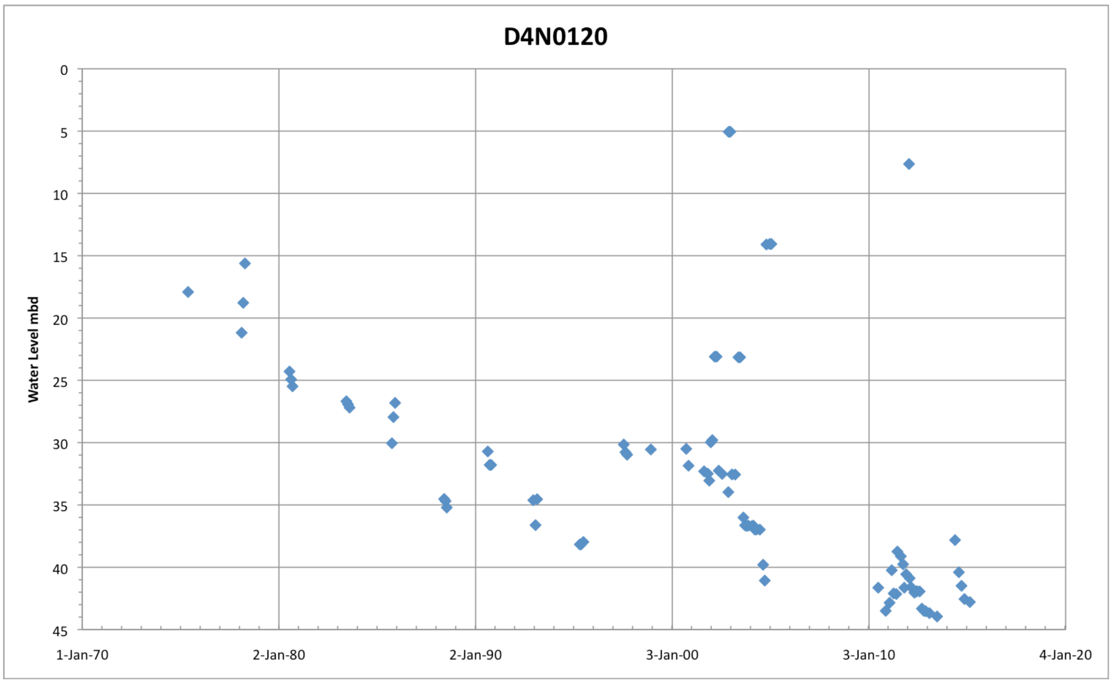
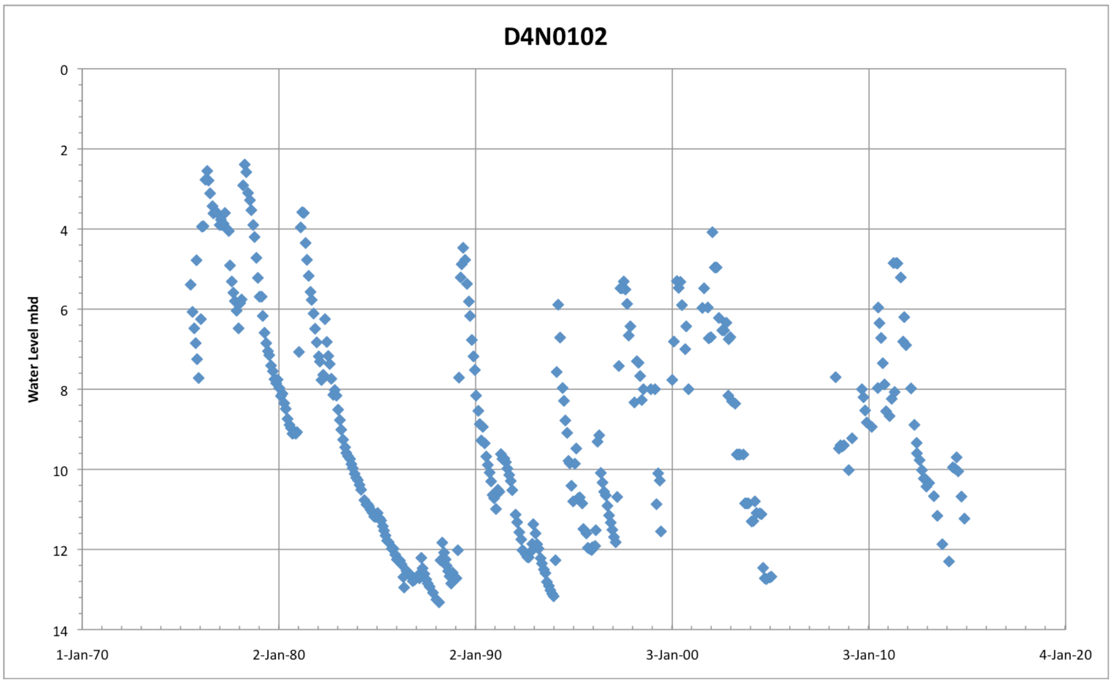
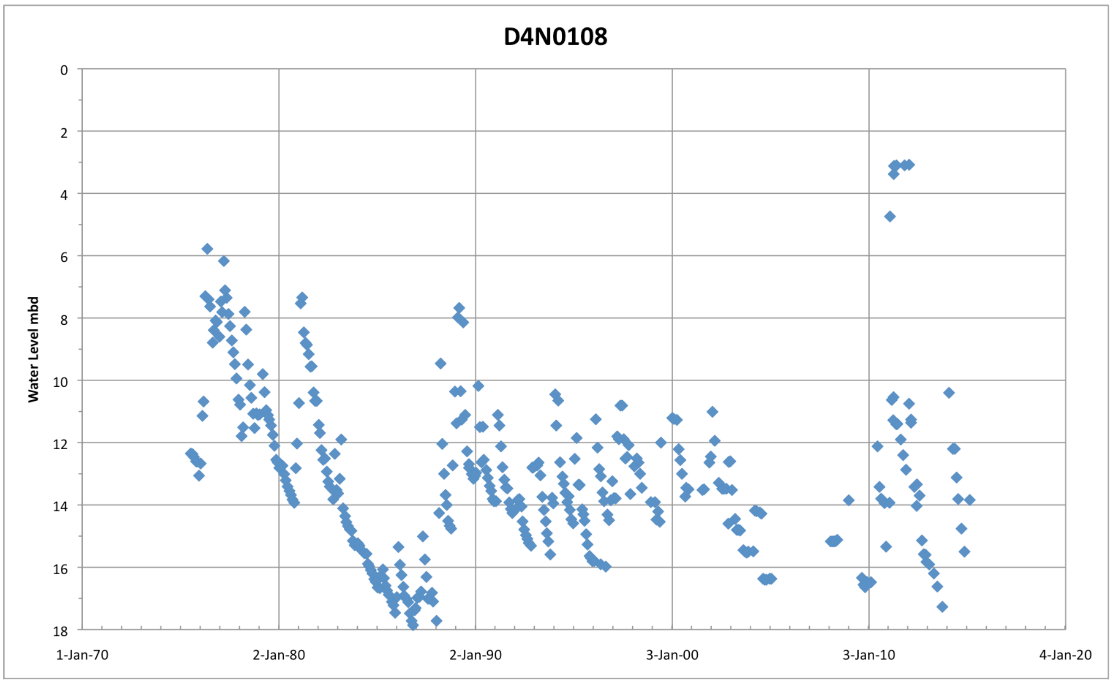
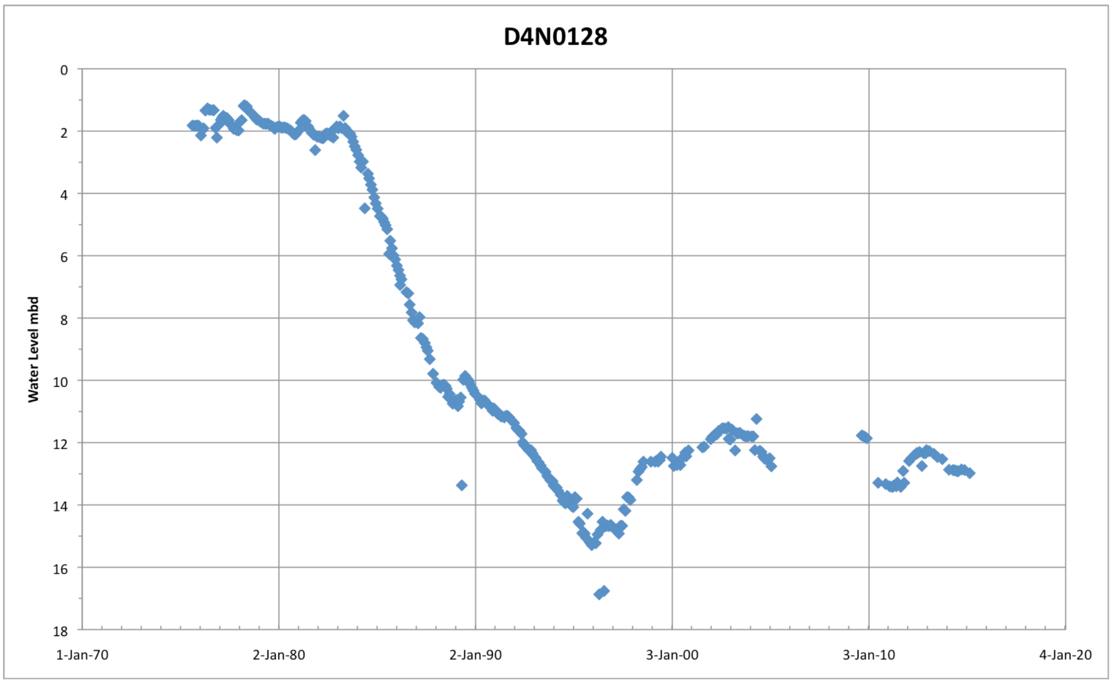
3-Jan-10
4-Jan-20

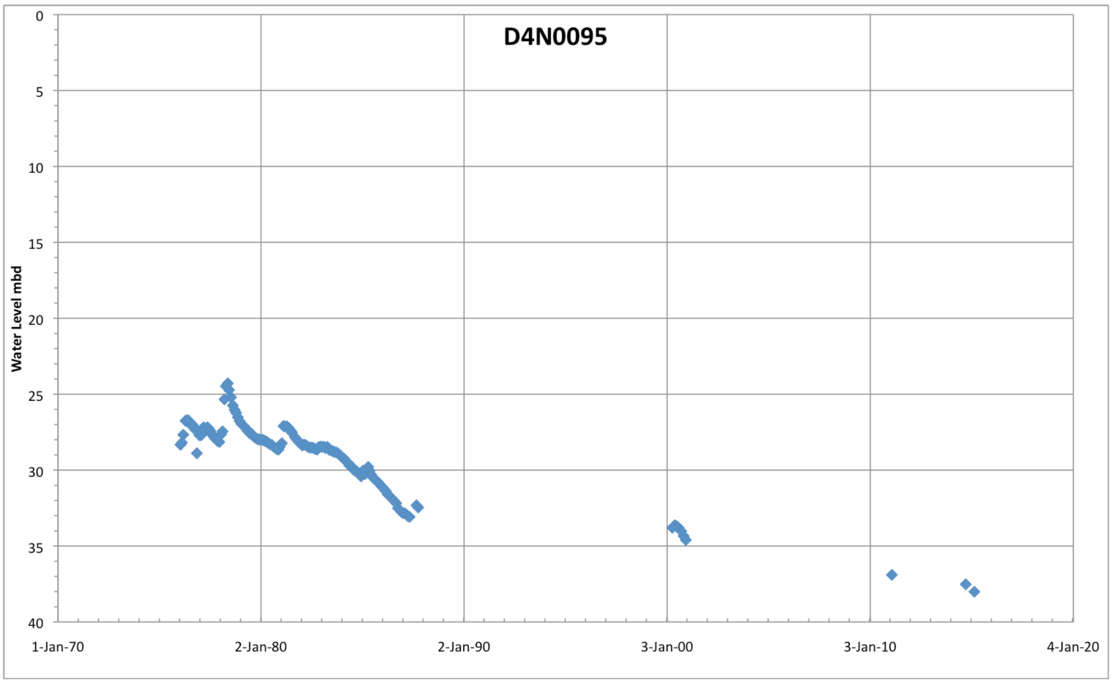

D4N0117
Water Level mbd
0
2
4
6
8
10
12
14
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20

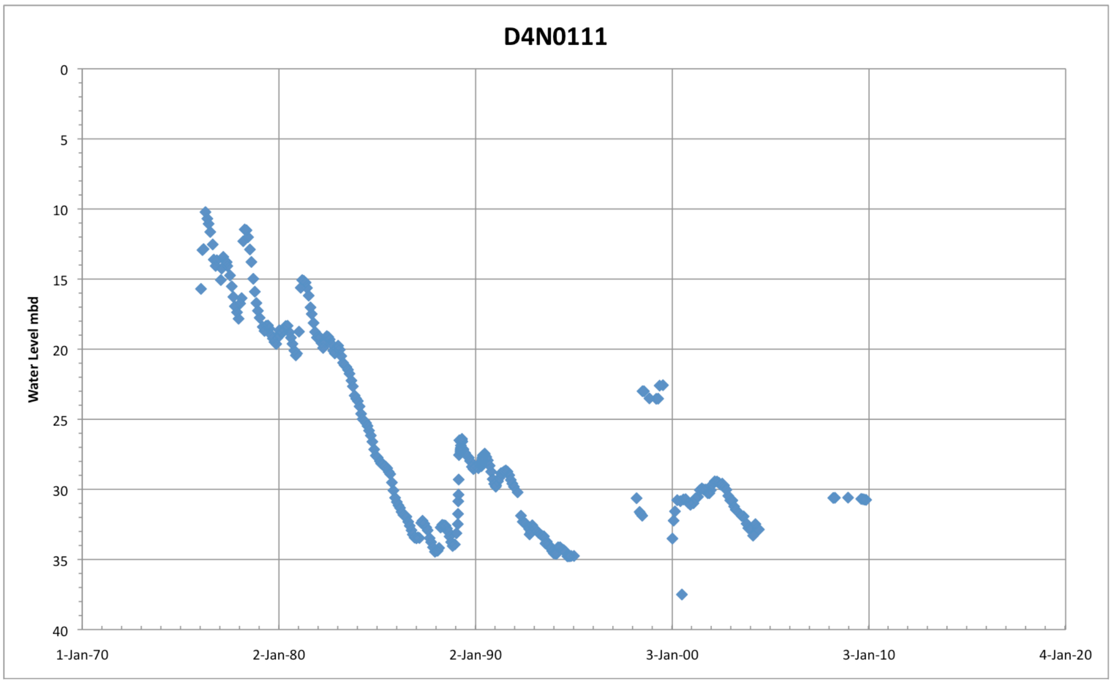

D4N0120
Water Level mbd
0
5
10
15
20
25
30
35
40
45
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20

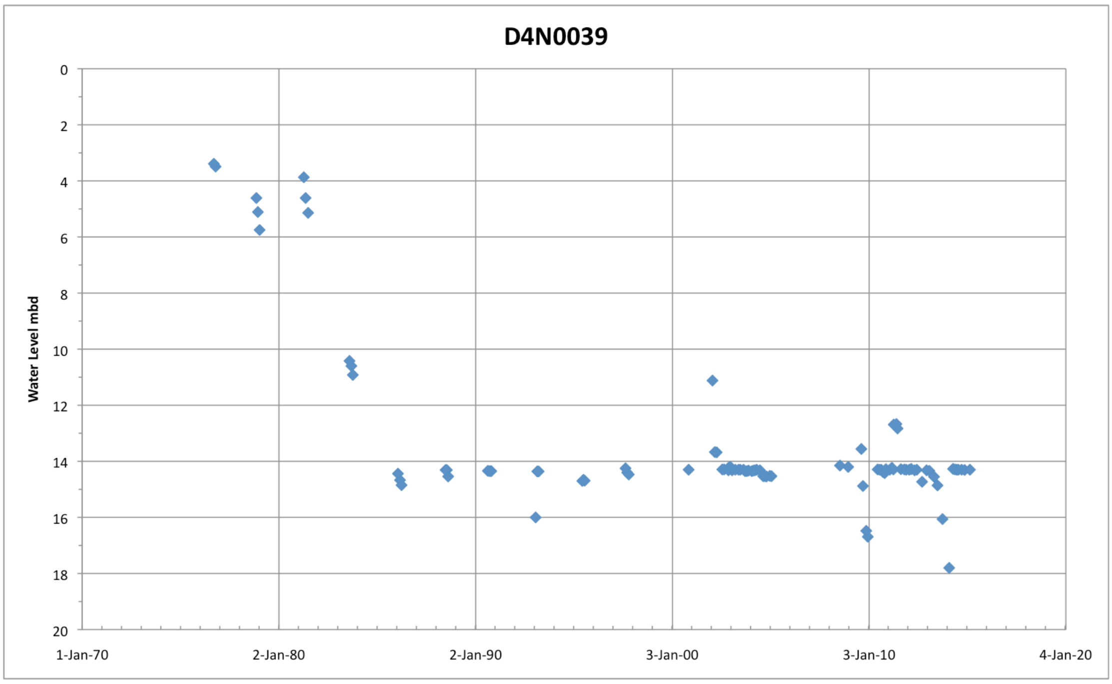

D4N0102
Water Level mbd
0
2
4
6
8
10
12
14
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20

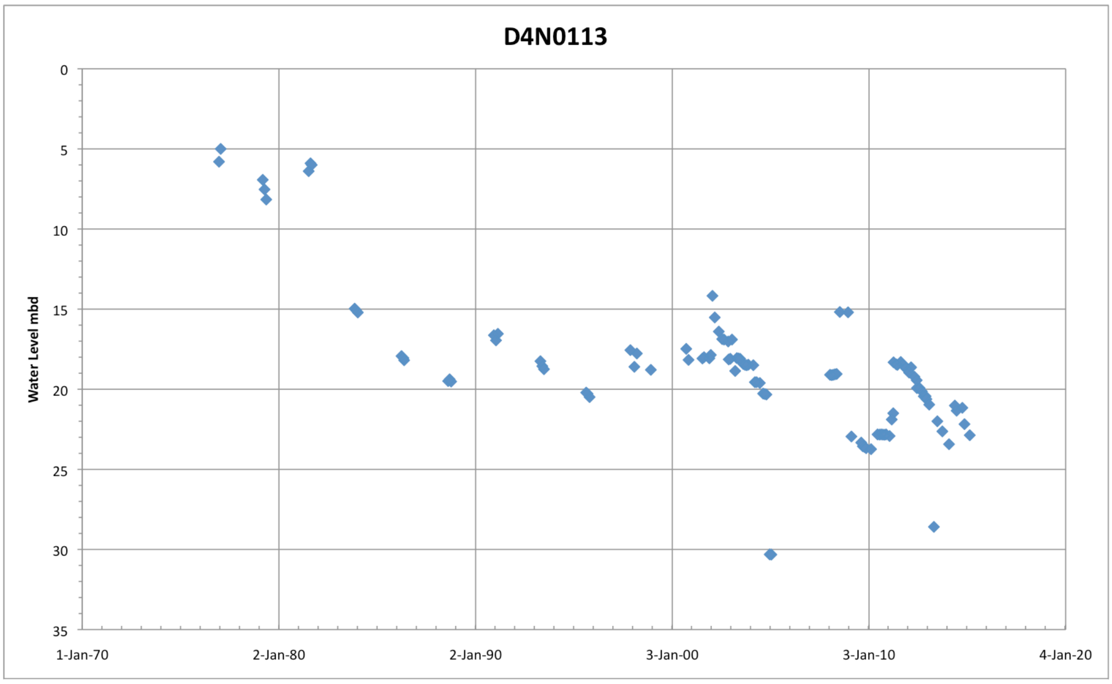

D4N0108
Water Level mbd
0
2
4
6
8
10
12
14
16
18
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20

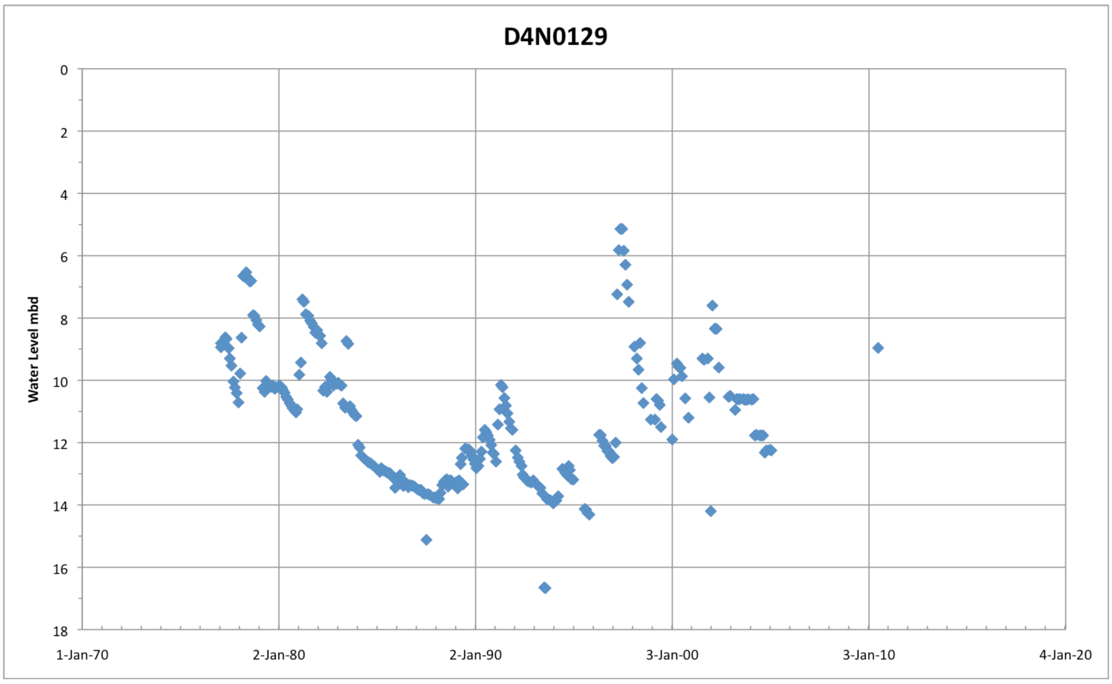

D4N0128
Water Level mbd
0
2
4
6
8
10
12
14
16
18
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20

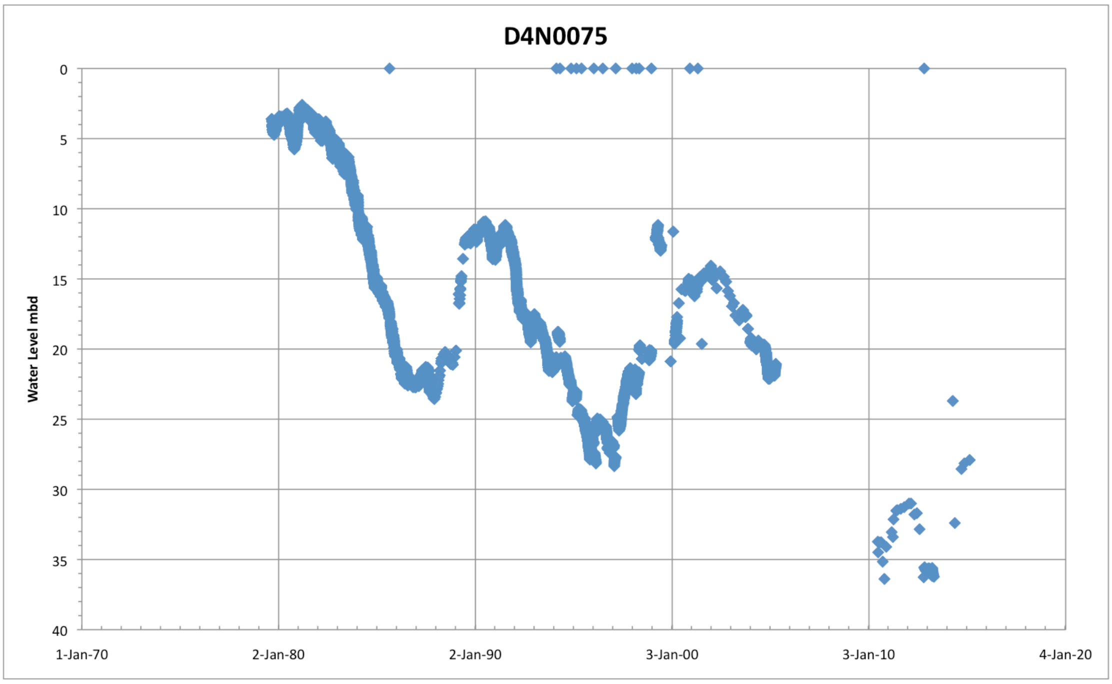

D4N0095
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20

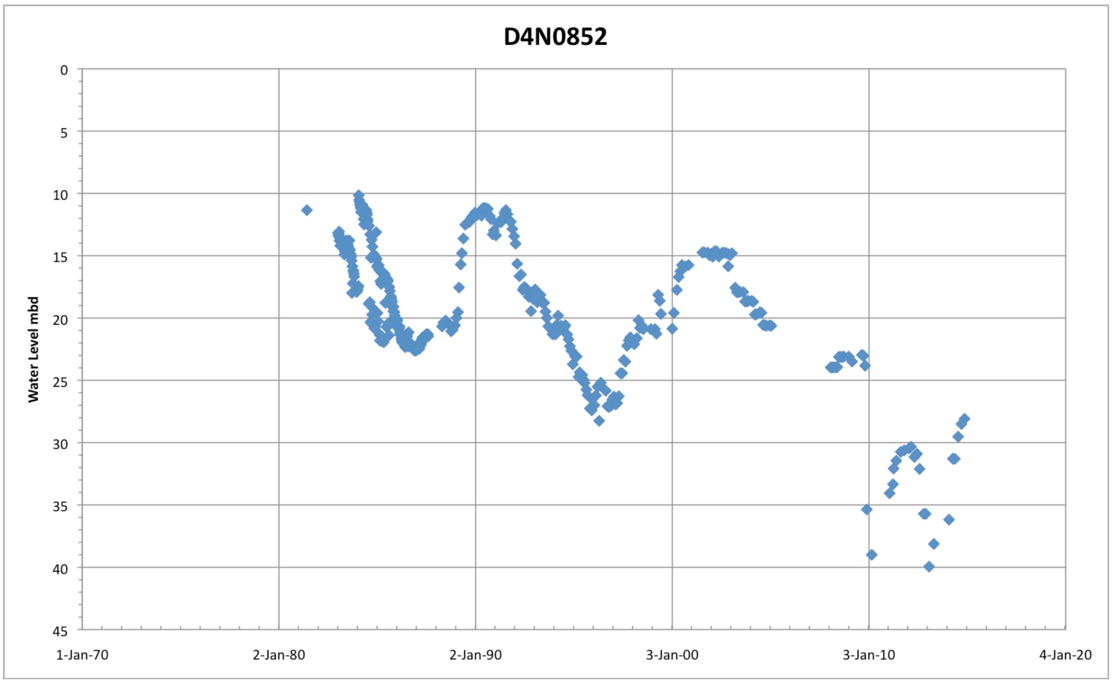

D4N0111
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0039
Water Level mbd
0
2
4
6
8
10
12
14
16
18
20
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0113
Water Level mbd
0
5
10
15
20
25
30
35
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0129
Water Level mbd
0
2
4
6
8
10
12
14
16
18
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0075
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0852
Water Level mbd
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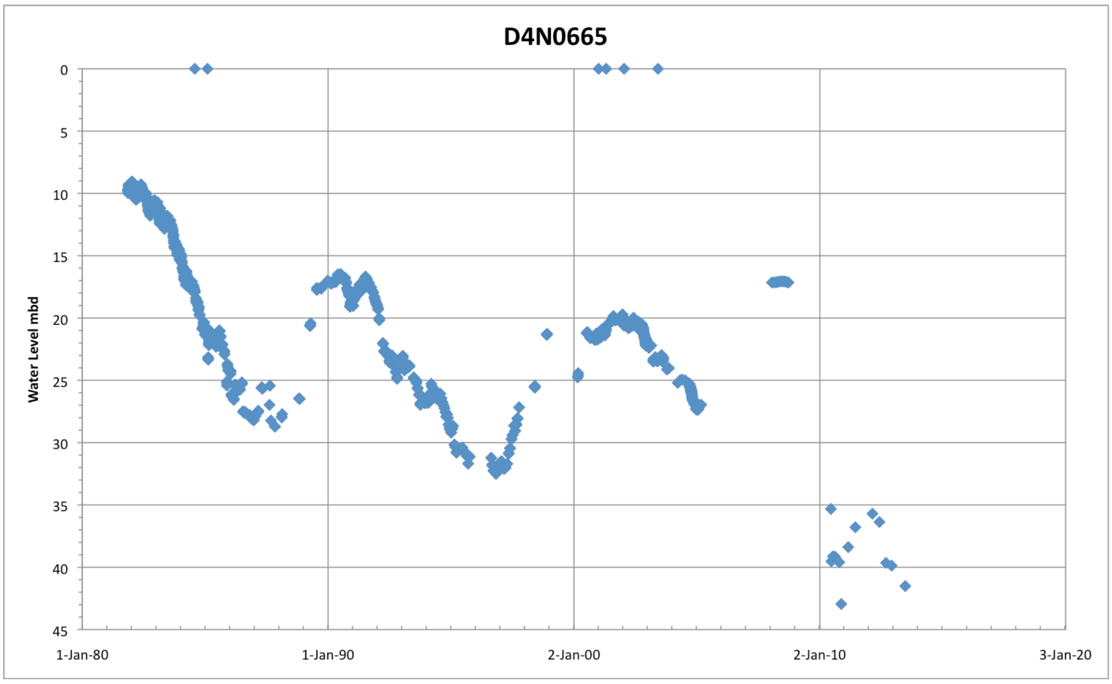
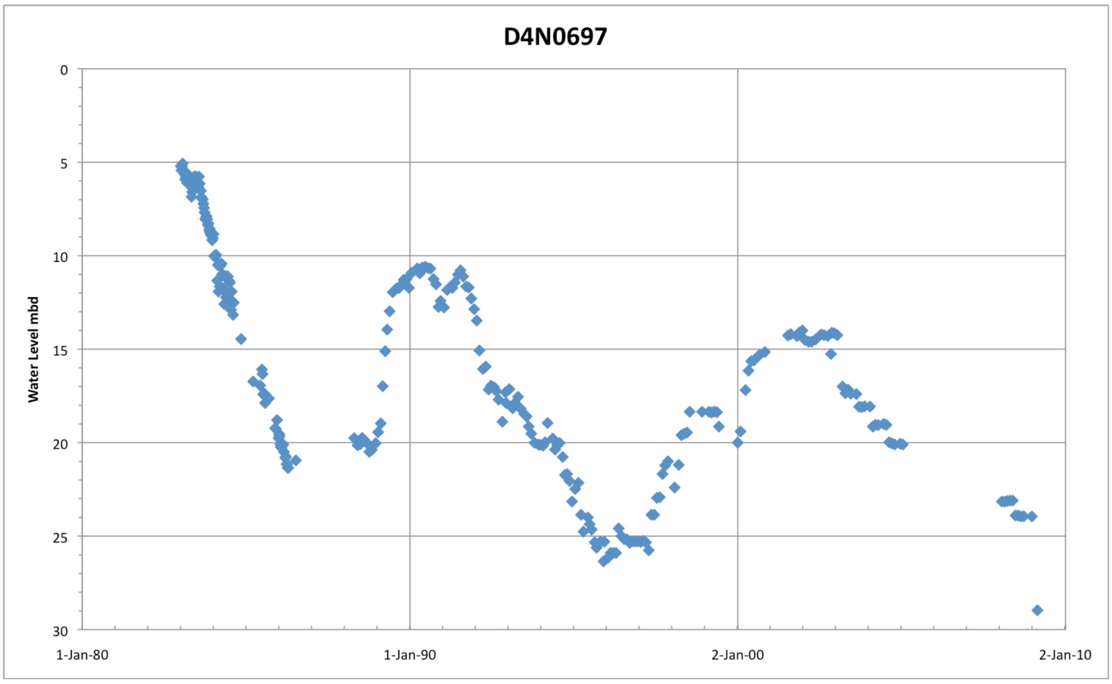
5
10
15
20
25
30
35
40
45
1-Jan-70
2-Jan-80
2-Jan-90
3-Jan-00
3-Jan-10
4-Jan-20


D4N0665
Water Level mbd
0
5
10
15
20
25
30
35
40
45
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10
3-Jan-20


D4N0697
Water Level mbd
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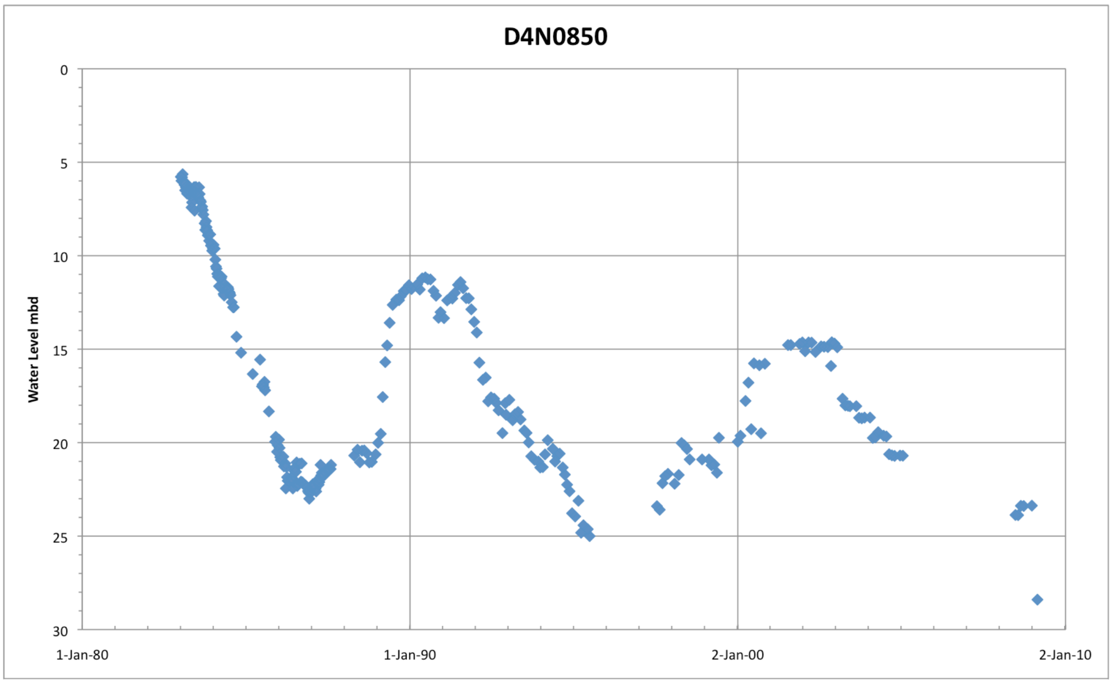
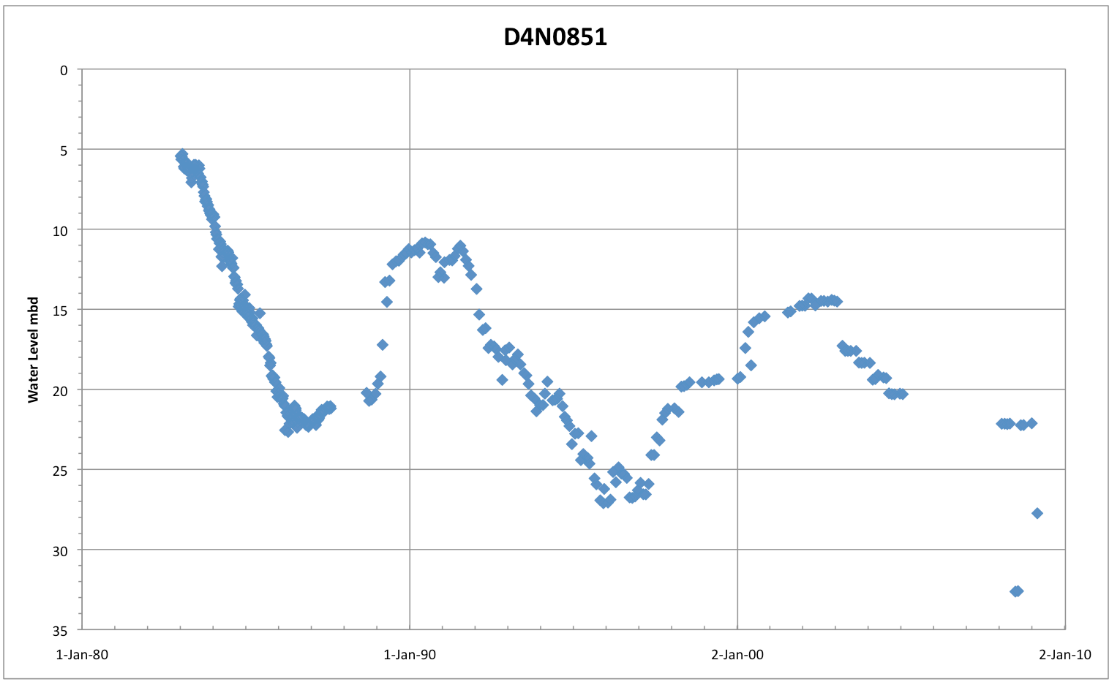
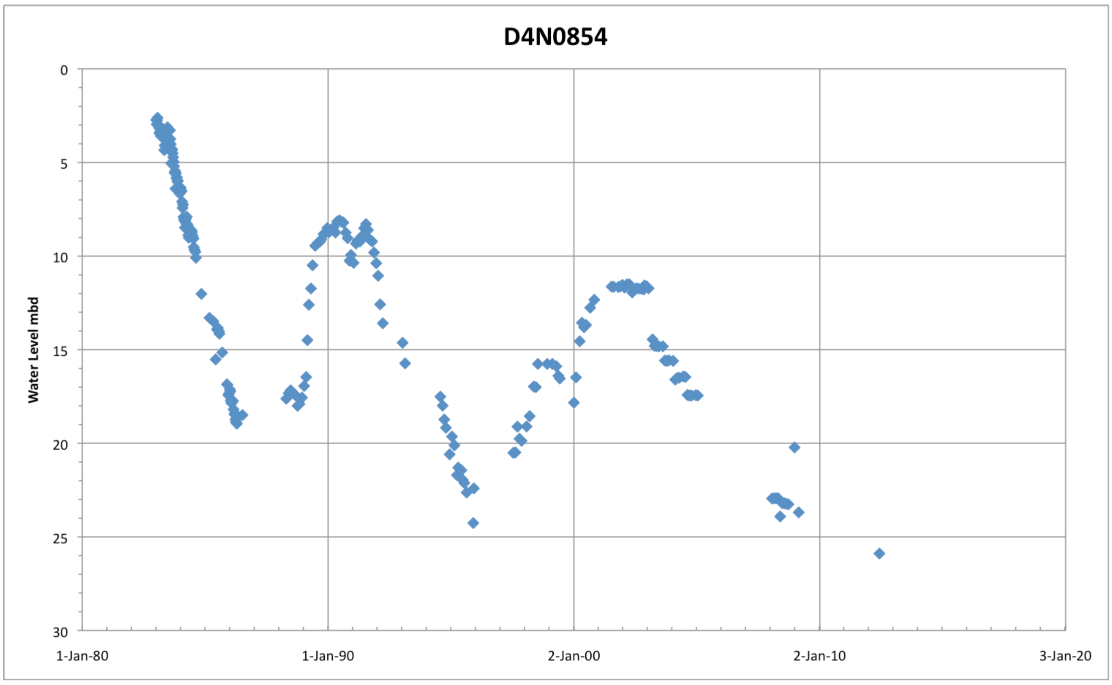
5
10
15
20
25
30
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10

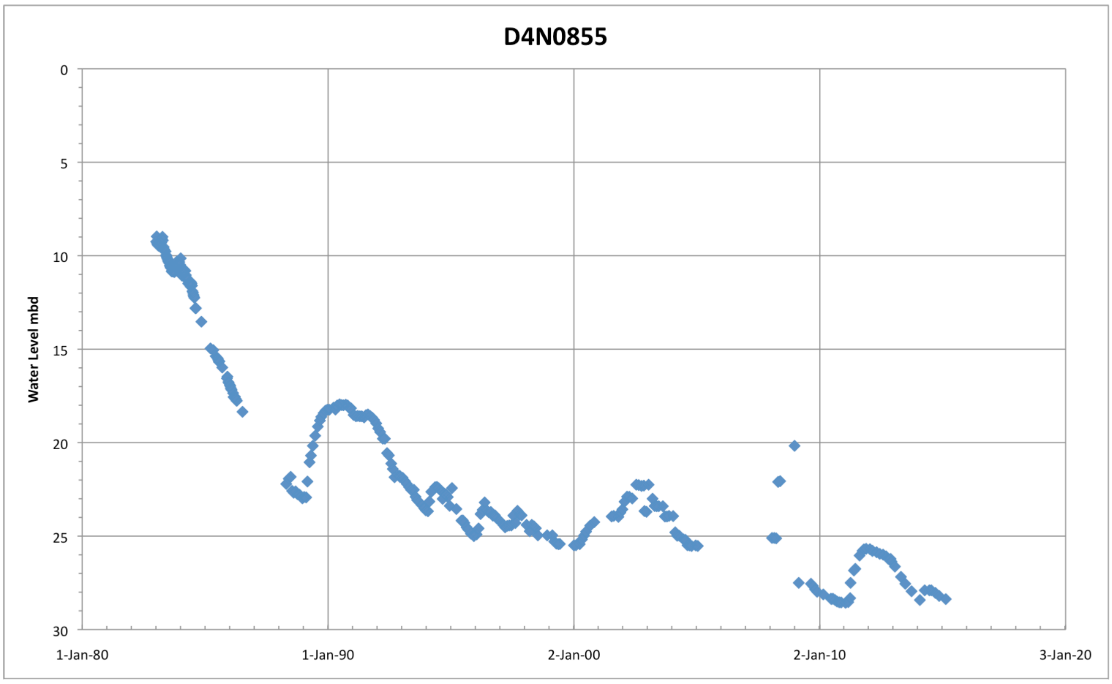

D4N0850
Water Level mbd
0
5
10
15
20
25
30
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10



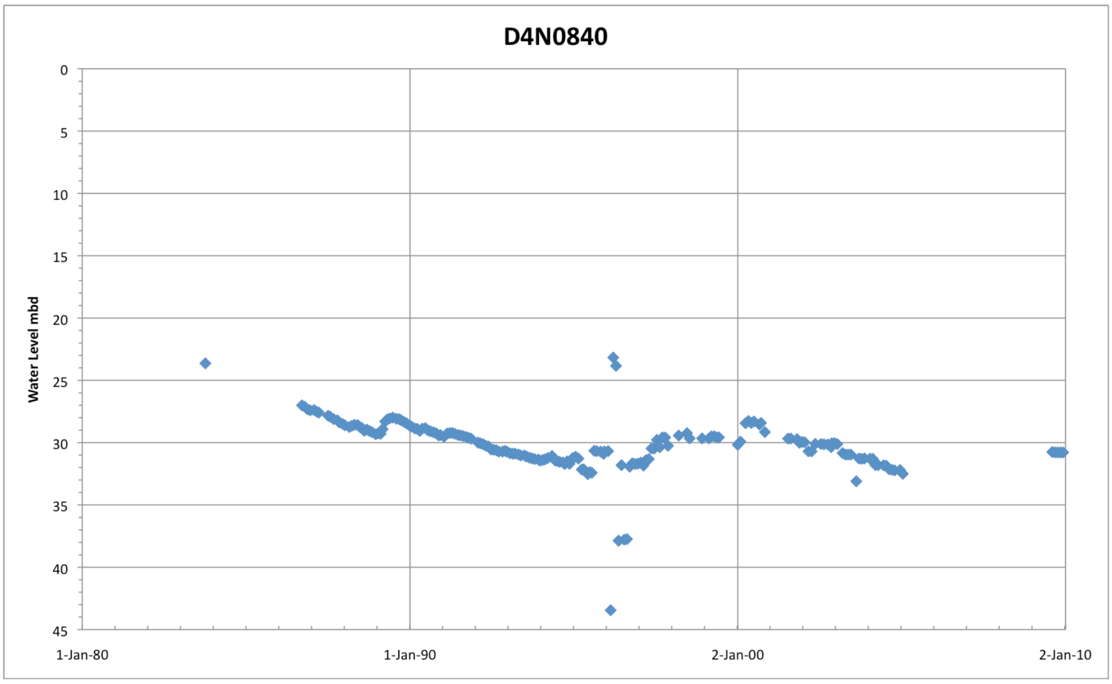
D4N0851
Water Level mbd
0
5
10
15
20
25
30
35
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10

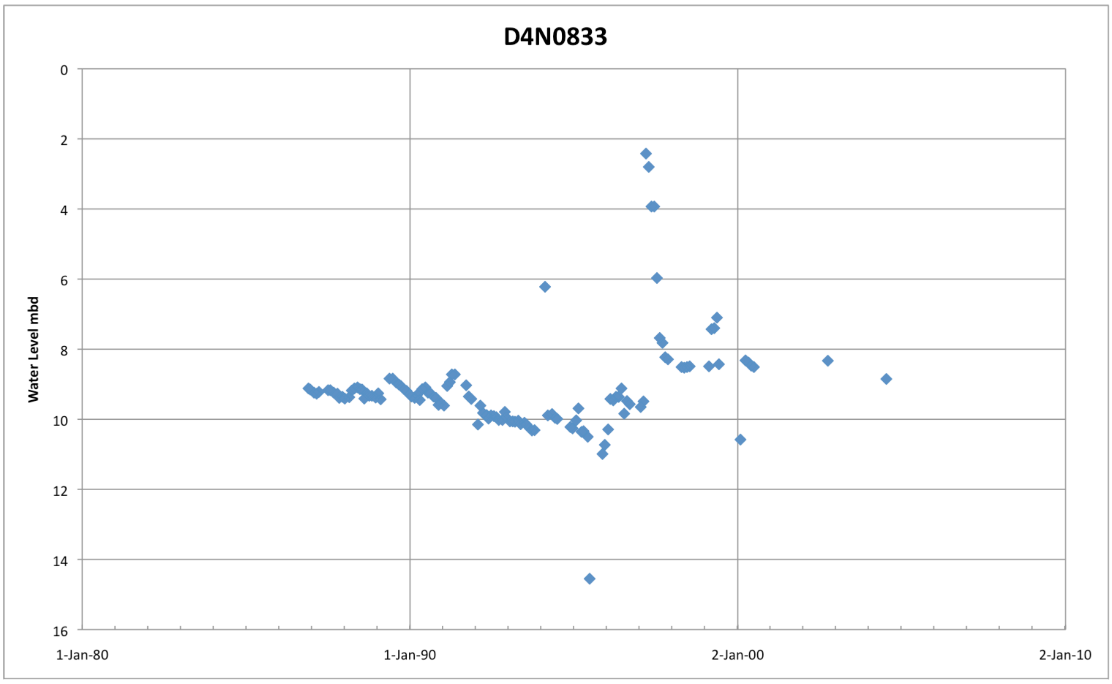
D4N0854
Water Level mbd
0
5
10
15
20
25
30
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10
3-Jan-20

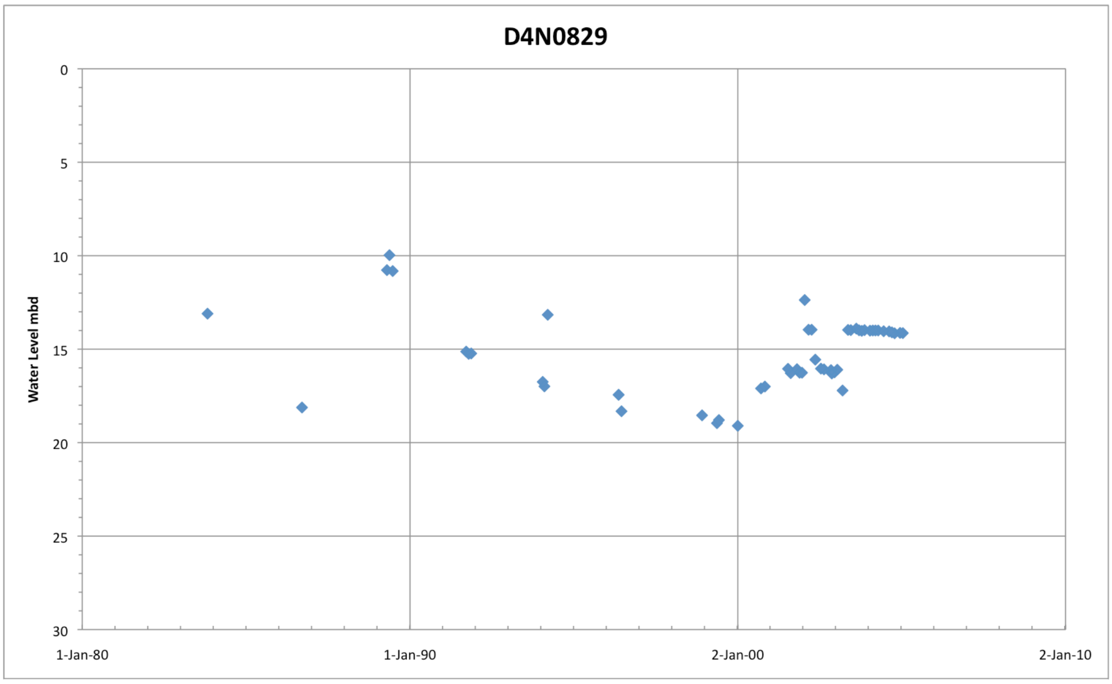


D4N0855
Water Level mbd
0
5
10
15
20
25
30
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10
3-Jan-20

D4N0840
Water Level mbd
0
5
10
15
20
25
30
35
40
45
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10


D4N0833
Water Level mbd
0
2
4
6
8
10
12
14
16
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10


D4N0829
Water Level mbd
0
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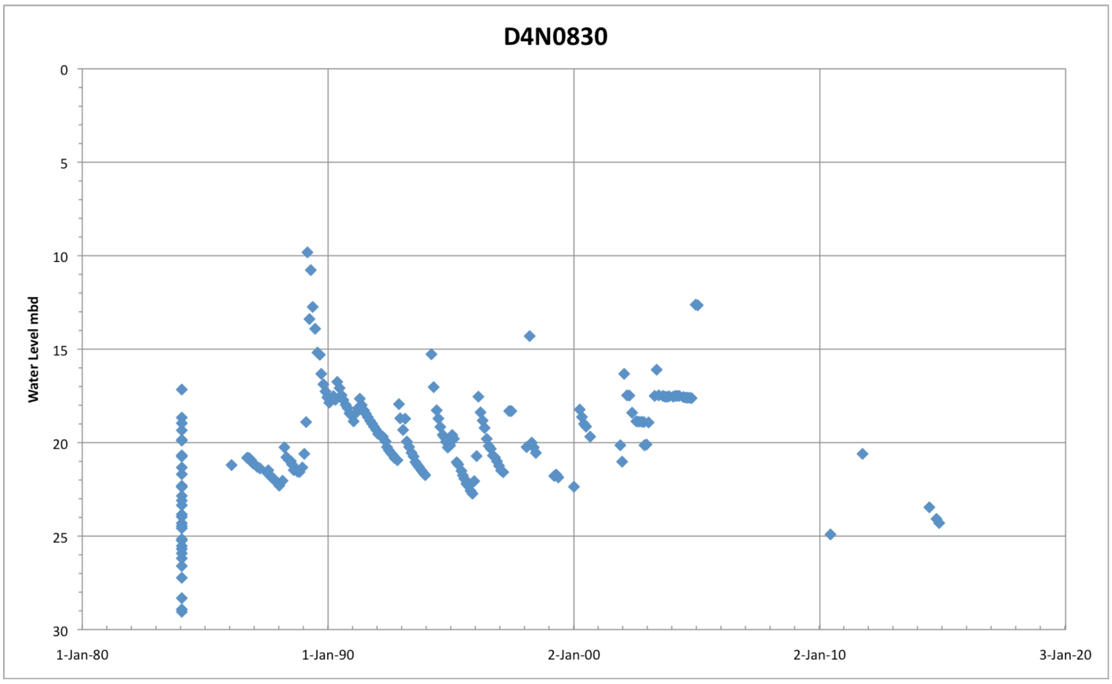
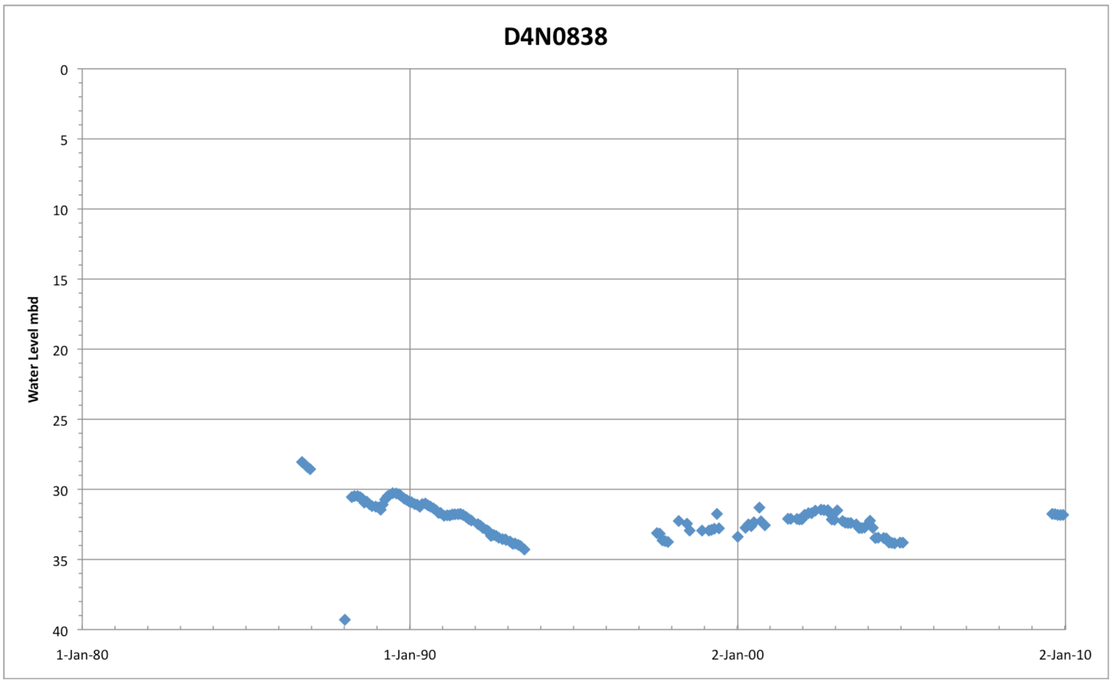
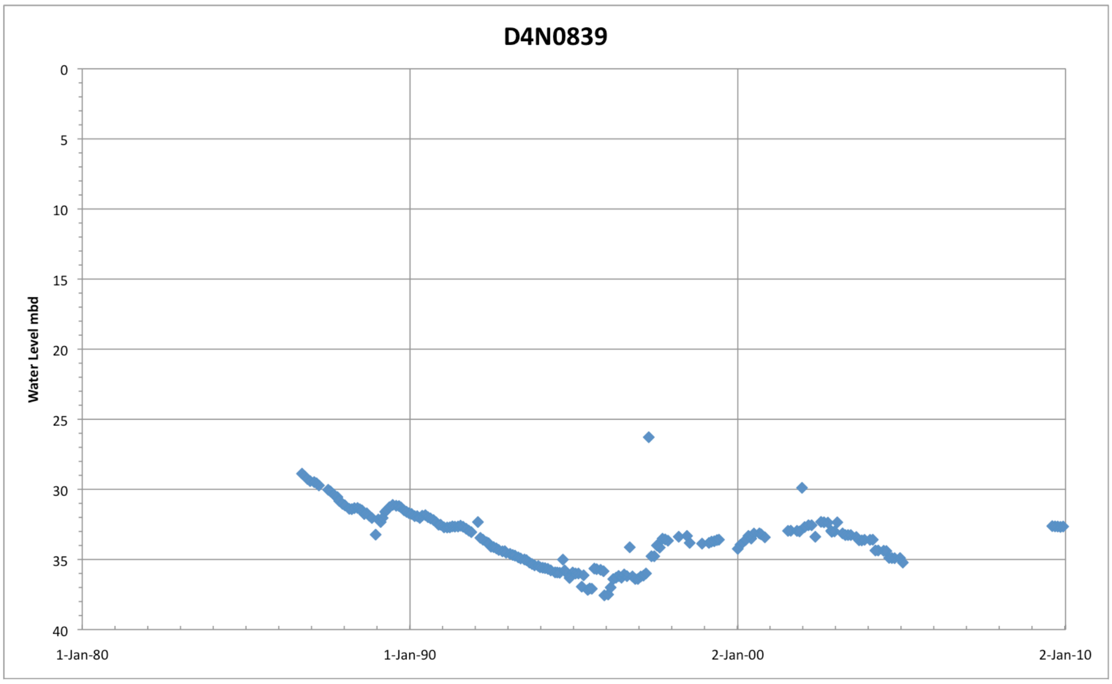
10
15
20
25
30
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10

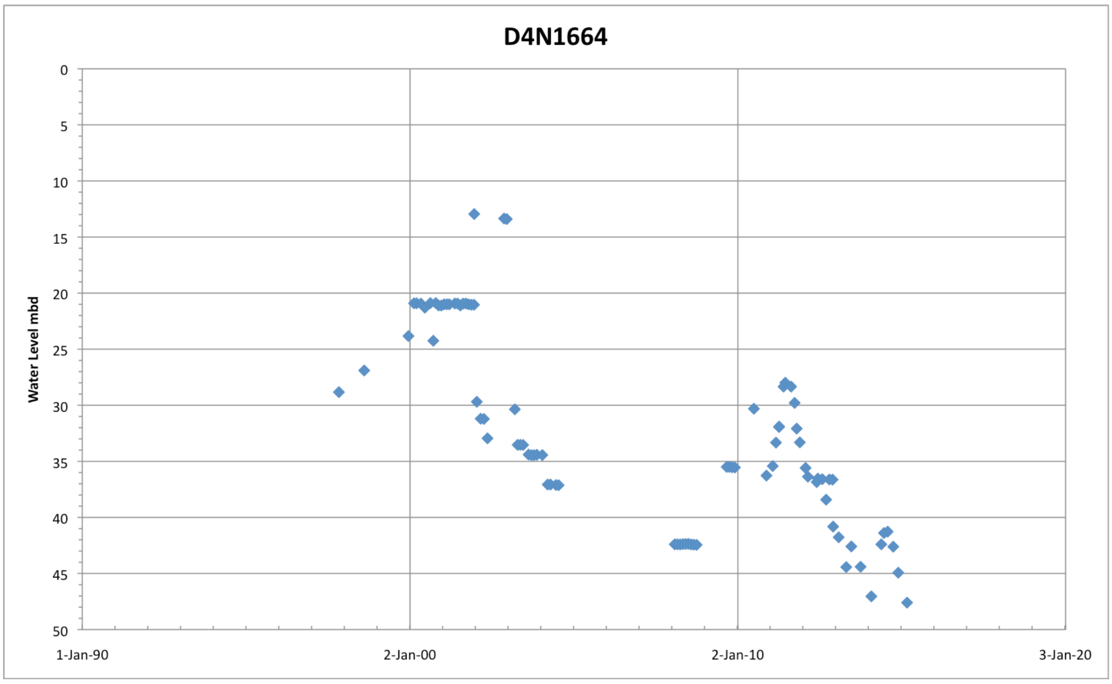


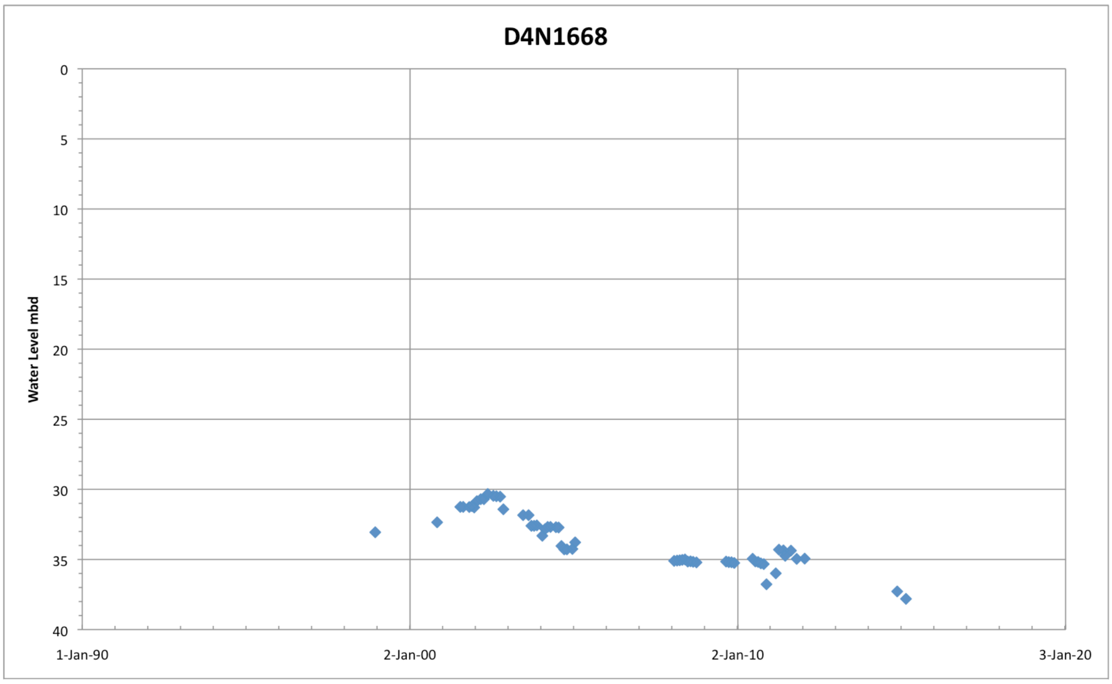
D4N0830
Water Level mbd
0
5
10
15
20
25
30
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10
3-Jan-20

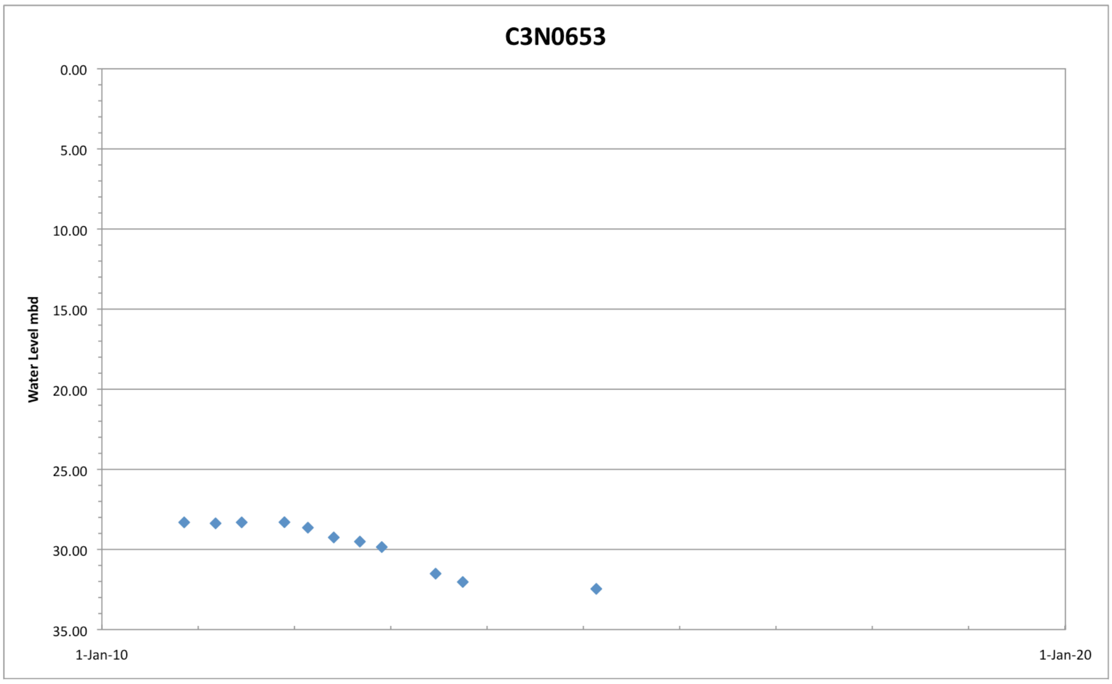



D4N0838
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10

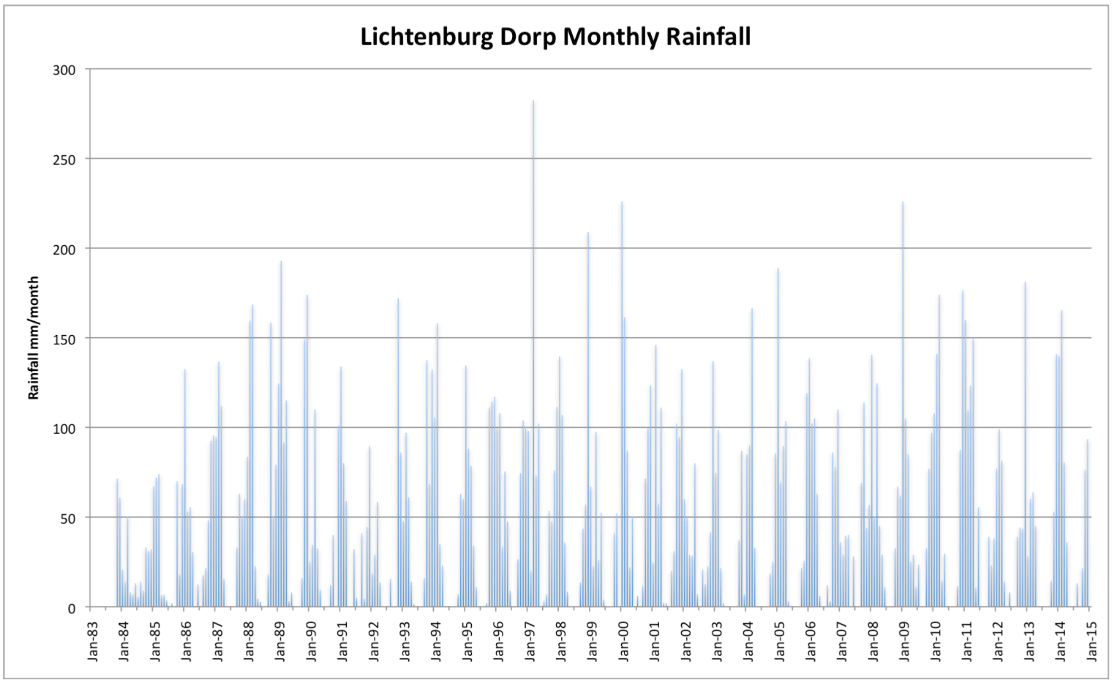

D4N0839
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-80
1-Jan-90
2-Jan-00
2-Jan-10

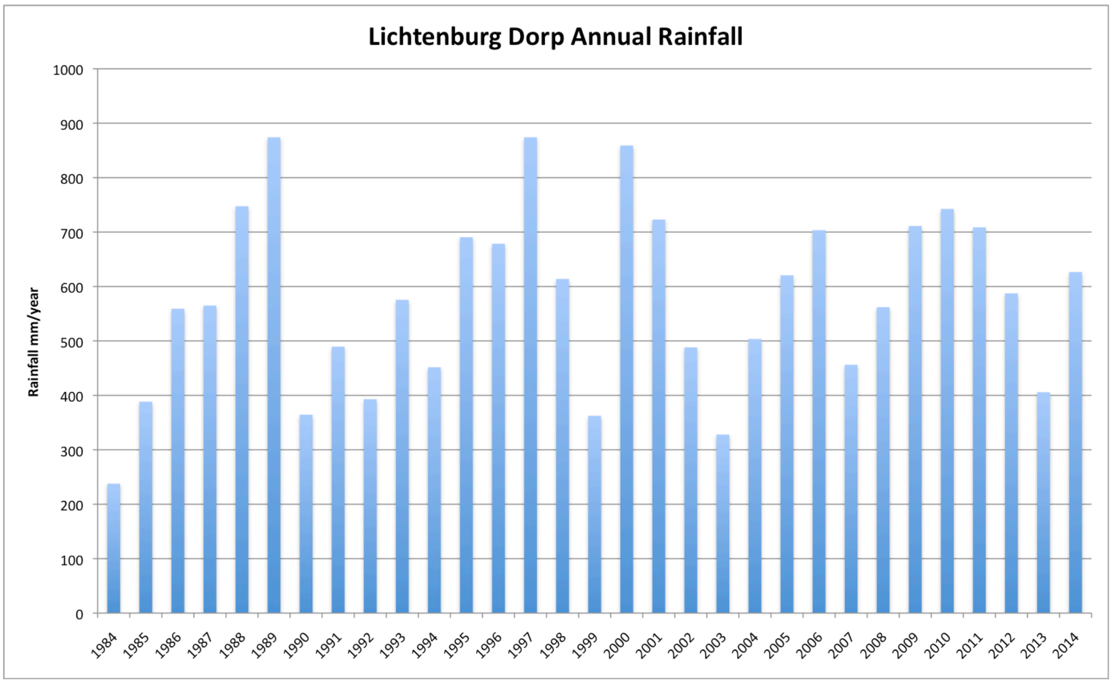

D4N1664
Water Level mbd
0
5
10
15
20
25
30
35
40
45
50
1-Jan-90
2-Jan-00
2-Jan-10
3-Jan-20


D4N1668
Water Level mbd
0
5
10
15
20
25
30
35
40
1-Jan-90
2-Jan-00
2-Jan-10
3-Jan-20


C3N0653
Water Level mbd
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
1-Jan-10
1-Jan-20

## 9.4. Appendix D: Rainfall charts


Lichtenburg Dorp Monthly Rainfall
Rainfall mm/month
300
250
200
150
100
50
0
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14
Jan-15


Lichtenburg Dorp Annual Rainfall
Rainfall mm/year
1000
900
800
700
600
500
400
300
200
100
0
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
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1999
2000
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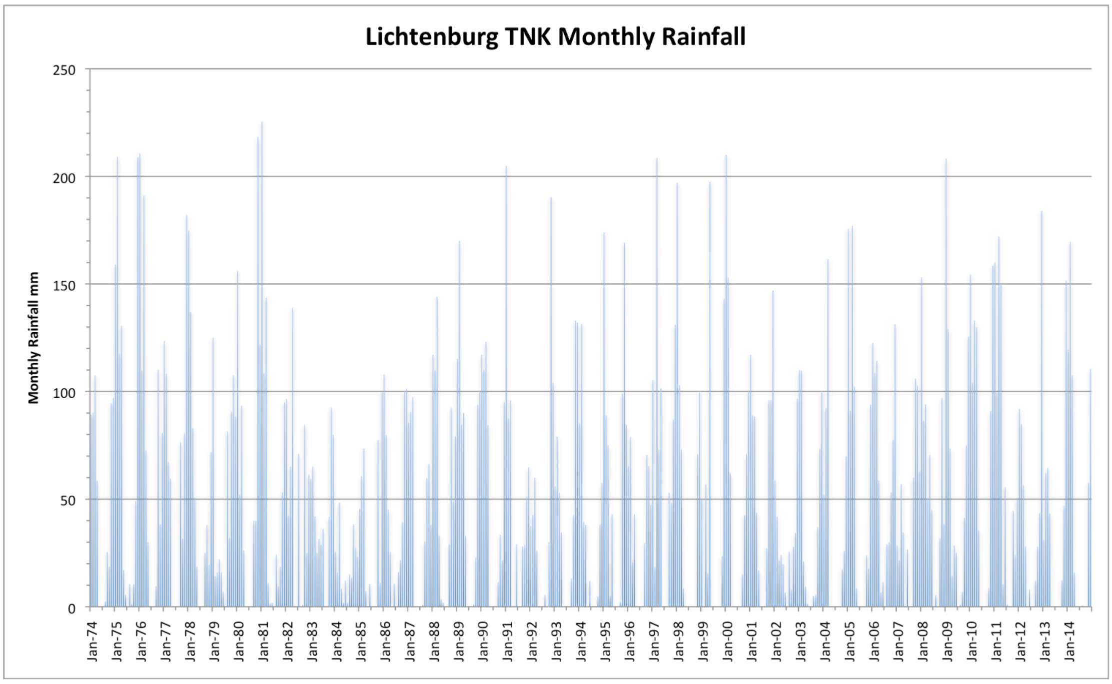
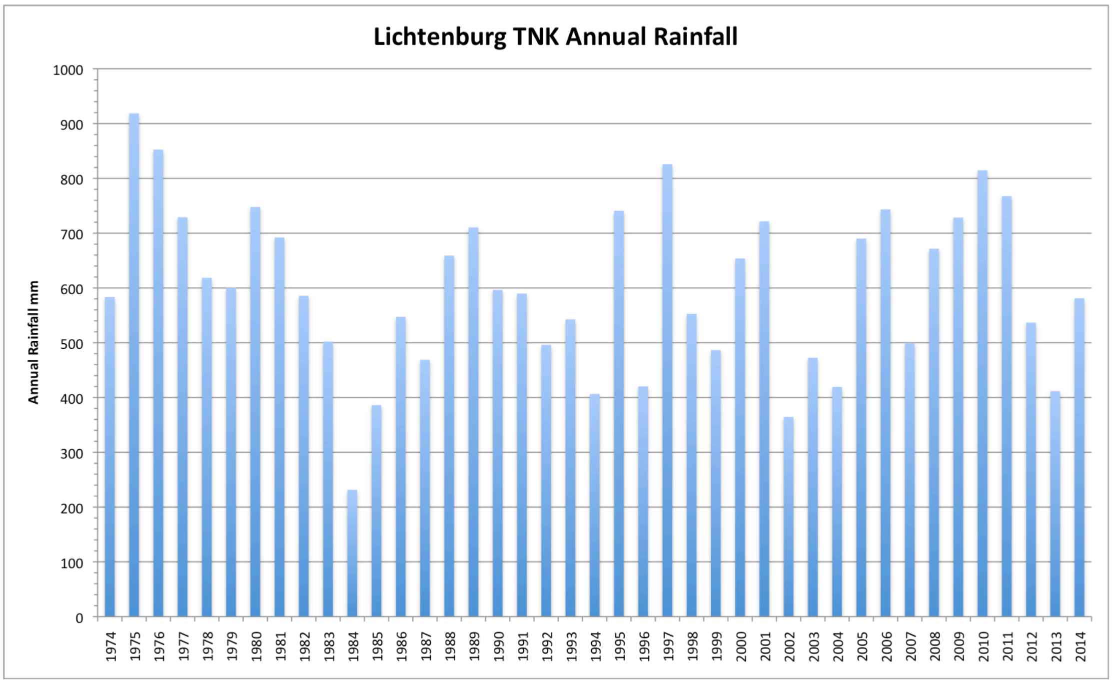
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014



Lichtenburg TNK Monthly Rainfall
Monthly Rainfall mm
250
200
150
100
50
0
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14

Lichtenburg TNK Annual Rainfall
Annual Rainfall mm
1000
900
800
700
600
500
400
300
200
100
0
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
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2000
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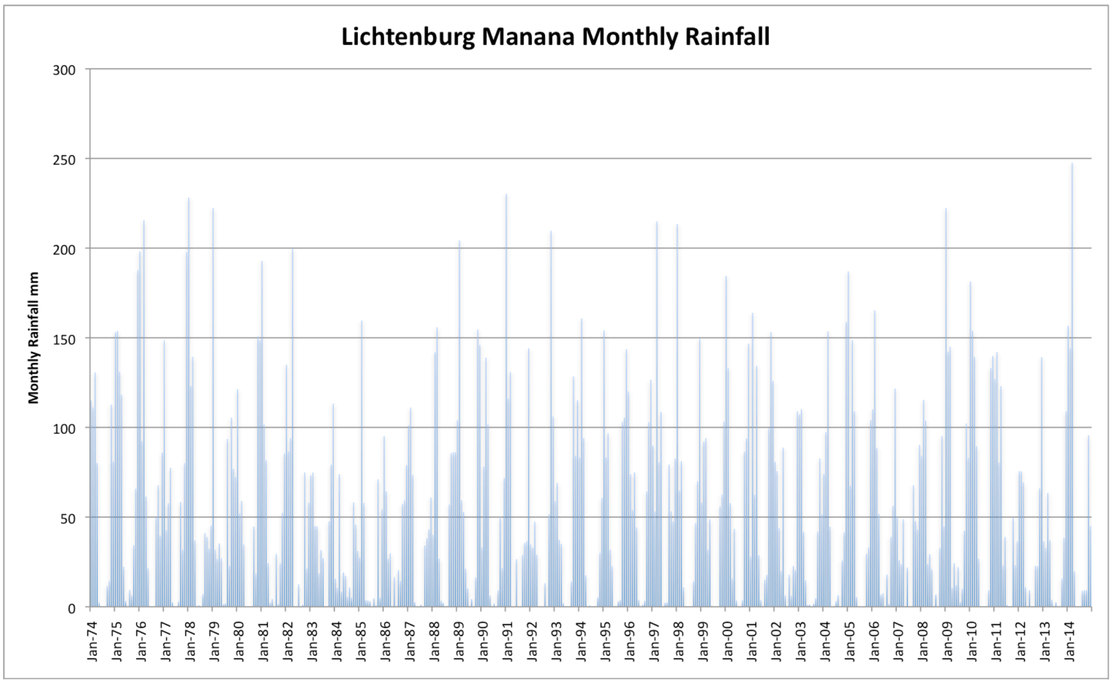
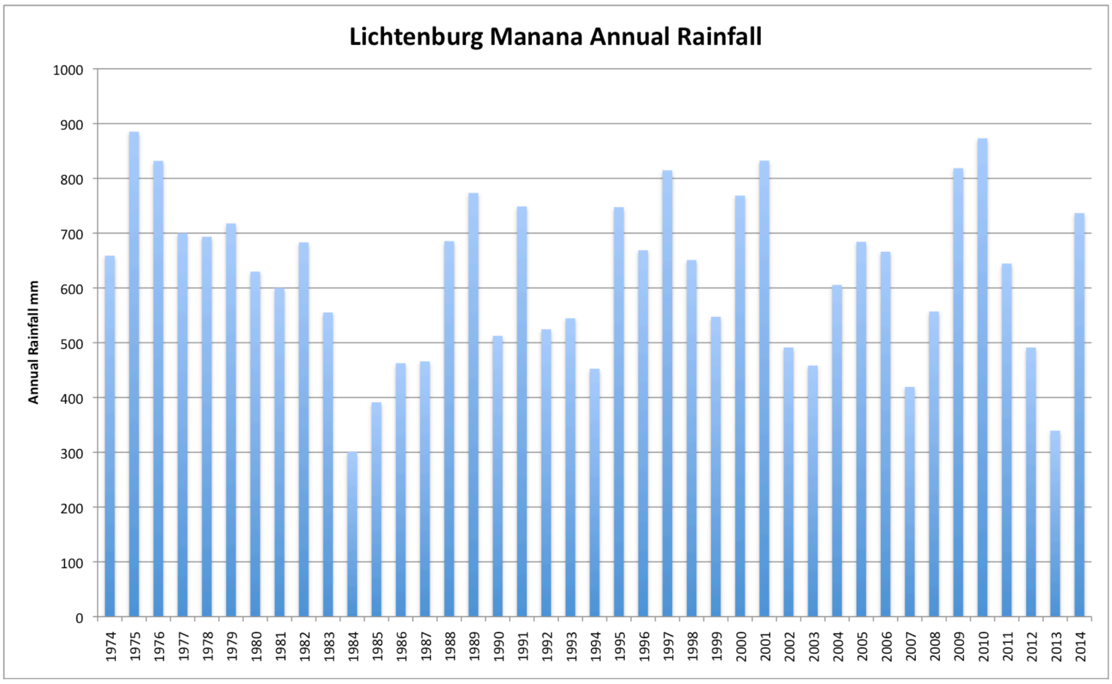
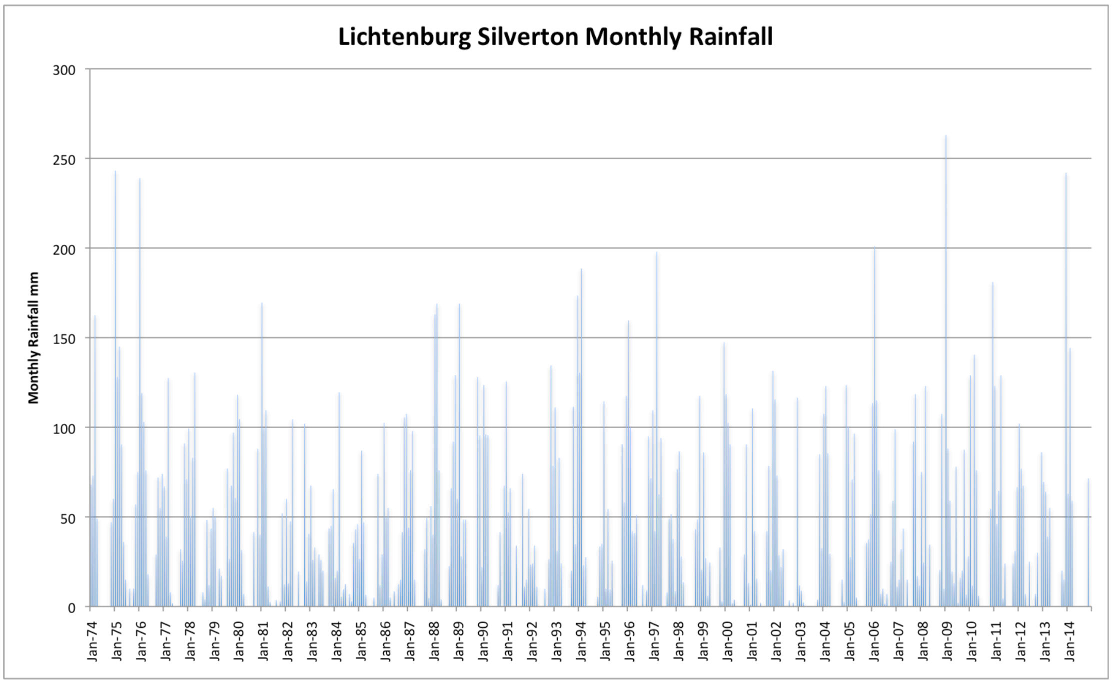
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

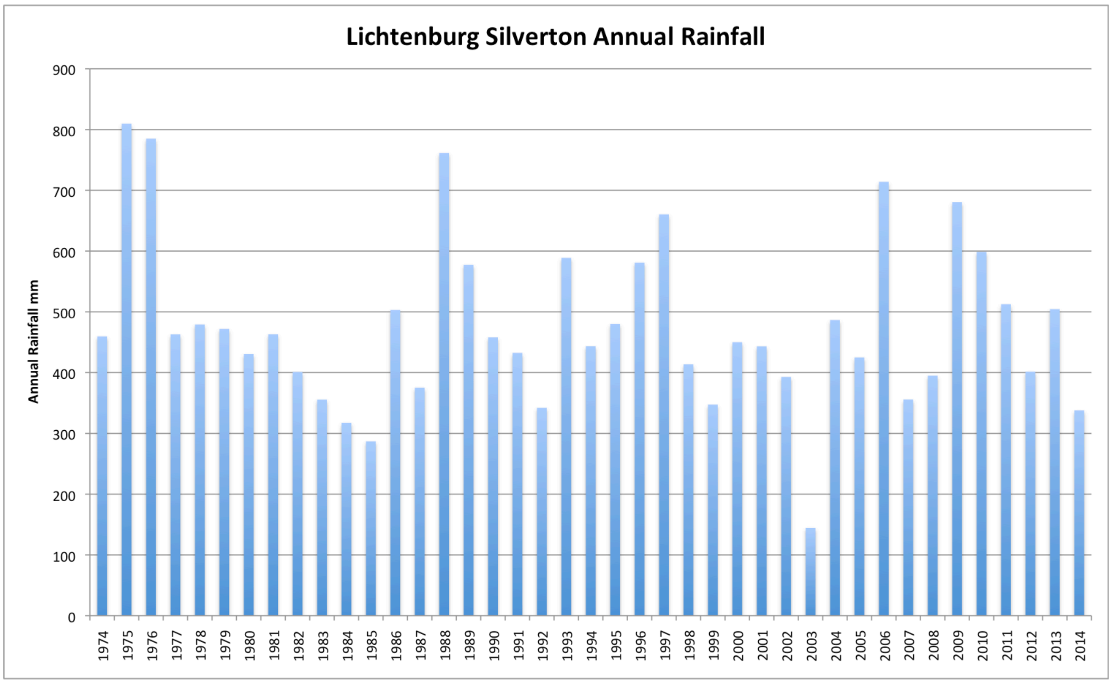


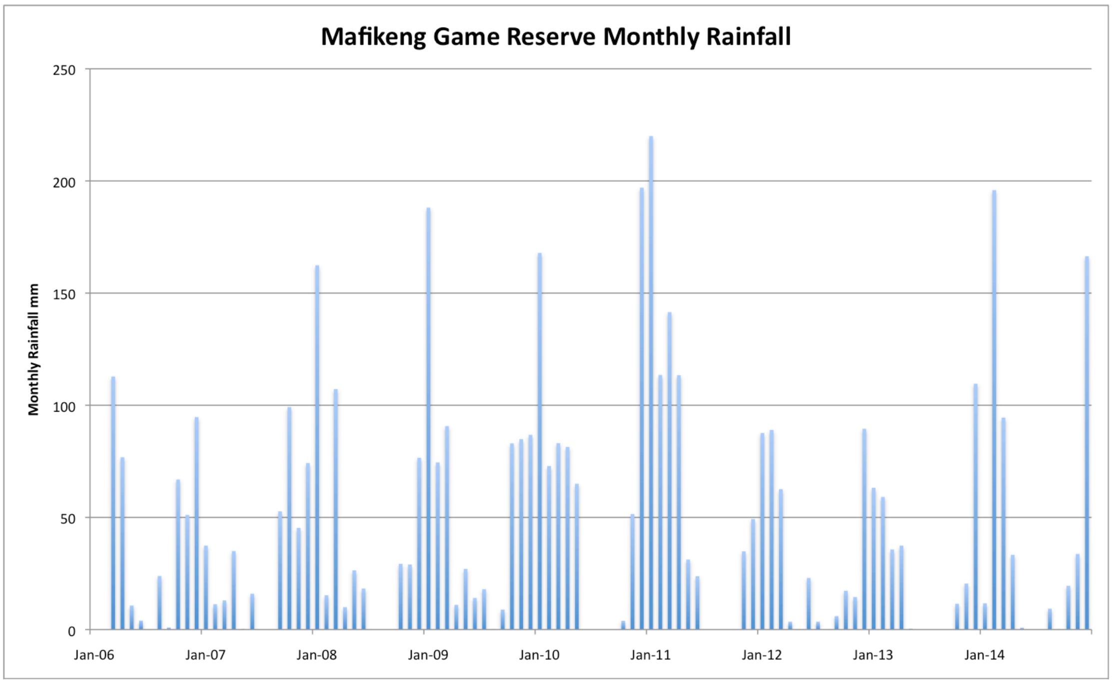
Lichtenburg Manana Monthly Rainfall
Monthly Rainfall mm
300
250
200
150
100
50
0
Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09 Jan-10 Jan-11 Jan-12 Jan-13 Jan-14

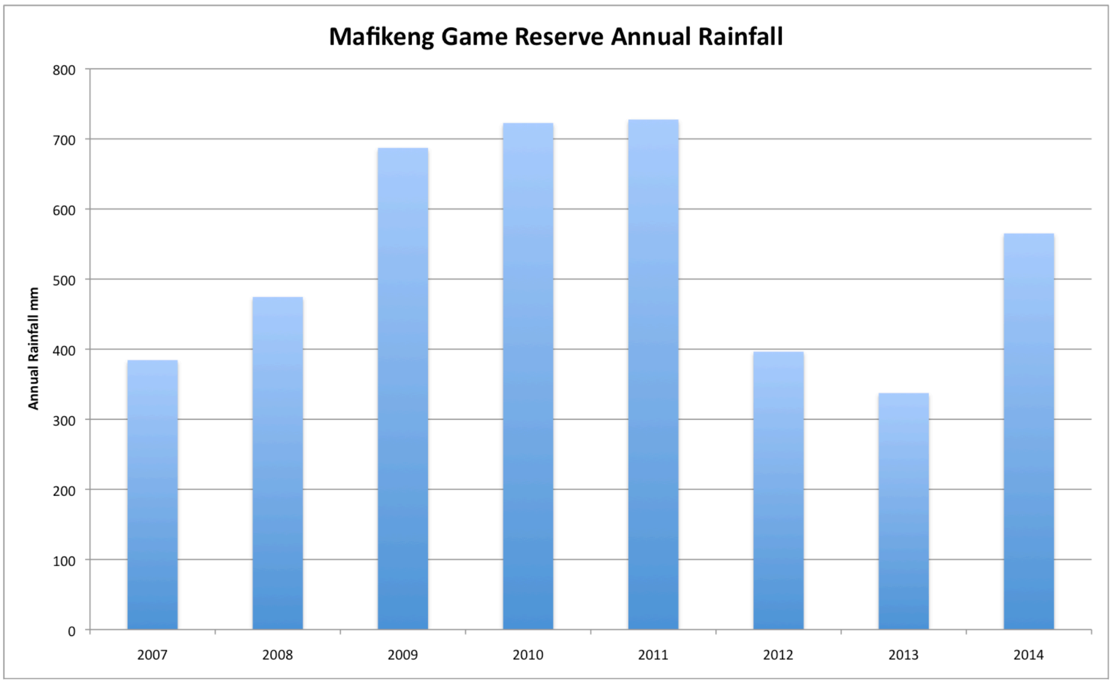



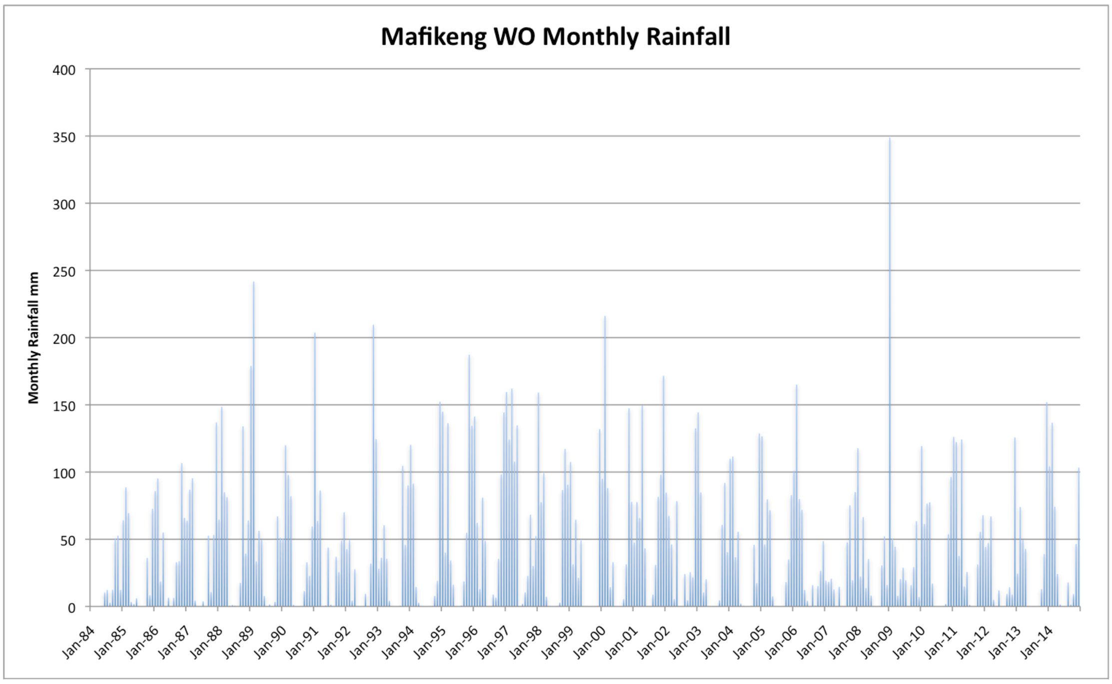
Lichtenburg Manana Annual Rainfall
Annual Rainfall mm
1000
900
800
700
600
500
400
300
200
100
0
1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

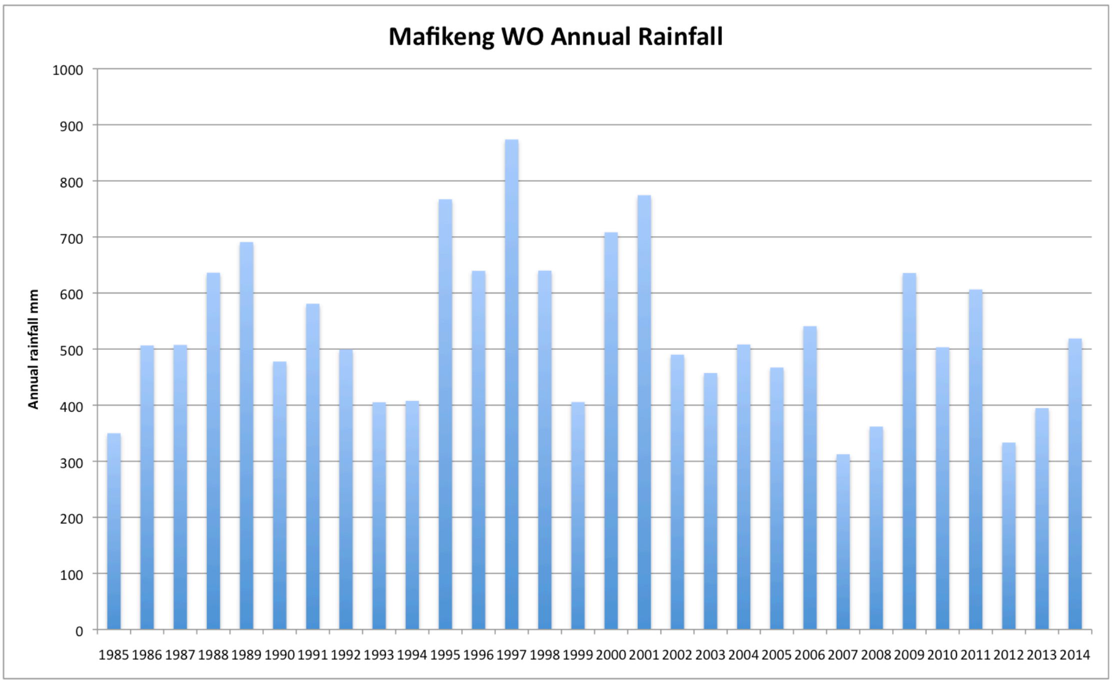

Lichtenburg Silverton Monthly Rainfall
Monthly Rainfall mm
0
50
100
150
200
250
300
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14


Lichtenburg Silverton Annual Rainfall
Annual Rainfall mm
0
100
200
300
400
500
600
700
800
900
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014


Mafikeng Game Reserve Monthly Rainfall
Monthly Rainfall mm
250
200
150
100
50
0
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14


Mafikeng Game Reserve Annual Rainfall
Annual Rainfall mm
800
700
600
500
400
300
200
100
0
2007
2008
2009
2010
2011
2012
2013
2014


Mafikeng WO Monthly Rainfall
Monthly Rainfall mm
400
350
300
250
200
150
100
50
0
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
Jan-10
Jan-11
Jan-12
Jan-13
Jan-14


Mafikeng WO Annual Rainfall
Annual rainfall mm
1000
900
800
700
600
500
400
300
200
100
0
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

## 9.5. Appendix E: Isotope analysis reports

National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

Environmental Isotope Laboratory

*Postal address: Private Bag 11, Wits, 2050, South Africa.*
*Physical Address: Empire Road (between Jan Smuts Avenue and Yale Road)*
*Tel ++27 11 351 7000/1 (switchboard/secretary), Fax ++27 11 351 7053*

# Report

Reference: NMMU007

**Date:** 28th July 2015

## Environmental isotope analysis on five (5) water samples

**submitted by Mr Jude Cobbing**
**Supervisor: Prof Maarten de Wit**

**Nelson Mandela Metropolitan University**

**Groundwater Management in South Africa: Linking the Physical Resource to Social, Institutional and Planning Requirements.**

— —

M.J. Butler, O.H.T. Malinga, M. Mabitsela

**confidential**

## 1. General

Five water samples were submitted by Mr J. Cobbing of the Nelson Mandela Metropolitan University for D/H ($^{2}H/^{1}H$), $^{18}O/^{16}O$ and tritium analysis. The samples were received on the 29th of May 2015.

## 2. Stable Isotope Analysis

Water D/H ($^{2}H/^{1}H$) and $^{18}O/^{16}O$ ratios were analysed in the laboratory of the Environmental Isotope Group (EIG) of iThemba Laboratories, Gauteng. The equipment used for stable isotope analysis consists of a PDZ Europa GEO 20-20 gas mass–spectrometer connected to peripheral sample preparation devices. A PDZ water equilibration system (WES), working in dual inlet mode is employed for hydrogen and oxygen isotope analysis of water. Equilibration time for the water sample with hydrogen is about one hour and $CO_2$ is equilibrated with a water sample in about eight hours. Laboratory standards, calibrated against international reference materials, are analysed with each batch of samples. The analytical precision is estimated at 0.1‰ for O and 0.5‰ for H.

Analytical results are presented in the common delta-notation:

$$\delta^{18}O(‰) = \left[ \frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right] \times 1000$$

which applies to D/H ($^{2}H/^{1}H$), accordingly. These delta values are expressed as per mil deviation relative to a known standard, in this case standard mean ocean water (SMOW) for $\delta^{18}O$ and $\delta D$.

## 3. Tritium Analysis

The samples were distilled and subsequently enriched by electrolysis. The electrolysis cells consist of two concentric metal tubes, which are insulated from each other. The outer anode, which is also the container, is of stainless steel. The inner cathode is of mild steel with a special surface coating. Some 500 ml of the water sample, having first been distilled and containing sodium hydroxide, is introduced into the cell. A direct current of some 10–20 ampere is then passed through the cell, which is cooled because of the heat generation. After several days, the electrolyte volume is reduced to some 20 ml. The volume reduction of some 25 times produces a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) are run in one cell of each batch to check on the enrichment attained.

For liquid scintillation counting samples are prepared by directly distilling the enriched water sample from the now highly concentrated electrolyte. 10 ml of the distilled water sample is mixed with 11 ml Ultima Gold and placed in a vial in the analyser and counted 2 to 3 cycles of 4 hours. Detection limits are 0.2 TU for enriched samples.

## 4. Results

The analytical results are presented in Tables 1 and 2 and partially illustrated in Figure 1.

The stable isotope analyses for all samples data could be well reproduced within the expected analytical error limits. Figure 1 shows these data in a $\delta^{18}O$ vs. $\delta D$ space relative to the Global Meteoric Water Line (GMWL, Craig, 1961).

## 5. References

**Craig, H.** (1961). Isotopic variations in meteoric waters. *Science*, **133**, 1702–1703.

**Table 1: Analytical Results**

| | | Deuterium | Oxygen-18 | Tritium | |
|---|---|---|---|---|---|
| Lab No | Field Name | δD‰ SMOW | $\delta^{18}$O‰ SMOW | TU | ± |
| | | | | | |
| NMMU 150 | 1 | -24.5 | -4.33 | 1.2 | 0.3 |
| NMMU 151 | 2 | -25.7 | -4.18 | 0.9 | 0.3 |
| NMMU 152 | 3 | -24.6 | -3.87 | 0.3 | 0.2 |
| NMMU 153 | 4 | -26.3 | -4.48 | 1.0 | 0.3 |
| NMMU 154 | 5 | +20.3 | +4.75 | 2.3 | 0.3 |

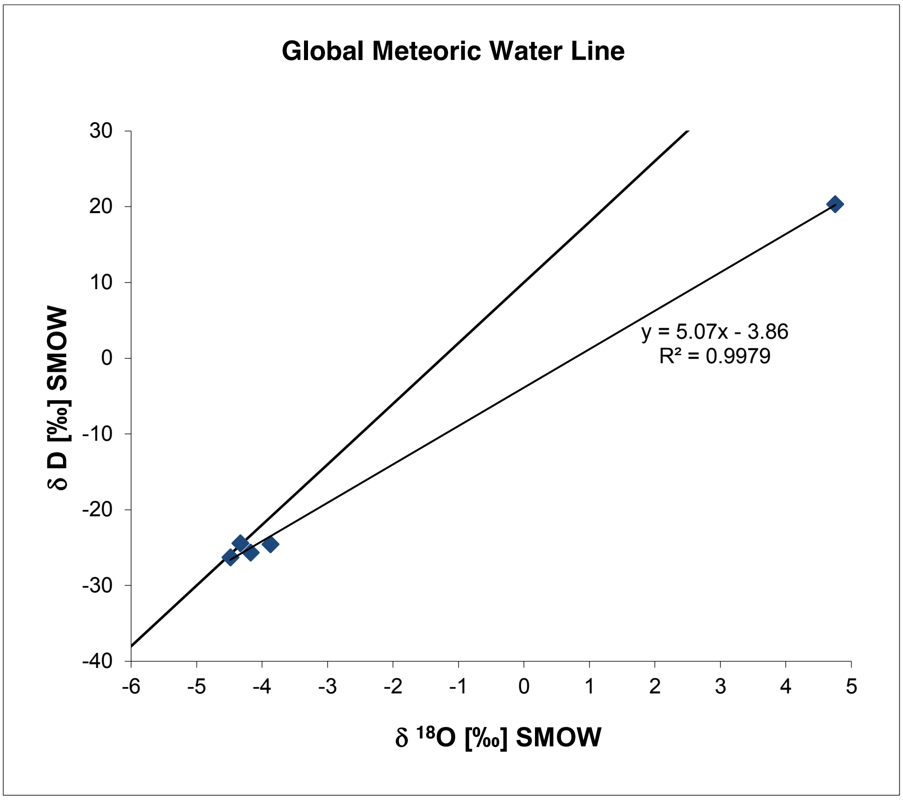



**Figure 1**: Stable isotope data relative to Global Meteoric Water Line (Craig, 1961).

**Table 2: Stable isotope aliquot determinations**

| Lab No. | Field Name: | Deuterium analysis | Deuterium Batch | **δD‰ SMOW** | Oxygen-18 analysis | Oxygen-18 Batch | **$\delta^{18}$O‰ SMOW** |
|---|---|---|---|---|---|---|---|
| NMMU 150 | 1 | a | 2015/07/14 | -24.4 | a | 2015/07/08 | -4.39 |
| | | b | | -24.5 | b | | -4.27 |
| | | | **avg.:** | **-24.5** | | **avg.:** | **-4.33** |
| | | | *diff.:* | *0.1* | | *diff.:* | *0.13* |
| NMMU 151 | 2 | a | 2015/07/14 | -25.9 | a | 2015/07/08 | -4.23 |
| | | b | | -25.4 | b | | -4.12 |
| | | | **avg.:** | **-25.7** | | **avg.:** | **-4.18** |
| | | | *diff.:* | *0.5* | | *diff.:* | *0.11* |
| NMMU 152 | 3 | a | 2015/07/14 | -24.2 | a | 2015/07/08 | -3.90 |
| | | b | | -24.9 | b | | -3.84 |
| | | | **avg.:** | **-24.6** | | **avg.:** | **-3.87** |
| | | | *diff.:* | *0.7* | | *diff.:* | *0.06* |
| NMMU 153 | 4 | a | 2015/07/14 | -26.7 | a | 2015/07/08 | -4.52 |
| | | b | | -26.0 | b | | -4.45 |
| | | | **avg.:** | **-26.3** | | **avg.:** | **-4.48** |
| | | | *diff.:* | *0.7* | | *diff.:* | *0.06* |
| NMMU 154 | 5 | a | 2015/07/14 | 20.6 | a | 2015/07/08 | 4.69 |
| | | b | | 20.0 | b | | 4.82 |
| | | | **avg.:** | **20.3** | | **avg.:** | **4.75** |
| | | | *diff.:* | *0.5* | | *diff.:* | *0.13* |

National Research Foundation | iThemba LABS — Laboratory for Accelerator Based Sciences

Environmental Isotope Laboratory

*Postal address: Private Bag 11, Wits, 2050, South Africa.*
*Physical Address: Empire Road (between Jan Smuts Avenue and Yale Road)*
*Tel ++27 11 351 7000/1 (switchboard/secretary), Fax ++27 11 351 7053*

# Report

Reference: NMMU008

**Date:** 23rd September 2015

## Environmental isotope analysis on eleven (11) water samples

**submitted by Mr Jude Cobbing**
**Supervisor: Prof Maarten de Wit**

**Nelson Mandela Metropolitan University**

**Groundwater Management in South Africa: Linking the Physical Resource to Social, Institutional and Planning Requirements.**

— —

M.J. Butler, O.H.T. Malinga, M. Mabitsela

**confidential**

## 1. General

Eleven water samples were submitted by Mr J. Cobbing of the Nelson Mandela Metropolitan University for D/H ($^2H/^1H$), $^{18}O/^{16}O$ and tritium analysis. The samples were received on the 25th of August 2015.

## 2. Stable Isotope Analysis

Water D/H ($^2H/^1H$) and $^{18}O/^{16}O$ ratios were analysed in the laboratory of the Environmental Isotope Group (EIG) of iThemba Laboratories, Gauteng. The equipment used for stable isotope analysis consists of a PDZ Europa GEO 20-20 gas mass–spectrometer connected to peripheral sample preparation devices. A PDZ water equilibration system (WES), working in dual inlet mode is employed for hydrogen and oxygen isotope analysis of water. Equilibration time for the water sample with hydrogen is about one hour and $CO_2$ is equilibrated with a water sample in about eight hours. Laboratory standards, calibrated against international reference materials, are analysed with each batch of samples. The analytical precision is estimated at 0.1‰ for O and 0.5‰ for H.

Analytical results are presented in the common delta-notation:

$$\delta^{18}O(‰) = \left[ \frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right] \times 1000$$

which applies to D/H ($^2H/^1H$), accordingly. These delta values are expressed as per mil deviation relative to a known standard, in this case standard mean ocean water (SMOW) for $\delta^{18}O$ and $\delta D$.

## 3. Tritium Analysis

The samples were distilled and subsequently enriched by electrolysis. The electrolysis cells consist of two concentric metal tubes, which are insulated from each other. The outer anode, which is also the container, is of stainless steel. The inner cathode is of mild steel with a special surface coating. Some 500 ml of the water sample, having first been distilled and containing sodium hydroxide, is introduced into the cell. A direct current of some 10–20 ampere is then passed through the cell, which is cooled because of the heat generation. After several days, the electrolyte volume is reduced to some 20 ml. The volume reduction of some 25 times produces a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) are run in one cell of each batch to check on the enrichment attained.

For liquid scintillation counting samples are prepared by directly distilling the enriched water sample from the now highly concentrated electrolyte. 10 ml of the distilled water sample is mixed with 11 ml Ultima Gold and placed in a vial in the analyser and counted 2 to 3 cycles of 4 hours. Detection limits are 0.2 TU for enriched samples.

## 4. Results

The analytical results are presented in Tables 1 and 2 and partially illustrated in Figure 1.

The stable isotope analyses for all samples data could be well reproduced within the expected analytical error limits. Figure 1 shows these data in a $\delta^{18}O$ vs. $\delta D$ space relative to the Global Meteoric Water Line (GMWL, Craig, 1961).

## 5. References

**Craig, H.** (1961). Isotopic variations in meteoric waters. *Science*, **133**, 1702–1703.

**Table 1: Analytical Results**

| | | | Deuterium | Oxygen-18 | Tritium | |
|---|---|---|---|---|---|---|
| Lab No | Field Name | Description | δD‰ SMOW | $\delta^{18}$O‰ SMOW | TU | ± |
| | | | | | | |
| NMMU 155 | 06 | 2015/06/22 | -24.6 | -4.46 | 0.9 | 0.3 |
| NMMU 156 | 07 | 2015/06/23 | -24.2 | -4.26 | 0.4 | 0.2 |
| NMMU 157 | 08 | 2015/06/23 | -24.7 | -4.39 | 1.0 | 0.3 |
| NMMU 158 | 09 | 2015/06/23 | -24.0 | -4.53 | 1.6 | 0.3 |
| NMMU 159 | 10 | 2015/06/23 | -25.6 | -4.40 | 1.1 | 0.3 |
| NMMU 160 | 11 | 2015/06/23 | -29.4 | -4.94 | 0.3 | 0.2 |
| NMMU 161 | 12 | 2015/06/24 | -26.6 | -4.81 | 1.7 | 0.3 |
| NMMU 162 | 13 | 2015/06/24 | -25.4 | -4.41 | 1.1 | 0.3 |
| NMMU 163 | 14 | 2015/06/24 | -25.0 | -4.37 | 0.7 | 0.2 |
| NMMU 164 | 15 | 2015/07/22 | -26.6 | -4.50 | 0.5 | 0.2 |
| NMMU 165 | 16 | 2015/07/23 | -24.1 | -4.55 | 0.3 | 0.2 |

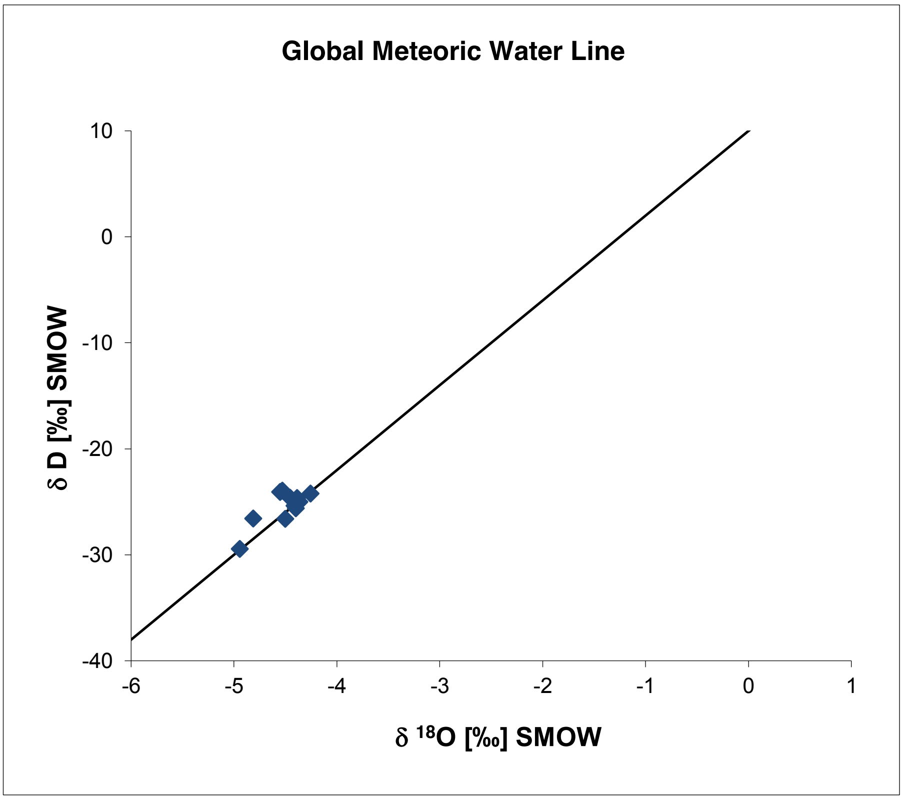



**Figure 1**: Stable isotope data relative to Global Meteoric Water Line (Craig, 1961).

**Table 2: Stable isotope aliquot determinations**

| Lab No. | Field Name: | Description | Deuterium analysis | Deuterium Batch | δD‰ SMOW | Oxygen-18 analysis | Oxygen-18 Batch | $\delta^{18}O$‰ SMOW |
|---|---|---|---|---|---|---|---|---|
| NMMU 155 | 06 | 2015/06/22 | a | 2015/09/09 | -24.1 | a | 2015/09/05 | -4.39 |
| | | | b | | -25.1 | b | | -4.52 |
| | | | | **avg.:** | **-24.6** | | **avg.:** | **-4.46** |
| | | | | *diff.:* | *1.0* | | *diff.:* | *0.13* |
| NMMU 156 | 07 | 2015/06/23 | a | 2015/09/09 | -24.0 | a | 2015/09/05 | -4.29 |
| | | | b | | -24.4 | b | | -4.23 |
| | | | | **avg.:** | **-24.2** | | **avg.:** | **-4.26** |
| | | | | *diff.:* | *0.4* | | *diff.:* | *0.06* |
| NMMU 157 | 08 | 2015/06/23 | a | 2015/09/09 | -25.0 | a | 2015/09/05 | -4.34 |
| | | | b | | -24.3 | b | | -4.44 |
| | | | | **avg.:** | **-24.7** | | **avg.:** | **-4.39** |
| | | | | *diff.:* | *0.7* | | *diff.:* | *0.10* |
| NMMU 158 | 09 | 2015/06/23 | a | 2015/09/09 | -24.0 | a | 2015/09/05 | -4.47 |
| | | | b | | -23.9 | b | | -4.59 |
| | | | | **avg.:** | **-24.0** | | **avg.:** | **-4.53** |
| | | | | *diff.:* | *0.2* | | *diff.:* | *0.12* |
| NMMU 159 | 10 | 2015/06/23 | a | 2015/09/09 | -25.5 | a | 2015/09/05 | -4.39 |
| | | | b | | -25.7 | b | | -4.41 |
| | | | | **avg.:** | **-25.6** | | **avg.:** | **-4.40** |
| | | | | *diff.:* | *0.3* | | *diff.:* | *0.03* |
| NMMU 160 | 11 | 2015/06/23 | a | 2015/09/09 | -29.2 | a | 2015/09/05 | -4.93 |
| | | | b | | -29.7 | b | 2015/09/23 | -4.96 |
| | | | | **avg.:** | **-29.4** | | **avg.:** | **-4.94** |
| | | | | *diff.:* | *0.5* | | *diff.:* | *0.03* |
| NMMU 161 | 12 | 2015/06/24 | a | 2015/09/09 | -26.7 | a | 2015/09/05 | -4.84 |
| | | | b | | -26.5 | b | | -4.79 |
| | | | | **avg.:** | **-26.6** | | **avg.:** | **-4.81** |
| | | | | *diff.:* | *0.2* | | *diff.:* | *0.05* |
| NMMU 162 | 13 | 2015/06/24 | a | 2015/09/09 | -25.3 | a | 2015/09/23 | -4.44 |
| | | | b | | -25.4 | b | | -4.38 |
| | | | | **avg.:** | **-25.4** | | **avg.:** | **-4.41** |
| | | | | *diff.:* | *0.1* | | *diff.:* | *0.06* |
| NMMU 163 | 14 | 2015/06/24 | a | 2015/09/09 | -25.2 | a | 2015/09/23 | -4.38 |
| | | | b | | -24.8 | b | | -4.35 |
| | | | | **avg.:** | **-25.0** | | **avg.:** | **-4.37** |
| | | | | *diff.:* | *0.5* | | *diff.:* | *0.03* |
| NMMU 164 | 15 | 2015/07/22 | a | 2015/09/09 | -27.0 | a | 2015/09/05 | -4.48 |
| | | | b | | -26.2 | b | | -4.53 |
| | | | | **avg.:** | **-26.6** | | **avg.:** | **-4.50** |
| | | | | *diff.:* | *0.7* | | *diff.:* | *0.05* |
| NMMU 165 | 16 | 2015/07/23 | a | 2015/09/09 | -24.4 | a | 2015/09/05 | -4.59 |
| | | | b | | -23.8 | b | | -4.52 |
| | | | | **avg.:** | **-24.1** | | **avg.:** | **-4.55** |
| | | | | *diff.:* | *0.6* | | *diff.:* | *0.07* |

## 9.6. Appendix F: Photographs

**Appendix F: Photographs**

The dry depression where the Grootfontein Eye used to flow.

One of the public water supply boreholes at Grootfontein, abandoned due to falling groundwater levels.

A centre pivot irrigation system at Grootfontein.

The polluted Setumo Dam to the west of Mahikeng.

The Molopo Eye spring to the north of Grootfontein.

The weir measuring the natural discharge of the Molopo Eye.

Maloney's Eye spring, the natural discharge point of the Steenkoppies dolomite compartment.

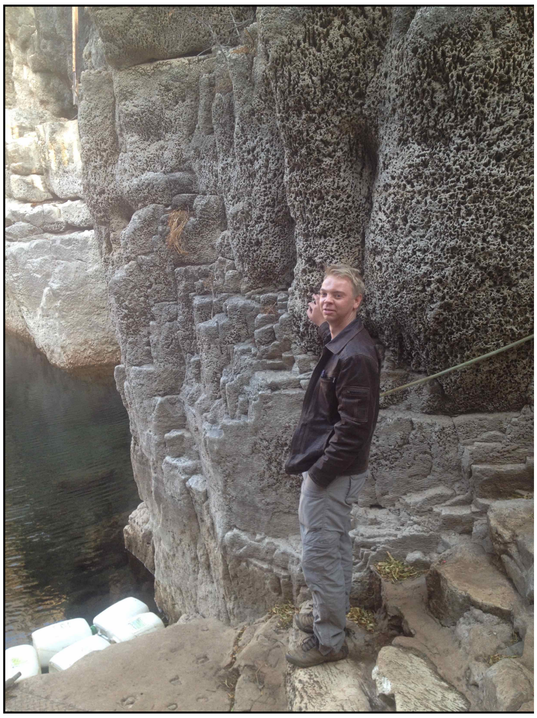

The Mmabatho Water Treatment works to the west of Mahikeng. This plant treats water from the Setumo Dam.

A sinkhole in the North West dolomites near Krugersdorp.

Sampling groundwater from irrigation boreholes at Grootfontein.

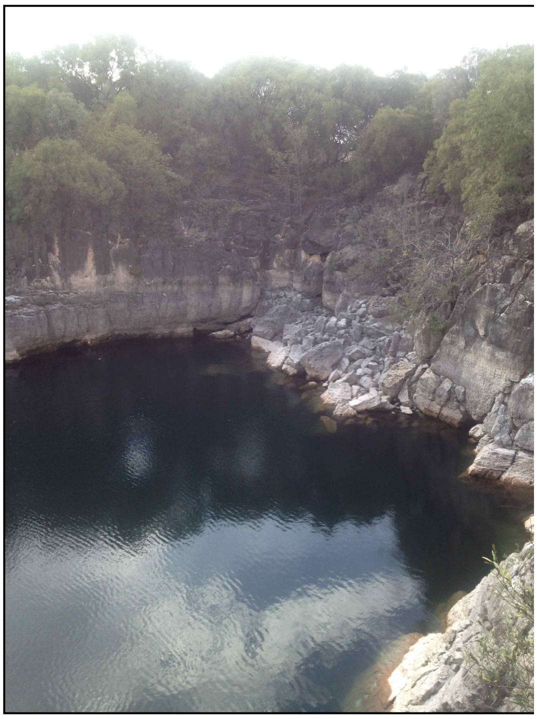
The Mafikeng Water Treatment Works, which receives water from the Molopo Eye and the Grootfontein boreholes.

One of the three remaining public water supply boreholes at Grootfontein.



Weathered dolomite at the Wondergat, a collapsed dolomite sinkhole to the north of Grootfontein.

Close-up of weathered dolomite at the Wondergat.



The Wondergat. The water here is more than 50 m deep: a rare "view" of the North West dolomite groundwater resource.

Grootfontein boreholes discharge into a concrete channel. The water is then piped to the Mafikeng Water Treatment Plant.


Public water supply borehole at Itsoseng, in the south of the Grootfontein aquifer.

A borehole used for irrigation at Grootfontein.