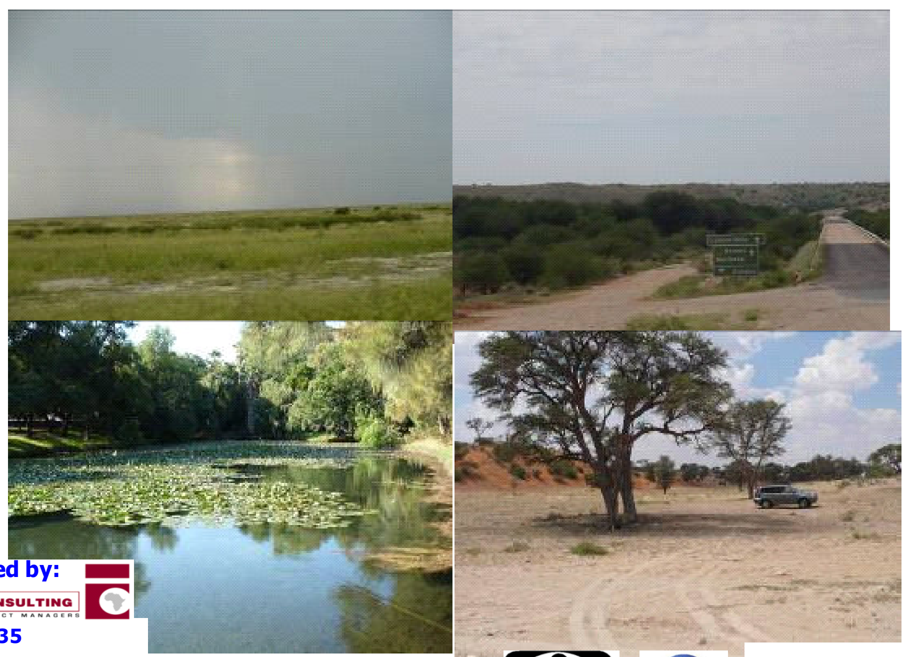
Sharing the Water Resources
Of the Orange-Senqu River Basin

Report No: 006/2009

Feasibility Study of the Potential for Sustainable Water Resources Development in the Molopo-Nossob Watercourse

Groundwater Report
Final



Submitted by:

ILISO CONSULTING

PO Box 68735
Highveld
0169
Tel: (012) 685 0900
Fax: (012) 665 1886
Contact: Dr M van Veelen

July 2009

Title:	***Groundwater Study***
Authors:	***Dr D Bredenkamp***
Project Name:	***Feasibility Study of the Potential for Sustainable Water Resources Development in the Molopo-Nossob Watercourse***
Status of report:	***Final***
ILISO Project No:	***700192***
Date:	*July 2009*
Keywords:	*Molopo River, Nossob River, Water Resources*

ILISO Consulting (PTY) LTD

Approved for and on behalf of ILISO Consulting (Pty) Ltd, Ninham Shand Incorporated, Schoeman and Partners and Conningarth Economists by

....	2009.07.13 ....
Dr M van Veelen	*Date*
Director: ILISO Consulting (Pty) Ltd	

ORANGE SENQU RIVER COMMISSION

Approved on behalf of ORESECOM by

....	2009.07.14 ....
Mr Lenka Thamae	*Date*
Executive Secretary - ORASECOM	

LIST OF STUDY REPORTS IN FEASIBILITY STUDY OF THE POTENTIAL FOR SUSTAINABLE WATER RESOURCES DEVELOPMENT IN MOLOPO-NOSSOB WATERCOURSE PROJECT:

This report forms part of a series of reports done for the Molopo-Nossob Feasibility Study, all reports are listed below:

Report Number	Name of Report
002/2008	Hydrology Report
003/2008	Catchment Status Inventory Report
006/2009	Ground-water Study
007/2009	Main Report

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ANNEXURES

LIST OF ACRONYMS

a	Recharge coefficient
CMB	Chorine Mass Balance Method
DWAF	Department of Water Affairs and Forestry (South Africa)
MAP	Mean Annual Precipitation
ORASECOM	Orange-Senqu River Commission
RF_{48}	Moving annual rainfall over 48 months
RSA	Republic of South Africa
RU	Resource Unit
TDS	Total Dissolved Solids

1. INTRODUCTION

1.1 OBJECTIVES OF THE STUDY

In view of the ORASECOM agreement the status and development potential of groundwater in the international river basin of the Molopo River drainage system (see **Figure 1-1**) has been examined.

It involved the following:

- A study of reports from the Department of Water Affairs and Forestry of South Africa on sustainable groundwater exploitation over a number of years,
- Information contained in the regional presentations of the surface water report.
- The impact of the groundwater exploitation on the base flow of the river systems and their periodic floods which is critical for the sustained utilisation of the groundwater recharge in close proximity of river channels in the semi- to arid parts of the Kalahari.
- The regional picture of the potential of exploration methods to locate new groundwater resources.
- A regional evaluation of the potential of groundwater in relation to the average annual rainfall.

It is clear that there is good correspondence between the regional stream density of the drainage areas (see **Figure 1-1**) and average annual rainfall (**Figure 1-2**) although the rainfall over the central Kalahari area is in fact controlled by the stationary stable high-pressure systems over the central area.

Ground-water schemes that have been successfully exploited for irrigation e.g. from the granite aquifers in the Coetzersdam-Louwna area (Botha 1992 and 1995) and that of the dolomitic aquifer at Tosca-Vergeleë by Van Dyk (2005) were assessed in greater detail. In addition the extent of irrigation developments in the dolomitic aquifers of the upper Molopo and Kuruman and their impact on the recharge which sustains the flow of major springs has also been put under scrutiny. The ground-water development in the Molopo drainage occurs mostly in the upper reaches of the drainage system where the recharge is the highest (see **Figure 1-3** – Hydrology Report, Ninham Shand 2008).

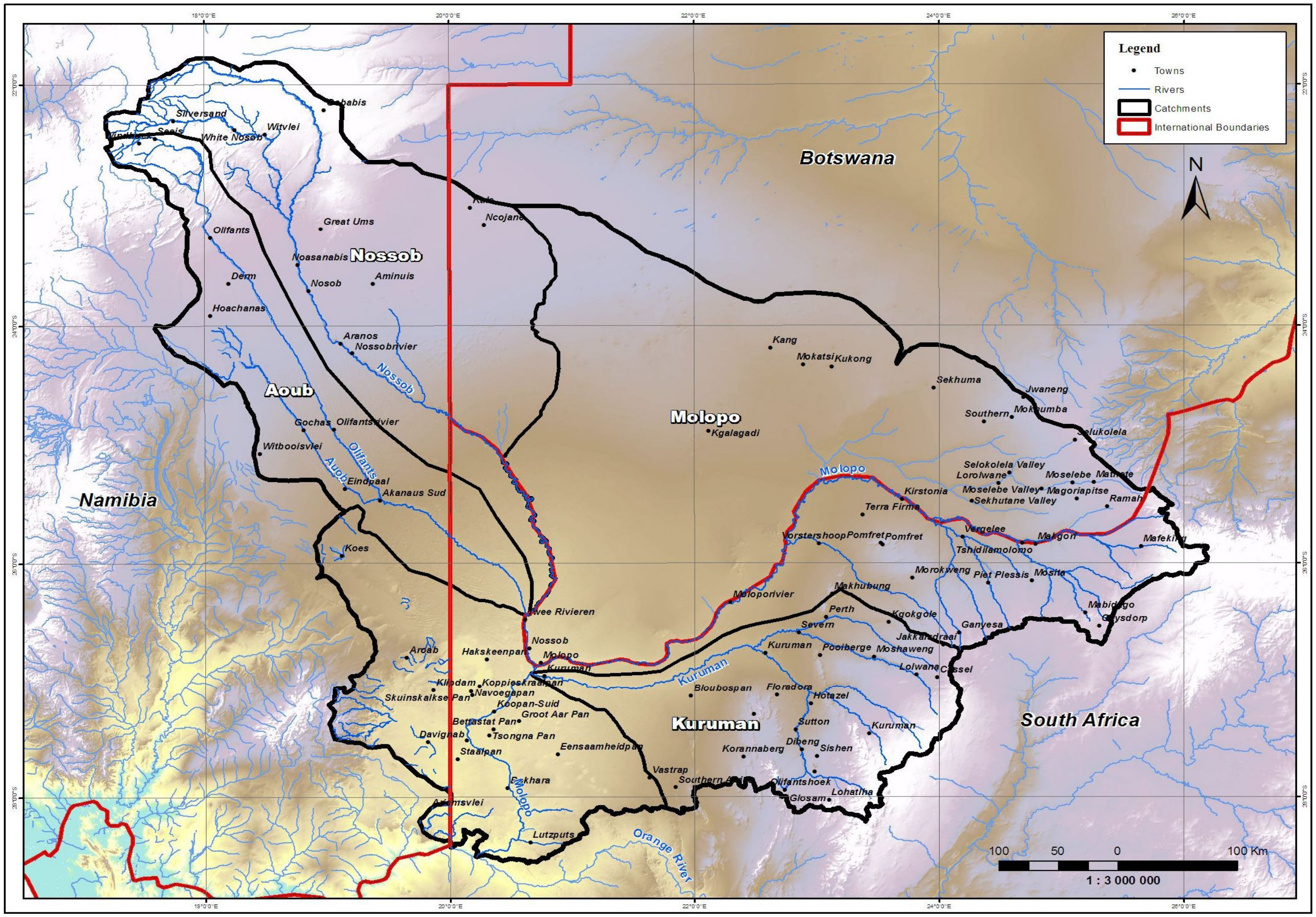


Figure 1-1: The regional drainage of the Auob-Nossob and Molopo River drainage systems

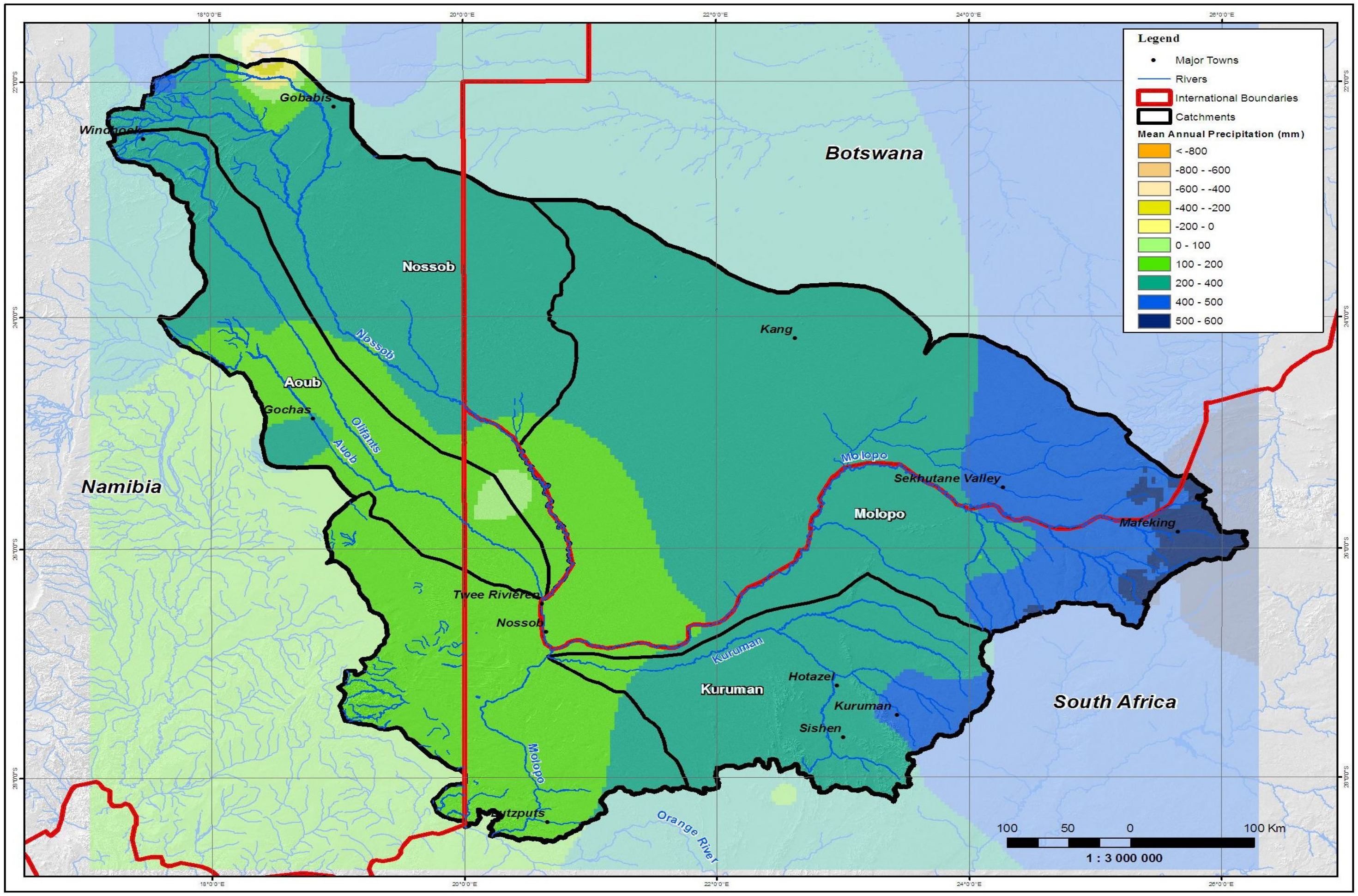


Figure 1-2: Mean Annual Precipitation of the drainage area

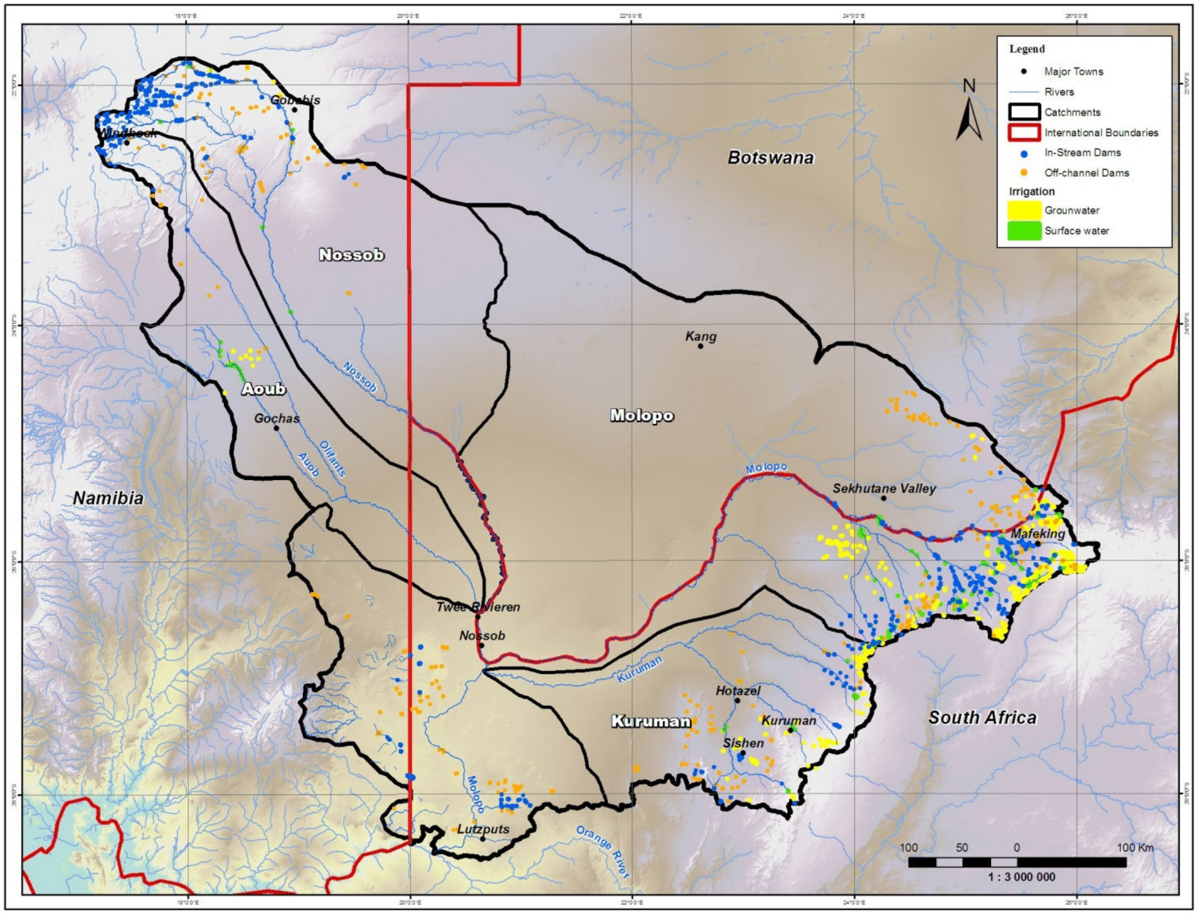


Figure 1-3: Map of the present irrigation areas

1.2 GENERAL PERSPECTIVES

In many respects ground-water is similar to surface water insofar that it is part of the hydrological distribution of rainfall, representing the portion of the rainfall that infiltrates to replenish the aquifers. These aquifers are underground reservoirs utilizing the capacity of different geological formations to store infiltrating water from where it could resurface in the form of springs or base flow or could be pumped out. The yield of the groundwater reservoirs is similar to that of a surface reservoir that is in-filled with material. The aquifers constitute natural storages that have been developed due to tectonic deformation of the geological formations or merely the storage within the porous rock matrix or unconsolidated aggregates that have been deposited into subsurface channels or basins. Although it is generally assumed that the losses from aquifers are negligible they are merely smaller than from open water sources, because flow losses to lower lying areas occur according to the hydraulic head and permeability of the aquifer. The evaporative losses occur as a result of transpiration by plants and capillary movement of moisture to the surface. The recharge of the aquifers is controlled by the overlying soils or geological outcropping formations but even more so by the availability of excess water to infiltrate to the deeper underground reservoir. The ground-water is therefore a function of the rainfall, the infiltrating characteristics of the overburden material and evapotranspiration losses. The processes involved are illustrated in **Figure 1-4** (after Lloyd, 1971).

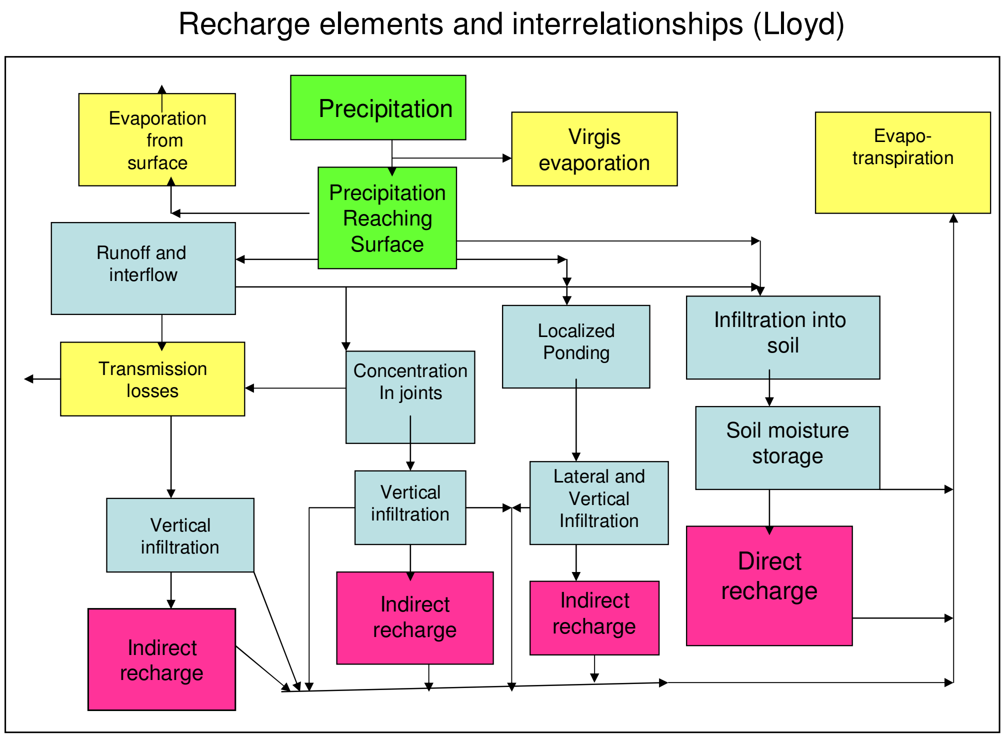


Figure 1-4: Schematic diagram of the different components of the hydrological distribution of rainfall into groundwater

As will be indicated the groundwater recharge is similar to runoff, which occurs when the rate of rainfall exceeds the infiltration capacity of the surface cover that overlies the aquifer. The runoff occurs mostly from short-duration high-intensity showers, whereas the groundwater recharge is affected by excess rainfall in relation to the average rainfall over a longer period. In both cases the response conforms to an exponential rainfall relationship. The rainfall also controls the quality of the groundwater; which due to higher evaporative losses and leaching is poorer than that of surface water. Further deterioration of the quality could result deeper down in the aquifer by continued leaching of salts from the aquifer matrix. The lower the recharge the higher the total dissolved salts (TDS) of the groundwater. The poor water quality in the low-rainfall Kalahari region thus indicates that the recharge must be small. More salts are dissolved if the unsaturated cover overlying the groundwater aquifer is thick. The leaching of salts contained in the deeper aquifer matrix, which in this case is Karoo formations of marine origin and its erosion products during glacial times, has caused further deterioration of the groundwater. The better quality of the granite and dolomite groundwater therefore indicates a higher rate of recharge. Ignorance of the chemical mass-balance concept has resulted in much effort and large sums of money being expended in drilling exploration for groundwater in the Kalahari. It explains why the exploration of groundwater in the low rainfall area of the western Kalahari has been mostly unsuccessful. In the Namibian part of the Kalahari a porous aquifer with reasonable amounts of water exists except in areas within the salt block where quality is poor due to leakage from the confined aquifers into the Kalahari. However due to the virtual absence of surface water collection possibilities, the economic viability of these low rainfall regions still is closely dependent on the availability of potable groundwater. The only solution for some areas eventually has been to pipe surface water from the Orange River to the areas with non-potable water e.g. the Kalahari east and west schemes. This has essentially replaced the earlier practise to harvest rainfall-runoff from pans, to be stored in trenches (so-called gatdamme) dug in the pans. These could provide sufficient drinking water to sustain economical sheep farming.

The main contribution of the present report is to provide first-order estimates of the potential of typical ground-water exploitation schemes in the study catchments based only on the rainfall. For this the focus has been on the dolomite aquifers in particular, because of their higher recharge and their contribution to the discharge by springs into the upper Molopo and Kuruman River. This includes the Molopo eye forming the source of the Molopo River and Grootfontein. These dolomite aquifers presently supply most of the water requirements of Mafikeng. The natural discharge into the upper Molopo River was irreversibly affected by the exploitation of the groundwater and by re-allocation of some of the water rights from agricultural to urban use. The groundwater resources of the dolomite have been extensively studied all over South Africa. Their potential has been assessed by a variety of methods that could be applied for the assessment and management of groundwater systems e.g. Kuruman, Sishen, Tosca and Vryburg (Louwna Coetzersdam).

Although the base flow of the Upper Molopo River has essentially been limited to discharge that occurs during periods of extremely high rainfall, its contribution to the flood events in the Molopo has been small but sustained. The diversion of the flows of Molopo and Grootfontein spring in any case presents a more efficient use of the resource, especially where no surface water could be developed for urban water supply as in the case of Mafikeng. This reallocation has had an insignificant impact on the water resources in the lower Molopo River as the floods there only takes place at large intervals. The same applies to the Kuruman spring, which no longer contributes to sustaining the perennial flow in the Kuruman River.

In the dolomite aquifers intrusive dykes act as barriers that impede the underground leakage to adjacent aquifers. These dykes constitute a unique characteristic of the dolomite aquifers of South Africa as their low permeability restricts the underground outflow water losses. In this way they retain the recharge from abnormally high rainfall for longer periods in the aquifers and thus causes more sustained flow of the springs from the different compartments during periods of drought. The leakage through the dykes and through the adjoining formations (e.g. the low permeability Oaktree Formations and Black Reef Series) provides an insignificant contribution to the base flow of the river systems. This has been conclusively demonstrated by extensive modelling of the Grootfontein and Molopo compartments (Van Rensburg private communication). The lower flows in the far western region of the Molopo catchment will however have a negative impact on the recharge close to the rivers, in particular the groundwater resources in the Kalahari areas, which are directly linked to periodic flood events in the Kuruman, the Gamagara and the Molopo rivers and their tributaries.

The rapid expansion of irrigation from boreholes by means of irrigation pivots and electrical pumping installations, are indicated in **Figure 1-3**. However, even though some are small groundwater schemes, they are of great economical value for food-crop farming and ensure limited risks of crop failure even in droughts.

1.3 RAINFALL

The mean annual rainfall over the Molopo and Kuruman catchments decreases fairly uniformly from more than 500 mm in the east (upper Molopo catchment) to approximately 150 mm in the vicinity of the Orange River confluence. In the Nossob and Auob catchments, mean annual rainfall decreases in a southerly direction and varies from about 400 mm in the upper Nossob catchment to less than 200 mm at the confluence with the Molopo River (see **Figure 1-2**) The daily rainfall could be as high as 87 mm, however, only if higher than average rainfall is sustained for a prolonged period, can it cause local recharge in the river beds and in areas of outcropping or shallow Kalahari formations.

1.4 DRAINAGE SYSTEM

The drainage is typical that of an ephemeral river system and consists of four main sub catchments viz. the Molopo, Kuruman, Nossob and Auob catchments. The locations of these catchments are shown in **Figure 1-1** and the catchment's areas per country are presented in **Table 1-1**.

Table 1-1: Main Sub catchments within the Molopo-Nossob System (Hydrology Report 2008)

Drainage systems	Catchment Area (km^2)			
	RSA	Namibia	Botswana	Total
Molopo	61 882	18 120	112 583	**192 585**
Kuruman	41 194	0	0	**41 194**
Nossob	4 704	46 928	17 426	**69 058**
Auob	5 589	34 601	0	**40 190**
Total	**113 369**	**99 649**	**130 009**	**343 027**

Occasional runoff occurs in the upper parts of the various sub catchments but evaporation and seepage losses, with additional interception of runoff by large storage dams in the upper Molopo and Nossob catchments, prevents the runoff from reaching the lower regions of the rivers. At periodic intervals abnormally high rainfall causes runoff in most of the tributaries and eventually causes floods in the Kuruman, the Gamagara and upper part of the Molopo River. These flood events have a significant impact on the replenishment of the groundwater along the flooded sections of these river courses e.g. in the Tosca Vergelee area.

Table 1-2: Flow Gauging Stations (Hydrology Report, 2008)

Country	River	Station Name	Id.	Period
South Africa	Mareetsane River	Neverset	D4H002	1905-1964
South Africa	Swartbas River	Rietfontein	D4H003	1941-1948
South Africa	Pipeline From Grootfontein-Eye	Valleifontein	D4H004	1958-1974
South Africa	Kuruman-Eye B	Kuruman	D4H006	1959-2004
South Africa	Manyeding-Eye	Manyeding Loc.	D4H007	1959-2005
South Africa	Little Koning Eye	Kono Loc	D4H008	1959-2004
South	Great-Koning-Eye	Kono Loc.	D4H009	1959-

Country	River	Station Name	Id.	Period
Africa				2005
South Africa	Bothetheletsa-Eye	Botheletsa Loc.	D4H010	1960-1993
South Africa	Tsineng-Eye	Lower Kuruman 83	D4H011	1960-1994
South Africa	Sewage Works	Mmabatho	D4H012	1997-2008
South Africa	Molopo River	Rietvallei	D4H013	1905-2007
South Africa	Molopo-Eye	Mallepoos-Eye	D4H014	1981-2008
South Africa	Polfontein	Matlabes Loc.	D4H019	1980-1985
South Africa	Compensation Water From Pipeline	Mallepoos-Eye	D4H030	1974-2007
South Africa	Leakage Water	Mallepoos-Eye	D4H031	1980-1981
South Africa	Mareetsane River	Neverset	D4H032	1927-1964
South Africa	Molopo River	Disaneng	D4H033	1996-2007
South Africa	Pipeline To Fisheries	Disaneng	D4H034	1995-1999
South Africa	Irrigation Pipeline	Disaneng	D4H035	1998-2001
South Africa	Canal From Modimola Dam	Molopo (Ratshidi)	D4H036	1996-2007
South Africa	Molopo River	Lotlamoreng Dam	D4H037	1995-2007
South Africa	Mafikeng Treatment Works	Molopo (Ratshidi)	D4H039	1999-2007
Namibia	Black Nossob	Mentz	3111M02	1973-2006
Namibia	Black Nossob	Daan Viljoen Dam.	3111R01	1969-2005
Namibia	White Nossob	Otjivero Main Dam	3112R02	1982-2005
Namibia	White Nossob	Amasib	3112M02	1973-2007
Namibia	Black Nossob	Tilda Viljoen Dam	3111R02	1998-2007
Namibia	Auob	Gochas	3124M01	1973-2007

Country	River	Station Name	Id.	Period
Namibia	Auob	Stampriet	3124M02	1977-2007
Namibia	Seeis	Ondekaremba	3125M01	1977-2006
Namibia	Olifants	De Duine	3126M01	1976-1997
Namibia	Usib	Nauaspoort Dam	3122R02	1987-2006
Namibia	Swartmodder	Swartmodder	3121M11	1990-2007
Namibia	Black Nossob	Henopsrus	3111M01	1969-2005

1.4.1 Nossob River

The Nossob River originates in the mountainous area to the north-east of Windhoek and its upper reaches are characterised by two main tributaries viz. the Black Nossob and the White Nossob. The Nossob River has its confluence with the Auob River at Twee Rivieren in the Kgalagadi Transfrontier Park and joins the Molopo River at Bokspits, 60 km south of the Auob confluence. The Auob River has its origin in the Karubeam Mountains in Namibia (north east) and the Stampriet artesian basin in the upper reaches of the Auob River is the only major local groundwater resource. The Olifants River originates in the mountainous areas surrounding Windhoek and flows into the Auob River. Windhoek is supplied with some of its water from boreholes located within fractured quartzitic horizons. Where these fractures are deep-seated some hot springs resulted. These stopped issuing as a result of the large-scale abstraction over a period of time.

Of the flow gauging stations listed in **Table 1-2** those in red represent springs emanating from the dolomite.

1.4.2 Kuruman River

The Kuruman River originates south east of Kuruman, where it is fed by various dolomitic springs, most notably the Great Koning Eye, Little Koning Eye and the Kuruman Eye. Originally, the river flowed in a north-westerly direction over a distance of approximately 140 km; it then turns west and flows parallel to the Molopo River, until it has its confluence with the Molopo River at Andriesvale, in close proximity to the Nossob/Molopo confluence. Various tributaries join the Kuruman River along its upper reaches, including the Ga-Mogara, Moshaweng, Mathlawareng and Kgokgole rivers.

The floods from the Auob River in particular replenish the groundwater of the game park but after joining the Kuruman and Molopo rivers the flood waters dissipate into pans and its flow is eventually stopped by the Kalahari dunes.

The occasional flow occurring along the lower Kuruman, Molopo, Nossob and Auob rivers are also linked to periodical flood events, but there is no record that flows in the Molopo River has ever reached the Orange River. Flows in the lower reaches of the Molopo and/or Kuruman rivers occurred in 1933, 1974/5 and 1975/76. Flow along the lower reaches of the Nossob and Auob rivers has been recorded in 1934, 1963, 1974 and 1999/2000.

1.4.3 Molopo River

2. OCCURRENCE OF GROUNDWATER

2.1 GENERAL

The Kalahari area typically features that of a semi-desert comprising of tertiary deposits of glacial origin, covered with sand deposited by wind action in more recent geological times. The geological features of the Kalahari are documented in much detail in a report by Van Wyk and Appelcryn. (1989) that also deals with the occurrence and recharge of groundwater in relation to the geology and the rainfall. The report also covers the prospects of improved siting of boreholes by geophysical methods and includes information contained in the thesis of Smit (1977). The reports collate information that has been gathered over an area of about 5800 km^2 covering a 50 km zone south of the Molopo River and 20 km south of the Kuruman River (see **Figure 2-1**).

Findings of a report by Thomas (1980) dealing with the geophysical surveying to the west of the delineated area, has also been examined. The runoff is not being measured in any of the rivers or tributaries. About 90 % of the investigated area is covered by dune sand.

An excellent thesis by Van Dyk (2005) covers in much detail the groundwater exploitation of the Tosca-Vergeleë dolomitic aquifer in relation to the geology and rainfall. The groundwater exploitation of the Louwna-Coetzersdam granite aquifer has been assessed by Botha (1995, 1997) by means of a reliable groundwater balance, from which the parameters of the aquifer and the recharge were calculated. The most complete overview of information is contained in the Vryburg Sheet (Van Dyk and van Kisten 2006 unpublished), which has collated the hydrogeology of the area covered by the 1:500 000 Vryburg map.

The rainfall in the delineated Kalahari area varies between 200 mm in the west to 400 mm per year in the east (see **Figure 1-2**) and the maximum occurs in January over the east of Botswana and during April-May in the southern Kalahari. The monthly pan evaporation is about 2 500 mm/a.

2.2 GEOLOGY AND GEOMOPHOLOGY

2.2.1 Kalahari region

The main geomorphologic feature is a regional basin structure and several smaller ones, eroded into the pre-Kalahari Karoo formations, which were in filled by glacial sediments of Karoo formations e.g. the deposition of the Dwyka Tillite that has been covered by Karoo formations and then by Aeolian sand in the late Cretaceous period. The thickness of the overlying recent Kalahari sand-cover could vary from 3 to 20 metres, and even up to 60 m downstream of the Auob-Nossob and Molopo confluence. A major sediment basin which developed in the late Palaeozoic and early Mesozoic period in the region of Jwaneng in Botswana was covered by Cenozoic Kalahari sediments ranging from 5 to 50 m in thickness. The stratification of the geology from surface to depth is shown in **Table 2-1** and the areal geology appears in **Figure 2-1**. A more complete stratigraphy of the geology underlying the area from the confluence of the Nossob and Molopo Rivers is shown in **Table 2-1** compiled from the Vryburg Sheet (Van Dyk and van Kisten 2006 unpublished).

Table 2-1: The geology of the region - summarized from Van Dyk and van Kisten 2006)

Simplified Geology of the Region	Description/Comments
Kalahari Group (T-Qk)	Quaternary and tertiary sediments pan sediments (sand and clay), diatomaceous limestone and aeolian sand ----extensive coverage all over the area
Dwyka Group (C-Pd)	Diamictite, tillite and dark shales in the western Kalahari
Mokolian Group (Mz)	Gabbro- limited distribution north of Ottosdal Similar formation in Botswana near Jwaneng and a good aquifer due to structural deformation
Pretoria Group (Vp)	Argillaceous, arenaceous rocks, meta-arenaceous rocks (previously called the Griquatown and Olifants Formations) ?
Volop Group (Vv)	Metamorphosed quartzites, areal distribution in the southwest
Lucknow Formation (Vlu)	Sediments composed of white and grey quartzites
Ghaap Group (Va) and Chuniespoort Group (Vh)	Predominantly carbonate rocks such as limestone, and dolomite with interbedded chert; lies conformably on Black Reef Formation which is the base of the dolomite
Vryburg Formation (Vry)	Consists of interbedded quartzites and lavas
Black Reef Formation (Vbl)	Consists of quartzite, flagstone and grit
Vaalian (V)	Amygdaloidal, basic lava of the Allanridge Formation (R-val) is poorly exposed
Gaberone Granite (Rga)	Intrusive rocks of various granitoids
Klipriviersberg Group (Rk)	Jointed basaltic lava, Kanye Formation (Rka) consisting of black felsitic rocks occur to north of Mmabatho
Randian (R)	Overlying the granite and gneiss - quartzites, conglomerates, lavas and sediments of the Dominion Group (Rd)
Kraaipan Group	Predominantly quartzite, chert, slate, phyllite and schists, extensively folded, sheared and veined (Moshaweng area)
Swazian (Z)	Basement granite and gneiss rocks. Pegmatite and quartz veins. are abundant

The Jwaneng groundwater occurs in the Mokolian Formation, which constitutes intrusive gabbro associated with block-faulting. The Mokolian group has limited distribution to the north of the town of Ottosdal in the RSA.

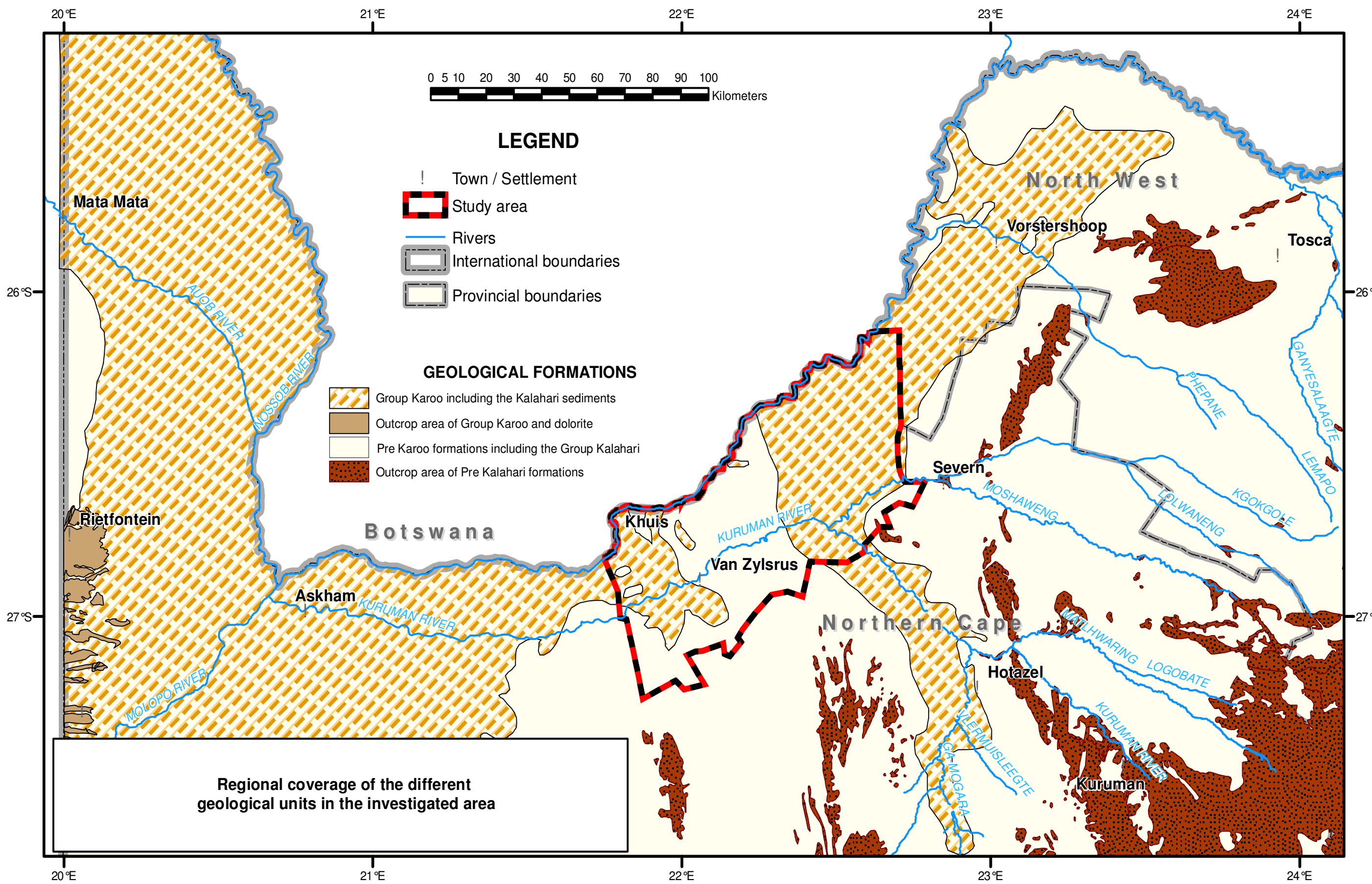


Figure 2-1: Simplified geological map of the delineated and surrounding areas of poor groundwater quality in the area close to the confluence at Askam

Discussion of the western Kalahari region (after Van Wyk and Appelcryn 1989)

Past erosions have incised the present river channels into the calcretes underlying the Kalahari sands). Extensive erosion has probably removed hundreds of metres of the original overlying Karoo formations. The pre Karoo formations consist of the Griquatown and Olifants Formations (renamed Mokolian) which are indicated in **Figure 2-1**. The groundwater in the latter formations are more actively recharged than areas covered by overlying alluvial sediments of Kalahari, which has a high water storage capacity. The presently dry riverbed channels were cut through the Kalahari layer and their deep erosion channels in the Molopo and Kuruman Rivers indicate that in the distant past they must have been flowing continuously. In recent times the rivers only carry water during extreme flooding in the upper reaches of the catchments as previously indicated.

Although Kalahari deposits cover the largest part of the Molopo drainage area (see **Figure 2-1**) (representing a simplified version of the geology of the western Kalahari), it is a poor aquifer (van Wyk and Appelcryn, 1989). In most cases water was intersected at great depth but was mostly of such poor quality that it did not comply with drinking standards for human consumption and often not for cattle use either. Notwithstanding this, extensive geophysical surveying has been tried to find potable groundwater but proved to be unsuccessful in view of the depth of groundwater strikes and a lack of understanding the interrelationship between the hydrogeology and the rainfall. However by selective drilling in areas close to the main river channels reasonably good subterranean water has been discovered. From these the geological and quality controlling factors have been sorted out.

The simplified geological stratigraphy underlying the Kalahari sediments (van Wyk and Appelcryn 1989) are shown in **Figure 2-2** whilst **Table 2-2** indicates the lithological stratification up to the dolomite in the Tosca Kuruman area and the granite further east. The largest part of the western area is underlain by the Karoo sediments with Dwyka (glacial deposits) at the bottom, overlain by Ecca comprising of blue shale with sandstone lenses in-between. The tertiary deposits known as the Kalahari layers vary in thickness from place to place and cover eroded-channels and basins in the pre-Kalahari formation.

2.2.2 Structural geology

The structural geology of the area is very complex and numerous theories have been proposed on the structural history of the area leading to the presently observed conditions towards the south on the Vryburg sheet (Du Plessis, 1979). The most recent work was done by the Geological Survey in 1979 (now the Council for Geoscience). The theory proposed was that an initial compression event from the east and west, gave rise to various folds with axes trending north. This was later followed by north-south compression, which superimposed broad, open folds on the existing folds. Intense localised shearing following this, has lead to faulting and intrusive dykes.

Faults abound in the area and have the same trend as the fold axes and most probably were formed contemporaneously with the folding event or shortly after. Numerous dykes have intruded along faults while others cut across faults and must consequently be younger. The dykes may therefore be dolerite dykes of post-Karoo age. **Figure 2-2** shows the major dykes and lineaments across the map area.

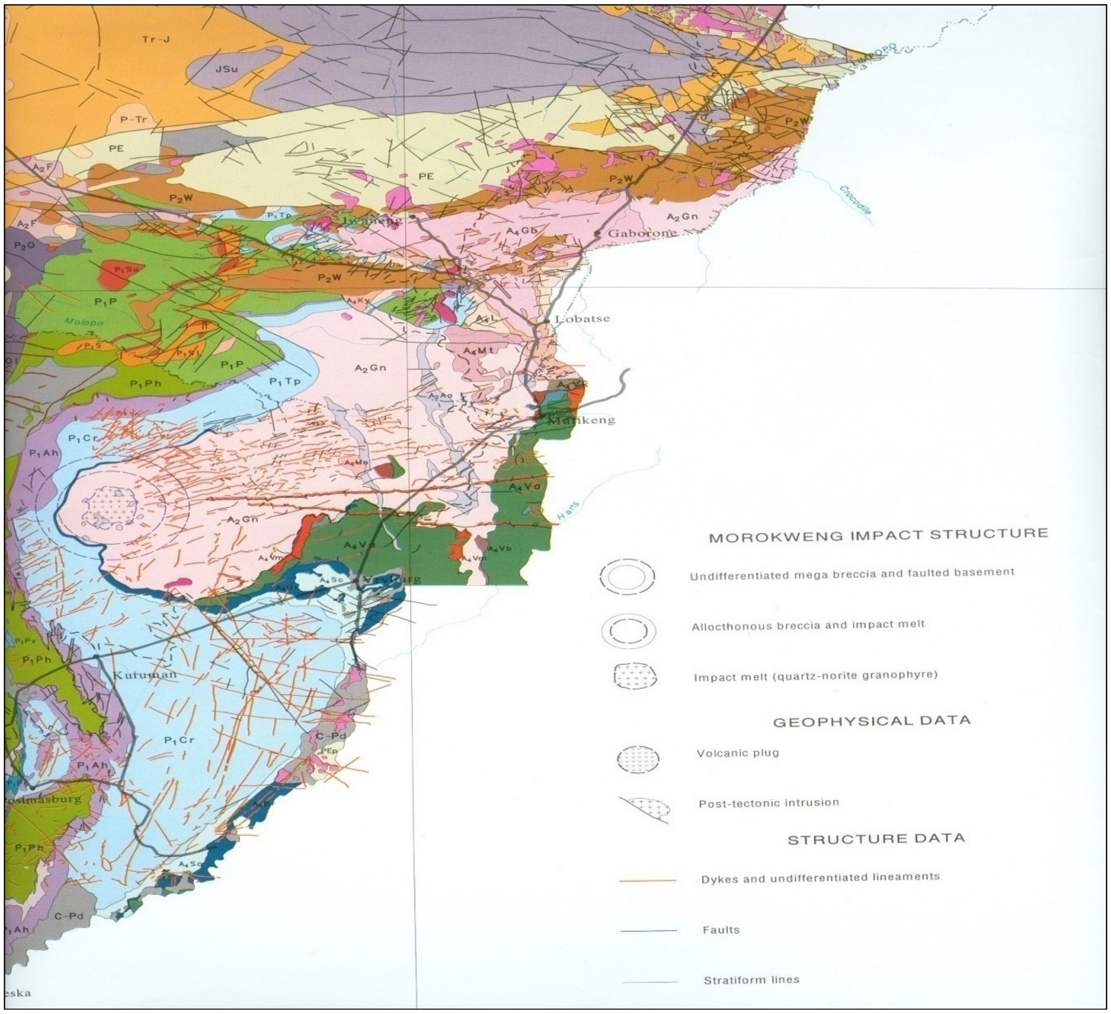


Figure 2-2: Regional geology of the Tosca area (after Van Dyk 2005) taken from Sub-Kalahari Geological Map by IG Haddon 2001

.

MOROKWENG IMPACT CRATER ACCORDING TO THE "EARTH IMPACT DATABASE", THE TOTAL NUMBER OF CONFIRMED IMPACT STRUCTURES IS CURRENTLY AT 172. WITHIN SOUTH AFRICA THERE ARE 4 NAMELY, VREDEFORT, TSWAING, KALKOP AND MOROKWENG (ADAPTED FROM HTTP://WWW.UNB.CA/PASSC/IMPACTDATABASE…).

The Morokweng crater was formed by an impact event some 145 million years ago. The crater has a diameter of approximately 70km and is located at Latitude 26°28'S and Longitude 23°32'E. It has been proposed that the impact that formed this crater could have been responsible for the mass extinction found at the Jurassic – Cretaceous boundary (adapted from http://www.planetary.org)

Figure 2-3: Locality of the Morokweng meteorite impact and satellite images

Dolerite dykes have been intersected or was magnetically identified all over the area. They are particularly numerous in the area east of Pomfret-Tosca, where the intrusions seems to be linked to the Morokweng impact crater (See **Figure 2-3**) This most prominent structural controlling impact occurred when a meteorite crashed into the earths crust. As a result of this impact-structure lineaments developed radially around this structure. The lineaments are faults often intruded by dolerite material and are aligned NE SW in the Tosca area. These faults and the contact zones of dykes are usually favourable sites to intersect groundwater.

2.3 GROUNDWATER IN THE KALAHARI FORMATIONS

Although groundwater can be found in small quantities all over the area the best yields of potable groundwater are intersected in the areas where the Kalahari is saturated with water. The groundwater levels remains fairly static as a result of the high storativity of the alluvial sediments, which without evidence of active recharge provides sufficient water to bridge periods of drought. The occurrence of groundwater away from the river channels is summarized in **Table 2-2** indicating the relative success of drilling in the area.

Table 2-2: Occurrence of groundwater in relation to the geological formations after van Wyk and Appelcryn

Area 1: Kalahari deposits South of the Kuruman River Fullifeesand to Massakloutjie	Good groundwater yields and quality in a zone of 3-5 km wide and 32 km into the dunes to the south of the river. The water occurs in a trough in the Kalahari bed filled in by gravel.
Area 2: 22 ^{0} E Quarzite folded and fractured Makolian	Quartzite folded and fractured. Good groundwater strikes e.g. 15 000 l/h Intersected at about 70m. Infrequent flows of the Kuruman river have caused the yields of boreholes to decline.
Area3: Khuis quartzite	South of Kuie Pan – farms Matlapanen, Lonely, The Heights Many dry boreholes has been frilled and many water holes have dried up
Block between Kuruman and Molopo Rivers	Good groundwater in the fractured quartzite (70-80m) but in the areas in-filled with tillite and shales in glacial valleys between the quartzite outcrops, the ground-waters are unpotable.
In the eastern Salt-block	No potable groundwater available and water is supplied from neighbouring farms.

Close to the Kuruman River - Keesi	Good groundwater in the alluvium and Kalahari close to the river (up to 9 l/s) but the yields and quality of groundwater is much poorer further north of the Kuruman River
Kalahari group - saturated Kalahari deposits and troughs in pre Kalahari formations	The gravels of the Kalahari sediments act as primary aquifers. Borehole yields are low in the Kalahari troughs farther from the river. Groundwater flow occurs in a trough about 15 km wide and can sustain an estimated yield of 40 m^3 per day.

2.4 DOLOMITE AQUIFERS

2.4.1 Geology

The dolomite formations of the Molopo and Kuruman area constitute excellent aquifers which give rise to large perennial springs. The dolomites of these two areas are similar in lithology although the members are named differently. The dolomite in each area comprises of sandwiched layers with alternating formations of chert-poor and chert-rich dolomite. The chert-poor dolomite is denser and is less karstified and therefore has poorer groundwater properties than the well developed chert-rich layers (see **Figure 2-4** and **Figure 2-5**)

The geological stratigraphy of the dolomite in the region of Molopo eye comprises of

- Black Reef (shales and sandstone) constituting the base of the dolomite basin overlain by
- The Oaktree (chert-poor), Monte Christo, (Chert-rich), Lyttelton (chert-poor) and Eccles (chert-rich) dolomite. Because of the uplifting of the continent the normal horizontally-layered succession has been tilted and through erosion the formations have been exposed at the surface. As a result of the dissolution of dolomite by rainwater highly productive aquifers have been formed with perennial springs emanating along dyke contacts at the topographical lowest point in the natural drainage.
- The Pretoria group comprises of the Rooihoogte formation forming the transition from the dolomite to the Timeball Hill formations (shale and quartzite) followed by the Karoo sequence with the Dwyka formation at the bottom overlain by mudstone and sandstone with interbedded coal seams in-between.

System/ Erathem	SEQUENCE	GROUP	FORMATION		LITHOLOGY AND MEMBER	THICKNESS (m)
PERMO-CARBONIFEROUS	KAROO	ECCA	DWYKA		Sandstone Mudstone Carbonaceous shale, coal Diamictite	
PROTEROZOIC	TRANSVAAL	PRETORIA	TIMEBALL HILL		Shale Diamictite Klapperkop Quartzite Mb wacke and ferruginous quartzite Graphitic and silty shale	270 - 660
			ROOIHOOGTE		Quartzite Shale Bevets Conglomerate Member Breccia	10 - 150
		CHUNIESPOORT	ECCLES		Chert-rich dolomite with large and small stromatolites	380
			LYTTELTON		Dark chert-free dolomite with large elongated stromatolitic mounds	150
			MONTE CHRISTO		Light coloured recrystallised dolomite with abundant chert; stromatolitic; basal part oolitic	700
			OAKTREE		Dolomite, becoming darker upwards Chocolate-coloured weathering	200
			BLACK REEF QUARTZITE		Shale Quartzite Arkosic grit	25 - 30

Figure 2-4: Diagram of the different formations of the Bo Molopo dolomite near Mafikeng in the NW Province

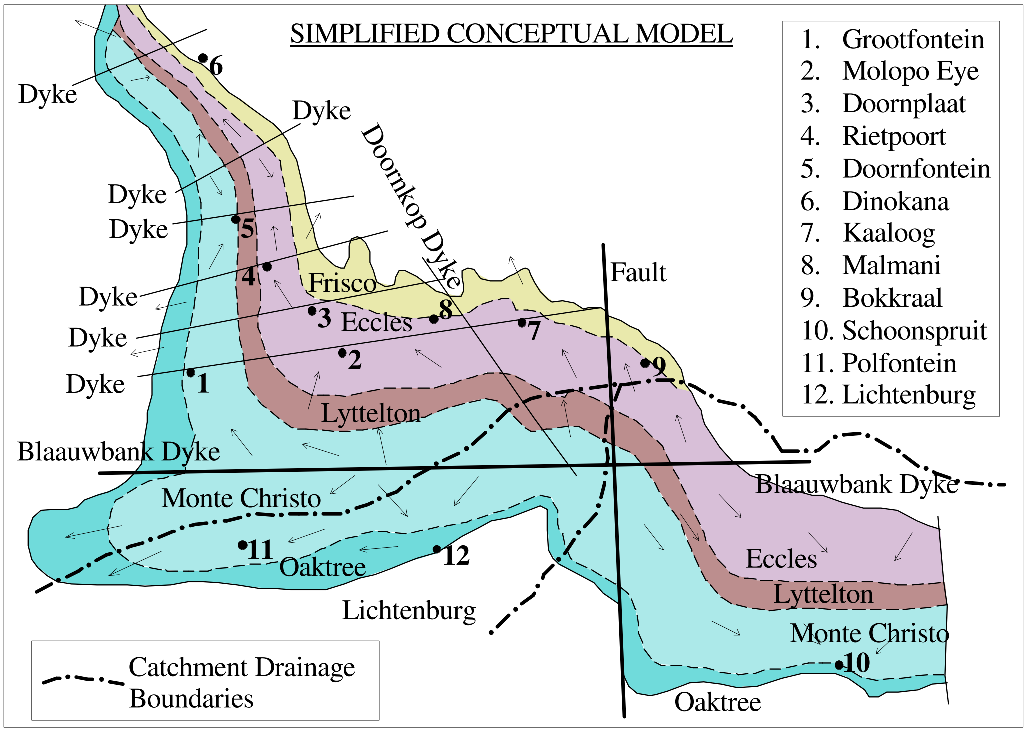


Figure 2-5: Simplified presentation of the different dolomitic formations in the Upper Molopo area that have been exposed to the surface

The different springs acting as drains of the recharge and the flow directions are shown. The groundwater drainage to the west and south west are relevant to the present study.

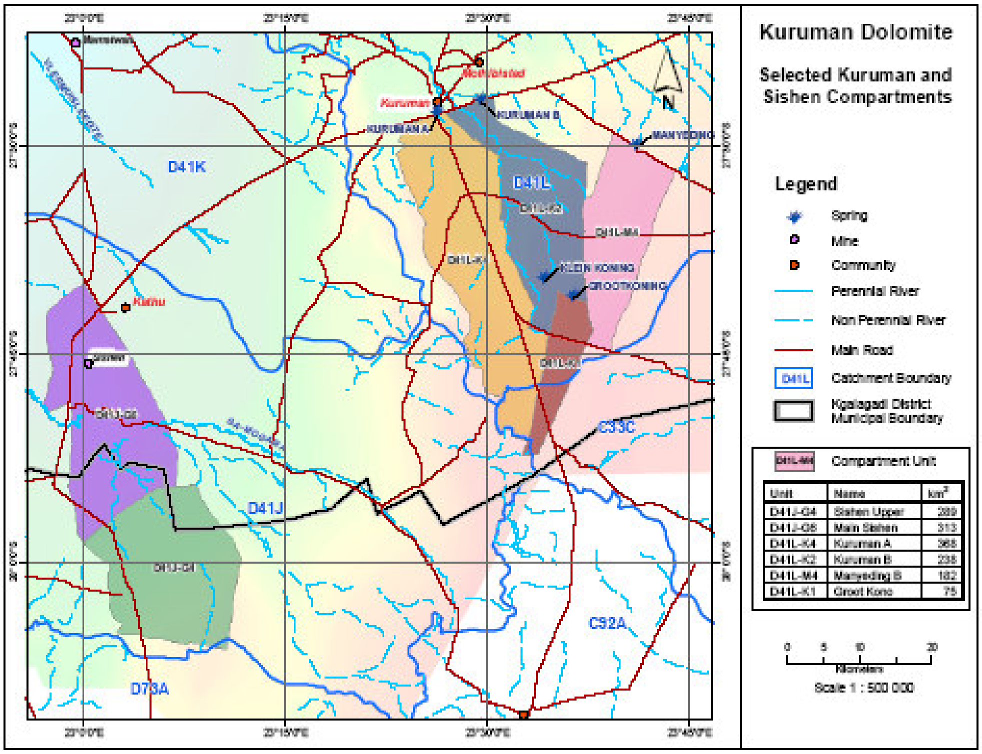


Figure 2-6: Delineation of dolomitic compartments in the Kuruman Sishen area

In **Figure 2-6**, the flows have been simulated as well as the reappearance of ^{14}C from nuclear bomb fall-out in the spring discharge.

2.5 ESTIMATION OF RECHARGE

The recharge of the dolomite occurs frequently but could be highly variable as it is controlled by the volumes, frequency and intensity and spreading of rainfall over time in the recharge area as well as by the thickness and type of overburden material. The daily and spatial variability of recharge is evened out by the surface overburden and equalisation of the water levels is affected because of the high transmissivity of the aquifer. The response of the groundwater levels react similar to the *cumulative departures of the rainfall* in excess of the long-term monthly average rainfall. Groundwater level fluctuations also correspond to the moving average rainfall over a characteristic period. These two methods are referred to as the CRD and MA methods (see **Annexure A**) from which quantitative estimates of recharge could be derived for all types of aquifers if water level measurements and rainfall data are available.

Although the quantification of recharge is difficult it could be calculated from a selected set of methods. The reliable and practical methods are listed in **Table 2-3**.

Table 2-3: List of practical methods to determine the parameters of aquifers

Parameter	Method	Comments/requirements
Storativity S	1. Water balance equation # 2. Pumping tests 3. CRD and MA simulation #	Require recharge, abstraction, water levels and storativity of the aquifer Requires water levels in pumping borehole or in an observation hole. Needs a reference recharge to ensure reliability of the parameters
Recharge	1. Chloride mass balance - the most independent method based on the ratio of Chloride concentrations of rain to that of groundwater	Chloride in rainfall is required, which be inferred from the springs but is presently being measured in rainfall samples collected over the country
	2. Bicarbonate method This method could be used If the CMB method fails because of too high Chloride in the groundwater	First has to be calibrated according to reliable estimates based on other methods of which the chloride mass balance method is the most reliable
	3. Equal volume interpretation of the water balance	Needs data of pumping or of spring flows or base flow or water levels
	4. CRD&MA methods # (see Annexure A)	Requires an estimate of S and the average recharge; also a fairly long series of monthly water level data
	5. Hydrodynamic modelling, which determines the water balance and flow between grid elements.	Depends on the reliability of the simulation of groundwater levels. Needs skilled modelling expertise
	6. Simulation of the re-appearance of bomb C14 in the rainfall in the spring discharge.	The recharge is separated in low and high rainfall recharge to incorporate fast and slow recharge that has different C14 inputs into the aquifer Recharge parameters as well as the turn-over time of the aquifer is determined. The latter represent the storage of the groundwater relative to the average recharge
	7. Using a recharge-rainfall relationship by which the variability of recharge can be simulated from rainfall records. This method has been used in the present study to derive regional estimates of the recharge purely from the rainfall.	Rainfall recharge equations have been derived for i. Selected dolomitic aquifers ii. The Coetzerdam granite aquifer iii. A quartzite aquifer at Rietondale Pretoria
Aquifer depth and thickness	MA method and CRD method – a simple technique	The only other methods to obtain this are by drilling and geophysics
	# See app 1 CRD&MA on methods	

2.6 ESTIMATION OF THE STORAGE CAPACITY OF AQUIFERS

The total water stored in an aquifer is very important but is difficult to determine reliably, mainly because the storativity that is usually determined from pumping tests or by means of a water balance represents the response of the groundwater levels at the water table of the aquifer. However by means of the CRD/MA method the depths of an aquifer can be determined from the interpretations of the water level responses. Thus the decrease in depth of the storativity could be derived to estimate the total depth of water stored in the aquifer profile down to the bottom of the aquifer. This could be related to the average annual recharge, allowing that to be related as multiples of the total water stored in the aquifer section.

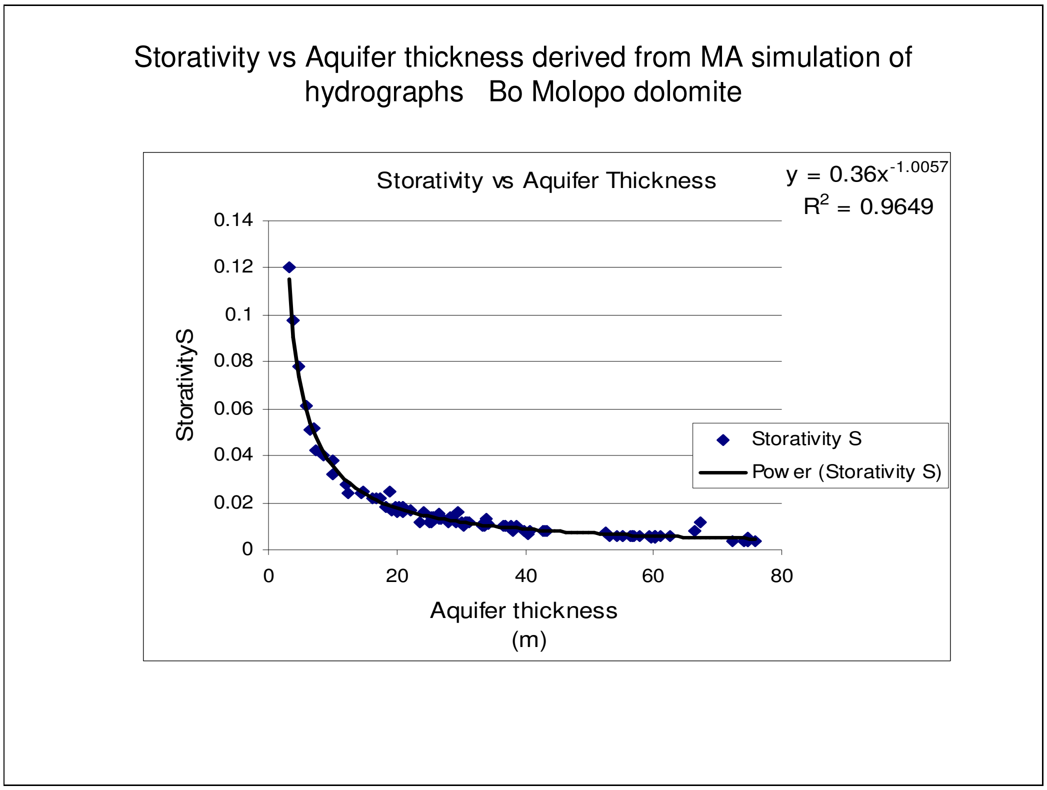


Figure 2-7: Decline in aquifer porosity with depth for Grootfontein dolomitc aquifer derived from CRD/MA interpretations of groundwater hydrographs

The ratio of total water in the column relative to the average recharge represents the turn-over time of water in the aquifer and it also represents the relative age of the water in the system. Although the turn-over time should also be represented by the age of the water such dating of the ground-water is not correct as the mode of infiltration affects the C14 concentrations and the age derived from it (Bredenkamp et al 2007). However in dolomite aquifers that sustains perennial flow of a spring the correct age of the water has been derived, so that the storage in relation to the recharge has been reliably inferred. The results that have been obtained for springs in the present study area are shown in **Table 2-4**.

Table 2-4: Summary of recharge and the storage-recharge ratios of different dolomitic aquifers obtained from the interpretation of C14 measurements in the springs discharge

SPRINGS	Buffelshoek Molopo	Grootftn Molopo	Rietgat Molo	Kuruman A	Kuruman B	Manyeding Eye Kuruman	Gt Kono Kuruman	Klein Kono Kuruman
Mix period young water months	36	36	36	240	250	36	1	36
Mix period 2 for deep flow months	348	338	No deep	597	502	288	280	288
Turnover time (years)	**11.6**	**12.8**	**1.5**	**22.4**	**27.3**	**7.4**	**8.6**	**10.9**
Recharge area (km^2)	32	92	38	286	72	106	39.2	12
Cl of spring (mg/l)	7.4	6.4	NA	5.3	5.1	10.8	11.3	10.6
Cl Recharge(% of Av Rf)	0.075	0.09	0.07	0.085	0.086	0.042	0.040	0.044
^{14}C Recharge (% of Av Rf)	0.075	0.10	0.10	0.08	0.075	0.042	0.040	0.06

The recharge coefficients of the different compartments depends on the characteristics of the recharge area and the turn-over times are higher for larger catchments than for smaller systems; however Kuruman B spring is an exception.

It is not possible to derive the turn-over time of other aquifers in the same way but it could be determined from graphs similar to **Figure 2-7**.

3. GROUNDWATER MANAGEMENT

It is critically important to properly manage a groundwater system in order to sustain its long-term utilization and requires the recharge ~~have~~ to be determined reliably.

3.1 APPLICABLE METHODS

The CRD and MA methods have the greatest potential in deriving several of the aquifer parameters and could be used to assess the impact of pumping or by a reduction of rainfall e.g. during periods of drought (see **Annexure A**).

The following data are required:

1. Reliable rainfall and groundwater level data in close proximity to the study area (an analysis in the Bo Molopo dolomitic area has indicated a high degree of correlation between the rainfalls over a distance of 70 km.
2. Measurements of monthly groundwater levels and spring flow extending over about three years.
3. Requires the chloride concentration of the rainwater, the groundwater and of springs to reliably determine the average recharge coefficient.

The degree of fit that can be obtained by the CRD and MA methods for an aquifer on top of a quartzite ridge at Rietondale Pretoria is shown in **Figure 3-1** and **Figure 3-2**.

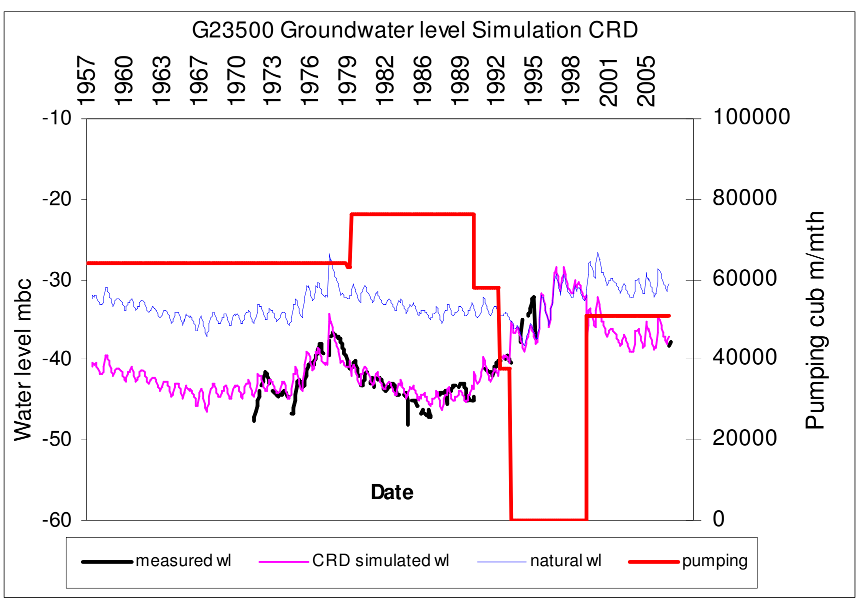


Figure 3-1: The simulation of groundwater levels in the Rietondale quartzite/shale aquifer

Figure 3-1 was simulated by means of the CRD method incorporating both abstraction and recharge. The blue graph indicates the natural groundwater level response for zero abstraction.

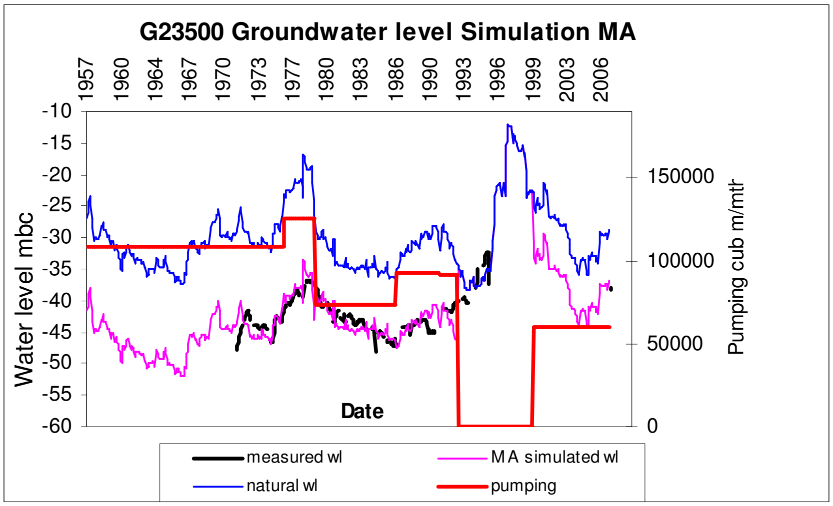


Figure 3-2: The simulation of the groundwater level series of borehole G23500 in the Rietondale aquifer

In **Figure 3-2** the simulation is situated on the quartzite ridge based on the MA method. The pumping, recharge and characteristics of the aquifer have been incorporated.

Figure 3-3 shows that an average rate of abstraction of 38 000 cub m per month could be sustained without depleting the water level below the natural fluctuations.

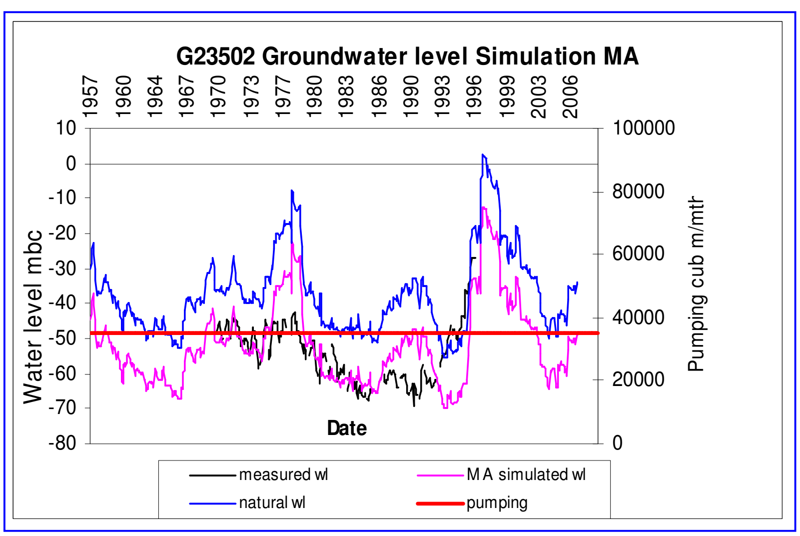


Figure 3-3: Simulated response of the Bryntirion aquifer at Rietondale with continuous abstraction of 35 000 cub m per month

This Figure indicates abstraction of 35 000 m^3/month, this is the maximum sustainable yield of the aquifer. The aquifer has been depleted to its natural maximum in 1983, 1993/4 and 2003.

Figure 3-4 indicates the relationship between the monthly recharge of this aquifer in relation to the average rainfall over 48 months. It conforms well to an exponential, a power or a polynomial function. **Most importantly the recharge pertaining to zero rainfall can be inferred from the different equations.** It turns out to be 0.284 mm for the exponential response, zero for the power simulation. In the case of the polynomial function the recharge would be zero at about 13 mm average rainfall.

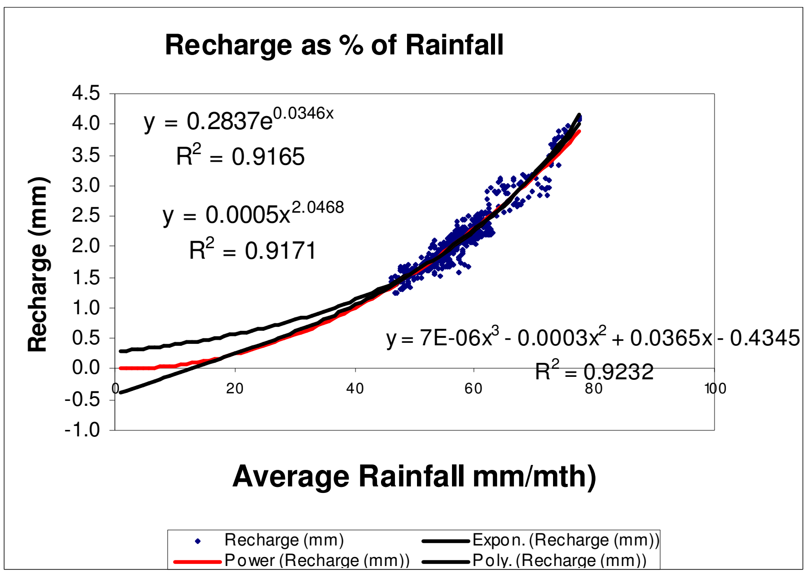


Figure 3-4: The best relationships between the rainfall and the natural recharge derived for the Rietondale aquifer by means of the MA method.

Corresponding rainfall-recharge relationships have been derived for different aquifers (see **Annexure A**) that could be applied to similar aquifer types in the Auob-Nossob and Molopo drainage systems to derive quantitative regional estimates of the groundwater potential of all the areas only from the rainfall. This is covered in the next section.

3.2 DERIVING A REGIONAL ESTIMATION OF RECHARGE FROM THE CRD/MA SIMULATIONS.

In order to derive an estimate of the groundwater recharge in the Molopo catchments e.g. in areas of low rainfall and where little to no information is available, a qualified regional estimate of the recharge can been obtained by method 7. In this way a comparative estimate of the recharge purely in relation to the rainfall and its seasonal variations but disregarding the effects of the thickness of overburden covering the aquifer, is obtained. The regional recharge estimations of the recharge pertaining to zero rainfall was derived from the different equations and substituting the average rainfall of the different groundwater areas in them. The different recharge equations appear in **Table 3-1** indicating that the variability of the monthly recharge conforms to an exponential response in relation to the moving average rainfall over the preceding 48 months. However in the case of Sishen the best regression fit has been obtained with the average monthly rainfall over 12 months, in excess of 27 mm. This stresses that recharge can only occur in excess of a monthly threshold rainfall value.

Application of the formulae for different target areas was selected; according to their similarity of the aquifer characteristics and recharge conditions. The results appear in **Table 3-1** which clearly shows that the recharge of the Kalahari region would effectively be zero because although in some months rainfall above 27 mm could occur, a surplus over the average of 12 months has to be affected. As the effective cut-off rainfall has to apply over a longer period a threshold rainfall of 20 mm has been used with the Sishen formula.

The recharge derived from the regional relationships has also been compared to the estimates that were obtained from a simple rainfall-recharge function, which was used in the reliable simulations of the water balances of the Coetzerdam and Tosca/Vergelee aquifers. These show excellent agreement with the regional estimates (see **Table 3-1**).

This regional approach is the only way to obtain basin-wide estimates of groundwater recharge for comparison and water resource assessment, planning and management in all areas, without having to conduct a water balance over several years. The different equations should be applied using monthly rainfall series inserted into the different rainfall-recharge equations. This would reveal the full characteristics of the recharge in relation to the rainfall variability of a specific area.

A similar approach should be adopted in the assessment of runoff on a regional scale. The runoff should also conform to an exponential response relative to the monthly variability of the rainfall. The relationship forthcoming could also be applied to other representative catchments and could then be applied to predict the runoff in any unknown area.

Table 3-1:Summary of the recharge estimates derived from the different regional estimates based on rainfall-recharge formulae of different aquifer systems (illustrated in Annexure A)

Recharge estimate from regional rainfall equations					
Aquifer	**Equation from which recharge is derived Ref. Annexure A**	**Average annual Rain (mm)**	**Average rainfall mm/mth**	**Estimated Recharge mm/mth**	**Simulated recharge Rech coef (%)**
Kalahari aquifers		200	16.7	0.00	0 %
Similar to Sishen	1) $Re = 0.898e^{0.032x1}$	250	20.8	0.38	1.8%
		300	25.0	0.43	1.7 %
Similar to Rietondale	3) $Re = 0.2837e^{0.0348x}$	200	16.7	0.22	1.3 %
Similar to Manyeding	2) $Re = 0.2744e^{0.0473x}$	200	16.7	-0.12	-0.7 %
Average recharge mm/mth		**200**	**16.7**	**0.18**	**1.1 %**
Tosca dolomite aquifer					
Similar to Sishen	1) $Re = 0.898e^{0.032x1}$	390	32.5	0.44	1.3 %
Similar to Manyeding	2) $Re = 0.2744e^{0.0473x}$	390	32.5	1.00	3.1 %
Similar to Kuruman	4) $Re = 0.7425e^{0.0538x}$	390	32.5	3.52	10.8 %
Average recharge mm/mth			32.5	**1.65 mm**	**1.71 mm** *(Van Dyk)*
Coetzersdam granite aquifer					

Similar to Sishen	1) $Re = 0.898e^{0.032x1}$	480	40.0	0.55	1.4 %
Similar to Rietondale	3) $Re = 0.2837e^{0.0348x}$	480	40.0	1.14	2.9 %
Similar to Manyeding	2) $Re = 0.2744e^{0.0473x}$	480	40.0	1.55	3.9 %
Average recharge mm/mth			27	**1.08 mm**	**1.11 mm** *(Botha)*
Orapa-Lethlakane Similar to Sishen	1) $Re = 0.898e^{0.032x1}$	500	14	1.40	3.45%
Similar to Rietondale	2) $Re = 0.2837e^{0.0348x}$	500	21	0.75	1.84%
Similar to Manyeding	3) $Re = 0.2744e^{0.0473x}$	500	21	0.59	1.44%
CRD method	3) $Re = 0.018 * Rf_{av}$	500	41	0.73	1.8%
Average recharge				**0.86 mm**	**2.1%**
x1= 12 mth mov av rainfall in excess of 27 mm				Values for different methods	
x = 48 month mov av rainfall					

3.3 DETERMINATION OF THE SUSTAINABLE EXPLOITATION POTENTIAL OF GROUNDWATER.

Wiegmans (unpublished) has derived the sustainable potential of dolomitic aquifers in the Kuruman area from the relationship between the rainfall and the recharge calculated by means of the CRD/MA simulations. This entails that the response of the spring flow, which is similar to deriving the water level fluctuations (**Figure 3-3**), in relation to the rainfall over a characteristic period. The sustainable yield would be represented by the lowest groundwater level of the system according to the rainfall record (see **Figure 3-3**). From the average rainfalls (e.g. over 48 months) the rainfall corresponding to the lowest natural status of the aquifer, its position in the rank order has been determined. This indicated that the average rainfall corresponds to a position higher than the average water level. This is because the recharge response of the water level is exponentially related to the average rainfall.

The following unpublished equation has been derived (by Wiegmans) to represent the exploitation potential of an aquifer:

$$Re = 0.68\ \{(a.Rf_{48})\}\ -3 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{eq. } 3.1$$

where Rf_{48} = the moving average rainfall over 48 months and a = the recharge coefficient that has been derived for different areas. The constant value in the equation represents the portion of the recharge that is reserved for the environment.

The application of this relationship provides a consistent determination of the sustainable exploitation potential of an aquifer in any region on which the allocation of abstraction permits could be based

3.4 LONG-TERM CYCLICAL RAINFALL FLUCTUATIONS

Of particular significance to the status of the water resources in general is the author's involvement in the prediction of recurrent variations of rainfall in accordance with the sunspot cycles. **Figure 3-5** shows the results obtained from a study of the runoff in the Vaal River relative to the sunspot cycles (Bredenkamp, 2008, submitted for publication in Water SA). According to this the flow of the Vaal Dam would substantially diminish during the period 2010 to 2014.

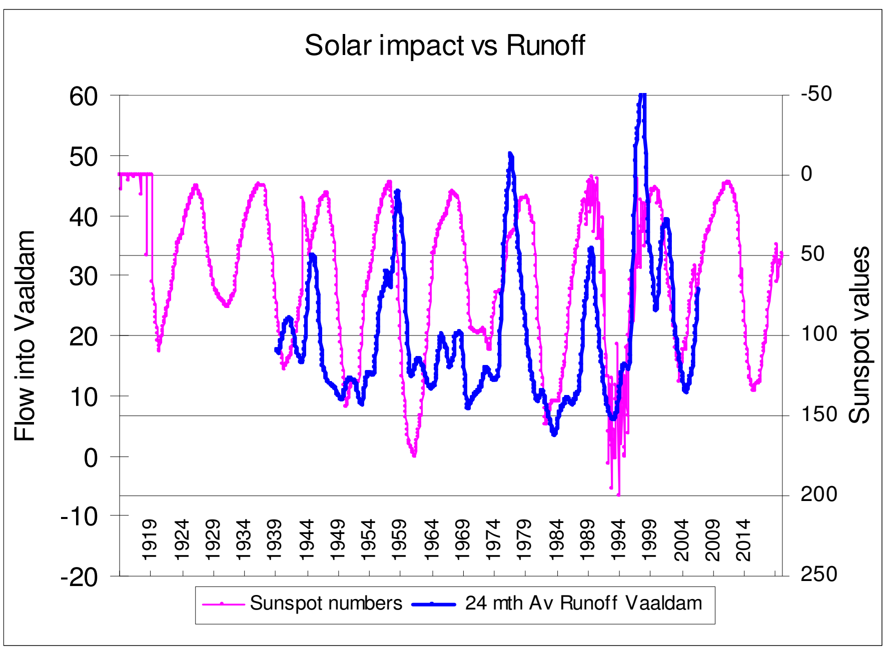


Figure 3-5: Depiction of relationship between sunspot cycles and runoff

Improved correspondences between the inversely plotted sunspot cycle and the Vaal River runoff, incorporating a lag of 18 months in the runoff response. (The inverse plot of the sunspot values reflects the energy relationship that gives the best correspondence).

As the rainfall over the entire summer rainfall areas is likely to behave in a similar way, the fluctuations of the groundwater levels would follow the same trend. This is manifested by the water levels of the Wondergat in relation to the sunspot cycle, which provides a useful method to predict the response of groundwater systems (see **Figure 3-6**).

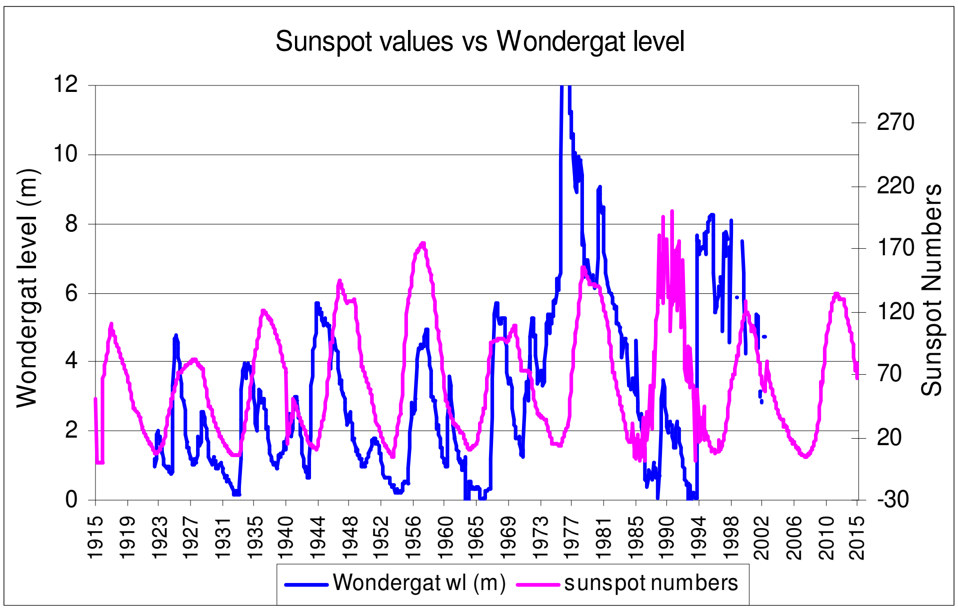


Figure 3-6: The response of groundwater levels of the Wondergat plotted in relation to the sunspot cycles

The sunspot values beyond 2008 represent simulated values obtained from the internet.

3.5 **IRRIGATION IN THE TOTAL DRAINAGE SYSTEM** (Hydrology Report, 2008)

The total irrigated crop area for the Molopo-Nossob catchment areas amounted to about 20 692 ha during the year 2000. Irrigation with groundwater (boreholes) totaled 16 651 ha or 81 % of the total irrigated area while irrigation from surface water resources amounted to 4 041 ha or 19 % of the total irrigation area (crop area). The extent of irrigation areas in the study area from both groundwater and surface water sources is shown in **Figure 1-3**.

It was assumed that all irrigation demands would be met from farm dams. However, in catchments with surface water irrigation but no farm dams, irrigation demand was supplied from rivers. During the hydrological modelling, irrigation demands were calculated by means of the WQT. Crop factors as proposed by Schoeman and Vennote were used.

4. CONCLUSIONS

The recharge in the areas covered by Kalahari sediments is negligible in areas with less that 300 mm/year and the quality of the groundwater is poor within areas but not all over the low rainfall areas within Namibia. The isolated areas of higher recharge e.g. in the vicinity of Van Zylsrust, at Keesi and Fullifeesand in close proximity to the Kuruman river are directly linked to recharge that occurs infrequently at times when floodwater reaches as far as the confluence of the Nossob-Limpopo Rivers. The groundwater exploitation from dolomitic aquifers is good even in the low rainfall areas like Tosca/Vergelee, as this aquifer is periodically being recharged by floods occurring in the Molopo River and it has sufficient storage to be exploited excessively during periods of low rainfall. Replenishment could occur in one year of high rainfall that has caused floods to reach the aquifer. Similarly the Louwna-Coetzersdam granite aquifer is regularly being recharge in view of higher local rainfall and a thin overburden of unsaturated material overlying the granite aquifer. In areas overlain by thick Kalahari sediments, representing about 70 % of the investigated drainage area, the recharge will be small as a result of the retention of potential recharge in the unsaturated zone, from where it is lost by evapotranspiration. This is the case in Jwaneng aquifer which receives most of its recharge from the outcropping area of the aquifer and nothing from infiltration through the Kalahari (Nijsten and Beekman 1997).

The occurrence of groundwater is closely related to the underlying geology and the structural deformation it has been subjected to e.g. faulting, folding, fracturing and intrusion of dolorite dykes. The selection of high-yielding drill sites remains difficult but the use of aero magnetic surveying and satellite imaging could reveal regional structures that are often related to higher-yielding boreholes. In view of the poor quality of the groundwater in the central Kalahari region the prospects of good groundwater supplies are zero. In these areas alternative sources of water e.g. from ‘gatdamme’ might still be viable if local rainfall-harvesting could be applied.

It is most important that the Hydrogeological Sheet of the Vryburg area be completed without delay and that that the information be conveyed to the water managers and water users.

The regional approach to assess the recharge potential of unknown areas is the only viable method that can be applied in a consistent way to derive a quantitative prediction of the rainfall-recharge of any aquifer from the exponential relationship between the recharge and the rainfall. In view of the similarities between larger part of the Kalahari in the RSA, Botswana and Namibia, much of the missing information could be ascertained from the regional models. The outcome indicates that the groundwater potential of the Kalahari areas would inevitably be small and thus requires that alternative resources be found. Such possibilities are almost non-existent but the use of ‘gatdamme’ for the collection of rainwater or by desalinisation of highly saline water, seems to be prospects in some areas.

The monitoring of rainfall, water levels and abstraction from groundwater is essential to derive the aquifer parameters that are required to model specific groundwater system reliably. It would however be rather fruitless to invest in expensive monitoring in the central dry Kalahari region. The hydrodynamic modelling of the large aquifers should be extended to incorporate the change of aquifer storativity with depth that specifically applies to the dolomitic aquifers. An aspect not to be neglected is proper management of the resource and the education of the water users to participate in this respect.

The results obtained from the CRD/MA simulations of the flows of dolomitic springs have potential to derive the sustainable exploitation potential of an aquifer as well as determining the reserve of the aquifer in a consistent way.

In view of the rainfall being the primary factor to cause recharge, the exploitation of groundwater will be affected by long-term cyclical recurrences of low and high rainfall, which appears to be synchronized with the sunspot variations. This is particularly important in view of sub-normal rainfall that could be expected in the period 2010 to 2014.

5. REFERENCES

Alexander W J R., Bailey F, Bredenkamp D. B., van der Merwe A and Willemse N (2008). Linkages between solar activity, climate predictability and water resource development. SAICE Journal, South Africa.

Botha L.J. (1995) Louwna-Coetzerdam : Re-evaluation of the groundwater potential. Technical report GH 3860, Department of Water Affairs and Forestry.

Bredenkamp D.B. (2007) Use of natural isotopes and groundwater quality for improved recharge and flow estimates in dolomitc aquifers. Water SA

Bredenkamp D.B. Vogel JC, Wiegmans FE, Xu Y and Van Rensburg HJ (2007) Use of natural isotopes and groundwater quality for improved estimations of recharge and flow in dolomitc aquifers. WRC report No. KV 177/07.

Bredenkamp D.B. (2009) A conceptual model towards verification of the impact of planetary interactions on the earth's climate fluctuations. Submitted for publication in Water SA 2009 (Water Research Commission of South Africa)

Dziembowski Z M and Appelcryn D T, (1987). Kalahari oos (Soutblok oos area) Grondwaterbronne, Distrik Kuruman, Technical report Gh 3531, Department of Water Affairs, Pretoria South Africa.

Kirchner J and Tredoux G. (1975) The Stampriet artesian basin with special reference to the salt-block.

Meyer E I .(1953) 'n Geologiese en geofisiese opname van die Kalahari langs die Molopo- en Kuruman rivieere in die Gordonia- en Kuruman distrikte, met spesiale verwysing nad ondergrondse water.Verslag 12/2/203, Geologiese Opname , SA Pretoria.

Nijsten G,J. and Beekman H.E. (1997) Groundwater flow study in the Llethlakeng-Botlhapatlou area Gress II Technical report : Groundwater recharge and resources in the Botswana Kalahari.

Smit, PJ, (1977). Die Geohidrologie in the opvanggebied van die Moloporivier in the Noordelike Kalahari. PhD Thesis, University Free State

Van Wyk E.and Appelcryn (1989). Grondwater ondersoek Area1, Springbok Berrange Distrik Kuruman.Department of Water Affairs and Forestry.

Van Dyk G. (2006). Managing of the Irrigation on the Tosca-Molopo Groundwater Resource. MSc Thesis . University of the Free State , Department of Geohydroloy, Bloemfontein

Van Dyk G and van Kisten S. (2006). An explanation of the 1: 500 000 General hydorgeological map (Vryburg 2522), Department of Water Affairs and Forestry.

Van Rensburg H Janse (Private communications)

Wiegman F.E, (Private communications) (VSA Group).

Reports examined but not specifically referenced:
Bredenkamp D B. (2000) Groundwater monitoring: A critical evaluation of groundwater monitoring in water resources evaluation and management. WRC project

Dziembowski Z M and Wessels M J.(1979). Preliminary report Gh 3149, Department of Water Affairs and Forestry .South Africa.

Gombar L. (1974) Hydrogeology in the vicinity of farm Pomfret, Vryburg District. Technical Report 2910, Directorate Geohydrology, Department of Water Affairs

Mulder M P (1978) Summary of geohydrological informationalong the Molopo River from Werda to Koopan North (Bokspits). Technical report Gh 3017, Department of Water Affiairs, Directorate Geohydrology.

Smit, PJ, (1964). Nasionale Gemsbokpark: Geohidrologiese aspekte. Report , Geological Survey, Department of Mines , Pretoria, South Africa

Smit, PJ, (1978). Grooundwater recharge in the dolomite of the Ghaap Plato near Kuruman in the Northern Cape, Republic of South Africa.. Water SA vol4, No. 2, April 1978.

Van Wyk E (1992). Watervoorsiening vir Middelputs, SAP Terrein, Distrik Kuruman.

Verhagen B T(1977) Geohydrological studies in the Gamagara Compartment using Environmental Isotopes and complementary techniques. Third annual report, Nuclear Physics Research Unit, University of the Witwatersrand, Johannesburg.

ANNEXURE A: METHODS OF ESTIMATING GROUNDWATER RECHARGE

A1. APPLICATION OF THE CRD/MA SIMULATIONS OF GROUNDWATER LEVELS – RIETONDALE QUARTZITE AQUIFER – A TYPICAL QUARTZITIC AQUIFER

It is clear from **Table A-1** that the recharge and storativity derived from borehole A2N034 in the Rietondale aquifer are higher than that derived for G23502 in the Bryntirion aquifer. The latter aquifer is situated on top of the quartzite ridge, whilst A2N034 is located in the shale aquifer at the foot of the hill. According to the CRD and MA simulations of the groundwater balances, the thicknesses as derived from the average and maximum depth of the aquifers are shown in **Table A-1**.

Table A-1. Thickness of aquifer and average depth of groundwater level for conditions of no pumping, derived from the CRD&MA methods

Borehole interpretation	Average depth from surface (mbc)	Average depth of bottom (mbc)	Thickness of aquifer (m)
A2N034	13.5	36.1	22.6
G23502	33.29	80.2	46.9

Sustainable abstraction from the two aquifers

The sustainable abstraction from the two aquifers has been derived from the best simulations according to the CRD simulation of the observed groundwater level fluctuations. (**Figure A-1**).

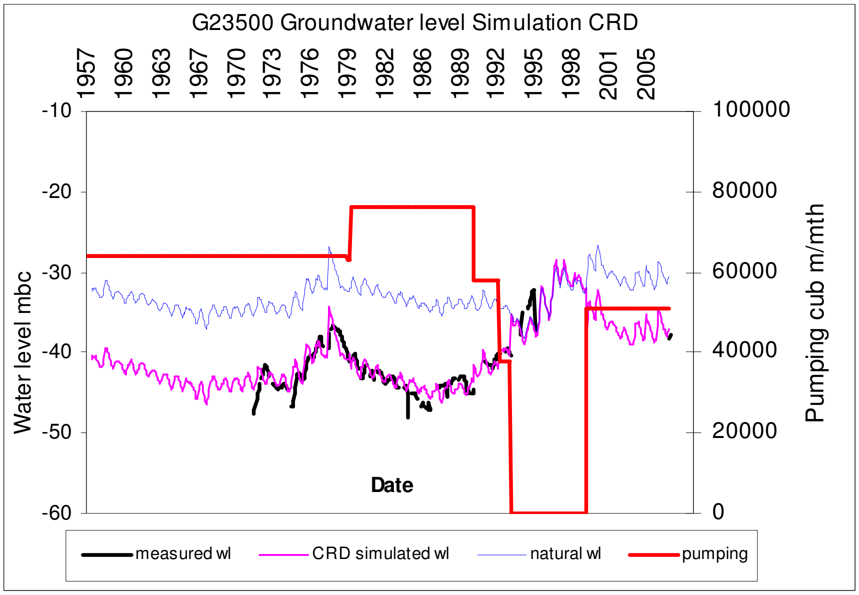


Figure A-1: Best CRD simulation of the groundwater levels of A2N034

According to **Figure A-1** the abstraction rate has varied between 40 000 and 120 000 m^3/month.

The groundwater level drawdown in relation to the natural groundwater levels clearly indicates that the maximum drawdown have occurred during the period 1986 to1995 with full recovery of the aquifer by 1998.

According to **Figure A-2**, the monthly recharge corresponds well to an exponential or binomial function in relation to the average rainfall over the preceding 48 months (method 7). The recharge corresponding to zero average rainfall over 48 months for both exponential functions is close to zero but for the binomial function the recharge would be zero if the 48 month average rainfall is about 12 mm.

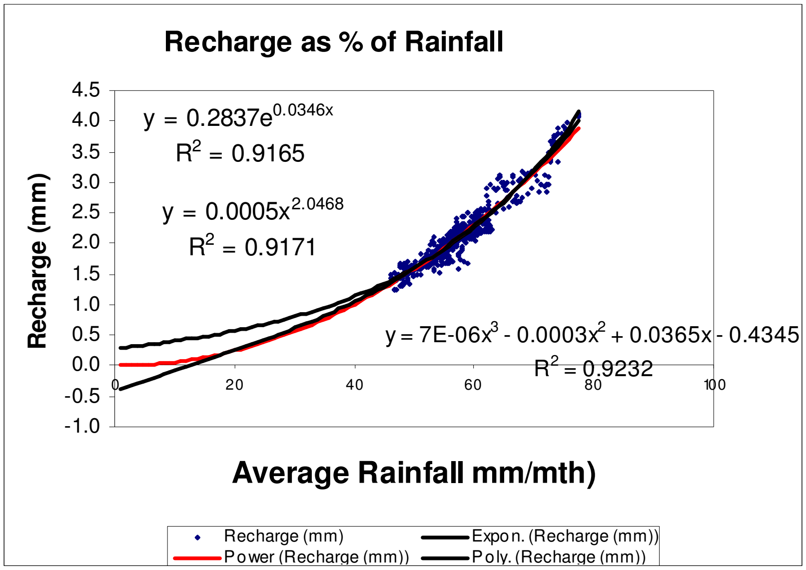


Figure A-2: Recharge corresponding to either an exponential or binomial relationship to the average rainfall over the preceding 48 months for Rietondale aquifer (hydrograph simulation of borehole A2N034 with x being the moving average rainfall over 48 months)

A2. RECHARGE OF DOLOMITE AQUIFERS DERIVED FROM SIMULATIONS OF SPRING FLOW

A binomial recharge relationship has also been obtained from the simulation of different dolomitic aquifers as is listed in **Table A-2**.

Table A-2: Recharge relationships derived for different dolomitic aquifers from the CRD/MA simulation of the spring flow

Aquifer	Recharge relationship	Comment	Figure reference
Pretoria dolomite			
– Rietvlei eye	Re = 1.961e $^{0.0377x}$ x = 72 mth av rainfall	Derived from the best C14 simulation	See Fig.
Molopo dolomite			
– Buffelshoek	Re = 0.9964e $^{0.0432x}$ x = 48 mth av rainfall	Derived from the flow of the spring	See Fig.
Kuruman dolomite			
– Kuruman main eye	Re = 0.7425e $^{0.0538x}$ x = 48 mth av rainfall	Recharge derived from a simple rainfall - recharge algorithm	See Fig.
– Manyeding eye	Re = 0.2744e $^{0.0473x}$ x = 48 mth av rainfall		See Fig.
– Sishen system	Re = 0.898e $^{0.032x}$ x = 48 mth av rainfall	Simulated water levels in the	See Fig.

Aquifer	Recharge relationship	Comment	Figure reference
model 1 – Sishen model 2	Re = 0.184e $^{0.0635x}$ x = 12 mth av of rainfall in excess of 27 mm	Sishen quarry	See Fig.
– Pretoria Rietondale Quartzite- shale	Re= 0.2837e $^{0.0348x}$ x = 48 mth av rainfall	Derived from MA relationship	See Fig.

Discussion of the rainfall-recharge relationships

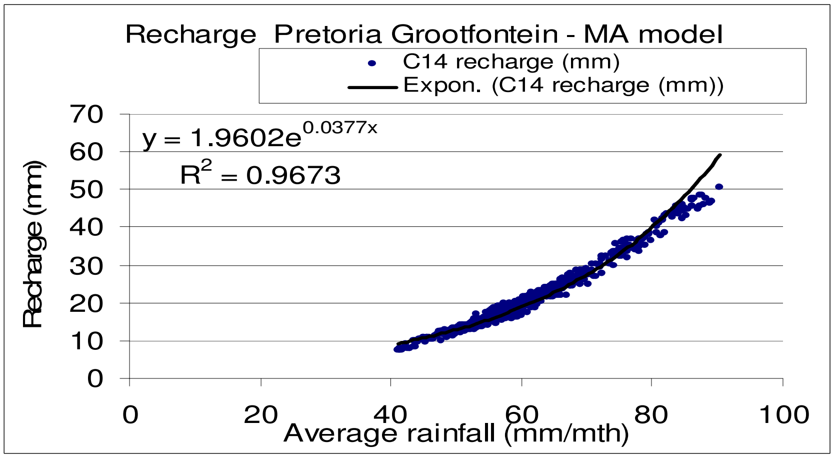


Figure A-3: The relationship between the 72 month average rainfall and the recharge for the Grootfontein aquifer in the Pretoria-Rietvlei dolomite

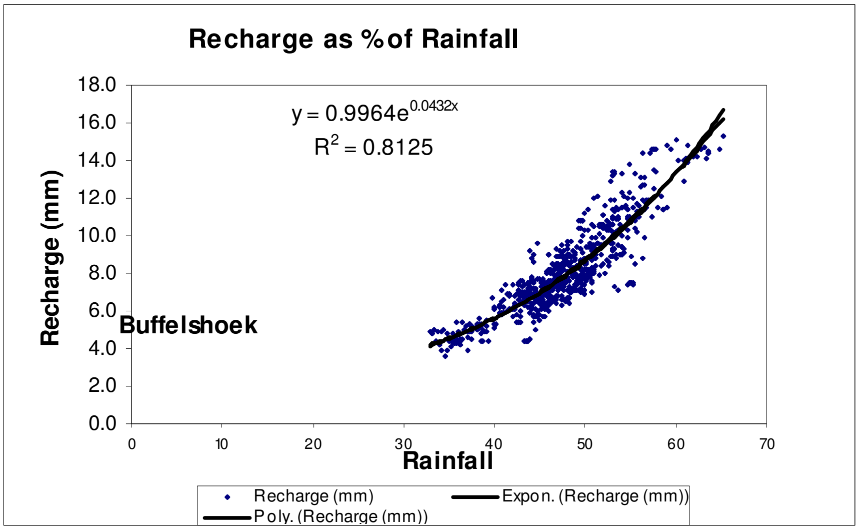


Figure A-4: The monthly recharge in relation to the 48 month average rainfall for the Buffelshoek spring.

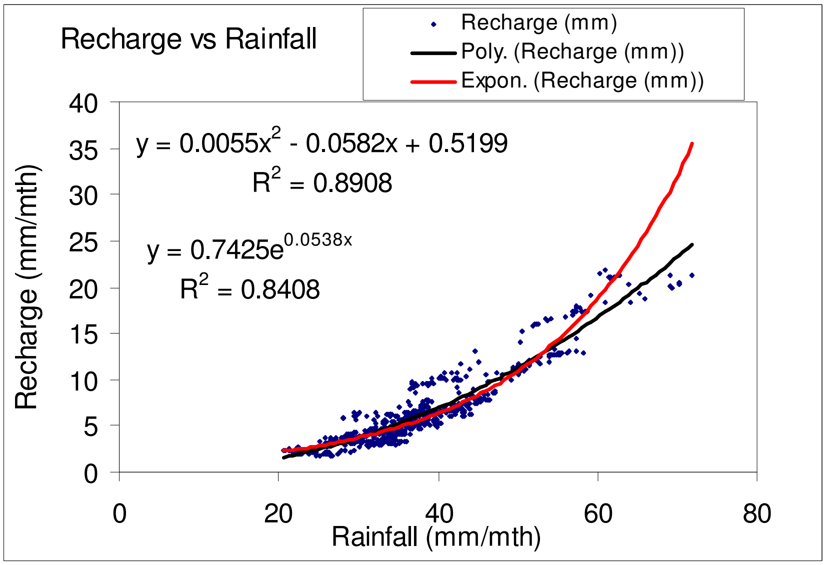


Figure A-5 The monthly recharge derived from the simulation of the flow of the Kuruman A spring by incorporating threshold rainfalls, correlated to the average rainfall over the preceding 48 months.

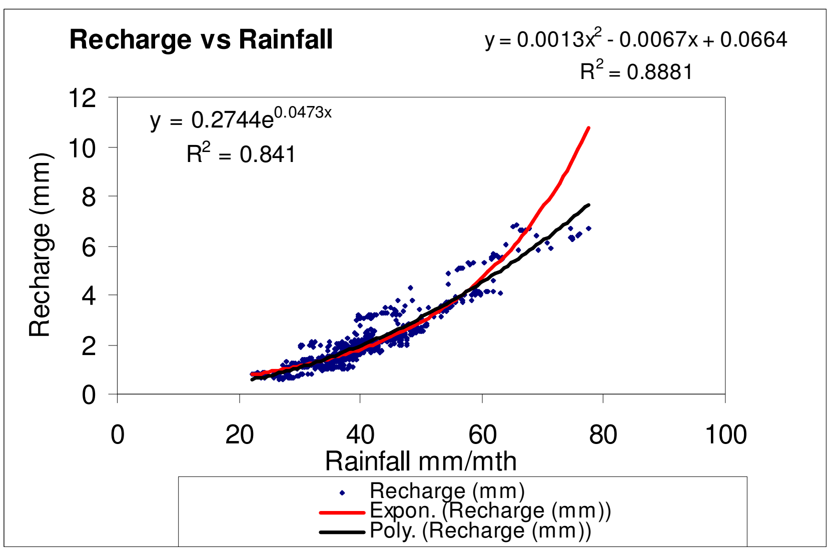


Figure A-6: Best fit for Manyeding eye between the monthly recharge, incorporating the threshold rainfalls and the average rainfall over the preceding 48 months without the threshold rainfalls.

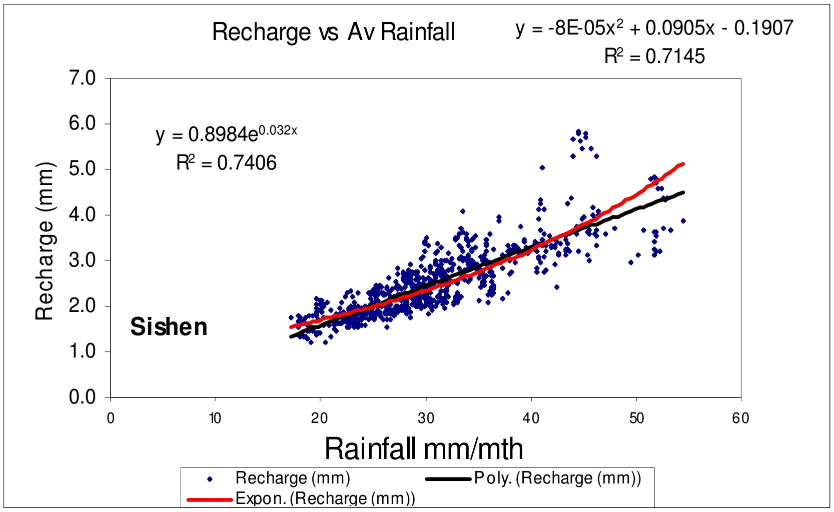


Figure A-7: Best relationship for Sishen between the simulated average rainfall over the preceding 48 months (without incorporating the threshold rainfall) and the monthly recharge derived from the effective rainfall exceeding the threshold rainfall

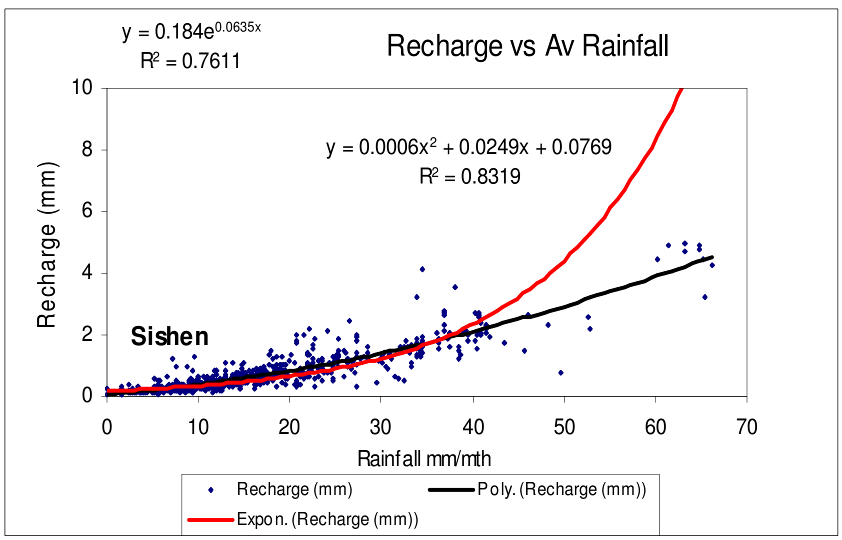


Figure A-8: Improved relationship for the Sishen aquifer between the estimated recharge against the effective average rainfall over 12 months i.e. in relation to monthly rainfalls in excess of 27 mm

A3. REGIONAL ESTIMATION OF RECHARGE (LOUWNA-COETZERSDAM AQUIFER)

In order to derive an estimate of the groundwater recharge e.g. in areas of low rainfall, like the Kalahari where little to no information is available, a qualified regional estimate of the recharge has been obtained by means of method 7. The application of the latter method has great value in obtaining a comparative estimate of the recharge purely in relation to the observed rainfall and its temporal variations. It presupposes that a rainfall record for the investigated area would be available or it could be based on the average annual rainfall of the target area. The regional recharge estimations of the different reference areas could be derived from the different equations and substituting the average rainfall of the different groundwater compartments in them. The results are shown in **Table 3-1** in the main section indicating that the variability of the monthly recharge conforms to an exponential response in relation to the moving average rainfall over the preceding 48 months. However in the case of Sishen the averaging period is over 12 months in respect of the monthly rainfall events that exceed 27 mm, which has produced the best relationship.

The formulae applicable to the referenced areas were selected according to those which best correspond to the aquifer conditions of the target aquifers. For each aquifer a regional estimate of the recharge was calculated by inserting the average monthly rainfall of the target area into the respective formulae.

The results appear in **Table 3-1** it clearly shows that good correspondence has been obtained for the recharge of the Louwna-Coetzersdam aquifer based on the regional recharge relationships.

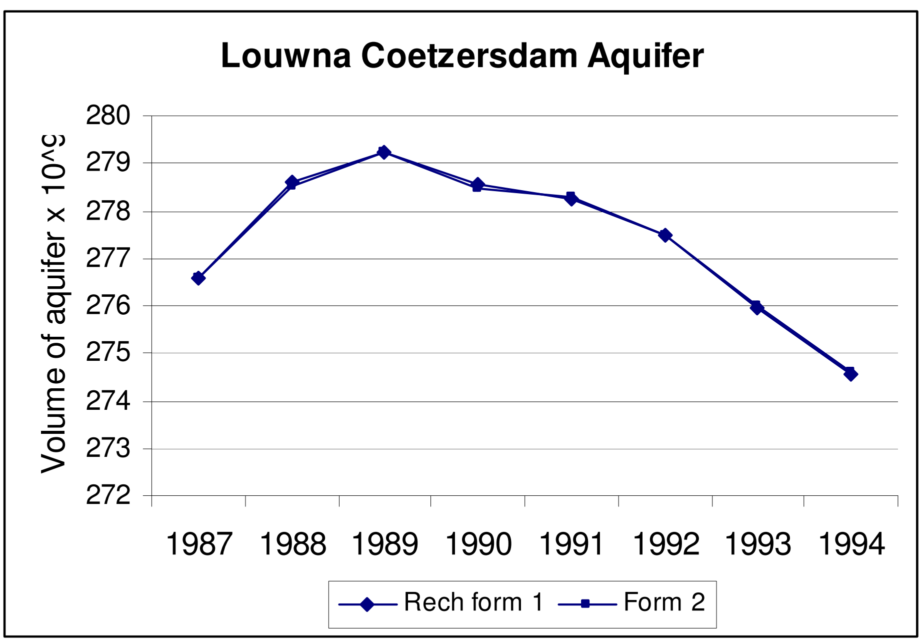


Figure A-9: Fit obtained for the simulation of the aquifer volumes over the period 1987 to 1994 using two recharge equations in water balance equation (cf Botha 1995)

The recharge derived from the regional relationships has been compared to the monthly estimates that were derived from a simple rainfall function applied to water balance model of the aquifer.

This is the only way to obtain basin-wide estimates and comparisons of groundwater potential that could be used for water resource assessment, planning and management. The different equations should be applied by using the actual monitored rainfall data, e.g. the records of Weather Bureau stations can be used to obtain more refined estimates of the regional recharge of this aquifer.

A4. THE COETZERSDAM GRANITE AQUIFER

The Louwna-Coezers dam aquifer, 1 330 km^2 in area, exploits groundwater from about 1987 and irrigates an area of at least 4 000 ha. From annual groundwater levels that have been monitored in May of each year at 117 boreholes covering the entire area, the integrated volume of the aquifer was calculated for each year. The electrical consumption of the irrigation installations were used to derive the best rainfall recharge relationship and storativity of the aquifer by solving the water balance of the system, using a multiple parameter optimization for the entire period from 1987 to 1994. Good correspondence between the measured and simulated levels has been obtained. (see **Figure A-9** (Botha 1995).

Consistent recharge values have been obtained using two rainfall formulae as is shown in **Table A-4**.

Table A-4: Parameter values derived from water balance of the Louwna-Coetzersdam aquifer

Recharge formula	Recharge (mm/a)	Storativity (S)	Equation parameters	Correlation coefficient
Re = a(Rf-b)	16.8	0.024	Re = 0.086(Rf-286)	0.986
Re = a(Rf * Rf/Rf_{av})	14.5	0.021	a* b = 24 mm	0.999
Re (CMB method) Re = Cl_{rf}/Cl_{gw} *Rf_{av}	Av = 15.6	Av = 0.0225	Cl_{rf} = 0.55 Cl_{gw} = 16.2 mg/l	

It is clear that both recharge equations yield acceptable results.

Orapa Lethlekane Aquifer

The recharge of this aquifer has been determined by means of the CRD method as is indicated in **Figure A-10**.

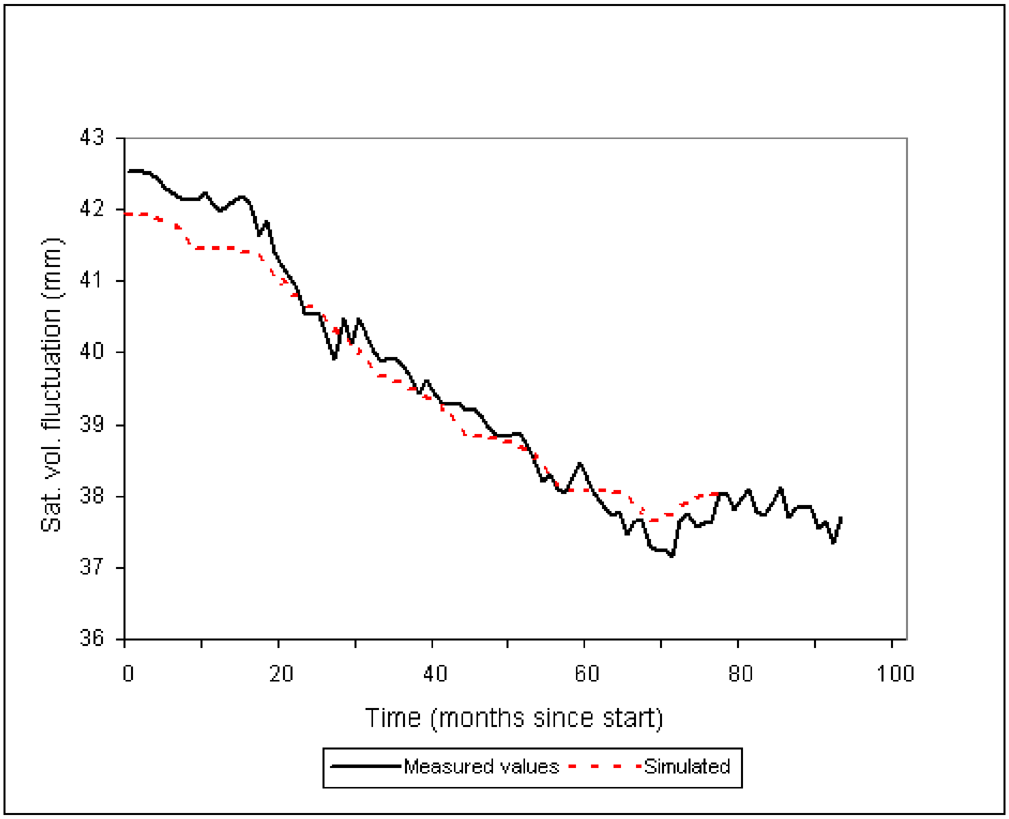


Figure A-10: Simulation of the groundwater levels response of the Orapa-Lethlakane aquifer by means of the CRD method of monthly rainfall relative to the longterm average rainfall. The best correspondence has been obtained by lagging the CRD response by 16 months.

The average recharge is equivalent to 1.8 % of the average rainfall which is equivalent to 0.74 mm/month. According to the formula of Wiegmans the sustainable exploitation potential of the aquifer is 0.68*0.74*12 – 3 = 3.1 mm/year. The fact that the best simulation is obtained for a lag of 156 months provides proof that there is active recharge but it takes 16 months for the water to percolate through the thick Kalahari and reach the water table.

The regional recharge formula derived for the Pretoria Rietondale aquifer and that of Coetzersdam best correspond to the Orapa-Lethlakane aquifer. The corresponding values of recharge based on these two formula are shown below.

A5. GROUNDWATER POTENTIAL OF THE TOSCA DOLOMITIC AREA (After VAN DYK , 2006)

This aquifer situated close to Vergelee on the NE and Tosca in the centre, has been exploiting the underlying dolomite aquifer since about 1990, when rapid development of irrigation transformed the socio-economic and environmental prospects in the area. By 2002 it was estimated from registration of irrigation, satellite images, surveys and reports from farmers that approximately 2 000 ha were irrigated consuming 18.9 million m^3 of water per year.

The groundwater occurs in the underlying dolomite with several dolerite dyke intrusions (see **Figure A-11**) that has intruded because of the impact of the Morokweng meteorite. The geological stratigraphy is shown in **Table A-5**.

Table A-5: Stratigraphy and lithological explanation

Sequence	Group	Formation	Description
	Kalahari	Gordonia Eden Budin Wessels	Red brown aeolian sand Calcareous sandstone and clay Red clay Sandstone and gravels
Post Karoo			Dolerite dykes and sills
Griqualand West		Makganyene	Diamictite
	Griquatown	Asbestos Hills	Banded ironstone, including jaspilite and chert
	Campbell	Ghaap Plateau Schmidtsdrift	Dolomite chert limestone Dolomite and shale
		Vryburg	Quartzite
Archaean			Granite

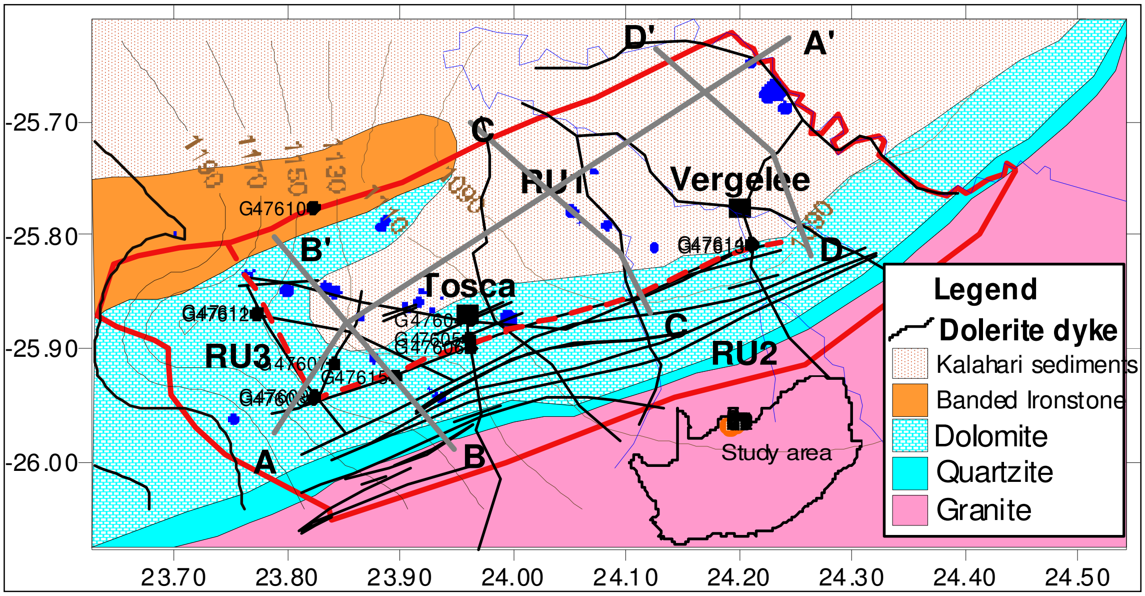


Figure A-11: Geology of the Tosca area with the major economical centres, roads, dry riverbeds, irrigation areas (blue circles) and surface elevation contours (mamsl)

In **Figure A-11** the resource units RU1, RU2, RU3 is divided by the red dot line. The units are

RU 1 – Tosca dolomite aquifer

RU 2 – Dolomite aquifer, area of post Karoo dolerite intrusive (dyke swarms)

RU 3 – Pomfret dolomite aquifer

These resource units are overlain by, low yielding, Kalahari sand aquifer which is only used extensively close to the Molopo River due to the good quality water available above the Budin clay formation. Away from the river very little groundwater is available in this formation.

Within the three identified Resource Units (RU1-3), smaller geohydrological response units exist. They are typically formed by the intrusion of dolerite into the dolomite aquifer forming small compartments, which may act as isolated units.

Table A-6 indicates the rapid rate at which irrigation development took place.

Table A-6: Increase in irrigation areas and volumes

Year	1990	1996	2000	2001	2002
Number of irrigation systems	2	22	32	40	45
Irrigation area (ha)	100	600	1182	1495	2000
Volume Irrigated (Mm^3/a)	0.77	4.6	9.1	11.1	18.9 #
Stock watering (Mm^3/a)	0.5	0.5	0.5	0.5	0.5
Human consumption (Mm^3/a)	0.5	0.5	0.5	0.5	0.5
Total abstraction (Mm^3/a)	1.8	5.6	10.1	12.1	19

All volumes estimated at 7500m^3/ha/annum.

 # Estimated after crop factors for the different crops used.

The groundwater of RU1 and RU3 are very similar in quality, generally low in total dissolved solids, indicating good recharge, while RU2 has an elevated salt content for all major cat ions and anions.

The results of the recharge estimation by three methods are given in **Table A-7**.

Only the CMB could be applied with confidence. With this method recharge is calculated to be between 0.2 to 28 mm/a of the MAP in the different areas of the aquifer. This harmonic mean for all groundwater analyzed is 1.7mm/a is the value that has been used as a reference in the regional rainfall recharge formula (see **Table A-3**) which corresponds well with the estimate of 1.65 mm/a. This confirms the reliability of the rainfall-recharge estimation.

Table A-7: Calculated recharge figures as a percentage of MAP from deductions and recharge tools.

Resource Unit	Recharge [(1)] [%/a of MAP] [mm/a of MAP]		
	Cl Method	Vegter	Harvest Potential
RU 1	0.13 – 9.2 6.4 - 45	0.75 – 3.0 3.7 – 14.7	6 – 53 29.5 - 260
RU 2	0.05 – 4.0 0.3 – 19.5	0.75 – 3.0 3.7 – 14.7	6 – 53 29.5 - 260

Resource Unit	Recharge [1] [%/a of MAP] [mm/a of MAP]		
	Cl Method	Vegter	Harvest Potential
RU 3	0.20 – 7.2 9.8 – 35.3	0.81 – 3.2 4 – 15.7	6 – 57 29.5 - 279

[1] Rainfall figures for Vergelegen (399 mm/a) have been used for RU1 and RU2, while figures from Pomfret (371 mm/a) have been used for RU 3.

The aquifer has been modelled by means of the MODFLOW PMWIN (Chiang 2000) software. A large-scale model covering 80 km east west and 50 km north south or 4000 km^2 was constructed. This has been used to simulate different scenarios of recharge and abstraction. From the model the potential areas at risk are shown in **Figure A-12** in terms of the expected decline in the groundwater levels.

Although the net return on irrigation farming is estimated at R2 887 per ha in comparison to R114 per ha of cattle farming, however it is questionable if this irrigation income utilizing 99 % of the water, justifies the risk of water loss (boreholes drying up) it poses to the stock industry with the potential income of R45.6 million annually for the area.

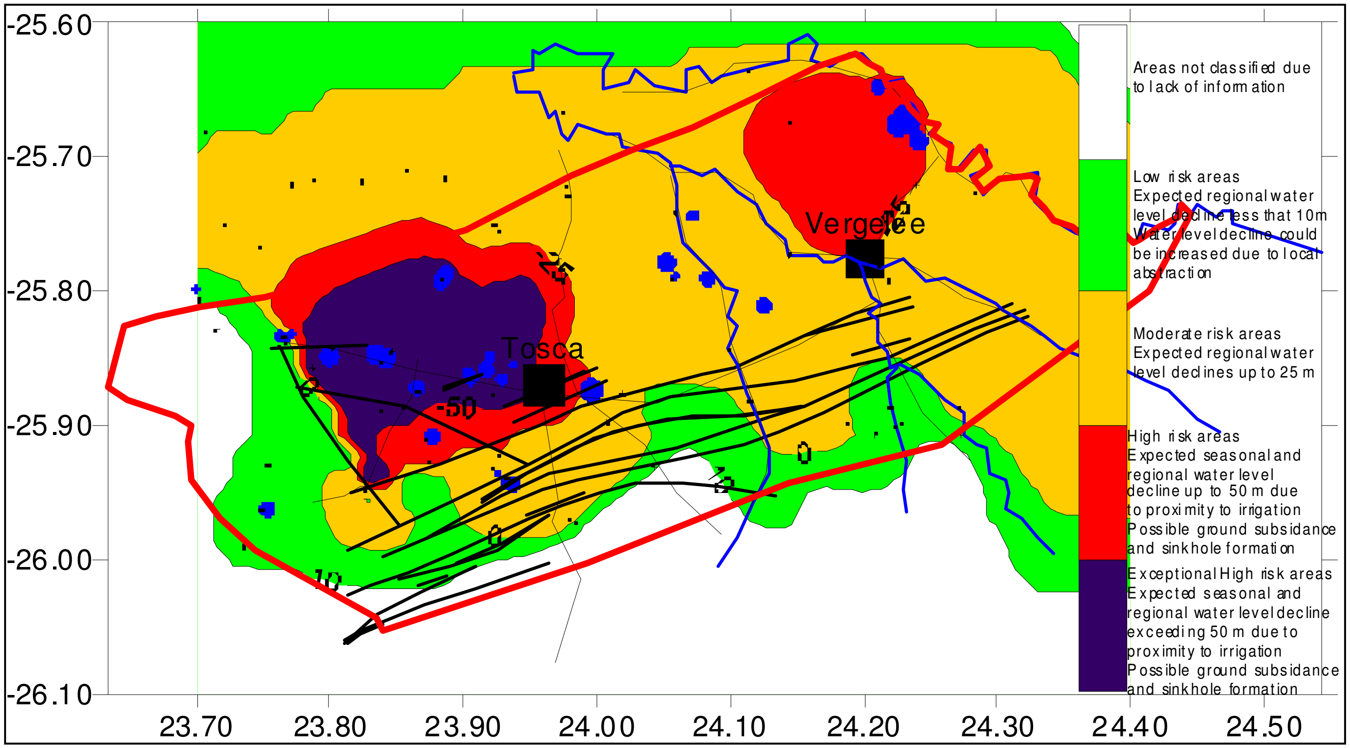


Figure A-12: Risk areas according to the simulation model of the aquifer (Van Dyk 2006).

Farm Dams

Information on farm dams in the study area was sourced by Schoeman and Partners, based on an evaluation of 1:50 000 topo-cadastral maps. A total of 687 farm dams were identified (in year 2 000) with a total storage capacity of some 125 Mm^3. These comprise of in-stream dams (369) with a total storage capacity of 120 Mm^3 (95.9 %) and off-channel dams (318) with a total storage of 5 Mm^3 (4.1 %).

For the purposes of hydrological modelling, individual farm dam areas and volumes within each modelling sub-catchment were summed to yield one “dummy” dam with an equivalent capacity representing all farm dams within that subcatchment. All in-channel dams were included in the model, while off-channel dams were not modelled based on the assumption that these dams store water abstracted from boreholes (groundwater sources).

The Stampriet Artesian Aquifer (Kirchner and Tredoux 1975)

The Stampriet artesian basin receives about 150 mm in the southwest to 350 mm in the north-east. The three main rivers the Auob, Olifants and Nossob rivers cross the underlying artesian. They flow only intermittently after heavy rains. The greater part of the basin is covered by Kalaharis beds overlying rocks of the Karoo Supergroup, which is underlain by the Fish River Formation of the Nama Group. The base of the Karoo is formed by Dwyka Tillite, overlain by black shale, the Nossob sandstone and Auob sandstone. Importantly the shale on top of the Nossob and Auob sandstones serves as the aquiclude causing confinement of the artesian sandstone aquifer. The Karoo rocks increase in thickness from 450m in the south west to 800 m in the east, dipping gently eastwards at an angle of about 1^0 .The Karoo rocks are covered by conglomerates or immature sandstone. Dune sand, calcretes and silcrete form the upper part of the Karoo beds.The thickness of these beds increases from zero in the south-east to about 180m in the south-west. The old course of the Auob River has incised a canyon of about 100 m deep through the shales covering the Aaob sandstone. These canyons are filled with Kalahari beds.

The aquifers comprise of Kalahari beds – where fresh water is struck in calcretes or permeable sandstone. The depth and yields of water strikes vary considerably e.g. about 130 to 150 m in the east. In the west the recharge is regarded to be zero. Recharge occurs mostly along faults, intrusive contacts or where the aquiclude has been eroded.

The Auob sandstone is exposed in the east and varies from 40 to 60 m in thickness and thins out in an easterly direction and forms thin lenses along the lower Nossob River. The Auob aquifer is about 40 to 60 m below surface in the eastern and northern parts. The depth increases from 60 to 200 m between Stampriet and Gochas and a maximum depth of 230 m has been observed. The depth of the aquifer is shallower in the eastern part (180 – 190 m). Flowing boreholes are found along the upper reaches of the Auob River and between Stampriet and the Olifants River. Water levels vary between 10 to about 100 m below surface. It is estimated that the entire artesian basin covers about 70 000 km^2 and sustains about 30 000 m^3 of water per day which is about 2.3 m^3/ day/ km^2. This converts to 840 m^3 /year or 0.84 mm of rainfall per annum , which yields an average recharge of 0.84/250 = 0.35 %. This indicates that in spite of such a low recharge the underlying aquifer is of vital importance to the economic viability of about 8.5 % of the total area of Namibia. The aquifer however does not lend itself to large scale abstraction at a point as that could permanently damage the artesian aquifer.

The Nossob sandstone is the main aquifer along the Nossob River and lies about 100 m below the Auob sandstone separated by black shale. Flowing boreholes occur in the Nossob valley; the water levels in boreholes outside the river valley drop from 20 to 40 m below surface at Aminuis and to 100 m further south. The recharge area of the artesian water is in the north-western area of the basin boundary in an area covered by 30 m sand with ample groundwater. The recharge is reckoned to be between 1 to 3 % of the precipitation but substantial recharge could occur from runoff in the central highland east of Windhoek. The quality of the groundwater varies considerably with minimum chloride concentrations of 23 mg/l, 25 % has less than 137 mg/l and 50 % of less than 356 mg/l. The low chloride values indicating a recharge of not more than 0.6/23 = 2.6 % of the average rainfall.

Table A-8 indicates the recharge percentage according to the chloride mass balance method, assuming the rainfall chloride to be 0.6 mg/l.

Table A-8: Recharge estimates according to the Chloride mass balance method (CMB)

Formation	Cl (mg/l 50% of boreholes	Estimated recharge %	Comments
Kalahari	297	0.20	Recharge is in accordance with the present exploitation
Auob	472	0.127	Very low recharge indicates probable Uptake of chloride from the formation
Nossob	431	0.139	Very low recharge same as above

ANNEXURE B KALAHARI WEST RURAL WATER SUPPLY SCHEME

The Kalahari West Rural water Supply Scheme was constructed in 1982 to supply farmers north of Upington with water for stock watering and domestic use. The scheme serves a total of 74 farms covering an area of 633 000 ha, which extends into the Molopo catchment. The scheme was implemented as an emergency scheme during a period when groundwater sources in the region started to fail and was designed to serve that part of the Kalahari experiencing the worst water shortages. The scheme sources water from Upington's municipal system, from where it is pumped via a number of balancing reservoirs and small booster pumpstations. The scheme's peak design capacity is 1.99 Ml/d. In 1995, the actual water abstraction via the scheme was estimated to be 0.42 Mm^3/a, which, taking peak factor requirements into account, implies that the scheme is being operated at or near capacity.

ANNEXURE C KALAHARI EAST RURAL WATER SUPPLY SCHEME

The Kalahari East Rural Water Supply Scheme was constructed in the early nineties to supply water to farmers in the Kalahari north of Upington (including parts of the Molopo catchment) with water for stock watering and domestic use. The scheme sources its water from the Vaal-Gamagara pipeline, which is currently underutilised. Water is abstracted from the Vaal-Gamagara pipeline at Kathu, north-east of Olifantshoek, from where water is distributed via a 32 km long rising main, a 4.3 Ml reservoir and an extensive gravity pipe network to serve an area of approximately 14 000 km^2. The scheme was designed to deliver a peak flow of 6.18 Ml/d, with provision having been made to increase this to 8.52 Ml/d. The actual water that was supplied by the scheme in 1995 equalled 1.3 Mm^3/a.