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The uMkhomazi Water Project Phase 1: Module 1: Technical Feasibility Study: Raw Water

HYDROLOGICAL ASSESSMENT OF THE UMKHOMAZI RIVER CATCHMENT REPORT

SUPPORTING DOCUMENT 1:

GROUNDWATER RESOURCES OF THE UMKHOMAZI CATCHMENT AND INTERACTION WITH SURFACE WATER

FINAL

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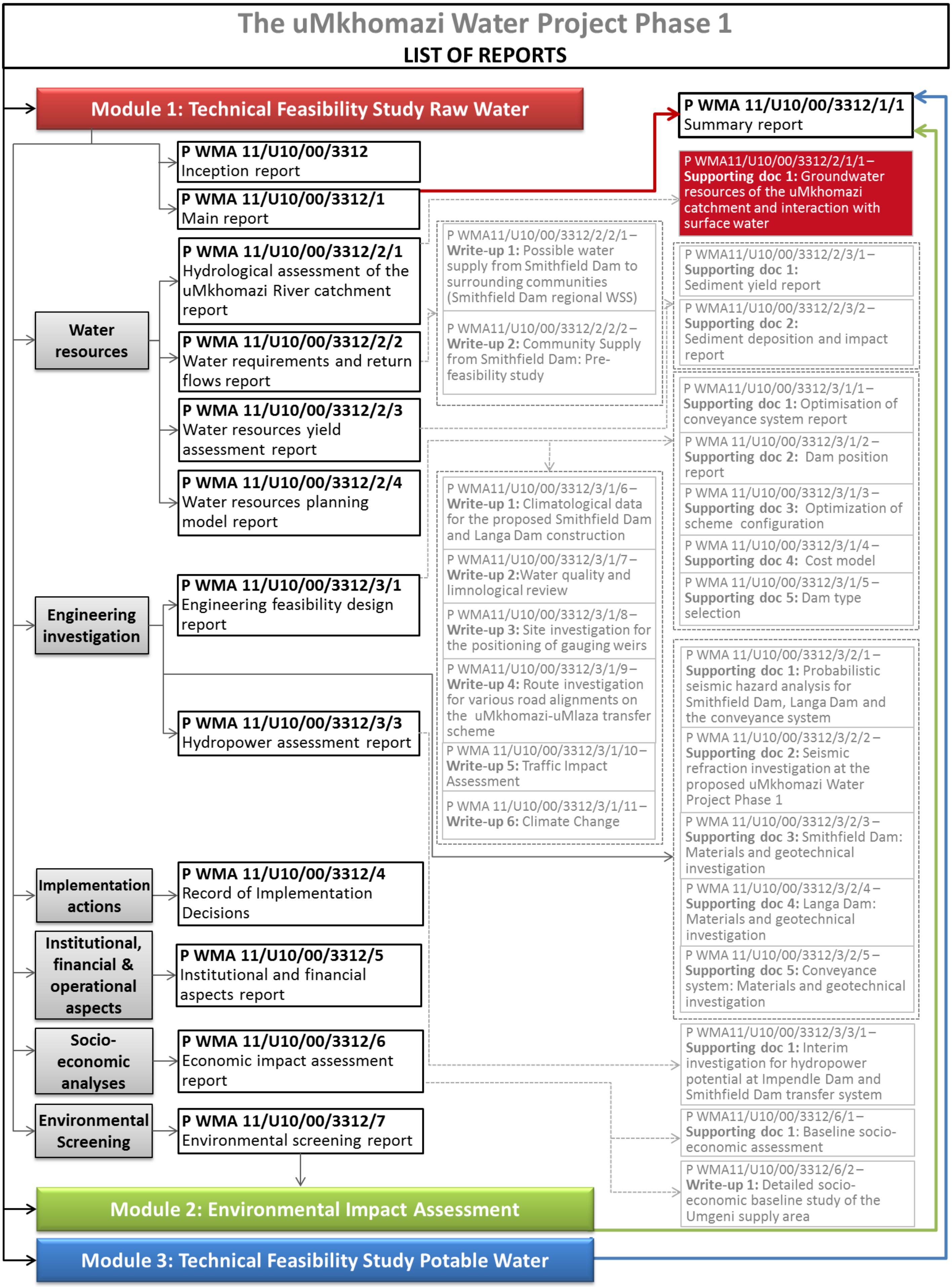
PREAMBLE

In June 2014, two years after the commencement of the uMkhomazi Water Project Phase 1 Feasibility Study, a new Department of Water and Sanitation was formed by Cabinet, including the formerly known Department of Water Affairs.

In order to maintain consistent reporting, all reports emanating from Module 1 of the study will be published under the Department of Water Affairs name.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EXECUTIVE SUMMARY

AGES was appointed by BKS to determine the groundwater resources of the uMkhomazi River secondary catchment and the groundwater-surface water interaction. Full details of the groundwater resources sub-task and scope of work is provided in the BKS inception report. The groundwater resources sub-task consists of two phases:

- *Phase 1: Desktop study, review of existing information, data evaluation and aquifer delineation;*
- *Phase 2: Groundwater flow balance modelling and reporting.*

The objective of the study was to determine the groundwater resources of the uMkhomazi catchment and its interaction with surface water at desktop level.

The study area is defined by the uMkhomazi River secondary catchment U1 watershed boundary. The uMkhomazi River catchment is situated in the Mvoti to uMzimkulu Water Management Area (WMA) in the KwaZulu Natal Province of South Africa. The uMkhomazi River catchment covers an area of approximately 4387 km² and includes the uMkhomazi River and all of its tributaries.

A groundwater flow balance model was used to assess at a desktop level the volumes of groundwater available in each catchment. The Groundwater Yield Model for the Reserve (GYMR) method was used for this assessment. These volumes were also compared with the Average Groundwater Exploitation Potential (AGEP) and the Utilisable Groundwater Exploitation Potential (UGEP) from the GRA2 project. Water qualities for groundwater in the uMkhomazi catchment were obtained from the NGA and GRIP borehole databases and evaluated using the DWA water quality guidelines.

The uMkhomazi River catchment is a relatively unique catchment in that it covers outcrop of the whole Karoo Supergroup sequence of rocks for the given area of South Africa. It also presents some structurally complex geology with numerous folds, faults, thrusts and nappes in the Namaqua-Natal Province to the south-west. The highest potential for groundwater exploitation lies in fractured and faulted Natal Group sandstones, Karoo Supergroup sediment rocks that are faulted or fractured and intruded by dolerite dykes and sills and alluvial porous aquifers if extensive enough and present in the study area.

Table i: Groundwater qualities of major constituents per quaternary catchment

Catchment	Overall Water Quality Class	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	CO_3 mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	F mg/l	N mg/l	Fe mg/l	Mn mg/l
U10A	Class 0	8.2	23.9	167.3	11.0	1.1	40.2	1.0	0.0	122.0	3.2	4.4	0.18	0.2	0.29	0.02
U10B	Class 1	7.8	27.0	178.1	16.4	6.9	35.3	1.7	0.0	118.2	8.1	11.4	0.49	0.6	0.76	0.06
U10C	Class 1	7.2	15.8	96.9	15.0	2.5	13.8	1.6	0.0	77.8	1.2	4.0	0.06	0.3	0.58	0.15
U10D	Class 1	7.3	64.8	416.0	55.4	23.8	60.4	1.7	0.0	210.0	10.0	124.0	0.31	0.4	0.09	0.14
U10E	Class 2	7.2	25.1	151.2	18.5	10.6	19.0	1.1	0.0	110.7	4.1	9.8	0.07	1.6	1.69	0.38
U10F	Class 2	7.4	23.2	228.8	19.4	6.4	28.5	1.2	0.0	103.4	10.2	19.2	0.36	1.7	1.39	0.09
U10G	Class 2	7.0	10.2	43.0	10.4	4.0	5.9	0.3	0.0	40.7	1.8	1.5	0.06	2.9	1.70	0.05
U10H	Class 0	7.4	25.2	178.8	11.6	6.8	26.0	1.9	0.0	83.2	22.0	1.6	0.11	2.0	0.36	0.04
U10J	Class 3	6.8	20.6	126.6	14.9	12.8	17.1	1.0	0.0	79.3	12.8	16.9	0.93	0.1	6.16	0.70
U10K*	Class 0	7.7	24.7	198.1	20.4	8.8	16.2	1.0	0.0	108.5	8.2	7.7	0.37	0.6		
U10L	Class 2	7.7	120.7	818.4	62.1	38.2	132.8	2.6	0.0	227.1	209.5	65.1	0.64	6.9	0.08	0.05
U10M	Class 3	7.3	108.0	802.0	90.5	36.2	155.7	3.1	0.0	231.8	205.2	101.2	1.90	2.2	4.51	0.21
DWA drinking WQ guidelines 1998																
Class 0: Ideal water quality		5.0<pH<9.5	70	450	80	70	100	25	N/A	N/A	100	200	0.7	6	0.5	0.1
Class 1: Good water quality		5.0>pH>9.5	150	1000	150	100	200	50			200	400	1	10	1	0.4
Class 2: Marginal water quality		4.5>pH>10.0	370	2400	300	200	400	100			600	600	1.5	20	5	4
Class 3: Poor water quality		4.0>pH>10.5	520	3400	300+	400	1000	500			1200	1000	3.5	40	10	10
Class 4: Unacceptable water quality		3.0>pH>11.0	520+	3400+		400+	1000+	500+			1200+	1000+	3.5+	40+	10+	10+

Table ii: Table with basic geological and hydrogeological units and properties in the uMkhomazi catchment – adapted from King (2002)

ERA	SUPERGROUP OR MAJOR STRATIGRAPHIC UNIT	INTRUSIVE ROCKS	GROUP	SUB-GROUP	FORMATION	LITHOLOGY DESCRIPTION	HYDROGEOLOGICAL GROUPING	YIELD RANGE (L/s)	HYDRAULIC CONDUCTIVITY (m/d)[King, 2002]	QUATERNARY CATCHMENTS	COMMENT
Cenozoic	Quaternary and Tertiary					alluvium and coastal sediments. unconsolidated sands and gravels	Intergranular	>2	120.0	No extensive aquifers in study area	Sustainability depends on aquifer thickness
Mesozoic	Karoo Supergroup		Drakensberg			flood basalt,igneous, fine grained	Intergranular and fractured			U10A, U10B, U10C, U10D	Very elevated areas. Springs.
		Karoo dolerite				hypabassal intrusive igneous rock, fine to medium grained	Intergranular and fractured	0.2 - 1.4	0.05 - 1.0	U10A, U10C, U10D, U10E, U10F, U10G, U10H, U10J, U10K	Good targets for aquifers
					Clarens	arenceous sandstone	Intergranular and fractured	1.2	0.05 - 0.5	U10C	
					Elliot	shale, mudstone, siltstone	Fractured	0.9	0.05 - 0.5	U10A, U10B, U10C, U10D	
					Molteno	sandstone, shale and conglomerate	Intergranular and fractured	1.2	0.05 - 0.5	U10B, U10C	
			Beaufort	Tarkastad		Greater abundance of sandstone and red mudstone than Adelaide. alternating fine grained sandstone, shale, mudstone and siltstone.	Fractured. Mostly bedding plane fractures	0.9	0.05 - 0.5	U10A, U10B, U10C, U10D, U10E, U10F, U10G	
Palaozoic				Adelaide		alternating fine grained sandstone, shale, mudstone and siltstone.				U10A, U10B, U10C, U10D, U10E, U10F, U10G, U10H	
			Ecca			predominantly shales, carbonaceous shales and mudstone.	Intergranular and fractured	0.9	0.05 - 0.5	U10F, U10G, U10H, U10J, U10K	
					Vryheid	arenaceous sandstones	Intergranular and fractured		0.05 - 0.5	U10G, U10H, U10J, U10K	
			Dwyka			diamictite	Fractured	0.1		U10J, U10K, U10L, U10M	
	Natal Group					arenaceous andstone	Fractured/ jointed due to brittle nature	0.1 - 2.0	0.4 - 7.7	U10K, U10L, U10M	Very good aquifers (King, 24: 2002)
Mokolian	Natal Sector of the Namaqua-Natal Province					igneous and metamorphic rocks. Granite, granitic gneiss, calc-silicate rocks, granulite, ampibolite & marble	Intergranular and fractured	0.1 - 0.4		U10L, U10M	

A large part of the study area is covered by the Karoo Supergroup and associated dolerite intrusions and thus moderately yielding boreholes can be successful at the opportunely located dykes and sills if good geophysical surveys and structural analysis is conducted. It is important to understand that successful boreholes will most probably yield in the order of 0.5 – 2.0 l/s on a 24 hour duty cycle over the long term and thus a number of adequately spaced boreholes will have to be drilled, creating a well field from which appreciable volumes of water can be abstracted and piped into the reticulation network.

The Groundwater Yield Model for the Reserve (GYMR) groundwater flow balance was set up in steady-state to assess potential groundwater flow balances on an annual basis per quaternary catchment. A combined transient (historic rainfall change over time) and Monte Carlo simulation of the GYMR was also run for each catchment on a monthly time step as a third scenario.

The quaternary catchments U10A – U10G are the most suited catchments for groundwater development based on volumes available in the GYMR with volumes of groundwater available after evapotranspiration ranging between 43.42 million m^3*/a (U10A) and 14.02 million* m^3*/a (U10F) in steady-state scenarios. Catchments U10A – U10G show a groundwater sink: groundwater source ratio (Groundwater Resource Directed Measures (GRDM) stress index) of between 4% and 32% based on a 95% level of assurance;*

Quaternary catchments U10H – U10M show lower potential for groundwater development based on GYMR groundwater volumes available. U10H – U10L have groundwater utilisation indices that range between 61% and 98% and are thus moderately stressed to critical. Volumes of groundwater recharged annually in U10H – U10L range between 7.00 million m^3*/a and -0.99 million* m^3*/a, meaning there is a groundwater deficit in U10K according to the steady-state GYMR model on a 95% level of assurance to account for a 1:20 year drought cycle.*

When the U10H – U10L catchments were simulated in transient state using the 84 year historic rainfall, the volumes of groundwater available annually in U10H – U10L ranged between 14.43 million m^3*/a and 3.31 million* m^3*/a.*

Table iii: GYMR usable groundwater from baseflow, AGEP and UGEP

Quaternary catchment	*Surface Area (km^2)*	*Usable GW component from Base Flow assured 95% (m^3/ km^2/ a)*	*Average groundwater exploitation potential (AGEP) (m^3/km^2/a)*	*Utilisable Groundwater Exploitation Potential (UGEP) (m^3/ km^2/ a)*	*Final Utilisable Groundwater per catchment (m^3/ km^2/a)*	*Final Utilisable Groundwater per catchment (million m^3/a)*
U10A	*418.2*	*103 894*	*51 839*	*46 147*	*46 147*	*19.30*
U10B	*392.1*	*77 613*	*42 848*	*39 398*	*39 398*	*15.45*
U10C	*267.0*	*67 590*	*37 921*	*33 030*	*33 030*	*8.82*
U10D	*337.0*	*63 231*	*35 932*	*31 013*	*31 013*	*10.45*
U10E	*327.2*	*61 873*	*39 568*	*36 441*	*36 441*	*11.92*
U10F	*379.0*	*35 336*	*30 855*	*27 628*	*27 628*	*10.47*
U10G	*353.1*	*40 274*	*33 239*	*29 352*	*29 352*	*10.37*
U10H	*457.8*	*15 801*	*30 633*	*26 747*	*15 801*	*7.23*
U10J	*505.1*	*16 808*	*24 337*	*20 855*	*16 808*	*8.49*
U10K	*364.4*	*-2 094*	*14 035*	*11 836*	*-2 094*	*-0.76*
U10L	*307.2*	*20 292*	*12 528*	*9 847*	*9 847*	*3.03*
U10M	*280.0*	*42 858*	*18 203*	*19 101*	*19 101*	*5.35*
Total	***4388.1***	***543 476***	***371 939***	***331 395***	***302 473***	***110.11***

*The final, but conservative groundwater volumes available per catchment are shown in **Table iii** comparing the GYMR and the Average Groundwater Exploitation Potential (AGEP) and the Utilisable Groundwater Exploitation Potential (UGEP) from the GRA2 project.*

Spring protection measures should be implemented in the upper quaternary catchments (U10A – U10D) of the uMkhomazi catchment due to the high number of spring occurrences there. These springs already supply water for domestic use and spring protection measures will ensure their sustainability and quality.

Based on the results from GYMR modelling, it is recommended that if large scale groundwater development is considered for catchments U10H, U10J, U10K, U10L, that a more thorough evaluation of the groundwater inflow and outflow components be performed there. These catchments show moderate to critical groundwater stress based on the desktop level groundwater flow balance using the GYMR method.

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NOTATIONS AND TERMS

Advection is the process by which solutes are transported by the bulk motion of the flowing groundwater.

Anisotropy is an indication of some physical property varying with direction.

Cone of depression is a depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a borehole from which water is being withdrawn. It defines the area of influence of a borehole.

A *confined aquifer* is a formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.

The *darcy flux*, is the flow rate per unit area (m/d) in the aquifer and is controlled by the hydraulic conductivity and the piezometric gradient.

Dispersion is the measure of spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities within and between pores.

Drawdown is the distance between the static water level and the surface of the cone of depression.

Effective porosity is the percentage of the bulk volume of a rock or soil that is occupied by interstices that are connected.

Groundwater table is the surface between the zone of saturation and the zone of aeration; the surface of an unconfined aquifer.

A *fault* is a fracture or a zone of fractures along which there has been displacement.

Hydrodynamic dispersion comprises of processes namely mechanical dispersion and molecular diffusion.

Hydraulic conductivity (K) is the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured perpendicular to the area [L/T]. Hydraulic conductivity is a function of the permeability and the fluid’s density and viscosity.

Hydraulic gradient is the rate of change in the total head per unit distance of flow in a given direction.

Heterogeneous indicates non-uniformity in a structure.

Karstic topography is a type of topography that is formed on limestone, gypsum, and other rocks by dissoloution, an is characterised by sinkholes, caves and underground drainage.

Mechanical dispersion is the process whereby the initially close group of pollutants are spread in a longitudinal as well as a transverse direction because of velocity distributions.

Molecular diffusion is the dispersion of a chemical caused by the kinetic activity of the ionic or molecular constituents.

Observation borehole is a borehole drilled in a selected location for the purpose of observing parameters such as water levels.

Permeability is related to hydraulic conductivity, but is independent of the fluid density and viscosity and has the dimensions L2. Hydraulic conductivity is therefore used in all the calculations.

Piezometric head is the sum of the elevation and pressure head. An unconfined aquifer has a water table and a confined aquifer has a piezometric surface, which represents a pressure head. The piezometric head is also referred to as the hydraulic head.

Porosity is the percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected.

Pumping tests are conducted to determine aquifer or borehole characteristics.

Recharge is the addition of water to the zone of saturation; also, the amount of water added.

Sandstone is a sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material.

Shale is a fine-grained sedimentary rock formed by the consolidation of clay, silt or mud. It is characterised by finely laminated structure and is sufficiently indurated so that it will not fall apart on wetting.

Specific storage (S0), of a saturated confined aquifer is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. In the case of an unconfined (phreatic, watertable) aquifer, specific yield is the water that is released or drained from storage per unit decline in the watertable.

Static water level is the level of water in a borehole that is not being affected by withdrawal of groundwater.

Storativity is the two-dimensional form of the specific storage and is defined as the specific storage multiplied by the saturated aquifer thickness.

Total dissolved solids (TDS) is a term that expresses the quantity of dissolved material in a sample of water.

Transmissivity (T) is the two-dimensional form of hydraulic conductivity and is defined as the hydraulic conductivity multiplied by the saturated thickness.

An *unconfined, watertable or phreatic aquifer* are different terms used for the same aquifer type, which is bounded from below by an impermeable layer. The upper boundary is the watertable, which is in contact with the atmosphere so that the system is open.

Vadose zone is the zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. This zone is limited above by the land surface and below by the surface of the zone of saturation, that is, the water table.

Water table is the surface between the vadose zone and the groundwater, that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

LIST OF ABBREVIATIONS

AGES	Africa Geo-environmental Engineering and Science
AGEP	Average Groundwater Exploitation Potential
BHN	Basic Human Needs
DWA	Department of Water Affairs
BKS	BKS (Pty) Ltd
CFB	Continental flood basalts
CRD	Cumulative Rainfall Departure
D	Aquifer thickness
EC	Electrical Conductivity
EKZN	Ezemvelo Kwazulu Natal Wildlife
EMPR	Environmental Management Programme Report
ET	Evapotranspiration
EWR	Ecological Water Requirement
GA	General Authorisation
GRA2	Groundwater Resource Assessment II
GRIP	Groundwater Resource Information Project
GYMR	Groundwater Yield Model for the Reserve
IFR	Instream Flow Requirements
LM	Local Municipality
masl	Metres Above Sea Level
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
mbgl	Metres Below Ground Level
MM	Metropolitan Municipality

NGA	National Groundwater Archive
NGDB	National Groundwater database
RDM	Resource Directed Measures
TDS	Total Dissolved Solids
UGEP	Utilisable Groundwater Exploitation Potential
WMA	Water Management Area

1 INTRODUCTION

Africa Geo-Environmental Engineering & Science (Pty) Ltd. hereafter referred to as AGES was appointed by BKS (Pty) Ltd[1] to determine the groundwater resources of the uMkhomazi River secondary catchment and its interaction with surface water.

The purpose of the investigation is to describe and determine the quantity and quality of the groundwater resources within the catchment at a desktop level. Specific reference is also made to the interaction between surface water and groundwater since the larger UMkhomazi Water Project is surface water driven.

1.1 BACKGROUND

The Mgeni River system in the Mvoti to Mzimkulu Water Management Area (WMA) supplies water to the eThekweni Metropolitan Municipality (MM), Umgungundlovu District Municipality (DM) as well as the Msunduzi Local Municipality (LM). It has been fully developed surface water wise with four dams; Nagle-, Midmar-, Albert Falls- and Inanda-dam constructed between 1950 and 1988 within the Mgeni system. The water volumes available from the Mgeni surface water system are however insufficient to meet the long-term water demands of the system (DWA, 2012). To this end, the Mooi-Mgeni Transfer scheme is currently being constructed with the Spring Grove Dam construction nearing completion (DWA, 2012). The Mooi-Mgeni River Transfer Scheme will only meet the short-term demands in the Mgeni-System and for this reason the uMkhomazi-Mgeni Transfer scheme was investigated and found to be the best option to supply in long-term demands of the Mgeni system. The uMkhomazi River is undeveloped at this stage and thus presents an opportunity for surface water development.

As part of the uMkhomazi Water Project Phase 1, groundwater resources of the uMkhomazi catchment are to be determined as well as its interaction with surface-water to determine the groundwater potential especially in the upper reaches of the uMkhomazi catchment as well as the effect groundwater development could have on the surface water system.

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1 On 1 November 2012, BKS (Pty) Ltd was acquired by AECOM Technology Corporation.

1.2 TERMS OF REFERENCE

AGES was appointed by BKS to determine the groundwater resources of the UMkhomazi River secondary catchment and the groundwater-surface water interaction. Full details of the groundwater resources sub-task and scope of work is provided in the BKS inception report. The groundwater resources sub-task consists of two phases:

- Phase 1: Desktop study, review of existing information, data evaluation and aquifer delineation;
- Phase 2: Groundwater flow balance modelling and reporting.

1.2.1 Objectives

Determine the groundwater resources of the UMkhomazi catchment and its interaction with surface water.

1.2.2 Scope of work

- Phase 1: Desktop study

  a. Spatial and temporal water requirements;
  b. Availability of groundwater relative to the exploitable yields;
  c. Groundwater quality and its influence on supply;
  d. Water use sectors within the study area;
  e. Rainfall distribution for quaternary catchments; and
  f. Estimates of the storage components and volumes of the main aquifer zones.

- Phase 2: Groundwater flow balance modelling and reporting

A temporal groundwater flow balance assessment was done based on the main inflow and outflow components. The modelling was done with a dynamic mass balance model with statistical analyses functionalities. The output of these models can be used to determine future groundwater allocations for application in the water use licensing process (BKS, 2012).

1.2.3 Study area and location

The study area is defined by the uMkhomazi River secondary catchment U1 watershed boundary. The uMkhomazi River catchment is situated in the Mvoti to Umzimkulu Water Management Area (WMA) in the Kwazulu Natal Province of South Africa (see **Figure 1.1**).

The uMkhomazi River catchment covers an area of approximately 4387 km^2 and includes the uMkhomazi River and all of its tributaries. The study area falls across 5 District Municipalities: Umgungundlovu-, Sisonke-, Ethekwini-, Ugu- and a very small part of the Uthukela-District Municipality.

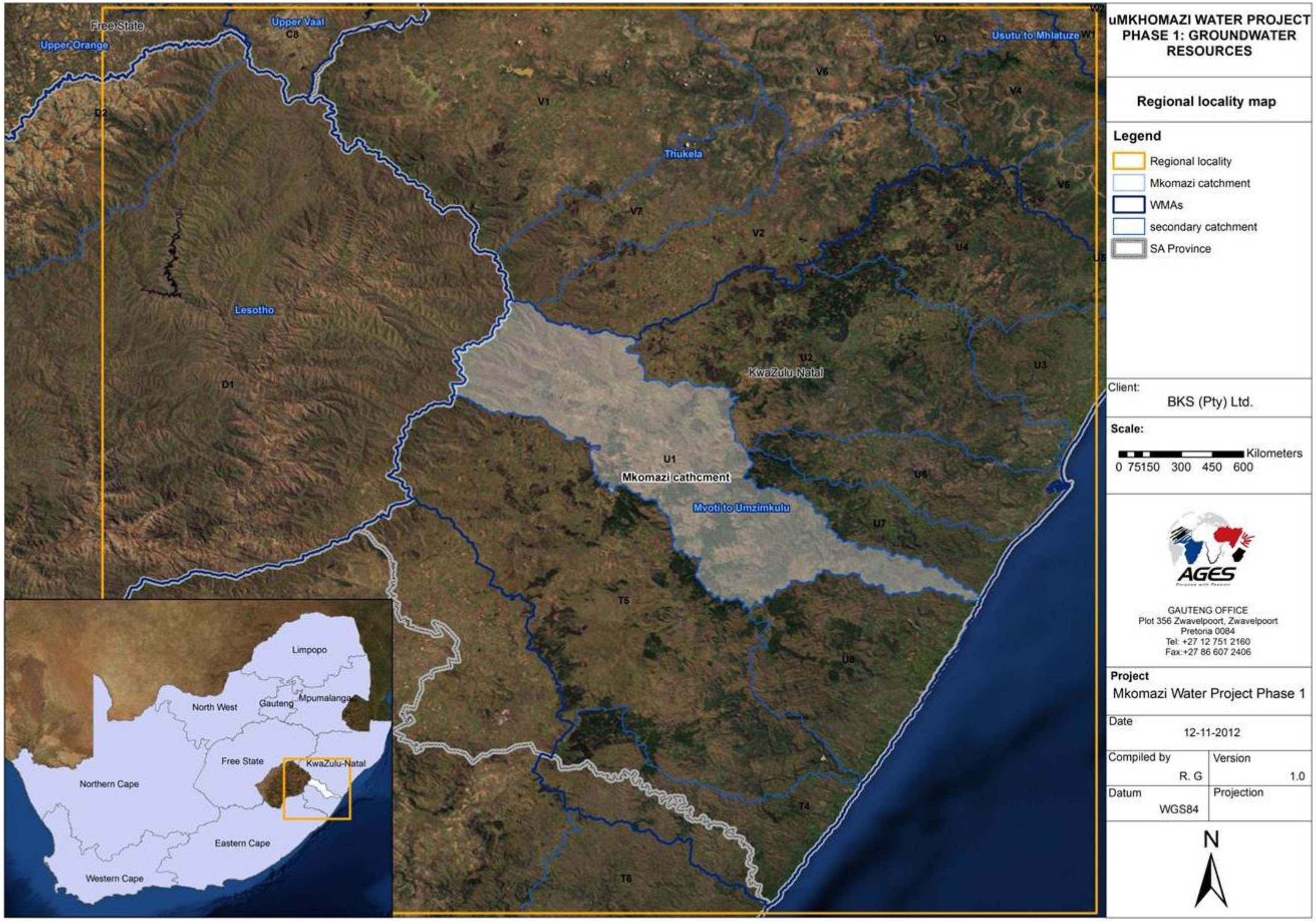

Figure 1.1: Regional locality map for the uMkhomazi River catchment

2 METHODOLOGY

2.1 GROUNDWATER YIELD MODEL FOR THE RESERVE (GYMR)

Due to its comprehensiveness, the methodology followed for conducting the GYMR is described in **Appendix A** of this report.

2.2 GROUNDWATER QUALITY

Groundwater quality results per borehole within the GRIP and NGA databases were evaluated and screened by identifying that all major water quality constituents are present per water sample result. The databases were clipped per quaternary catchment and the databases cleaned so that only borehole water quality results that are representative, non-conspicuous and complete with all major constituents were used in statistics and water quality evaluations.

Results were evaluated by using the document: Quality of Domestic Water Supplies; Volume 1; Assessment Guide; Second Edition 1998; Water Research Commission No. TT101/98.

This guide allows the quality of water supplied for domestic use to be assessed by using a simple classification system. The system shows the nature of the effects of water quality on the domestic user for a range of concentration values for those substances commonly encountered in water. The information is presented in a simplified format so that a wide spectrum of users of the Guide will be able to understand the concepts of water quality as it affects the domestic user. (AGES, 2010)

Table 2.1: Water Quality Class and assessment guide (DWA, 1998)

Class 0	Ideal water quality	Natural water. Suitable for lifetime use
Class 1	Good water quality	Suitable for use, rare instances of negative effects.
Class 2	Marginal water quality	Conditionally acceptable. Negative effects may occur in some sensitive groups
Class 3	Poor water quality	Unsuitable for use without treatment. Chronic effects may occur.
Class 4	Dangerous water quality	Totally unsuitable for use. Acute effects may occur.

3 STUDY AREA DESCRIPTION

3.1 LAND USE

The 2008 KZN Land cover mapping project had land cover mapping performed from circa 2008 SPOT 5 imagery for the Ezemvelo KZN Wildlife Biodiversity Research programme (GeoTerraImage, 2010). The KZN land cover mapping was an extensive mapping project during which 36 land cover types were mapped out from SPOT 5 raster imagery. For more details the reader is referred to the data and metadata report by GeoTerraImage (2010).

A pie chart was compiled to summarise the % land cover area of the total mapped area for each type of land cover mapped as applicable to the uMkhomazi catchment (see **Figure 3.1**). The largest land cover/ land use by far is grassland with 53% land cover. This land cover is followed by plantations area at 13% and thereafter dense bush has the third largest land use at 10% of the total land use mapped.

3.2 TOPOGRAPHY

The uMkhomazi River Catchment is at highest elevation approximately 3341 masl in the Drakensberg Mountains in U10A, and it’s lowest elevation being sea level (0 masl) at the mouth of the uMkhomazi River in U10M. The upper reaches of the uMkhomazi River catchment and its associated quaternary catchments (U10A-U10D), is mountainous and the landscape has steep slopes. The geomorphology and topography of the mountains however create concave and even slopes vs. sharp and jagged slopes due to the Karoo Supergroup sedimentary rocks, mountains capped by basalt and the climate. The middle section of the uMkhomazi River catchment (U10E-U10H, U10K) has a gentler slope and topography. As such it also has higher population figures and land use especially forestry.

The lower part (U10J, U10L, U10M) of the uMkhomazi catchment topography is again controlled by the geology which is the Natal Group sandstones as well as the Mzumbe Terrane of the Namaqua-Natal Province. The more erosion resistant Natal Group sandstones create cliffs and large contrasts between plateaus and valleys.

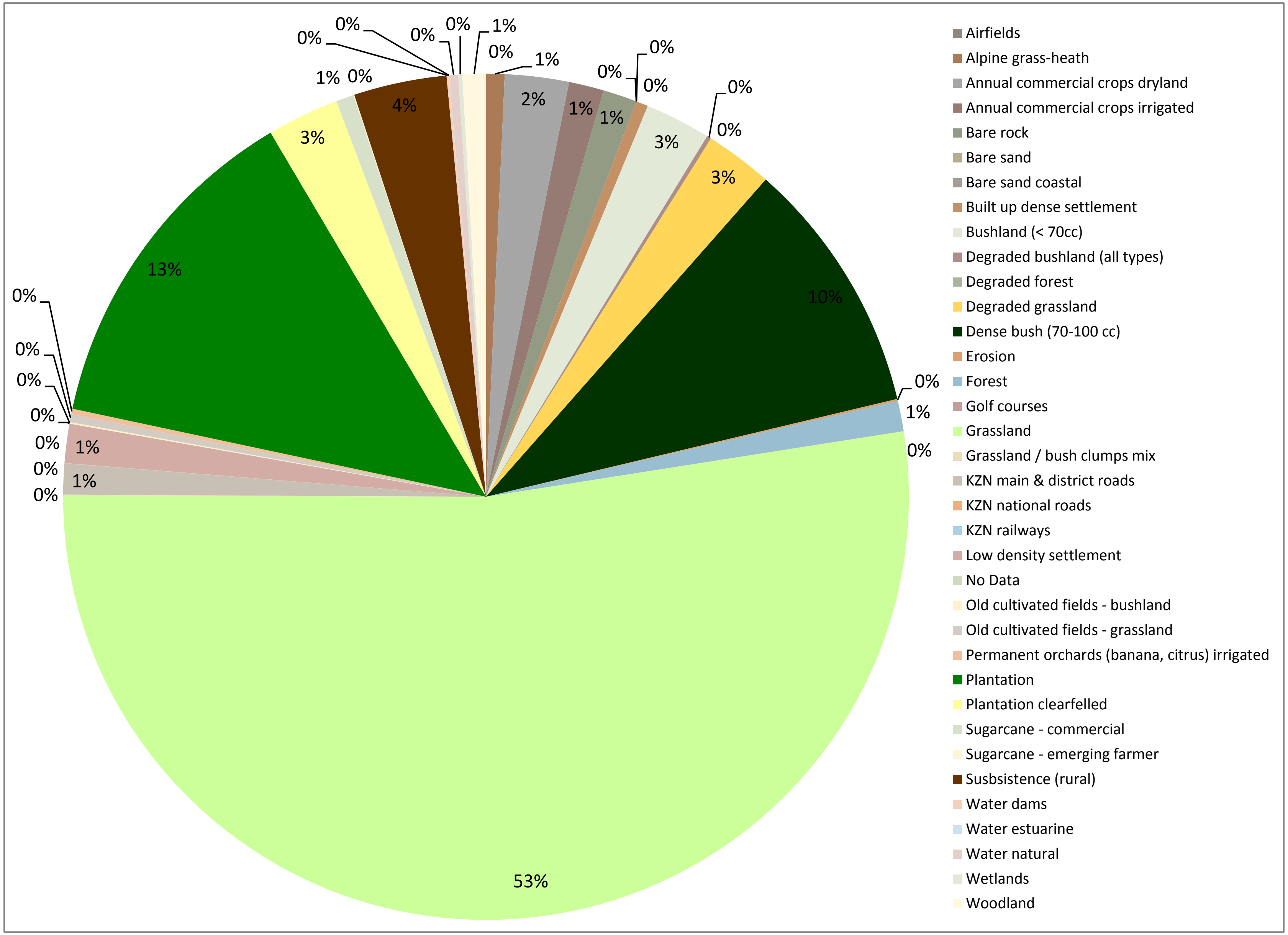

Figure 3.1: Pie chart showing land cover % of total land cover mapped in uMkhomazi River catchment (EKZN, 2010)

The Mzumbe Terrane granites and gneisses weather and erode to produce large rounded hills with a gently sloping topography and scattered large boulders.

3.3 HYDROLOGY AND DRAINAGE

The uMkhomazi River catchment includes all tributaries of the uMkhomazi River, from its headwaters in the Drakensberg Mountains to its mouth at the Indian Ocean.

The UMkhomazi River catchment in itself is defined as the secondary catchment U1 that falls within the Mvoti to Umzimkulu Water Management Area (WMA) of South Africa. Within the secondary catchment U1, there are 12 quaternary catchments, U10A – U10M.

The more mountainous catchments U10A-U10D are situated against the Drakensberg Mountains and have steeper slopes. High runoff coefficients are expected for these catchments and are confirmed in the hydrology data from BKS (2012). The drainage channel pattern in these catchments is easily identifiable as a parallel pattern and dominates due to the steep slopes.

River channel gradients become less in the central part (U10E-U10H, U10K) of the uMkhomazi River catchment and less runoff is expected here. Based on the topography, runoff again increases in U10J, U10L and U10M. Especially steep slopes are again found in the U10L catchment due to the predominantly Natal Group sandstone and Mzumbe Terrane geology of the catchment, creating incised drainages and valleys.

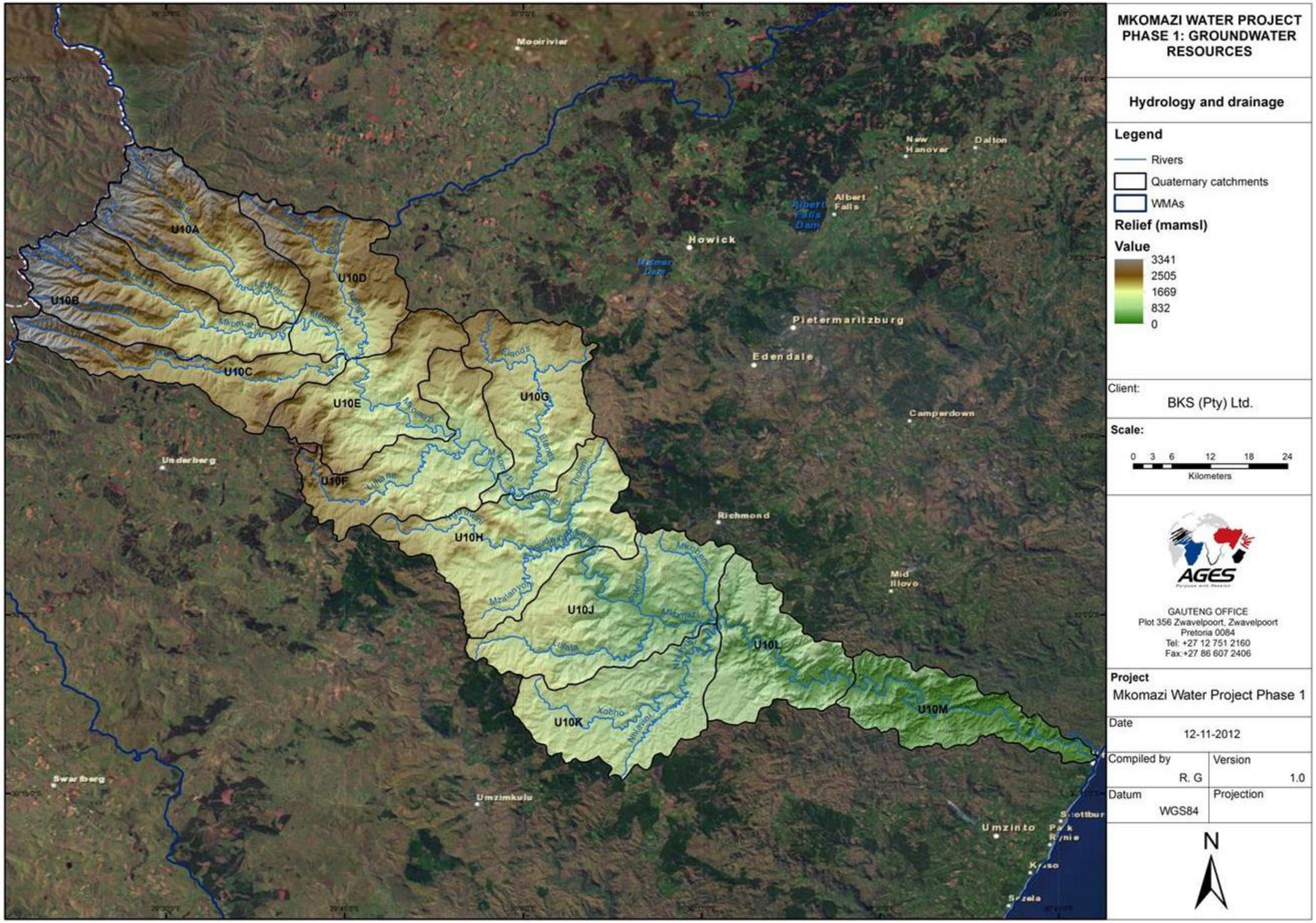

Figure 3.2: Shaded relief map with catchments, primary- and secondary-rivers of the uMkhomazi catchment

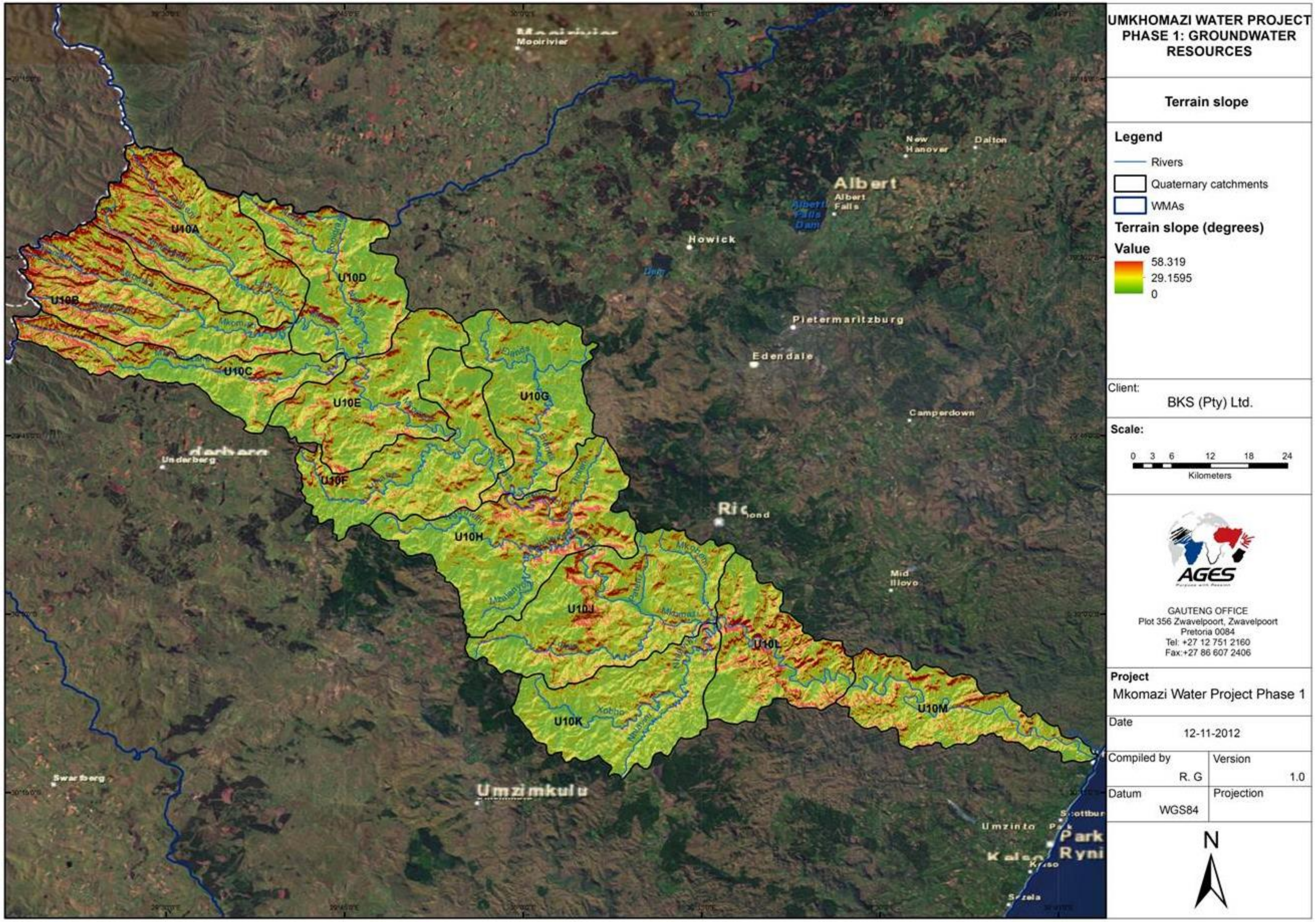

Figure 3.3: Terrain slope of the uMkhomazi catchment

3.4 GEOLOGY

The uMkhomazi River catchment is a relatively unique catchment in that it covers outcrop of the whole Karoo Supergroup sequence of rocks for the given area of South Africa. It also presents some structurally complex geology with numerous folds, faults, thrusts and nappes in the Namaqua-Natal Province to the south-west. This section discusses the geology and its significance to groundwater.

3.4.1 Mzumbe Terrane of the Namaqua-Natal Province

There are some different views to the naming convention of this unit found in the uMkhomazi catchment. It is formally referred to as the Mzumbe Terrane of the Namaqua Natal Province (Johnson *et al.*, 2006), but this unit is also just referred to as the Natal Metamorphic Province (King, 2002) on the 1: 500 000 scale hydrogeological map. The Mzumbe Terrane consists of an older sequence of amphibolite-grade gneisses known as the Mapumulo Group. The Mapumulo Group was later intruded by multiple plutonic suites of which the oldest (1210 Ma) is the Mzumbe Suite (Johnson *et al.* 2006). The Mzumbe Suite is described as an I-type granitoid orthogneiss association (Johnson *et al.*, 2006). More notably of these multiple plutonic intrusive suites is the megacrystic UMkhomazi Gneiss and Mahlongwa Granite. These suites are broadly described as foliated S-type granites and were formed when the arc terranes were accreted northwards which resulted in crustal thickening and melting (Johnson *et al*., 2006).

The Mapumulo Group and its associated granite intrusions present low to medium yielding aquifers where they have been fractured and weathered closer to surface. High yielding boreholes are possible in faulted granites and gneisses where weathered surface rock material is also present. The weathered surface material have good groundwater storage properties, but low hydraulic conductivity due weathering feldspar minerals of the granites and gneisses, mostly producing clay material. These upper weathered zones of the Mzumbe Terrane however represent groundwater reservoirs that supply the underlying fractured gneisses and granites with water. Where the gneisses and granites are not weathered, fractured or jointed they present low groundwater potential.

The contact of the Mzumbe Terrane with the Natal Group Sandstone and Karoo Supergroup also represents an area for further groundwater investigation.

Most of the faulting present in the Natal Sector of the Namaqua-Natal Province has occurred after the deposition and lithification of the Natal Group as well as the Dwyka-, Ecca- and Beaufort-Groups of the Karoo Supergroup. This sequence of faulting represents more groundwater potential than if the faulting had occurred prior to the deposition and forming of the mentioned lithological units.

From the 1: 250 000 scale geological map the contact between the Natal Group sandstone and Mzumbe Terrane is faulted along its entire length in the U10L catchment. This prominent fault is referred to as the Nhlazuka fault.

There is also the possibility that the contact zone fault melted the adjacent quartzitic Natal Group sandstone in which case the hydraulic conductivity associated with the contact will be lower. The pressure produced by the faulting can produce methamorphic and thermal effects which change or melt the adjacent country rock walls. Lithological logs of boreholes drilled into and through the contact/ fault will have to be evaluated to confirm whether the fault is water bearing or not. Existing aquifer test data could also confirm the fault’s status. Such effects on the Dwyka-Mzumbe faulted contact will however be less, due to the predominantly mudstone matrix of the diamictite.

3.4.2 Natal Group

The Natal Group underlies the Karoo Supergroup and is present in three quaternary catchments (U10K, U10L and U10M) in the study area (see **Figure 3.4**). The Natal Group and Msikaba Formation were thought to be similar, but have recently been separated based on isotopic evidence and the Msikaba Formation only occurs south of Kwazulu-Natal.

The Natal Group consists of well-bedded, pinkish, erosion resistant arkosic sandstone and quartzite (King, 2002). Minor shale is also encountered within the unit. Due to the high quartz content of the Natal Group, it behaves in a brittle manner when subjected to tectonic forces. Fault zones along the coast in the Natal Group have created important high yielding groundwater target zones (King, 2002). The Natal Group due to its brittle nature also has well developed joints that when interconnected, present possible aquifers.

3.4.3 Karoo Supergroup

In the uMkhomazi catchment, sedimentary rocks from the Dwyka-, Ecca- and Beaufort-Groups as well as the Molteno-, Elliot- and Clarens-Formations can be found as outcrop respectively. Additionally, igneous intrusive and extrusive rocks of the Karoo Supergroup are present in the Drakensberg Group and the Karoo dolerite intrusive rocks.

a) Dwyka Group

The Dwyka Group is found outcropping in the southern and central parts of the UMkhomazi River catchment; in U10J, U10K, U10L and to a lesser extent U10M. The Dwyka group is a lithified glacial till deposit and consists predominantly of diamictite. It is a poorly sorted sedimentary rock with a dark coloured, fine grained mudstone matrix that also contains an erratic distribution of larger clasts of various resistant rock types such as quartzite, gneiss and chert. The clasts can range in size from pebbles to boulders (King, 2002).

b) Ecca Group

The Ecca Group is a sedimentary rock unit that has been differentiated in the UMkhomazi Catchment into three different formations. The two argillaceous formations in the Ecca Group are the Pietersburg and Folksrust formations (King, 2002). These formations consist of dark coloured shales and mudstones that are well laminated, with thin interlayering of sandstone. Fissures and fine jointing often occur in the rock due to erosional unloading (King, 2002). Fractures and joints are often mineralised with iron pyrite. When they are exposed to oxygen due to puncturing during drilling, the borehole could have a sulphur smell due to the H2S released from the oxidation of pyrite. The third formation in the Ecca Group is the Vryheid Formation consisting mainly of arenaceous sandstone. Higher groundwater yields are anticipated in bedding plane fractures and general fracturing in the Vryheid Formation.

c) Beaufort Group

The Beaufort Group is comprised of generally horizontally bedded, alternating layers of mudstone and sandstone. Hydrogeologically speaking, the Beaufort Group is an argillaceous sequence of rocks in the north and north-eastern parts of the Karoo basin, i.e. the study area. This translates into more mudstone and siltstone and less arenaceous sandstone where sandstones form better aquifers.

The Beaufort Group consists of two sub-groups: the mudstone rich Adelaide Sub-group and the generally more sandstone rich Tarkastad Sub-group. As mentioned above, the sandstone to mudstone ratio however decreases moving northward in the Karoo basin and in the uMkhomazi catchment the two sub-groups are then relatively similar in rock texture. Both sub-groups cover extensive parts of the uMkhomazi catchment as shown in **Figure 3.4** and defined in **Table 3.1**.

d) Molteno, Elliot and Clarens Formations

These are three distinct formations in the upper part of the Karoo Supergroup sequence of sedimentary rocks. The Molteno Formation is sandstone rich sedimentary rock with conglomerate as well. The Molteno Formation in general presents one of the better aquifers in the Karoo Supergroup. Sporadic coal seams are also associated with the Molteno Formation. The Elliot Formation is a mudstone rich formation with lower yielding aquifer capabilities. The top of Karoo Supergroup sequence of sedimentary rocks is represented by the Clarens Formation, a massive sandstone unit. Groundwater storage and release in this unit is good but at its very high elevation, it is difficult to find good parts of accessible Clarens that are below the regional water table and it is normally associated with perched aquifers. The Clarens formation does create numerous springs though that can be used for water supply.

3.4.4 Karoo Dolerite intrusions (Jd)

Dolerite intrusive structures are the solidified remnants of the old pipe or “plumbing” network along which magma flowed up and extruded as lava onto the surface, causing continental flood basalt (CFB) outpouring and the formation of the Drakensberg Mountains around 183 Ma ago. Dolerite intrusions occur mostly as sill (sub-horizontal) or dyke (sub-vertical) structures that have typically followed bedding plane fractures (sill) or sub-vertical fractures where the magma pressure forced through weak spots in the sedimentary strata and flowed vertically upwards (dyke). The magma slowly solidified within these conduits and, through millions of years of weathering and erosion, have become exposed at surface. Other structures such as dolerite sill- and ring-complex structures and smaller dolerite batholiths can also be found.

Within the uMkhomazi catchment there are a number of dolerite intrusive structures outcropping. The quaternary catchments that these occur in according to the geological map are shown in **Table 3.1**.

Within the Karoo basin and Karoo Supergroup sequence of rocks, dolerite intrusions, especially dolerite dykes are the preferred groundwater targets. Their contacts with sedimentary country rock represent chill margins where the baked zones often have thermal jointing and fracturing, are more easily weathered and often transgressive fracturing can form that extends through the dykes to some distance into the country rock. The dyke-country rock zones then form definite groundwater targets as well as the dolerite itself.

3.4.5 Drakensberg Group (Jdr)

The Drakensberg Group of igneous rocks are continental flood basalts (CFB) associated with one of the largest flood basalt outpourings in the world. These are the rocks that also constitute the famous Drakensburg Mountains of Lesotho and South Africa. The Drakensberg Group are dark to black coloured, fine grained crystalline mafic rocks and are only found in the upper reaches of the uMkhomazi River catchment. Due to their very high elevation, little groundwater exploration and development have been performed on these rocks. The Drakensberg Group does however create good springs on their contact with the underlying Clarens sandstone formation. It is recommended that a spring survey be performed to quantify the feasibility of using these springs as viable means of water supply for the very upper reaches of the uMkhomazi catchment. They are already used for domestic water supply in this region, but they can be optimised as sustainable water sources by implementing spring protection measures and by determining their spatial distribution.

3.4.6 Cenozoic deposits

Cenozoic deposits in the study area include quaternary and tertiary fluvial deposits, that is to say unconsolidated transported deposits of younger age (era of geologic time extending from ~65.5 million years to present (Oxford, 2008)) than the rocks discussed above. These include alluvial sands associated with flood plains and valleys that with depth often form some of the best aquifers.

Within the study area based on the 1: 500 000 and 1: 250 000 geological maps there are limited alluvial deposits and those present are mostly associated with the uMkhomazi River channel. Thus if these aquifers are targeted and over-exploited it will have an adverse effect on the runoff and volumes of surface water available to downstream dams and the surface water system.

3.4.7 Structural geology and tectonics

There are numerous faults, folds and nappes in the Namaqua-Natal Province geology of the uMkhomazi catchment. There are also a number of faults in the Natal Group of the uMkhomazi catchment (mostly U10A). The faults are a consequence of rifting that has taken place along the coastal and coastal hinterland region of Kwazulu-Natal (King, 2002). Faulting occurs predominantly as normal or extensional faulting. Most of the faulting present in the Natal Sector of the Namaqua-Natal Province has occurred after the deposition and lithification of the Natal Group as well as the Dwyka-, Ecca- and Beaufort-Groups of the Karoo Supergroup and thus represent more potential than if the faulting had occurred prior to the formation of the mentioned lithological units.

From the 1: 250 000 scale geological map the contact between the Natal Group sandstone and Mzumbe Terrane is faulted along its entire length in the U10L catchment. This prominent fault is referred to as the Nhlazuka fault. The contact between the Natal Group and Dwyka Group also occurs in the U10L catchment where these contacts are at most places faulted by the Nhlazuka fault as well as other northeast-southwest (NE-SW) trending faults.

There is also the possibility that the contact zone fault melted the adjacent quartzitic Natal Group sandstone in which case the hydraulic conductivity associated with the contact will be lower. The pressure produced by the faulting can produce methamorphic and thermal effects which change or melt the adjacent country rock walls. Lithological logs of boreholes drilled into and through the contact/ fault will have to be evaluated to confirm whether the fault is water bearing or not. Existing aquifer data could also confirm the fault’s status. Such effects on the Dwyka-Mzumbe faulted contact will however be less due to the dominant mudstone matrix of the diamictite.

Although most faulting occurs along the coastal and coastal hinterland regions within the Namaqua-Natal Metamorphic Province and adjacent Natal Group, there is also some minor neo-tectonic faulting that occurs perpendicularly to the upper reaches of the UMkhomazi River valley (King, 2002). This faulting is very limited compared to the faulting along the coastal regions, but it does provide some future targets for groundwater exploration in the upper quaternary catchment of the uMkhomazi River.

Table 3.1: Table with basic geological and hydrogeological units and properties in the uMkhomazi catchment – adapted from King (2002)

ERA	SUPERGROUP OR MAJOR STRATIGRAPHIC UNIT	INTRUSIVE ROCKS	GROUP	SUB-GROUP	FORMATION	LITHOLOGY DESCRIPTION	HYDROGEOLOGICAL GROUPING	YIELD RANGE (L/s)	HYDRAULIC CONDUCTIVITY (m/d)[King, 2002]	QUATERNARY CATCHMENTS	COMMENT
Cenozoic	Quaternary and Tertiary					alluvium and coastal sediments. unconsolidated sands and gravels	Intergranular	>2	120.0	No extensive aquifers in study area	Sustainability depends on aquifer thickness
Mesozoic	Karoo Supergroup		Drakensberg			flood basalt,igneous, fine grained	Intergranular and fractured			U10A, U10B, U10C, U10D	Very elevated areas. Springs.
		Karoo dolerite				hypabassal intrusive igneous rock, fine to medium grained	Intergranular and fractured	0.2 - 1.4	0.05 - 1.0	U10A, U10C, U10D, U10E, U10F, U10G, U10H, U10J, U10K	Good targets for aquifers
					Clarens	arenceous sandstone	Intergranular and fractured	1.2	0.05 - 0.5	U10C	
					Elliot	shale, mudstone, siltstone	Fractured	0.9	0.05 - 0.5	U10A, U10B, U10C, U10D	
					Molteno	sandstone, shale and conglomerate	Intergranular and fractured	1.2	0.05 - 0.5	U10B, U10C	
			Beaufort	Tarkastad		Greater abundance of sandstone and red mudstone than Adelaide. alternating fine grained sandstone, shale, mudstone and siltstone.	Fractured. Mostly bedding plane fractures	0.9	0.05 - 0.5	U10A, U10B, U10C, U10D, U10E, U10F, U10G	
Palaozoic				Adelaide		alternating fine grained sandstone, shale, mudstone and siltstone.				U10A, U10B, U10C, U10D, U10E, U10F, U10G, U10H	
			Ecca			predominantly shales, carbonaceous shales and mudstone.	Intergranular and fractured	0.9	0.05 - 0.5	U10F, U10G, U10H, U10J, U10K	
					Vryheid	arenaceous sandstones	Intergranular and fractured		0.05 - 0.5	U10G, U10H, U10J, U10K	
			Dwyka			diamictite	Fractured	0.1		U10J, U10K, U10L, U10M	
	Natal Group					arenaceous andstone	Fractured/ jointed due to brittle nature	0.1 - 2.0	0.4 - 7.7	U10K, U10L, U10M	Very good aquifers (King, 24: 2002)
Mokolian	Natal Sector of the Namaqua-Natal Province					igneous and metamorphic rocks. Granite, granitic gneiss, calc-silicate rocks, granulite, ampibolite & marble	Intergranular and fractured	0.1 - 0.4		U10L, U10M	

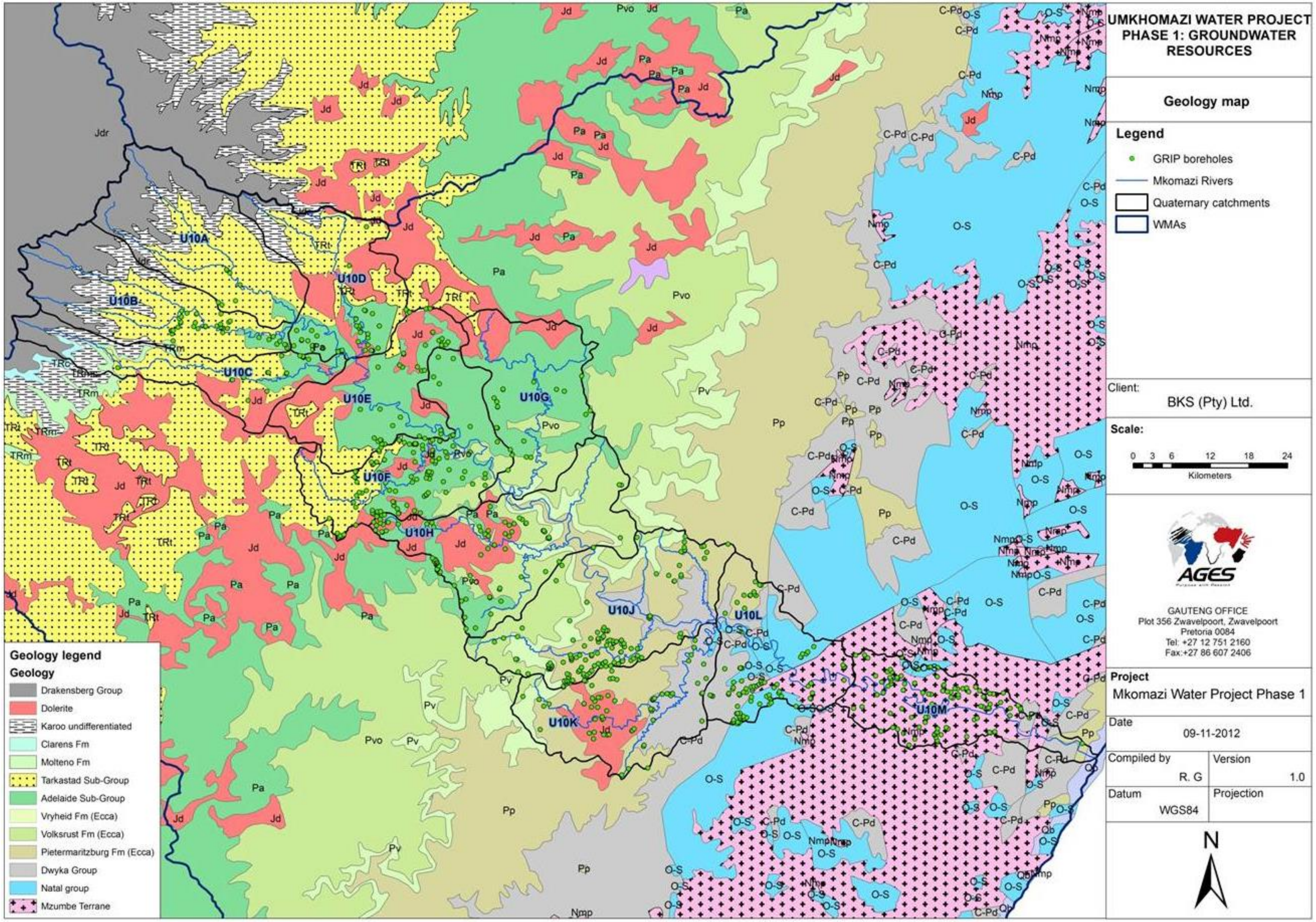

Figure 3.4: Basic geology map for the uMkhomazi River catchment

3.5 HYDROGEOLOGY

A number of aquifer types are found in the study area. These aquifer types differ in terms of the quantity and quality of groundwater that can be obtained from them as well as their hydraulic character. They are described in this section and are also linked to the geologic units of the uMkhomazi catchment in **Table 3.1**. The important hydrogeological characteristics of each major lithological unit have also been discussed in the geology (**Section 3.4**).

3.5.1 Unconfined or phreatic (water table) aquifers: Porous aquifers

These aquifers are associated mostly with the unconsolidated sediments found in the valleys and stream channels as alluvium. Depending on the thickness of the alluvial deposit (hence the total storage and increased Transmissivity), the volumes of groundwater that can be obtained from these deposits can be significant. The alluvium creates a porous aquifer with multiple microscopic stream paths that when combined into one laminar macroscopic flow, result in a comparably high hydraulic conductivity for the aquifer. If the deposits are of substantial saturated thickness (~ greater than 10m) and also have good lateral extent then borehole yields in excess of 5 l/s can be expected.

3.5.2 Semi-confined aquifers: Fractured rock aquifers

These aquifers in the study area are mostly associated with the dolerite sill and dyke intrusions in the Karoo sedimentary rock formations. Fractures are often created along the contact margins between the dolerite and surrounding sedimentary rocks. These vertical and horizontal fractures create conduits for groundwater flow with the surrounding sedimentary rocks acting like reservoirs to these fractures. Successful boreholes targeting these fracture zones can generally yield 2-5 l/s on a 12 hour duty cycle.

Fractures are also associated with the contact zones between sedimentary rock strata. These bedding parallel fractures form the main fracture types in the Karoo sedimentary rocks. Unfractured or only locally fractured sedimentary rocks will have a low to very low yield.

3.5.3 Perched aquifers

A special type of aquifer that is observed in the study area is a perched aquifer. Due to the mountainous topography in the upper regions of the uMkhomazi catchment and the great variation of sedimentary rock units associated with each geological subgroup in the study area, multiple perched aquifers are created. Rainfall infiltrates and moves through some of the sedimentary rock units with higher permeability which was formed through weathering of these units. When the infiltrated water reaches a more impermeable unfractured sedimentary rock unit, it follows the dip angle of the rock formation and exits the formation to form a spring on the surface.

A perched aquifer is unique because it is not actually linked to the groundwater table and saturated aquifer in the formations below.

3.6 RAINFALL ANALYSIS

Rainfall records for each quaternary catchment in the uMkhomazi River catchment were made available by BKS (2012). These rainfall records were given in monthly time steps as percentages of MAP. For the purposes of annual and even monthly rainfall time steps and statistical analysis, a single set of rainfall records per quaternary catchments is required. If rainfall records of multiple rainfall stations have to be processed for a quaternary catchment, some form of weighted averaging needs to be applied to the data at monthly time step interval in order to obtain a single representative monthly rainfall record set per quaternary catchment.

Rainfall records per quaternary catchment stretched from October 1925 to October 2009, a total of 84 years of monthly rainfall records. Statistics were performed on each rainfall dataset including the calculation of the upper and lower 95% levels of assurance for rainfall, to account for 1 in 20 year drought cycles.

U10A rainfall data in **Figure 3.5** provides an example of how rainfall was calculated for each quaternary catchment.

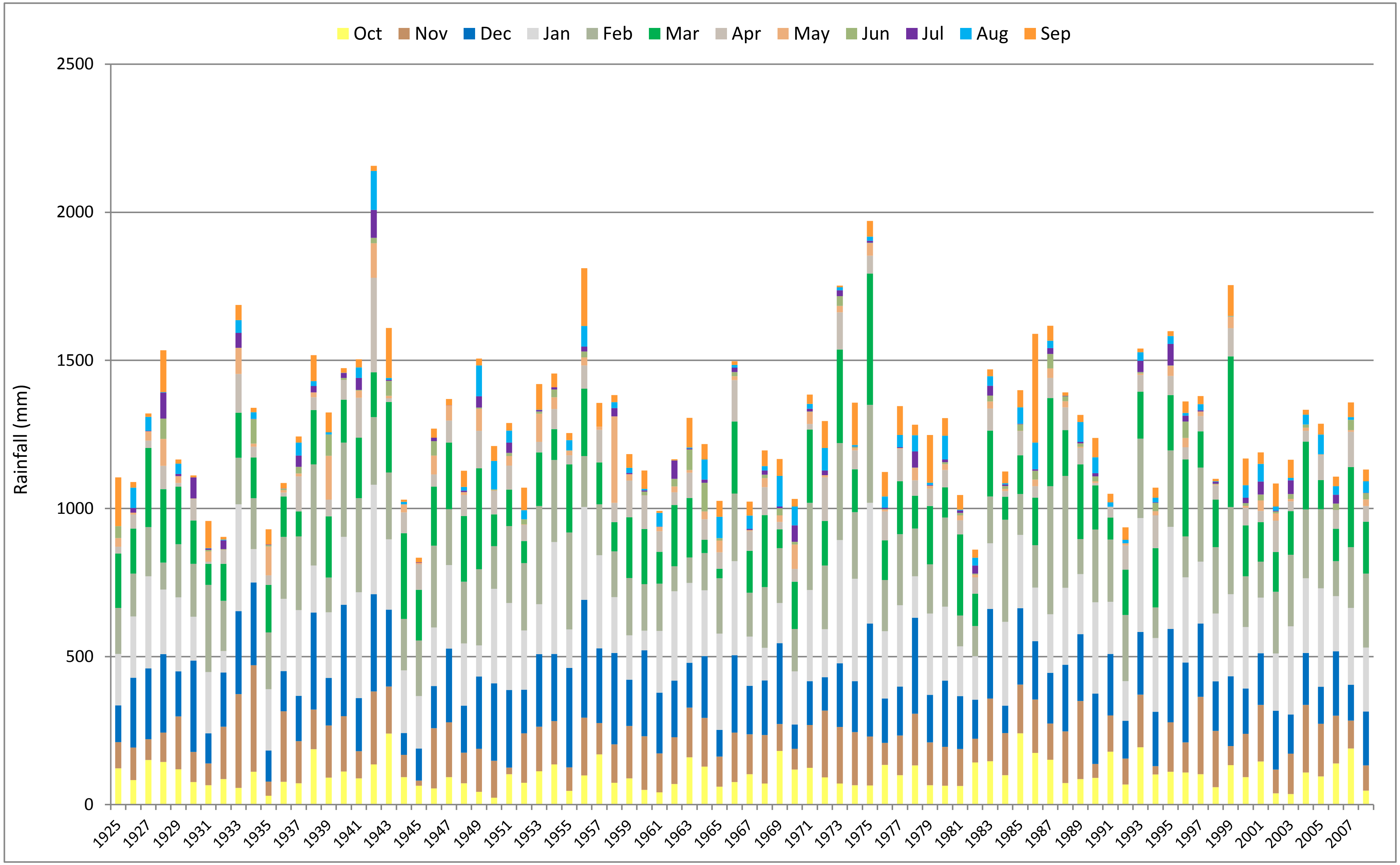

Figure 3.5: **U10A Rainfall from October 1925 to October 2009**

3.7 GROUNDWATER QUALITY

The groundwater quality of the aquifers and groundwater resources of the uMkhomazi River catchment were evaluated from good existing GRIP water qualities as well as older NGA water qualities. The results of the groundwater qualities are summarised in **Table 3.2**, where major water quality constituent concentrations have been evaluated per quaternary catchment against DWA drinking water quality standards. Notes on the calculations of the water qualities are provided per quaternary catchment.

3.7.1 U10A

There is limited groundwater information in catchment U10A. The groundwater quality information available is good however and a full aquifer test was conducted during which a water sample was taken near the end of the constant discharge test. As can be expected for a groundwater that is so close to the watershed and replenishing source, the groundwater quality is very good, DWA Class 0 i.e. Natural water quality. This is primarily because the groundwater is recently recharged (young) and it has not had enough residence time yet to react with the minerals in local formations and become mineralised.

3.7.2 U10B

Mean constituent concentrations were calculated from 12 boreholes sampled and 11 out of the 12 boreholes were sampled at the end of aquifer testing or purging of 3 borehole volumes. This provides higher confidence in the groundwater quality results obtained and ensures a representative sample from the aquifers. Results are shown in **Table 3.2**.

3.7.3 U10C

Mean constituent concentrations were calculated from 3 representative sampled groundwater qualities analysed by Umgeni Water services. In all cases the samples were collected during development of the borehole by airlifting after drilling or near the end of aquifer testing.

Table 3.2: Groundwater qualities of major constituents per quaternary catchment

Catchment	Overall Water Quality Class	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	CO_3 mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	F mg/l	N mg/l	Fe mg/l	Mn mg/l
U10A	Class 0	8.2	23.9	167.3	11.0	1.1	40.2	1.0	0.0	122.0	3.2	4.4	0.18	0.2	0.29	0.02
U10B	Class 1	7.8	27.0	178.1	16.4	6.9	35.3	1.7	0.0	118.2	8.1	11.4	0.49	0.6	0.76	0.06
U10C	Class 1	7.2	15.8	96.9	15.0	2.5	13.8	1.6	0.0	77.8	1.2	4.0	0.06	0.3	0.58	0.15
U10D	Class 1	7.3	64.8	416.0	55.4	23.8	60.4	1.7	0.0	210.0	10.0	124.0	0.31	0.4	0.09	0.14
U10E	Class 2	7.2	25.1	151.2	18.5	10.6	19.0	1.1	0.0	110.7	4.1	9.8	0.07	1.6	1.69	0.38
U10F	Class 2	7.4	23.2	228.8	19.4	6.4	28.5	1.2	0.0	103.4	10.2	19.2	0.36	1.7	1.39	0.09
U10G	Class 2	7.0	10.2	43.0	10.4	4.0	5.9	0.3	0.0	40.7	1.8	1.5	0.06	2.9	1.70	0.05
U10H	Class 0	7.4	25.2	178.8	11.6	6.8	26.0	1.9	0.0	83.2	22.0	1.6	0.11	2.0	0.36	0.04
U10J	Class 3	6.8	20.6	126.6	14.9	12.8	17.1	1.0	0.0	79.3	12.8	16.9	0.93	0.1	6.16	0.70
U10K*	Class 0	7.7	24.7	198.1	20.4	8.8	16.2	1.0	0.0	108.5	8.2	7.7	0.37	0.6		
U10L	Class 2	7.7	120.7	818.4	62.1	38.2	132.8	2.6	0.0	227.1	209.5	65.1	0.64	6.9	0.08	0.05
U10M	Class 3	7.3	108.0	802.0	90.5	36.2	155.7	3.1	0.0	231.8	205.2	101.2	1.90	2.2	4.51	0.21
DWA drinking WQ guidelines 1998																
Class 0: Ideal water quality		*5.0<pH<9.5*	*70*	*450*	*80*	*70*	*100*	*25*	*N/A*	*N/A*	*100*	*200*	*0.7*	*6*	*0.5*	*0.1*
Class 1: Good water quality		*5.0>pH>9.5*	*150*	*1000*	*150*	*100*	*200*	*50*			*200*	*400*	*1*	*10*	*1*	*0.4*
Class 2: Marginal water quality		*4.5>pH>10.0*	*370*	*2400*	*300*	*200*	*400*	*100*			*600*	*600*	*1.5*	*20*	*5*	*4*
Class 3: Poor water quality		*4.0>pH>10.5*	*520*	*3400*	*300+*	*400*	*1000*	*500*			*1200*	*1000*	*3.5*	*40*	*10*	*10*
Class 4: Unacceptable water quality		*3.0>pH>11.0*	*520+*	*3400+*		*400+*	*1000+*	*500+*			*1200+*	*1000+*	*3.5+*	*40+*	*10+*	*10+*

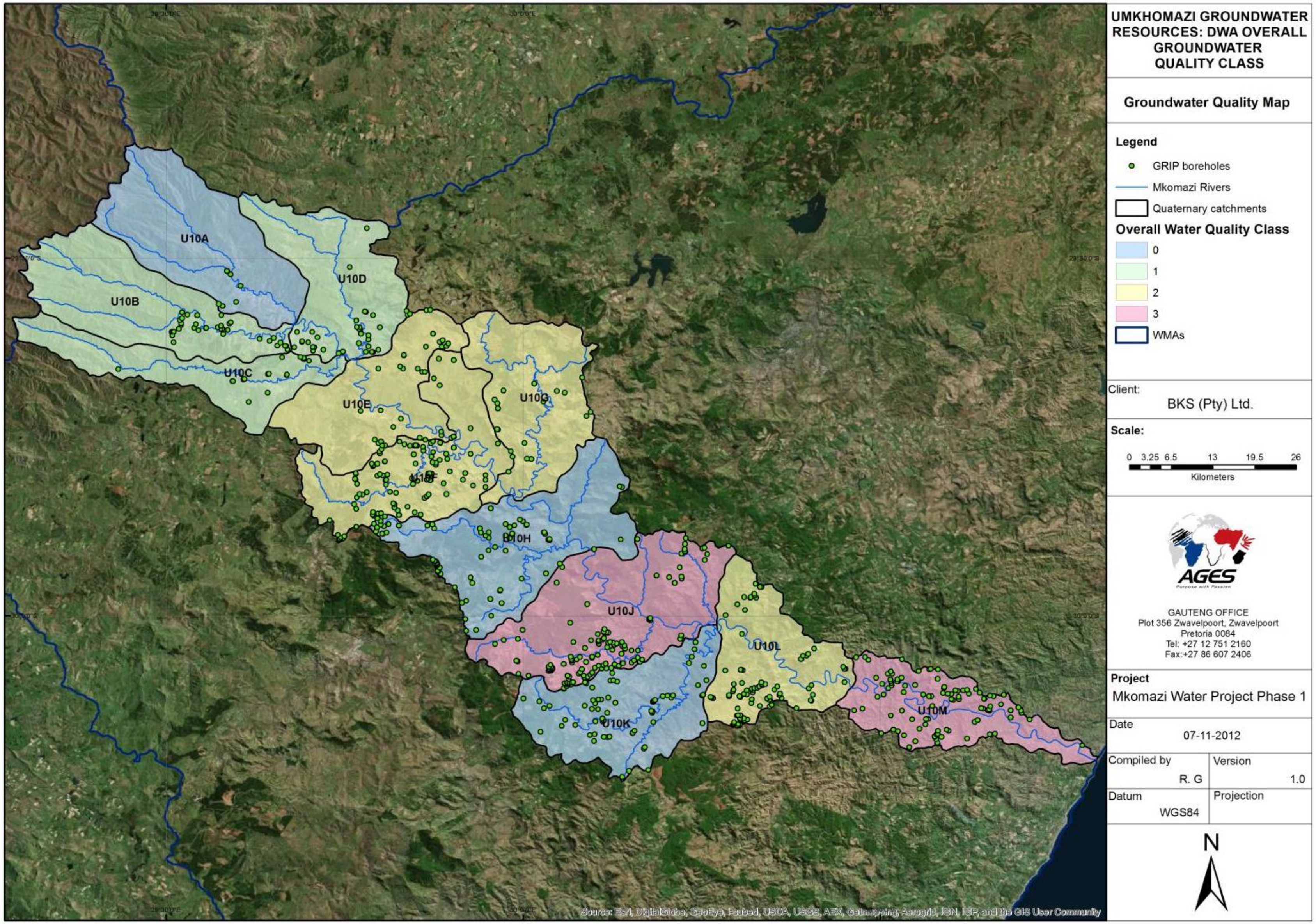

Figure 3.6: Overall water quality Class per catchment

3.7.4 U10D

The only sample that has been analysed for all major constituents for comparison is shown for catchment U10D in **Table 3.2**. This sample was taken during airlift development immediately after the borehole had been drilled and so could be influenced to some extent by drilling. The former mentioned sample's EC of 64.8 mS/m was compared to the EC of other boreholes in U10D were field measurements of EC and pH were taken, often these are better representations that lab EC's. Water quality field measurements were taken at 17 groundwater sources (15 boreholes, 2 springs) in the U10D catchment during the GRIP hydrocensus and the mean EC calculated from these measurements was 16 mS/m. It is expected that the argillaceous sequences within the Tarkastad Subgroup of the Karoo Supergroup have influenced the SO_4 values in the sample shown in **Table 3.2.**

3.7.5 U10E

Mean constituent concentrations were calculated from 3 representative sampled groundwater qualities analysed. Only samples where a full analysis of the major constituents was done were used for calculating means. The results are shown in **Table 3.2**.

3.7.6 U10F

14 Samples were used for calculating the arithmetic mean for each major water quality constituent. One iron concentration outlier was identified with a concentration of 12.2 mg/l and was excluded from calculating the mean.

3.7.7 U10G

After data cleaning was performed only 2 samples were used for the calculation of the mean constituent concentrations. One sample had an iron concentration of 3.26 mg/l and the other a concentration of 0.13 mg/l. Although the iron concentrations seem to appreciate in the presence of dolerite intrusions and as one descends down toward the coast, it is recommended that if decisions are to be made regarding groundwater development based on quality, more boreholes should be sampled for a better groundwater quality representation.

3.7.8 U10H

Fourteen Samples were used in calculating the arithmetic mean for each major water quality constituent shown in **Table 3.2**. In many cases the groundwater quality sample was obtained during aquifer testing or pumping, resulting in a representative aquifer water quality sample.

3.7.9 U10J

Eighteen samples were used in calculating the arithmetic mean for each major water quality constituent shown in **Table 3.2**. The dissolved iron concentration is highly elevated in the U10J catchment. When the drilling dates and dates sampled are compared however, it can be seen that many boreholes are unused and thus the groundwater has been stagnant in the borehole for a few years and the casing has started to rust. This is thought to be one explanation for highly elevated (18 mg/l, 20 mg/l, 25 mg/l) iron concentrations in some boreholes. It is recommended that when sampling will be conducted, water qualities be obtained from boreholes where abstraction takes place or that groundwater samples be obtained after 3 borehole volumes have been purged.

3.7.10 U10K

The groundwater qualities available for the U10K catchment in the GRIP database do not have a complete analysis of major constituents available. The NGA groundwater qualities were then also sourced from DWA for this catchment and here 8 samples were available with all macro elements analysed. Because only macro elements were analysed in the NGA database samples, no values for iron and manganese were available. It is however recommended that when a groundwater investigation for DWA is done again in this quaternary catchment or DWA groundwater quality monitoring, proper groundwater sampling be conducted with a good spatial distribution as well. The sampling protocol should try and target boreholes that are in use in order to obtain a good representative groundwater quality of the aquifers in the catchment. Often the rusting casings of unused boreholes result in elevated iron concentrations that are not representative of the aquifer itself.

3.7.11 U10L

Only 3 samples were available from the GRIP database with 11 out of the 15 major constituent concentrations present. The NGA groundwater qualities were then also sourced from DWA for U10L, 10 samples were available with all macro elements analysed. Because only macro elements were analysed in the NGA database samples, no values for iron and manganese were available. Iron and manganese concentrations are however available from the 3 GRIP water quality samples analysed and the mean Fe and Mn concentrations are shown in **Table 3.2**. Constituents that were not analysed in the GRIP database and expected to be present were total dissolved solids (TDS), potassium (K), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). A more mineralised groundwater is present in U10L and the effect of the mineralised coastal aquifers is more apparent from U10L and further downstream.

3.7.12 U10M

Thirty groundwater samples were used in calculating the arithmetic mean for each major water quality constituent shown in **Table 3.2** for U10M. A highly mineralised groundwater is apparent from the groundwater qualities in the GRIP dataset and **Table 3.2** and the mineralised groundwater character is expected to be the result of the coastal location of the U10M catchment. The groundwater qualities are however not expected to be as saline towards the interior, but still within the catchment and the location of groundwater sampling points should be spatially evenly distributed during future studies for groundwater development, if necessary. The saline character could however be present in the groundwater across the catchment if coastal alluvial aquifers and shallow weathered aquifers are predominantly used. These could be influenced by on-shore see breezes blowing in humid sodium and chloride saturated water vapour onto the mainland soils and outcrops, where rainwater again infiltrates and carries down these salts.

4 GROUNDWATER YIELD MODEL FOR THE RESERVE (GYMR) RESULTS & DISCUSSION

4.1 GROUNDWATER RECHARGE AND RAINFALL

The percentage of recharge to groundwater from rainfall is one of the most important parameters in the calculation of a minimum groundwater flow balance. Given the total volumes of water that fall annually within the borders of a quaternary catchment, this parameter is highly sensitive in the groundwater balance and it is then important to calculate and choose this parameter correctly. For the study two methods were used to determine two different values of this parameter. Firstly the chloride mass balance method was used where enough chloride concentrations were available in a quaternary catchment from the GRIP or NGA datasets. Some of the chloride estimates were good and agreed with what was known for a specific formation in South Africa, but some provided too high a recharge percentage. To be consistent the other method was used, whereby representative means for recharge were calculated per quaternary catchment from the GRA2 raster for the country. The groundwater recharge percentage ranged between 5 and 13 % for quaternary catchments U10A to U10M.

Rainfall data were statistically analysed and 95% assurance of supply rainfall calculated in order to account for drought cycles. Based on the 95% assurance level, rainfall (mm) ranged between 552 and 940 mm/a for the uMkhomazi catchment. For the same rainfall data, but on a MAP level of assurance (50%), the rainfall ranges between 758 and 1287 mm/a.

4.1.1 Assurance levels

The rainfall values in the section above show the deviation between the lower 95th percentile (95% level of assurance) and the MAP for the uMkhomazi River quaternary catchments. The MAP does not account for dry periods and is markedly higher than the 95% level of assurance rainfall.

Using the available data from the rainfall records the lower 95th percentile was calculated for the uMkhomazi quaternary catchments. The deviation of the lower 95th percentile from the MAP indicates the severity of droughts. The more constant the rainfall, the closer the lower 95th percentile is to the MAP (AGES, 2010). A negligible difference (small difference between MAP and 95th percentile) would have been an ideal rainfall-recharge scenario in terms of aquifer sustainability. The lower 95th percentile in U10A for instance is 940 mm/a, which is 27% less than the average MAP of 1287 mm/a, where the 95% percentile in Karoo regions of the country can be in the order of 50% lower than the MAP.

A transient (time varying) simulation of the GYMR using the approximately 84 years of historic rainfall available was also performed. These figures are comparable with the MAP figures from the steady-state GYMR scenarios.

4.2 BOREHOLE YIELDS AND GROUNDWATER LEVELS

4.2.1 Existing borehole information

Existing borehole and groundwater information was sourced from the GRIP and NGA groundwater databases. The KwaZulu Natal GRIP information is good and a total of 806 boreholes were identified in the uMkhomazi River catchment during spatial queries. These boreholes were sub-divided between the 12 quaternary catchments for further data analysis. NGA information was used in addition where the GRIP information did not completely cover the study component such as water quality.

4.2.2 Water levels

From the GRIP database, representative water level records were identified in each of the quaternary catchments U10A – U10M. The mean water levels were further used to calculate groundwater volumes in storage per quaternary catchment (see **Table 4.1**). The uMkhomazi River catchment has a minimum water level depth of 0 mbgl i.e. artesian, a maximum water level depth of 55 mbgl and a mean water level depth of 24 mbgl.

Table 4.1: Groundwater storage estimates calculated for each quaternary catchment

Quaternary catchment	Surface Area (km^2)	Depth to water level GRIP (mbgl)	Min depth to water level GRIP (mbgl)	Max aquifer depth GRAII (mbgl)	Water level management constraint (mbgl)	Aquifer storativity	Groundwater volume in storage (m^3)	Max usable groundwater volume in storage (m^3)	Max usable groundwater volume in storage (million m^3)
U10A	418.2	-7.4	-2.4	-140.9	-42.6	0.0010	33 506 708	16 822 349	16.82
U10B	392.1	-17.8	0.0	-139.6	-52.7	0.0010	28 668 515	20 653 993	20.65
U10C	267.0	-11.1	-7.7	-138.5	-45.7	0.0010	20 414 882	10 161 816	10.16
U10D	337.0	-32.4	-1.0	-136.8	-66.6	0.0010	21 117 983	22 093 268	22.09
U10E	327.2	-24.6	0.0	-136.7	-58.8	0.0010	21 997 264	19 240 044	19.24
U10F	379.0	-29.8	-1.3	-139.9	-64.7	0.0010	25 046 850	24 060 745	24.06
U10G	353.1	-24.3	-4.6	-136.6	-58.4	0.0010	23 812 759	19 009 474	19.01
U10H	457.8	-13.5	0.0	-139.6	-48.4	0.0010	34 652 342	22 140 758	22.14
U10J	505.1	-26.2	-1.1	-156.4	-65.3	0.0010	39 461 440	32 416 315	32.42
U10K	364.4	-25.4	-10.0	-160.1	-65.4	0.0010	29 444 734	20 203 738	20.20
U10L	307.2	-55.1	-2.7	-175.7	-99.0	0.0010	22 236 659	29 584 055	29.58
U10M	280.0	-21.1	0.0	-178.8	-65.8	0.0010	26 488 107	18 428 801	18.43
Total	**4388.1**						**326 848 243**	**254 815 356**	**254.82**

4.3 HYDROGEOLOGY

4.3.1 Aquifer types

The hydrogeology of the study area has been described in the **Geology** and **Hydrogeology sections** and the reader is referred to the former mentioned sections.

4.3.2 Groundwater resource units

The 12 quaternary catchments of the uMkhomazi River catchment were used as the groundwater management units in the GYMR. There are two views on groundwater management units. The first is to use the quaternary catchments, which is in line with the hydrological approach. This can be done if the groundwater head elevation follows the topography within a good or acceptable correlation. Since the uMkhomazi catchment is also largely undeveloped, quaternary catchments were used.

4.4 MINING

There were no large operating mines identified in the uMkhomazi River catchment and consequently there were no mining groundwater uses in the uMkhomazi GYMR.

4.5 SPRINGS

Springs form an important component to the groundwater flow balance in the GYMR especially in mountainous regions and the type of geology in the uMkhomazi catchments U10A – U10H. Spring outflows are expected to be higher in the upper quaternary catchments (U10A – U10G) especially associated with the Karoo Supergroup layering of argillaceous and arenaceous rocks. Springs surveyed during the GRIP hydrocensus are limited and not perceived as representative of the actual number of springs in the catchments. Where a more realistic number of springs were found, these numbers where linearly applied to catchments with similar hydrogeological character that only had few springs. It is recommended that a satellite imagery spring count be done in the upper uMkhomazi catchments for a given hydrogeologically representative area, that count per area be extrapolated for similar hydrogeology and a follow up field census of the hydrogeological area surveyed be done to confirm satellite imagery results.

4.6 COMMUNITIES AND BASIC HUMAN NEEDS (BHN)

Rural and urban water requirements were obtained from BKS (2012) which were also split into those currently supplied from groundwater and those supplied from surface water. These figures were incorporated into the GYMR groundwater flow balance.

Through the National Water Supply and Sanitation Policy (1994) and the Constitution (1996), every person in South Africa has a right to 25 litres of potable water per day for basic human needs (BHN). The BHN forms one part of the Reserve and it is the reason why Reserve Determinations are of utmost importance. The water requirement for the Reserve as set by the Reserve Determination has to be taken out of the available surface or groundwater in a catchment before any other uses can be granted or licensed.

Although not the purpose of the study, the groundwater Reserve for basic human needs (BHN) was determined and taken into consideration in the GYMR. The BHN for the uMkhomazi catchment and quaternaries were calculated based on population estimates received from BKS, extrapolated to 2012 present day. 60 litres per person per day was allocated to ensure an adequate BHN, in the case where there are actually more people than estimated. The total BHN for the uMkhomazi catchment was calculated at 4.35 Mm3/a.

4.7 GENERAL AUTHORISATIONS (GA'S)

General authorisations were taken into account as a water use in Scenario 2 of the Groundwater Yield Model for the Reserve (GYMR). General Authorisations were applied to all types of irrigable and cultivated land cover per hectare (ha) as mapped out during the EKZN land cover mapping. General Authorisations from groundwater have been determined for each quaternary catchment in South Africa. These volumes per hectare per annum are published in the Government Gazette No. 26187 as the document, *Revision of General Authorisations in terms of section 39 of the National Water Act, 1998 (Act no. 36 of 1998)*.

4.8 WETLANDS

Wetland figures as determined from the BKS hydrology outputs (2012) and estimated from the EKZN-W (2008) SPOT 5 land cover study were used in the GYMR.

4.9 RIPARIAN VEGETATION

Riparian vegetation occurs along drainage lines and is associated with the wetter soils on the banks of the rivers and streams as well as the water of the streams themselves.

Riparian vegetation water use was determined during the BKS hydrology study. Evapotranspiration loss and associated water loss from riparian vegetation is however already accounted for in the evapotranspiration losses in the GYMR and the riparian vegetation water use component was consequently not included as a separate component in the GYMR.

4.10 EVAPOTRANSPIRATION

The lengths of all secondary drainages in the study area were accumulated to a total length of 933 km. A width of 5.0 m on each side or bank of the drainage was then used to calculate, with the cumulative drainage length, the total evapotranspiration for the study area and separately for each quaternary catchment.

4.11 BASEFLOW

Groundwater baseflow is the final outflow out of a groundwater system as well as the GYMR groundwater flow balance. This analytical volume of groundwater baseflow as the final component of the water balance equation was compared to groundwater baseflow values obtained from monthly measured and simulated mean annual runoff (MAR) values, simulated by BKS (2012) for the uMkhomazi Water Project. Simulated MAR values were plotted on hydrographs and a technique similar to the Cumulative Rainfall Departure (CRD) was used to determine a rough estimate of monthly baseflow. No daily baseflow records were available for CRD analysis.

The hydrograph of U10A in **Figure 4.1** is an example of one of the baseflow graphs analysed for the last 10 years of data and also shows by black horizontal line the approximate point where baseflow values were estimated and baseflow value obtained from the simulated MAR data.

4.12 ECOLOGICAL WATER REQUIREMENT (EWR)

Existing reports on the Instream Flow Requirements (IFR) or the EWR of the uMkhomazi catchments and its quaternary catchments were not available at the time of the study. In the absence of direct site evidence and measurements, assumptions were made regarding the EWR. It was assumed for the purposes of the GYMR; that the groundwater contribution to the EWR amounts to 10% of the net baseflow after total outflows and losses (Evapo-transpiration) has been subtracted from the flow balance.

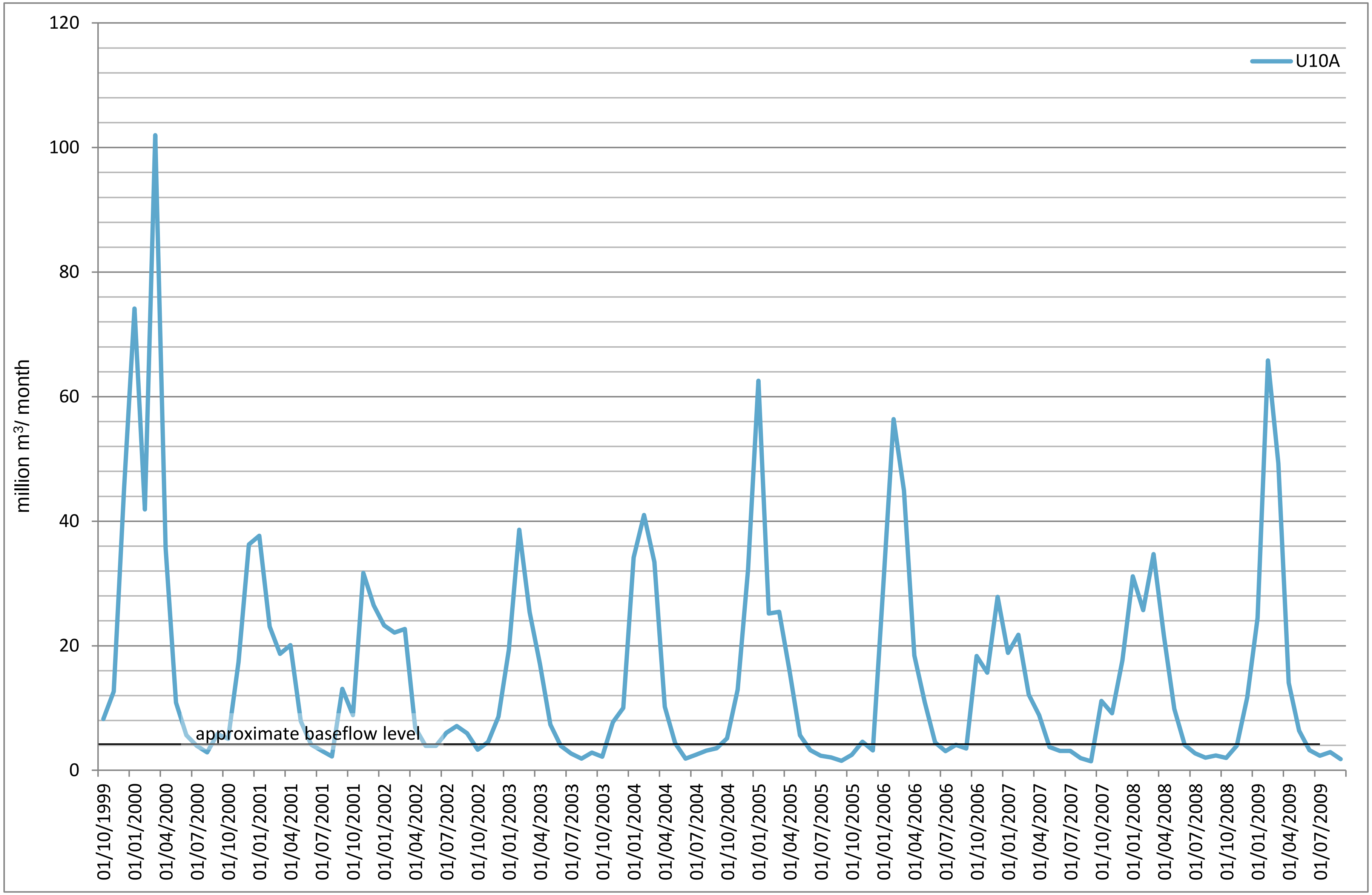

Figure 4.1: **U10A Hydrograph of last 10 years of MAR records as example of baseflow analysis**

4.13 GROUNDWATER FLOW BALANCE SCENARIOS

The GYMR groundwater flow balance was set up in steady-state to assess potential groundwater flow balances on an annual basis per quaternary catchment. A combined transient (historic rainfall change over time) and Monte Carlo simulation of the GYMR was also run for each catchment as a third scenario on a monthly basis. Recommendations on management options based on the outcome of the assessments are made, for the DWA and Resource Directed Measured (RDM) office's decision making purposes.

Three scenarios were simulated with the difference being the application of General Authorisations (GA's) as well as the third scenario being a transient and Monte Carlo simulation.

1. Scenario1: Groundwater recharge 95% assurance of supply, GA's excluded, steady state – groundwater volumes available based on annual recharge to aquifers excluding groundwater storage effects in aquifers were simulated with GRA2 recharge estimate percentages applied to rainfall at 95% level of assurance. This scenario accounts for drought cycles, GW losses and the GW base flow component (EWR volumes assumed to be 10% of net base flow).GA's are excluded from this scenario;

2. Scenario 2: Groundwater recharge 95% assurance of supply, GA's included, steady state – groundwater volumes available based on annual recharge to aquifers excluding groundwater storage effects in aquifers were simulated with GRA2 recharge estimate percentages applied to rainfall at 95% level of assurance. This scenario accounts for drought cycles, GW losses and the GW base flow component (EWR volumes assumed to be 10% of net base flow). GA's are included in this scenario to determine the effect these allocations have on the groundwater balance and if all GA's can be assigned;

3. Scenario 3: Transient simulation with 84 year historic rainfall and Monte Carlo simulation with 1000 realisations sampled across truncated normal distributions of recharge coefficient and borehole abstraction to account for uncertainty. GA's are excluded.

4.13.1 Groundwater reserve determination – GYMR approach

It must be noted that this groundwater flow balance is based on the assumption that water is e.g. allocated to irrigation and basic human needs (community water supply). The "allocable" groundwater balance will differ from the "actual" groundwater flow balance. In the absence of direct site information, conservative assumptions were made in the favour of the Reserve, for example riparian- and alien- vegetation surface areas that deplete groundwater until it can be proven otherwise.

In equilibrium, the recharge should be balanced by borehole abstraction, evapo-transpiration losses to the streams, springs, wetlands and groundwater base flow (**Appendix A**). The groundwater inflow components are recharge from rainfall and inflow from dam seepages.

The GYMR model process applied the following conservative approaches in this study:

1. Groundwater recharge was determined as a percentage of the lower 95th percentile of rainfall to cater for drought low flows in Scenario 1 and 2. Historic rainfall was used in Scenario 3;

2. The model simulated groundwater flow balances in which case storativity was assumed to be low. Water levels indicate low storativity;

3. The groundwater flow losses (evapotranspiration) were calculated by using a 5.0 m strip along both sides of the cumulative river lengths in each catchment.

Both GYMR groundwater flow balance scenario 1 GA’s excluded and scenario 2 GA’s included with their associated inflow and outflow components for each quaternary catchment are shown in **Table 4.5** to **Table 4.8** and **Figure 4.2** and **Figure 4.4** respectively. Groundwater baseflow and the usable groundwater component per month are shown in **Table 4.10** for Scenario 3: Transient simulation results. Water levels for the transient simulation with Monte Carlo realisations to show normal distribution ranges and uncertainty are shown in water level graphs in **Figure 4.6 to Figure 4.17**. The results are discussed in **section 4.14**.

Table 4.2: Scenario 1: Present day 95% assurance, GA's excluded – Sources of groundwater

No	Quaternary catchment	Surface Area (Km2)	MAP BKS, 2012 (mm/a)	Rainfall 95% assurance (mm/a)	Recharge avg. per catchment GRA2 (% of MAP)	Recharge 95% assured (m3/a)	Recharge MAP (m3/a)	Dam Seepage Area EKZN & BKS (km2)	Total dam seepage (m3/a)	Total inflow before losses (m3/a)	Total inflow before losses (million m3/a)
1	U10A	418.2	1 287	940	13%	51 079 171	69 961 404	0.12	11 677	51 090 848	51.1
2	U10B	392.1	1 176	859	12%	41 091 362	56 281 441	0.14	14 041	41 105 402	41.1
3	U10C	267.0	1 091	839	11%	25 379 057	33 006 323	0.32	32 376	25 411 433	25.4
4	U10D	337.0	999	738	11%	27 334 649	37 008 732	0.85	84 919	27 419 569	27.4
5	U10E	327.2	1 034	782	12%	29 937 723	39 566 667	0.13	13 430	29 951 153	30.0
6	U10F	379.0	963	727	8%	23 216 722	30 750 335	0.55	55 258	23 271 980	23.3
7	U10G	353.1	981	752	9%	24 322 824	31 749 096	1.51	150 636	24 473 460	24.5
8	U10H	457.8	924	689	9%	27 958 271	37 505 227	2.95	295 071	28 253 343	28.3
9	U10J	505.1	878	651	8%	27 451 258	37 038 484	0.38	38 481	27 489 739	27.5
10	U10K	364.4	793	577	6%	11 821 260	16 240 784	1.91	191 004	12 012 265	12.0
11	U10L	307.2	758	552	6%	10 804 385	14 843 737	0.19	18 596	10 822 981	10.8
12	U10M	280.0	858	620	9%	16 234 656	22 457 835	0.00	194	16 234 850	16.2
	TOTAL	**4 388**				**316 631 338**	426 410 064	**9.1**	**905 683**	**317 537 021**	**317.5**

Table 4.3: Scenario 1: GA's excluded – Groundwater sinks in the uMkhomazi River catchment (table 1 of 2)

No	Quaternary catchment	Number of abstraction boreholes (Other)	Total borehole abstraction GRIP (m3/a)	Average Farm irrigation area (ha)	Total livestock farm usage BKS (m3/a)	Population in catchment (BKS 2012 calculated)	Rural & Urban GW use BKS (m3/a)	BHN Reserve Based on full population (60 L/p/d)	Farm irrigation water use BKS (m3/a)
1	U10A	3	-113 530		-362 758	3 813	-39 597	-83 505	0
2	U10B	13	-122 990		-102 058	4 404	-46 480	-96 448	0
3	U10C	6	-167 456		-23 171	3 001	-47 861	-65 722	-47 000
4	U10D	21	-624 413		-292 463	11 732	-142 229	-256 931	-112 000
5	U10E	19	-179 755		-225 494	24 883	-551 625	-544 938	0
6	U10F	45	-1 192 061		-261 353	24 881	-412 494	-544 894	0
7	U10G	12	-788 400		-274 886	6 260	-133 244	-137 094	-296 000
8	U10H	36	-2 570 184		-215 510	21 505	-313 040	-470 960	-570 000
9	U10J	67	-1 570 493		-302 134	30 207	-131 369	-661 533	-183 000
10	U10K	49	-3 358 584		-406 000	11 693	-193 878	-256 077	-252 000
11	U10L	38	-1 296 130		-193 006	13 830	-158 061	-302 877	0
12	U10M	39	-879 854		0	42 697	-5 361	-935 064	0
	Total	**348**	**-12 863 850**		**-2 658 834**	**198 906**	**-2 175 240**	**-4 356 041**	**-1 460 000**

Table 4.4: Scenario 1: GA's excluded – Groundwater sinks in uMkhomazi catchment continued (table 2 of 2)

No	Quaternary catchment	Average Forestry area EKZN-W SPOT5 (km2)	Average Forestry water use (m3/a)	Average Alien veg (km2)	Alien veg water use BKS (m3/a)	Wetlands BKS (km2)	Wetland water use (m3/a)	No of springs GRIP	Spring flow (m3/a)	Total outflow before losses (sinks) m3/a	Total outflow before losses (sinks) million m3/a
1	U10A	4.7	-879 524	1.4	-375 357	1.40	-350	10	-31 536	-1 886 156	-1.89
2	U10B	22.9	-4 264 048	6.5	-1 463 452	1.30	-326	10	-31 536	-6 127 337	-6.13
3	U10C	20.8	-3 288 214	4.1	-812 143	2.48	-620	8	-25 229	-4 477 416	-4.48
4	U10D	3.2	-415 476	4.5	-868 333	4.30	-1 076	6	-18 922	-2 731 842	-2.73
5	U10E	35.8	-4 820 357	3.7	-656 429	0.82	-206	8	-25 229	-7 004 033	-7.00
6	U10F	54.5	-4 695 952	3.0	-324 048	1.43	-358	6	-18 922	-7 450 081	-7.45
7	U10G	56.7	-5 549 167	2.9	-364 048	1.36	-340	6	-18 922	-7 562 100	-7.56
8	U10H	150.4	-14 348 333	3.7	-408 452	0.98	-246	4	-12 614	-18 909 340	-18.91
9	U10J	143.0	-13 350 952	4.2	-419 405	1.89	-471	8	-25 229	-16 644 586	-16.64
10	U10K	92.7	-6 744 762	4.4	-346 786	2.89	-723	4	-12 614	-11 571 424	-11.57
11	U10L	18.3	-1 235 833	2.7	-154 167	0.12	-29	11	-34 690	-3 374 793	-3.37
12	U10M	1.5	-118 452	2.7	-175 595	0.18	-44	1	-3 154	-2 117 526	-2.12
	Total	**604**	**-59 711 071**	**43.8**	**-6 368 214**	**19.2**	**-4 789**	**82**	**-258 595**	**-89 856 635**	**-89.86**

Table 4.5: Scenario 1: Present day GA' excluded, 95% assured rainfall and recharge

No	Quaternary catchment	Surface Area (Km^2)	Total inflow (million m^3/a)	Total outflow before losses (sinks) million m^3/a	Evapo-transpiration flow loss 2 - streams (million m^3/a)	Net groundwater baseflow GYMR (million m^3/a)	Net baseflow measured from monthly MAR (million m^3/a)	Net baseflow required by EWR - Low flow (million m^3/a)	Usable groundwater volume from baseflow 95% assured (million m^3/a)	Usable groundwater volume from baseflow MAP 50% assured (million m^3/a)	GW outflow / GW inflow without ET or EWR accounted (million m^3/a)	GRDM Present status category
1	U10A	418.2	51.09	-1.89	-0.93	-48.27	48.84	-4.83	**43.44**	62.33	4%	A
2	U10B	392.1	41.11	-6.13	-1.17	-33.81	35.04	-3.38	**30.43**	45.62	15%	B
3	U10C	267.0	25.41	-4.48	-0.88	-20.05	20.64	-2.00	**18.04**	25.67	18%	B
4	U10D	337.0	27.42	-2.73	-1.01	-23.68	21.00	-2.37	**21.31**	30.98	10%	B
5	U10E	327.2	29.95	-7.00	-0.45	-22.49	21.48	-2.25	**20.24**	29.87	23%	C
6	U10F	379.0	23.27	-7.45	-0.94	-14.88	10.92	-1.49	**13.39**	20.93	32%	C
7	U10G	353.1	24.47	-7.56	-1.11	-15.80	14.28	-1.58	**14.22**	21.65	31%	C
8	U10H	457.8	28.25	-18.91	-1.31	-8.04	16.80	-0.80	**7.23**	16.78	67%	E
9	U10J	505.1	27.49	-16.64	-1.41	-9.43	15.84	-0.94	**8.49**	18.08	61%	D
10	U10K	364.4	12.01	-11.57	-1.13	0.69	8.28	0.07	**-0.76**	3.66	96%	F
11	U10L	307.2	10.82	-3.37	-0.52	-6.93	6.00	-0.69	**6.23**	10.27	31%	C
12	U10M	280.0	16.23	-2.12	-0.78	-13.33	8.16	-1.33	**12.00**	18.22	13%	B
	Total	**4388.1**	**317.5**	**-89.9**	**-11.7**	**-216.0**	**227.3**	**-21.6**	**194.3**	**304.1**		

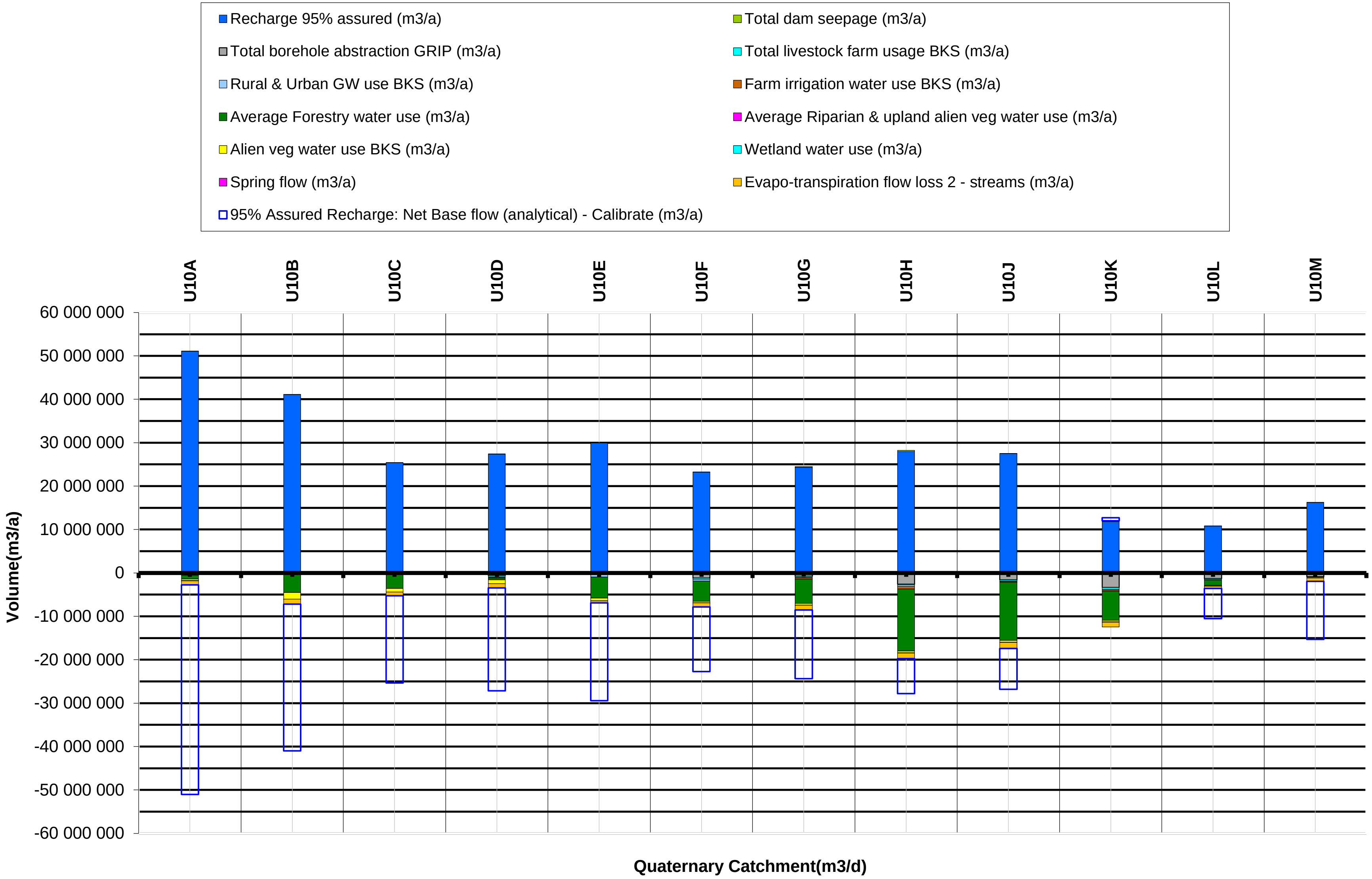

Figure 4.2: Scenario 1 GA's excluded: Graph indicating GYMR water balance components and volume magnitude

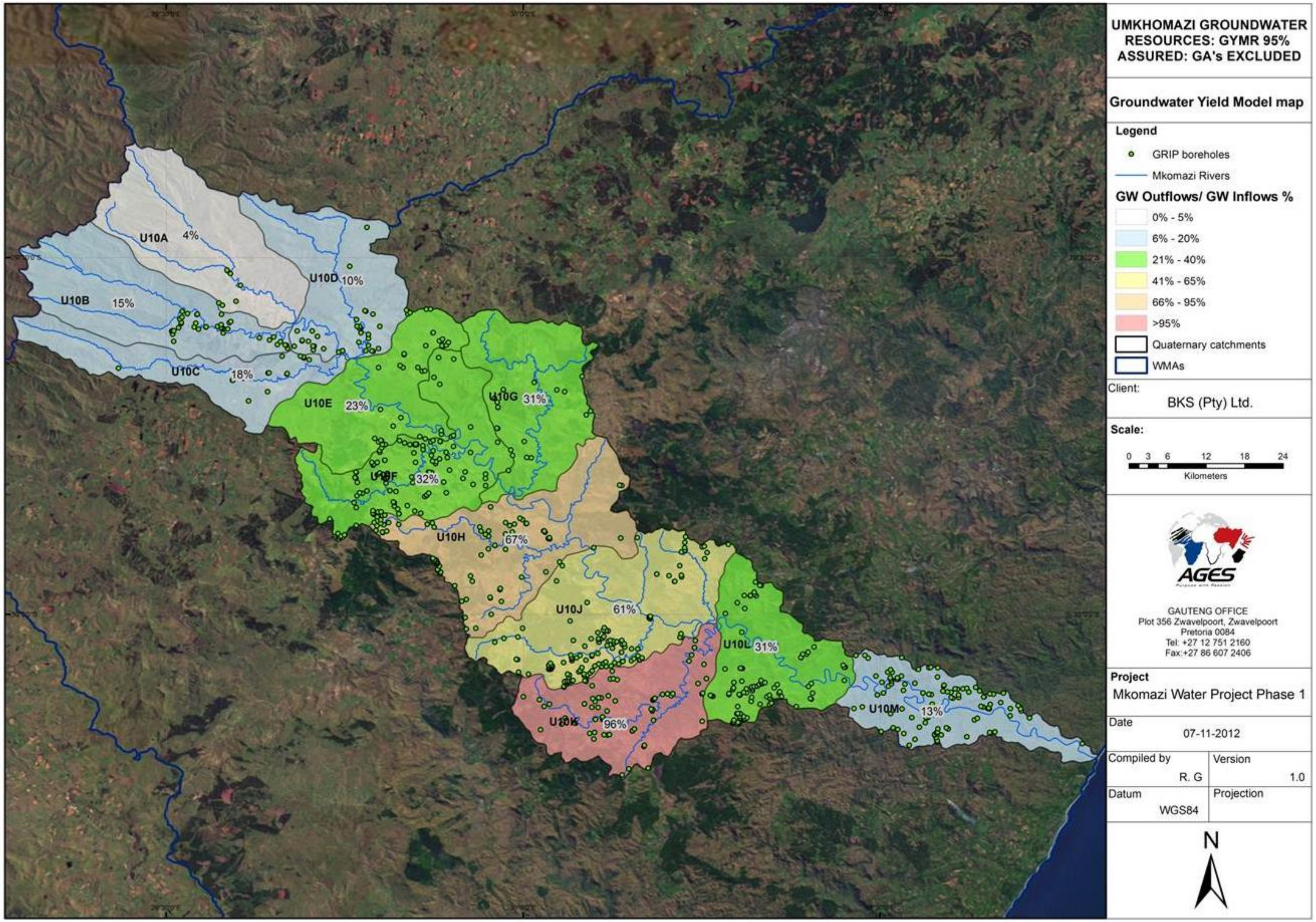

Figure 4.3: Scenario1: Map showing GYMR steady-state results with GA’s excluded: GW outflow divided by GW inflow

Table 4.6: Scenario 2: GA's included – Groundwater sources, 95% assured rainfall & recharge

No	Quaternary catchment	Surface Area (km^2)	MAP BKS, 2012 (mm/a)	Rainfall 95% assurance (mm/a)	Recharge avg. per catchment GRA2 (% of MAP)	Recharge 95% assured (m3/a)	Recharge MAP (m3/a)	Dam Seepage Area EKZN & BKS (km2)	Total dam seepage (m3/a)	Total inflow before losses (m3/a)	Total inflow before losses (million m3/a)
1	U10A	418.2	1 287	940	13%	51 079 171	69 961 404	0.1	11 677	51 090 848	51.1
2	U10B	392.1	1 176	859	12%	41 091 362	56 281 441	0.1	14 041	41 105 402	41.1
3	U10C	267.0	1 091	839	11%	25 379 057	33 006 323	0.3	32 376	25 411 433	25.4
4	U10D	337.0	999	738	11%	27 334 649	37 008 732	0.8	84 919	27 419 569	27.4
5	U10E	327.2	1 034	782	12%	29 937 723	39 566 667	0.1	13 430	29 951 153	30.0
6	U10F	379.0	963	727	8%	23 216 722	30 750 335	0.6	55 258	23 271 980	23.3
7	U10G	353.1	981	752	9%	24 322 824	31 749 096	1.5	150 636	24 473 460	24.5
8	U10H	457.8	924	689	9%	27 958 271	37 505 227	3.0	295 071	28 253 343	28.3
9	U10J	505.1	878	651	8%	27 451 258	37 038 484	0.4	38 481	27 489 739	27.5
10	U10K	364.4	793	577	6%	11 821 260	16 240 784	1.9	191 004	12 012 265	12.0
11	U10L	307.2	758	552	6%	10 804 385	14 843 737	0.2	18 596	10 822 981	10.8
12	U10M	280.0	858	620	9%	16 234 656	22 457 835	0.0	194	16 234 850	16.2
	TOTAL	**4388.1**				**316 631 338**	**426 410 064**	**9.1**	**905 683**	317 537 021	**317.5**

Table 4.7: Scenario 2: Groundwater sinks in uMkhomazi catchment (table 1 of 2)

No	Quaternary catchment	General authorizations DWAF m3/ha/a	General authorizations (m3/a)	Number of abstraction boreholes (Other)	Total borehole abstraction GRIP (m3/a)	Average Farm irrigation area (ha)	Total livestock farm usage BKS (m3/a)	Population in catchment (BKS 2012 calculated)	Rural & Urban GW use BKS (m3/a)	BHN Reserve Based on full population (60 L/p/d)	Farm irrigation water use BKS (m3/a)
1	U10A	45	-22 271	3	-113 530		-362 758	3 813	-39 597	-83 505	0
2	U10B	45	-14 678	13	-122 990		-102 058	4 404	-46 480	-96 448	0
3	U10C	45	-49 936	6	-167 456		-23 171	3 001	-47 861	-65 722	-47 000
4	U10D	45	-131 998	21	-624 413		-292 463	11 732	-142 229	-256 931	-112 000
5	U10E	45	-161 594	19	-179 755		-225 494	24 883	-551 625	-544 938	0
6	U10F	45	-231 762	45	-1 192 061		-261 353	24 881	-412 494	-544 894	0
7	U10G	45	-224 126	12	-788 400		-274 886	6 260	-133 244	-137 094	-296 000
8	U10H	45	-261 825	36	-2 570 184		-215 510	21 505	-313 040	-470 960	-570 000
9	U10J	45	-235 009	67	-1 570 493		-302 134	30 207	-131 369	-661 533	-183 000
10	U10K	45	-203 189	49	-3 358 584		-406 000	11 693	-193 878	-256 077	-252 000
11	U10L	150	-432 956	38	-1 296 130		-193 006	13 830	-158 061	-302 877	0
12	U10M	150	-162 562	39	-879 854		0	42 697	-5 361	-935 064	0
	Total		**-2 131 906**	**348**	**-12 863 850**		**-2 658 834**	**198 906**	**-2 175 240**	**-4 356 041**	**-1 460 000**

Table 4.8: Scenario 2: Groundwater sinks in uMkhomazi catchment continued (table 2 of 2)

No	Quaternary catchment	Average Forestry area EKZN-W SPOT5 (km2)	Average Forestry water use (m3/a)	Average Alien veg (km2)	Alien veg water use BKS (m3/a)	Wetlands BKS (km2)	Wetland water use (m3/a)	No of springs GRIP	Spring flow (m3/a)	Total outflow before losses (sinks) m3/a	Total outflow before losses (sinks) million m3/a
1	U10A	4.7	-879 524	1.4	-375 357	1.40	-350	10	-31 536	-1 908 428	-1.91
2	U10B	22.9	-4 264 048	6.5	-1 463 452	1.30	-326	10	-31 536	-6 142 016	-6.14
3	U10C	20.8	-3 288 214	4.1	-812 143	2.48	-620	8	-25 229	-4 527 352	-4.53
4	U10D	3.2	-415 476	4.5	-868 333	4.30	-1 076	6	-18 922	-2 863 840	-2.86
5	U10E	35.8	-4 820 357	3.7	-656 429	0.82	-206	8	-25 229	-7 165 627	-7.17
6	U10F	54.5	-4 695 952	3.0	-324 048	1.43	-358	6	-18 922	-7 681 843	-7.68
7	U10G	56.7	-5 549 167	2.9	-364 048	1.36	-340	6	-18 922	-7 786 225	-7.79
8	U10H	150.4	-14 348 333	3.7	-408 452	0.98	-246	4	-12 614	-19 171 165	-19.17
9	U10J	143.0	-13 350 952	4.2	-419 405	1.89	-471	8	-25 229	-16 879 596	-16.88
10	U10K	92.7	-6 744 762	4.4	-346 786	2.89	-723	4	-12 614	-11 774 613	-11.77
11	U10L	18.3	-1 235 833	2.7	-154 167	0.12	-29	11	-34 690	-3 807 749	-3.81
12	U10M	1.5	-118 452	2.7	-175 595	0.18	-44	1	-3 154	-2 280 088	-2.28
	Total	**604.4**	**-59 711 071**	**43.8**	**-6 368 214**	**19.2**	**-4 789**	**82**	**-258 595**	**-91 988 541**	**-91.99**

Table 4.9: Scenario 2: Present day GA' included, 95% assured rainfall and recharge

No	Quaternary catchment	Surface Area (km^2)	Total inflow (million m^3/a)	Total outflow before losses (sinks) million m^3/a	Evapo-transpiration flow loss 2 - streams (million m^3/a)	Net groundwater baseflow GYMR (million m^3/a)	Net baseflow measured from monthly MAR (million m^3/a)	Net baseflow required by EWR - Low flow (million m^3/a)	Usable groundwater volume from baseflow 95% assured (million m^3/a)	Usable groundwater volume from baseflow MAP 50% assured (million m^3/a)	GW outflow / GW inflow without ET or EWR accounted	GRDM Present status category
1	U10A	418.2	51.09	-1.91	-0.93	-48.25	48.84	-4.82	**43.42**	62.31	4%	A
2	U10B	392.1	41.11	-6.14	-1.17	-33.80	35.04	-3.38	**30.42**	45.61	15%	B
3	U10C	267.0	25.41	-4.53	-0.88	-20.00	20.64	-2.00	**18.00**	25.63	18%	B
4	U10D	337.0	27.42	-2.86	-1.01	-23.55	21.00	-2.35	**21.19**	30.87	10%	B
5	U10E	327.2	29.95	-7.17	-0.45	-22.33	21.48	-2.23	**20.10**	29.73	24%	C
6	U10F	379.0	23.27	-7.68	-0.94	-14.65	10.92	-1.46	**13.18**	20.72	33%	C
7	U10G	353.1	24.47	-7.79	-1.11	-15.58	14.28	-1.56	**14.02**	21.45	32%	C
8	U10H	457.8	28.25	-19.17	-1.31	-7.78	16.80	-0.78	**7.00**	16.55	68%	E
9	U10J	505.1	27.49	-16.88	-1.41	-9.20	15.84	-0.92	**8.28**	17.87	61%	D
10	U10K	364.4	12.01	-11.77	-1.13	0.90	8.28	-0.09	**-0.99**	3.61	98%	F
11	U10L	307.2	10.82	-3.81	-0.52	-6.49	6.00	-0.65	**5.84**	9.88	35%	C
12	U10M	280.0	16.23	-2.28	-0.78	-13.17	8.16	-1.32	**11.86**	18.08	14%	B
	Total	**4388.1**	**317.5**	**-92.0**	**-11.7**	**-213.9**	**227.3**	**-21.6**	**192.32**	302.3		

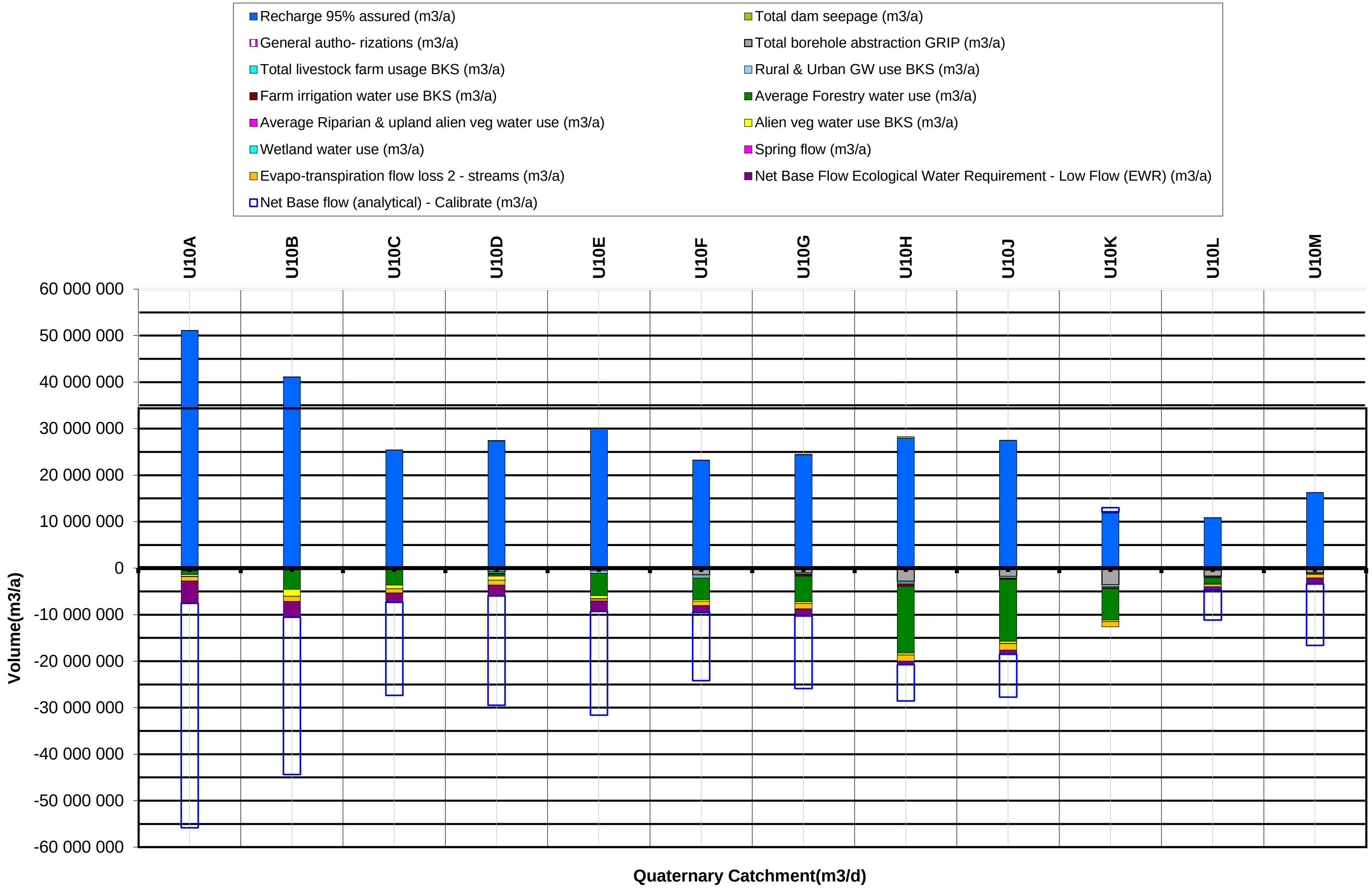

Figure 4.4: Scenario 2 GA's included: Graph indicating GYMR water balance components and volume magnitude

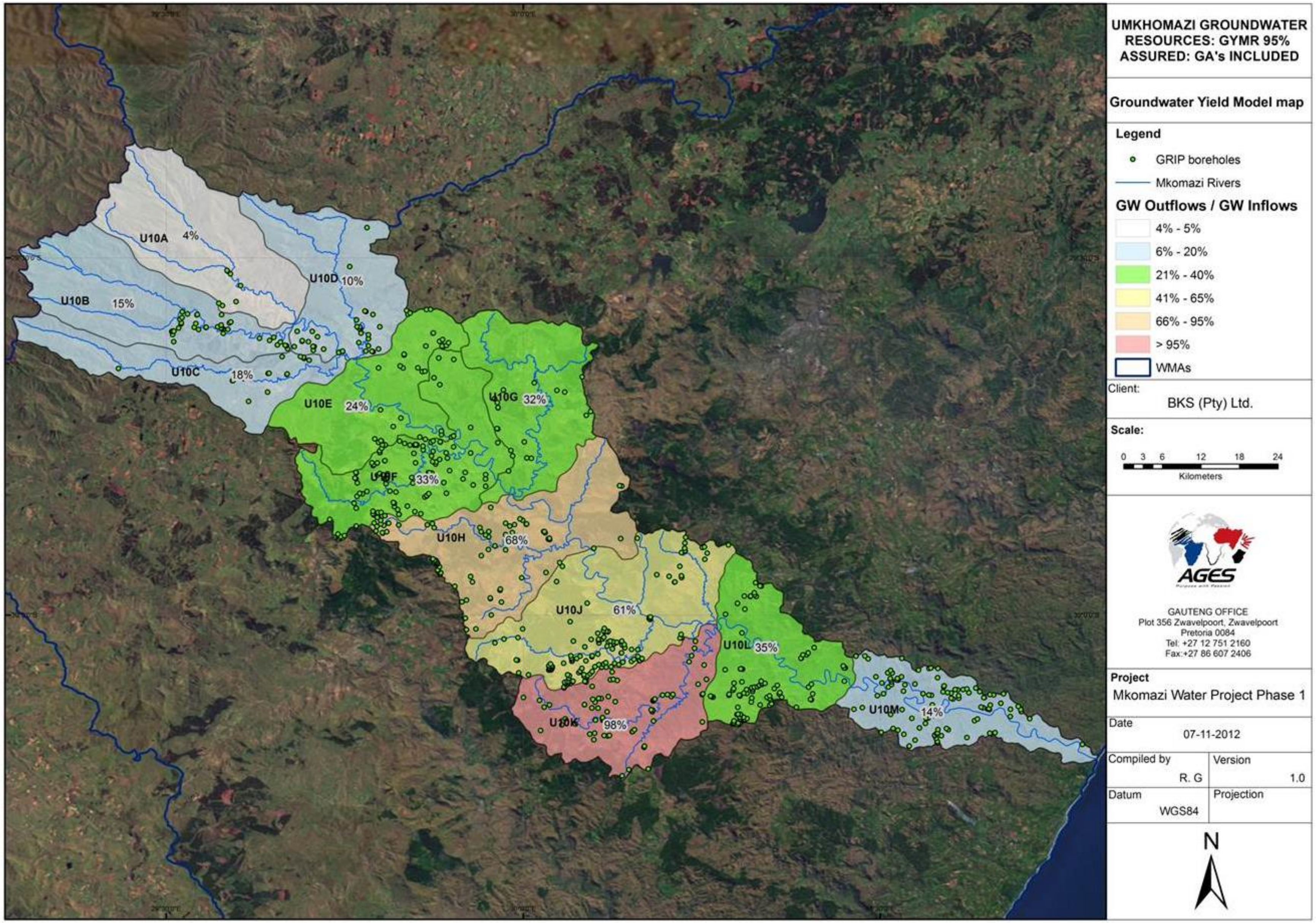

Figure 4.5: Scenario 2: Map showing GYMR steady-state results with GA's included: GW outflow divided by GW inflow

Table 4.10: Scenario 3: Transient GYMR simulation historic rainfall – monthly groundwater baseflows and usable groundwater

MEAN BASEFLOW AND USABLE GROUNDWATER FROM TRANSIENT GYMR SIMULATION																								
Catchment	*October*		*November*		*December*		*January*		*February*		*March*		*April*		*May*		*June*		*July*		*August*		*September*	
	Baseflow	Usable GW$_1$	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1
U10A	6 647 312	5 982 581	9 577 514	8 619 763	12 164 443	10 947 999	12 352 520	11 117 269	10 680 890	9 612 801	6 717 333	6 045 600	2 507 809	2 257 028	1 010 091	909 082	686 595	617 936	1 050 727	945 655	2 070 237	1 863 214	4 117 570	3 705 813
U10B	4 628 230	4 165 407	6 860 096	6 174 086	8 843 769	7 959 392	9 007 034	8 106 330	7 743 833	6 969 450	4 719 065	4 247 159	1 504 607	1 354 146	488 698	439 828	288 516	259 664	520 060	468 054	1 196 343	1 076 709	2 707 108	2 436 398
U10C	2 576 425	2 318 782	3 809 472	3 428 525	4 985 605	4 487 044	5 198 516	4 678 665	4 440 922	3 996 830	2 640 964	2 376 868	773 665	696 299	253 968	228 571	136 914	123 222	251 760	226 584	576 439	518 795	1 416 557	1 274 901
U10D	3 244 174	2 919 756	4 666 288	4 199 659	5 874 197	5 286 777	5 832 553	5 249 298	5 013 923	4 512 531	3 250 739	2 925 665	1 229 932	1 106 939	515 942	464 348	315 245	283 720	436 821	393 138	890 401	801 361	1 895 530	1 705 977
U10E	3 233 191	2 909 872	4 628 518	4 165 667	5 732 105	5 158 895	5 721 049	5 148 944	5 014 936	4 513 443	3 214 825	2 893 342	1 006 280	905 652	350 410	315 369	349 755	314 780	495 711	446 140	781 822	703 640	1 828 514	1 645 662
U10F	2 173 071	1 955 763	3 027 144	2 724 430	3 570 498	3 213 448	3 551 742	3 196 567	3 217 304	2 895 574	2 104 196	1 893 777	550 784	495 705	183 148	164 833	127 382	114 644	127 977	115 180	236 006	212 405	959 003	863 102
U10G	2 095 064	1 885 557	2 921 555	2 629 400	3 403 741	3 063 366	3 254 385	2 928 947	3 030 833	2 727 750	1 950 062	1 755 056	498 888	448 999	202 206	181 985	143 875	129 488	149 806	134 826	286 491	257 842	1 071 365	964 229
U10H	1 291 855	1 162 669	1 967 874	1 771 086	2 557 917	2 302 125	2 615 760	2 354 184	2 530 684	2 277 615	1 462 052	1 315 847	228 870	205 983	82 421	74 179	48 307	43 477	66 278	59 650	147 125	132 413	570 899	513 809
U10J	1 740 203	1 566 183	2 545 300	2 290 770	2 903 716	2 613 345	2 788 635	2 509 772	2 613 056	2 351 751	1 589 969	1 430 972	304 713	274 242	119 104	107 193	99 299	89 369	100 620	90 558	267 391	240 652	790 291	711 262
U10K	108 079	97 271	382 045	343 840	800 806	720 725	800 162	720 146	833 161	749 845	416 398	374 758	55 128	49 615	31 652	28 487	6 001	5 401	0	0	36 814	33 133	52 020	46 818
U10L	1 232 139	1 108 925	1 602 070	1 441 863	1 751 095	1 575 985	1 671 467	1 504 321	1 569 113	1 412 202	1 067 785	961 007	342 705	308 434	140 163	126 147	98 882	88 994	102 329	92 096	258 253	232 428	701 212	631 091
U10M	2 181 956	1 963 760	2 510 026	2 259 023	2 621 434	2 359 291	2 477 655	2 229 889	2 389 056	2 150 150	1 820 430	1 638 387	935 607	842 046	543 189	488 870	414 673	373 206	456 617	410 955	875 374	787 837	1 596 253	1 436 628

95% ASSURED BASEFLOW AND USABLE GROUNDWATER FROM TRANSIENT GYMR SIMULATION																								
Catchment	*October*		*November*		*December*		*January*		*February*		*March*		*April*		*May*		*June*		*July*		*August*		*September*	
	Baseflow	Usable GW	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1	Baseflow	Usable GW^1
U10A	3 375 973	3 038 376	4 755 286	4 279 757	7 391 920	6 652 728	7 811 232	7 030 109	6 744 581	6 070 123	2 915 870	2 624 283	794 930	715 437	0	0	0	0	0	0	101 793	91 613	1 709 502	1 538 552
U10B	2 138 933	1 925 039	3 180 908	2 862 817	5 211 643	4 690 478	5 568 109	5 011 298	4 744 775	4 270 297	1 809 321	1 628 389	185 983	167 385	0	0	0	0	0	0	0	0	861 147	775 032
U10C	1 153 604	1 038 244	2 008 476	1 807 629	3 019 579	2 717 621	3 000 145	2 700 130	2 410 250	2 169 225	1 104 537	994 083	7 825	7 043	0	0	0	0	0	0	0	0	406 661	365 995
U10D	1 771 240	1 594 116	2 503 389	2 253 050	3 712 883	3 341 594	3 488 758	3 139 883	3 092 916	2 783 624	1 388 154	1 249 339	229 046	206 141	0	0	0	0	0	0	0	0	749 384	674 446
U10E	1 795 176	1 615 658	2 470 840	2 223 756	3 443 907	3 099 516	3 344 859	3 010 373	2 992 450	2 693 205	1 311 676	1 180 509	5 756	5 180	0	0	0	0	0	0	0	0	627 398	564 659
U10F	1 025 416	922 875	1 298 678	1 168 810	2 058 236	1 852 413	2 014 843	1 813 358	1 823 932	1 641 539	545 889	491 300	0	0	0	0	0	0	0	0	0	0	0	0
U10G	949 542	854 588	1 451 430	1 306 287	1 950 918	1 755 826	1 680 571	1 512 514	1 540 033	1 386 030	436 520	392 868	0	0	0	0	0	0	0	0	0	0	0	0
U10H	285 301	256 771	542 592	488 333	981 180	883 062	1 098 511	988 660	926 372	833 735	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U10J	50 131	45 118	851 098	765 988	1 255 304	1 129 774	1 067 603	960 843	1 042 951	938 656	5 530	4 977	0	0	0	0	0	0	0	0	0	0	0	0
U10K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U10L	636 239	572 615	761 165	685 049	852 420	767 178	889 439	800 495	814 284	732 855	351 923	316 731	0	0	0	0	0	0	0	0	0	0	0	0
U10M	1 093 104	983 793	1 306 883	1 176 195	1 346 047	1 211 442	1 130 251	1 017 226	1 100 282	990 253	598 354	538 519	7 085	6 376	0	0	0	0	0	0	41 510	37 359	536 126	482 514

All volumes given in m ^{3}

[1] Usable GW refers to the usable component of groundwater (GW) from baseflow after the Ecological Water Requirement (EWR) has been taken into account

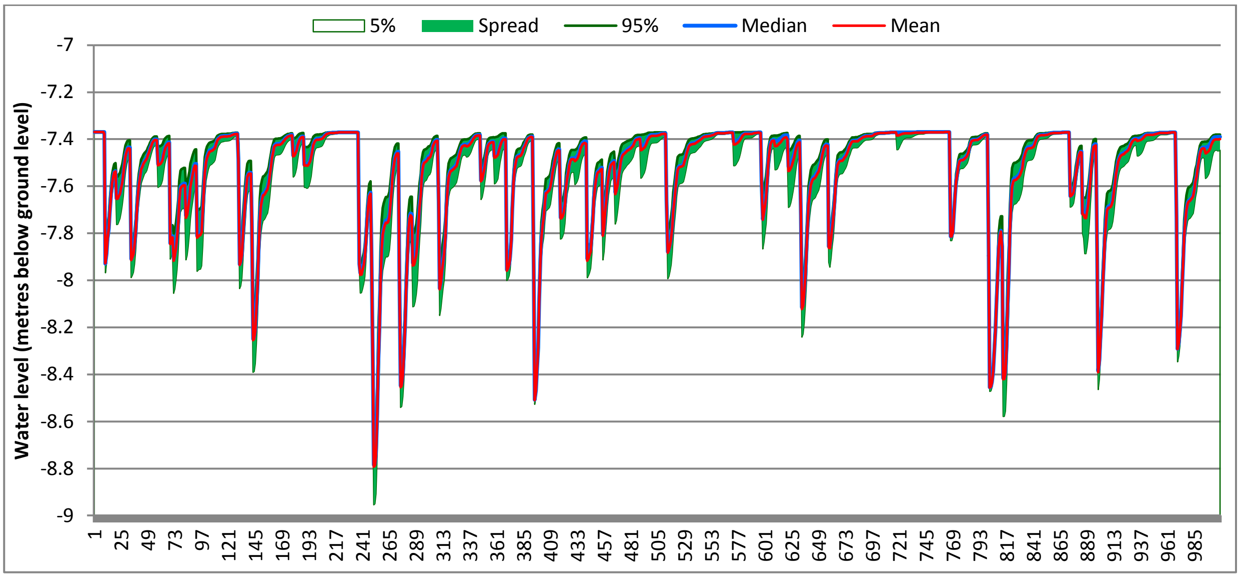

Figure 4.6: U10A Water level from Monte Carlo simulation

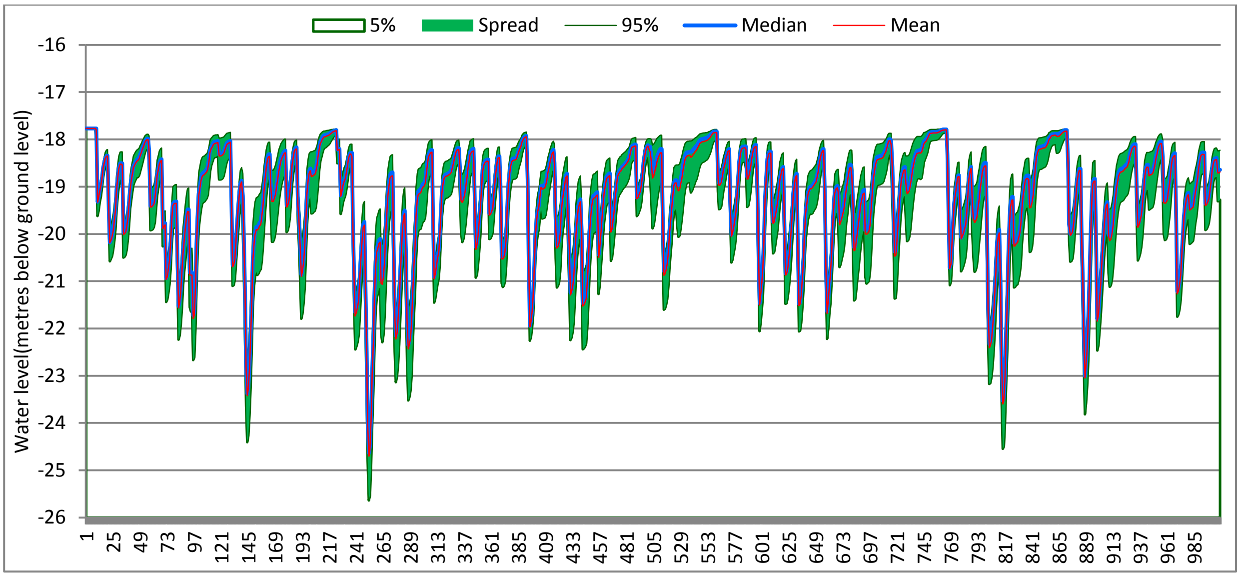

Figure 4.7: U10B Water level from Monte Carlo simulation

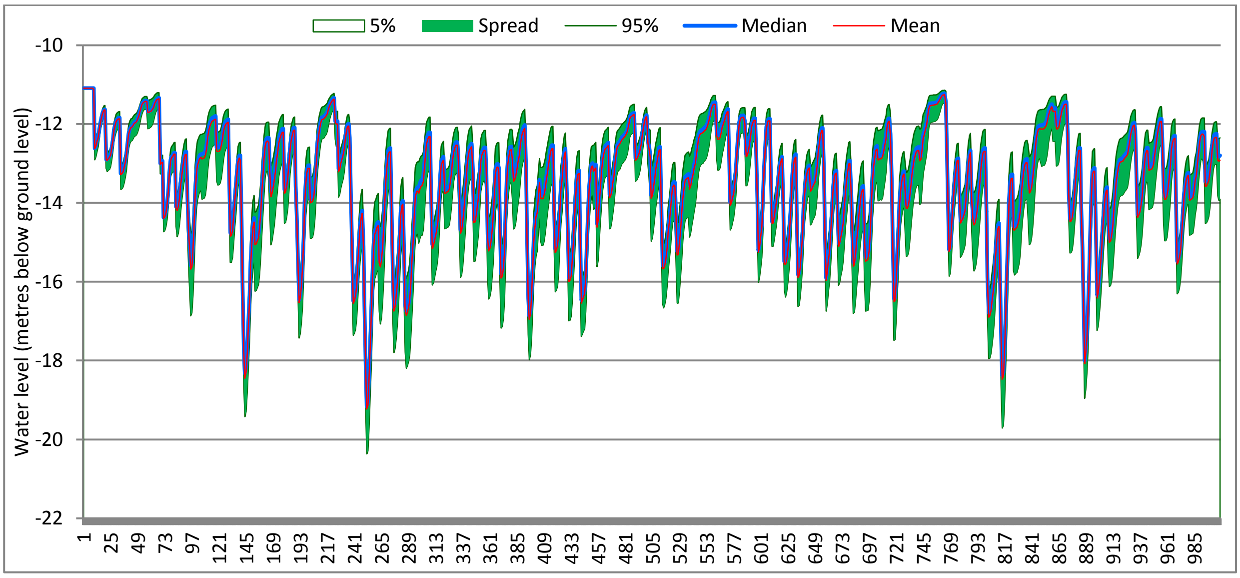

Figure 4.8: U10C Water level from Monte Carlo simulation

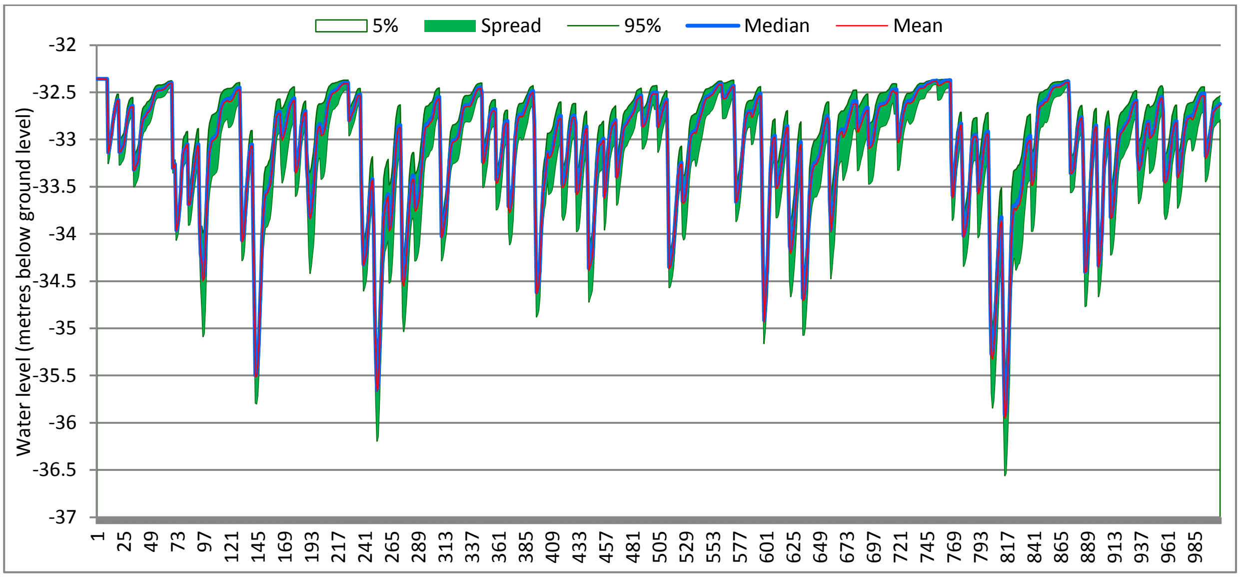

Figure 4.9: U10D Water level from Monte Carlo simulation

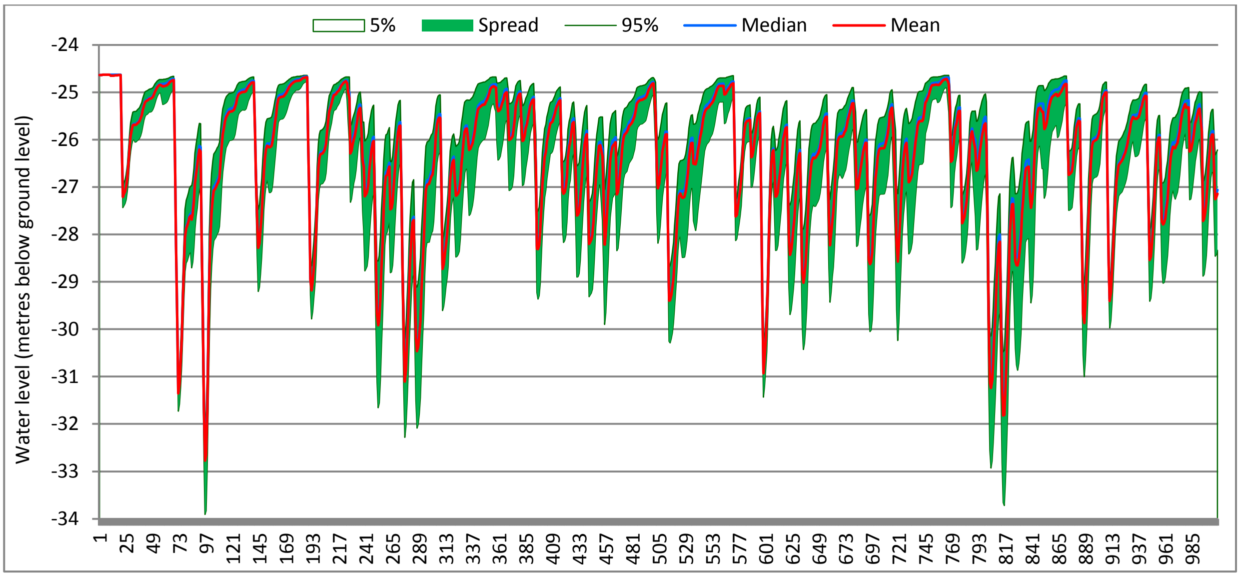

Figure 4.10: U10E Water level from Monte Carlo simulation

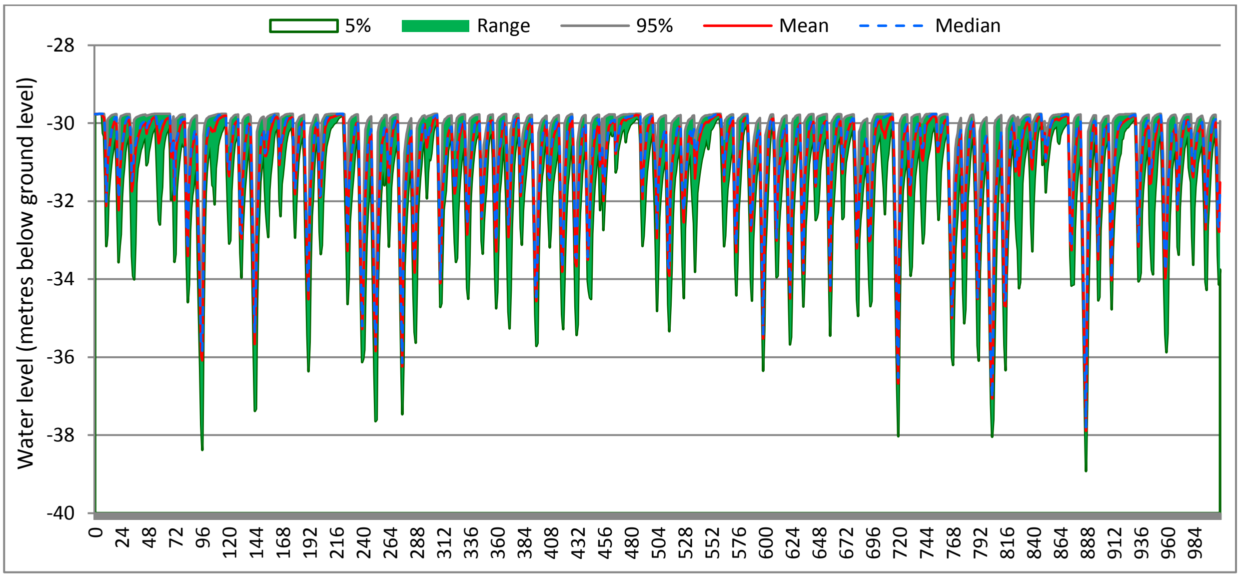

Figure 4.11: U10F Water level from Monte Carlo simulation

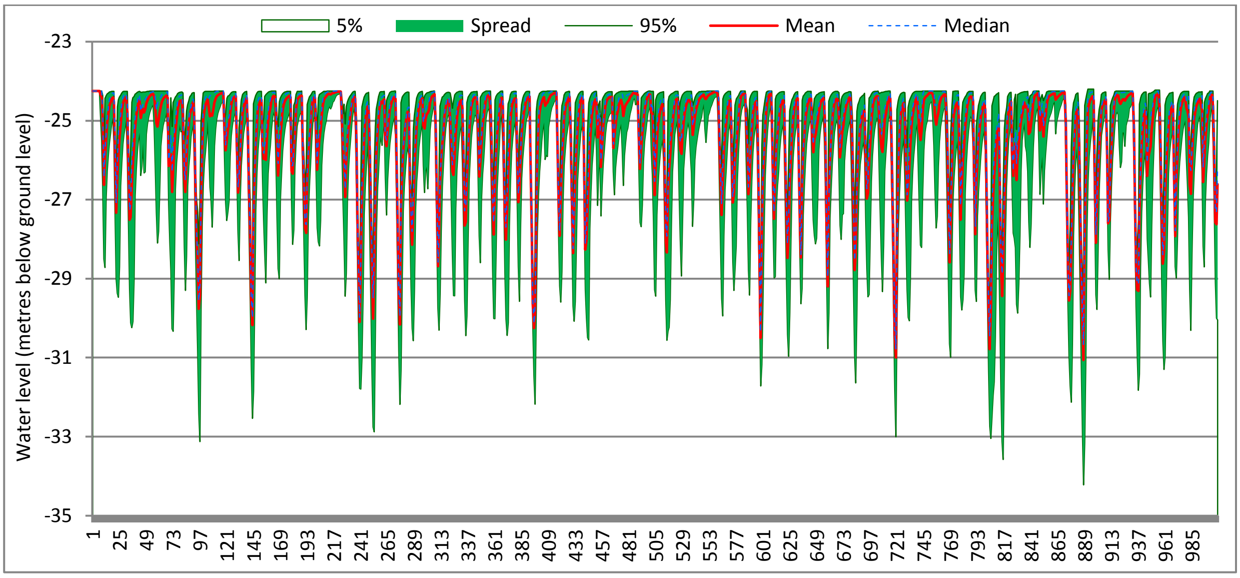

Figure 4.12: U10G Water level from Monte Carlo simulation

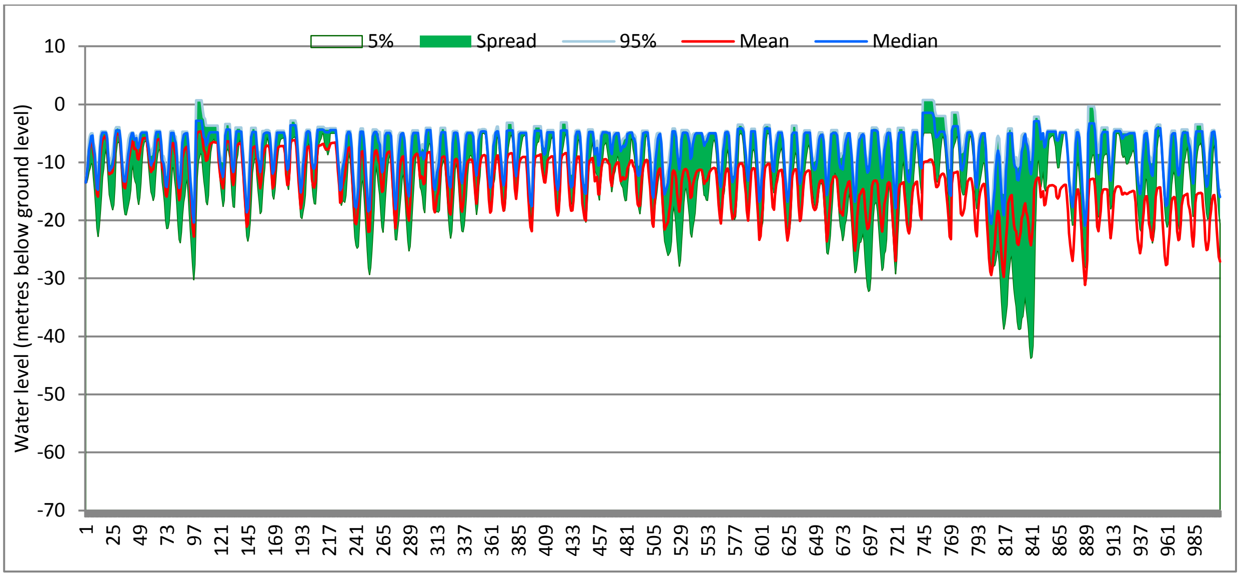

Figure 4.13: U10H Water level from Monte Carlo simulation

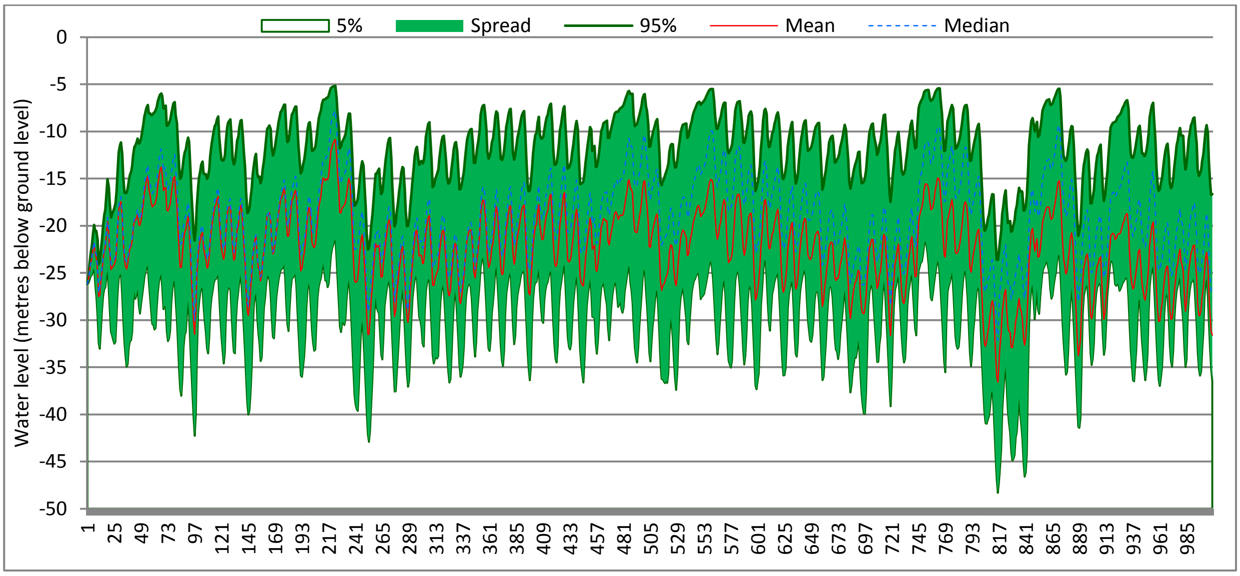

Figure 4.14: U10J Water level from Monte Carlo simulation

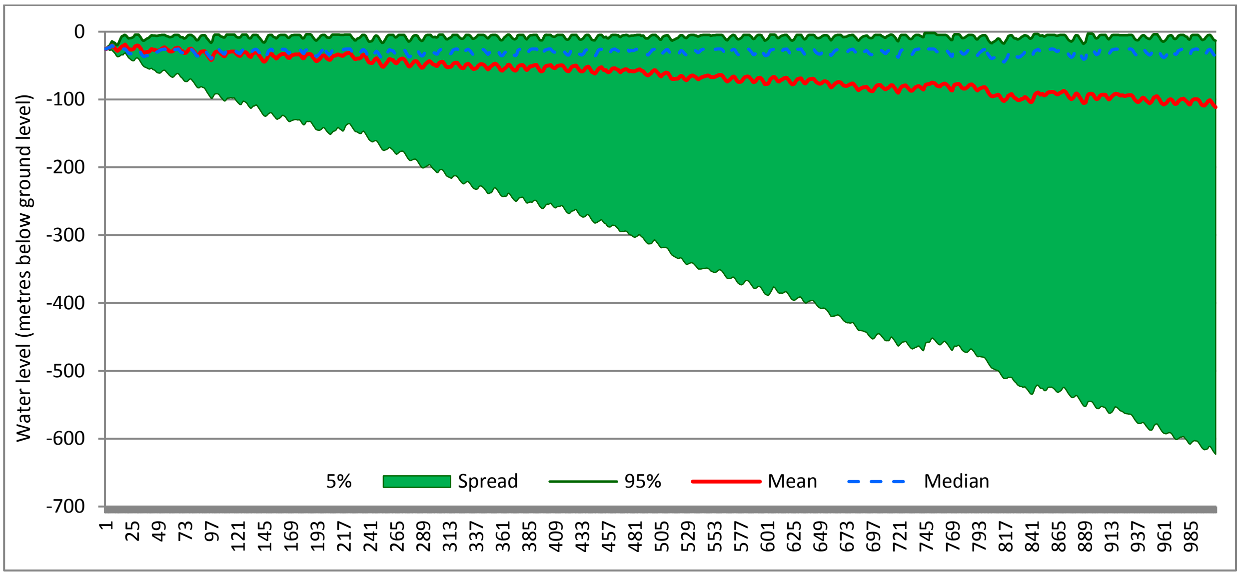

Figure 4.15: U10K Water level from Monte Carlo simulation

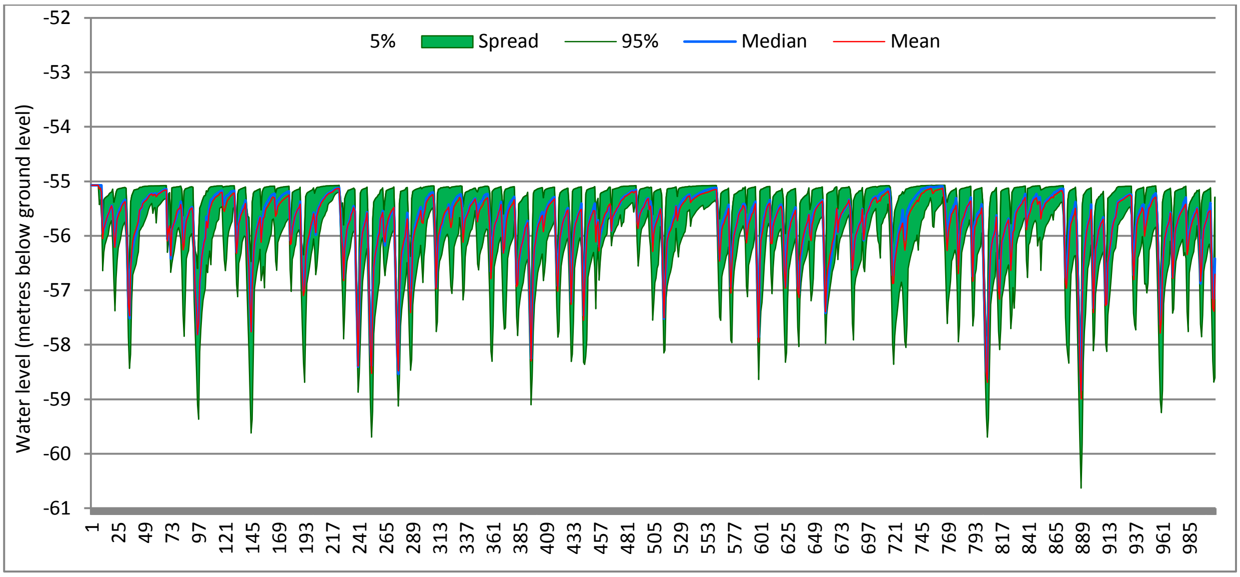

Figure 4.16: U10L Water level from Monte Carlo simulation

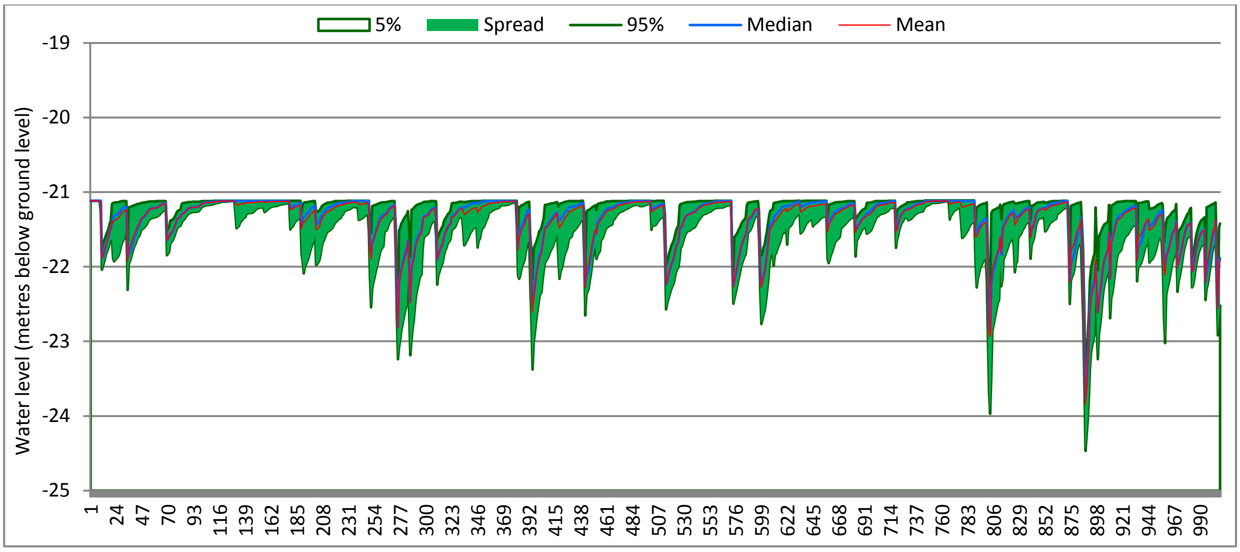

Figure 4.17: U10M Water level from Monte Carlo simulation

4.14 DISCUSSION OF GYMR FLOW BALANCE RESULTS

The groundwater flow balance for quaternary catchments U10A – U10M was successfully simulated using the GYMR model and the following results summarise the minimum groundwater flow balance:

- The quaternary catchments U10A – U10G are the most suited catchments for groundwater development based on volumes available in the GYMR with volumes of groundwater available after evapotranspiration ranging between 43.42 million m^3/a (U10A) and 14.02 million m^3/a (U10F) in steady-state scenarios. Catchments U10A – U10G show a groundwater sink: groundwater source ratio (GRDM stress index) of between 4% to 32% based on a 95% level of assurance;
- Quaternary catchments U10H – U10M show lower potential for groundwater development based on GYMR groundwater volumes available. U10H – U10L have groundwater utilisation indices that range between 61% and 98% and are thus moderately stressed to critical. Volumes of groundwater recharged annually in U10H – U10L range between 7.00 million m^3/a and -0.99 million m^3/a, meaning there is a groundwater deficit in U10K according to the steady-state GYMR model on a 95% level of assurance to account for a 1:20 year drought cycle;
- When the same U10H – U10L catchments were simulated in transient state using the 84 year historic rainfall, the volumes of groundwater available annually in U10H – U10L ranged between 14.43 million m^3/a and 3.31 million m^3/a;
- From **Figure 4.4** and GYMR groundwater users the overall largest groundwater user is forestry with groundwater use ranging between -0.12 and -14.35 million m^3/a, with a total use of -59.71 million m^3/a in the uMkhomazi catchment;
- The groundwater deficit in U10K is in most part due to a significantly lower groundwater recharge percentage as obtained from the GRA2 dataset compared to other catchments as well as the highest existing borehole abstraction based on the GRIP data borehole status and equipment. U10L also has a comparably lower recharge percentage from the GRA2 dataset that was in large part derived from chloride mass balance assessments (Woorford, 2005). Borehole abstractions are assigned per well based on equipment installed with the typical higher yield of the particular equipment assigned rather than its lower yield. This is done to account for boreholes not in the database as well as a conservative approach; if the boreholes are not abstracting as much water, the catchment will have more water rather than less water if incorrectly estimated;

- Catchment U10M is not stressed at a groundwater sink: groundwater source ratio of 12%, but it is already supplied with surface water and it's aquifer water qualities are not good as determined from the desktop study;
- Total groundwater inflows to the UMkhomazi River secondary catchment amount to 317.5 million m^3/a based on 95% assured rainfall;
- Total groundwater outflows before natural losses such as evapotranspiration and baseflow amount to -92.0 million m^3/a. These outflows include all spring outflow as well;
- Spring outflows are expected to be higher in the upper quaternary catchments (U10A – U10G) especially associated with the Karoo Supergroup layering of argillaceous and arenaceous rocks. Springs surveyed during the GRIP hydrocensus are limited and not perceived as representative of the actual number of springs in the catchments. Where a more realistic number of springs were found, these numbers where linearly applied to catchments with similar hydrogeological character that had only a few springs. It is recommended that a satellite imagery spring count be done in the upper UMkhomazi catchments for a given area, that count per area be extrapolated for similar hydrogeology and a follow up field census of the hydrogeological area surveyed be done to confirm satellite survey results;
- Groundwater baseflow is the final outflow out of a groundwater system as well as the GYMR groundwater flow balance. This analytical volume of groundwater baseflow as the final component of the water balance equation was compared to groundwater baseflow values obtained from monthly measured and simulated mean annual runoff (MAR) values, simulated by BKS (2012) for the UMkhomazi Water Project. The 'Net groundwater baseflow GYMR' and the 'Net baseflow measured from monthly MAR' in **Table 4.5** compare well with the exception of catchments U10H – U10K. These are also the catchments that are moderately stressed to critical. If future groundwater development or resource assessments are considered for these catchments, their groundwater balance inflow and outflow components should be more carefully assessed. These components include recharge, borehole abstraction, forestry and daily baseflow records. One or more of these inflow or outflow components are under or overestimated, hence the deviation from measured baseflow in **Table 4.5**. For these catchments, a more focused analysis is required;
- The Instream Flow Requirements (IFR) at this stage is uncertain and 10% of baseflow was assumed and subtracted for the Ecological Water Requirement (EWR) before arriving at the final 'Usable groundwater volume from baseflow 95% assured' volume in **Table 4.5**;
- The amount of groundwater recharged annually and theoretically available for allocation including GA's, basic human need (BHN) Reserve and EWR, based on the 95% level of assurance rainfall is given in **Table 4.5**, in the column 'Usable groundwater volume from baseflow 95% assured'.

5 RECHARGE VOLUMES, AVERAGE GROUNDWATER EXPLOITATION POTENTIAL AND UTILISABLE GROUNDWATER EXPLOITATION POTENTIAL

The usable groundwater volumes available from baseflow from the GYMR groundwater flow balance were compared to the average groundwater exploitation potential (AGEP) and utilisable groundwater exploitation potential (UGEP) of the GRA2 project. The AGEP and UGEP have the unit of m^3/ km²/ a. One of the biggest factors limiting the abstraction of groundwater volumes that are for instance given in the GYMR, is the inability to construct a network of suitably spaced production boreholes to abstract all the groundwater recharged to an aquifer system or regional scale catchment (DWA, 2005). The inability to construct such borehole networks are due to factors such as the low permeability or transmissivity of some aquifer units, aquifer heterogeneity, inaccessibility of some terrain to drilling rigs as well as unknown aquifer boundary conditions (DWA, 2005).

To this end the AGEP takes into consideration the hydrogeologic character of the different formations in South Africa as well as practical problems such as inaccessibility of some terrain to drilling rigs.

It is also recognized that there are often legislative, anthropogenic and ecological considerations that also need to be taken into account during groundwater resource development. The UGEP was also developed during the Groundwater Resource Assessment II (GRA2) project and takes the above mentioned aspects such as the basic human needs Reserve into consideration. Water quality was also taken into consideration in the UGEP.

Spatial queries of the AGEP and UGEP raster layers in ArcGIS where made per quaternary catchment by gauging the percentage surface area coverage of a certain AGEP or UGEP zone of the total quaternary catchment surface area and ensuring that the AGEP or UGEP zones in each quaternary catchment are correctly represented in the calculation of a mean AGEP or UGEP value per quaternary catchment.

Table 5.1 shows how the usable groundwater available from baseflow from the GYMR compares to the Average Groundwater Exploitation Potential (AGEP) and the Utilisable Groundwater Exploitation Potential (UGEP), all in m^3/ km²/a. The column to the right 'Final utilisable groundwater per catchment' provides a conservative estimate of groundwater that will be available in each catchment per km² with higher confidence. There will be more groundwater than is shown in this column, but to abstract it a suitably spaced production borehole network will need to be developed to sustainably abstract the water. **Table 5.2** additionally shows how the GYMR steady-state, transient monte carlo and transient historic rainfall simulations compare to the Utilisable Groundwater Exploitation Potential (UGEP) from the GRA2 project.

Table 5.1: Scenario 2 GYMR groundwater from baseflow, AGEP and UGEP

Quaternary catchment	Surface Area (km²)	Usable GW component from Base Flow assured 95% (m^3/ km²/ a)	Average groundwater exploitation potential (AGEP) (m^3/km²/a)	Utilisable Groundwater Exploitation Potential (UGEP) (m^3/ km²/ a)	Final Utilisable Groundwater per catchment (m^3/ km²/a)	Final Utilisable Groundwater per catchment (Million m^3/a)
U10A	418.2	103 894	51 839	46 147	46 147	19.30
U10B	392.1	77 613	42 848	39 398	39 398	15.45
U10C	267.0	67 590	37 921	33 030	33 030	8.82
U10D	337.0	63 231	35 932	31 013	31 013	10.45
U10E	327.2	61 873	39 568	36 441	36 441	11.92
U10F	379.0	35 336	30 855	27 628	27 628	10.47
U10G	353.1	40 274	33 239	29 352	29 352	10.37
U10H	457.8	15 801	30 633	26 747	15 801	7.23
U10J	505.1	16 808	24 337	20 855	16 808	8.49
U10K	364.4	-2 094	14 035	11 836	-2 094	-0.76
U10L	307.2	20 292	12 528	9 847	9 847	3.03
U10M	280.0	42 858	18 203	19 101	19 101	5.35
Total	**4388.1**	**543 476**	**371 939**	**331 395**	**302 473**	**110.11**

Table 5.2: Comparison of transient GYMR simulation results to steady-state GYMR and GRA2 values

Catchment	Surface Area (km^2)	GYMR steady-state calibration				GYMR transient Monte Carlo: 1000 realisations				GYMR transient Historic Rainfall simulation (monthly)				Annual GYMR transient historical rainfall figures compared to GRA2 Utilisable GW Exploitation potential (UGEP) (m^3/a)				
		MAP Baseflow (m^3/month)	95% assured Baseflow (m^3/month)	GYMR MAP usable GW (m^3/month)	95% assured usable GW (m^3/month)	Mean - Optimized Baseflow (m^3/month)	95% Assured Baseflow (m^3/month)	Mean - Optimized usable GW (m^3/month)	95% Assured usable GW (m^3/month)	Mean -Baseflow (m^3/month)	95% Assured Baseflow (m^3/month)	Mean Usable GW (m^3/month)	95% Assured Usable GW (m^3/month)	Mean - Baseflow (m^3/a)	95% Assured Baseflow (m^3/a)	Mean Usable GW (m^3/a)	95% assured Usable GW (m^3/a)	Utilisable Groundwater Exploitation Potential (UGEP) (m^3/ a)
U10A	418	5 596 103	4 022 583	5 036 492	3 620 325	5 798 592	4 877 824	5 218 733	4 390 042	5 798 587	2 966 757	5 218 728	2 670 081	69 583 042	35 601 085	62 624 738	32 040 977	19 296 590
U10B	392	4 083 566	2 817 726	3 675 209	2 535 953	4 042 353	3 239 130	3 638 118	2 915 217	4 042 280	1 975 068	3 638 052	1 777 561	48 507 359	23 700 819	43 656 623	21 330 737	15 447 747
U10C	267	2 306 374	1 670 768	2 075 736	1 503 691	2 255 087	1 837 895	2 029 578	1 654 106	2 255 101	1 092 590	2 029 591	983 331	27 061 207	13 111 077	24 355 086	11 799 969	8 817 955
U10D	337	2 779 306	1 973 132	2 501 375	1 775 819	2 763 613	2 258 634	2 487 251	2 032 771	2 763 812	1 411 314	2 487 431	1 270 183	33 165 744	16 935 770	29 849 170	15 242 193	10 451 986
U10E	327	2 676 778	1 874 366	2 409 100	1 686 929	2 696 486	2 136 397	2 426 837	1 922 757	2 696 426	1 332 672	2 426 784	1 199 405	32 357 117	15 992 062	29 121 405	14 392 855	11 922 638
U10F	379	1 867 847	1 240 046	1 681 062	1 116 041	1 652 340	822 057	1 487 106	739 851	1 652 355	730 583	1 487 119	657 525	19 828 255	8 766 993	17 845 429	7 890 294	10 470 930
U10G	353	1 935 703	1 316 846	1 742 132	1 185 162	1 584 047	548 906	1 425 643	494 016	1 584 023	667 418	1 425 620	600 676	19 008 271	8 009 015	17 107 444	7 208 114	10 365 235
U10H	458	1 465 389	669 809	1 318 850	602 828	1 136 550	221 761	1 022 895	199 585	1 130 837	319 496	1 017 753	287 547	13 570 041	3 833 956	12 213 037	3 450 561	12 245 013
U10J	505	1 585 005	786 070	1 426 505	707 463	1 323 730	316 425	1 191 357	284 782	1 321 858	356 051	1 189 672	320 446	15 862 297	4 272 617	14 276 068	3 845 355	10 533 702
U10K	364	310 499	-57 795	279 449	-63 574	320 626	0	288 563	0	293 522	0	264 170	0	3 522 267	0	3 170 040	0	4 312 880
U10L	307	913 811	577 198	822 430	519 479	878 065	388 350	790 258	349 515	878 101	358 789	790 291	322 910	10 537 213	4 305 470	9 483 492	3 874 923	3 025 040
U10M	280	1 629 846	1 111 248	1 466 861	1 000 123	1 568 513	1 001 356	1 411 661	901 220	1 568 523	596 637	1 411 670	536 973	18 822 271	7 159 642	16 940 044	6 443 677	5 348 685

6 GROUNDWATER AND SURFACE WATER

6.1 INTRODUCTION

Given that most of the ideal locations for surface water dams have been used in South Africa, groundwater resources are increasingly being used for potable water supply. There are however some challenges that accompany the sole use of groundwater in large water supply schemes such as the uMkhomazi Water Project.

6.2 BULK WATER DEMAND

Groundwater is the ideal water resource for rural water supply and water supply to small isolated towns and scattered villages, as found in the Eastern Cape. Sustainable groundwater sources such as perennial springs where present are also good sources of potable water supply to small villages at higher elevations and steep slopes in mountainous areas.

The most challenging aspect of using groundwater for the total water supply of the uMkhomazi water supply project is the total demand of 220 million m^3/a. This equates to ±6 976 ℓ/s. It is unlikely that groundwater can supply such a large volume without have an immense network of successfully sited boreholes at high density across the whole study area. Extensive pipeline networks to the different boreholes are required and this also places a large burden on the maintenance of such schemes.

6.3 RECHARGE, BOREHOLE YIELD AND SPACING

Aquifers are continually filled/ recharged from rainfall as surface water dams are continually filled from direct precipitation and runoff from rainfall. Another challenge in groundwater is the inability to construct an adequately spaced production borehole network to abstract all the groundwater recharged to an aquifer. This is largely due to factors such as the low permeability or transmissivity of some aquifer units, aquifer heterogeneity, inaccessibility of some terrain to drilling rigs as well as unknown aquifer boundary conditions (DWA, 2005).

The total recharge based on a lower 95 % assurance is 316 million m^3/a. A yield of 220 million m^3/a would represent 70% of recharge, which is a very high abstraction ratio. Apart from this, the borehole yields are very low at ±1 ℓ/s, which would require +6 900 boreholes across the uMkhomazi catchment area. This would be a physically impractical task, taking the piping and electrical reticulation into account. It would require a borehole drilled every 800 m if it would be done on a grid, which given the limits imposed by the topography would be impossible.

6.4 CONJUNCTIVE USE

Conjunctive use is recommended where groundwater is developed along surface water infra-structure to supplement surface water and for rural water supply.

7 CONCLUSIONS

1. Existing data was evaluated for the desktop study phase and the data available was found to be adequate to perform the desktop study components as well as use in the analytical groundwater flow balance modelling. BKS (2012) supplied AGES with good spatial and temporal water requirements- and water user-data and this data was processed and used in the GYMR groundwater flow balance modelling. One component where data was perceived as perhaps too coarse was MAR data that was only available on a monthly time step. For the level of hydrological study currently conducted this is however the adequate level of detail. This data was used to obtain a rough estimate of groundwater baseflow;

2. The Groundwater Yield Model for the Reserve (GYMR) groundwater flow balance model was used to successfully simulate 3 scenarios for the 12 quaternary catchments involved. Two scenarios were set up in steady state were Scenario 1 – Present day, GA's excluded based on 95% assured rainfall and Scenario 2 – Present day, GA's included based on 95% assured rainfall. A combined transient (historic rainfall change over time) and Monte Carlo simulation of the GYMR was also run for each catchment as a third scenario on a monthly basis;

3. The quaternary catchments U10A – U10G are the most suited catchments for groundwater development based on volumes available in the GYMR with volumes of groundwater available after evapotranspiration ranging between 43.42 million m^3/a (U10A) and 14.02 million m^3/a (U10F) in steady-state scenarios. Catchments U10A – U10G show a groundwater sink: groundwater source ratio (GRDM stress index) of between 4% to 32% based on a 95% level of assurance;

4. Quaternary catchments U10H – U10M show lower potential for groundwater development based on GYMR groundwater volumes available. U10H – U10L have groundwater utilisation indices that range between 61% and 98% and are thus moderately stressed to critical. Volumes of groundwater recharged annually in U10H – U10L range between 7.00 million m^3/a and -0.99 million m^3/a, meaning there is a groundwater deficit in U10K according to the steady-state GYMR model on a 95% level of assurance to account for a 1:20 year drought cycle;

5. When the same U10H – U10L catchments were simulated in transient state using the 84 year historic rainfall, the volumes of groundwater available

annually in U10H – U10L ranged between 14.43 million m^3/a and 3.31 million m^3/a, and no deficit in U10K occurs;

6. **Table 4.10** shows Scenario 3 monthly simulated baseflow and usable groundwater for natural historic rainfall conditions as well as 95% assured monthly volumes;

7. The groundwater deficit in U10K under 95% assured conditions is in most part due to a significantly lower groundwater recharge % as obtained from the GRA2 dataset as well as the highest existing borehole abstraction based on the GRIP data borehole status and equipment. U10L has compared to other catchments, a lower recharge % from the GRA2 dataset that was in large part derived from chloride mass balance assessments (Woorford, 2005). Borehole abstractions are assigned per well based on equipment installed with the typical higher yield of the particular equipment assigned rather than its lower yield. This is done to account for boreholes not in the database as well as a conservative approach; if the boreholes are not abstracting as much water, the catchment will have more water rather than less water available if incorrectly estimated;

8. From **Figure 4.4** and GYMR groundwater users the overall largest groundwater user is forestry with groundwater use ranging between -0.12 and -14.35 million m^3/a, with a total use of -59.71 million m^3/a in the uMkhomazi catchment;

9. From the measured monthly baseflow volumes that were simulated and patched again by BKS (2012), there is appreciable baseflow to drainages in each quaternary catchment. Baseflow from groundwater is highest in the upper quaternary catchments of the uMkhomazi River catchment and depreciates moving downstream towards the coast. The GYMR groundwater flow balance assessment would however indicate that a losing river system is present in U10K and a groundwater deficit. Recharge in this catchment is comparably low and it also has the highest existing borehole abstraction that was estimated to the high end. The simulated and measured baseflow values obtained from the simulated MAR data are regarded as more representative. This indicates that groundwater plays a large role in sustaining the rivers during winter time and thus the groundwater-surface water interaction is more of a one way movement of groundwater to contribute to surface water. This also implies that a good follow up hydrocensus be done around the uMkhomazi River in order to survey and better quantify groundwater abstraction that could turn the uMkhomazi River system from a gaining river system to a losing river system, especially in the presence of alluvial bank storage aquifers;

10. The usable groundwater volumes available from baseflow as determined by the GYMR were compared to the Average Groundwater Exploitation Potential (AGEP) and the Utilisable Groundwater Exploitation Potential (UGEP) of the GRA2 project. Both the AGEP and UGEP take other practical considerations for groundwater abstraction into account such as terrain accessibility, hydraulic limitations of aquifers and feasibility of borehole networks. The comparison is detailed in **Table 5.1** as well as **final** conservative groundwater volumes available in $m^3/km^2/a$ per quaternary catchment. These values are also provided in million m^3/a per catchment. It should be noted that these volumes of groundwater are regarded as a minimum per quaternary catchment and more groundwater should be available.

8 RECOMMENDATIONS

1. Spring protection measures should be implemented in the upper catchments due to the high number of spring occurrences there. These springs already supply water for domestic use and spring protection measures will ensure their sustainability and quality;

2. Based on the results from GYMR modelling, it is recommended that if large scale groundwater development is considered for catchments U10H, U10J, U10K, U10L, that a more thorough evaluation of the groundwater inflow and outflow components be performed there. These catchments show moderate to critical groundwater stress based on the desktop level groundwater flow balance using the GYMR method;

3. Although it is very good to see full macro element type analysis in the KwaZulu Natal GRIP database, it is recommended that future groundwater quality monitoring or groundwater investigations also focus their hydrocensus survey toward sampling boreholes that are in use, aquifer tested or purged and thus represent the aquifer water quality. High iron concentrations were encountered in many samples and it is expected that that these are a result of unused boreholes with rusted casings that are sampled. It is also critical that as much groundwater quality information per relevant geosite be uploaded to the KwaZulu Natal GRIP database, to make an already successful project more successful;

4. Spring outflows are expected to be higher in the upper quaternary catchments (U10A – U10G) especially associated with the Karoo Supergroup layering of argillaceous and arenaceous rocks. Springs surveyed during the GRIP hydrocensus are limited and not perceived as representative of the actual number of springs in the catchments. Where a more realistic number of springs were found, these numbers were linearly applied to catchments with similar hydrogeological character that had only a few springs. It is recommended that a satellite imagery spring count be done in the upper UMkhomazi catchments for a given area, that count per area be extrapolated for similar hydrogeology and a follow up field spot check of the hydrogeological area surveyed be done to confirm satellite survey results;

5. If not already done it is recommended that the Instream Flow Requirements (IFR) be determined for the UMkhomazi River catchment so that the volume of water required from baseflow for the EWR is better known.

9 ACKNOWLEDGEMENTS

AGES would like to thank BKS for sharing their hydrology results and calculated water requirements with the groundwater project team. Without this data, the groundwater resources sub-task would have taken considerably longer due to the independent sourcing and processing of water requirement data.

10 REFERENCES

AGES. 2010. Resource Directed Measures: Reserve Determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua (Knysna and Swartvlei) catchment. Groundwater RDM Report. Pretoria: AGES.

AGES. 2010. Intermediate Reserve Determination Study for the Integrated Vaal River System: Lower Vaal Water Management Area Groundwater Component. Pretoria: AGES.

BKS. 2011. The uMkomazi Water Project Phase 1: Module 1: Technical Feasibility Study: Raw Water – W0259: Inception report. 59 p

BKS. 2012. The uMkhomazi Water Project Phase 1: Module 1: Technical Feasibility Study Raw Water - Water Requirements and Return Flows report. P WMA 11/U10/00/3312/3.

DEPARTMENT OF WATER AFFAIRS. 2005. Groundwater Resource Assessment Phase II. Pretoria: State printer.

DEPARTMENT OF WATER AFFAIRS. 2010. The Mkomazi Water Project Phase 1: Module 1: Technical Feasibility Study: Raw water – Terms of reference. Pretoria: government printer. 61 p.

DUNCAN, A. R. & MARSH, J. S. 2006. The Karoo Igneous Province. In: JOHNSON, M. R., ed., ANHAEUSSER, C. R., ed. & THOMAS, R. J. ed. 2006. The Geology of South Africa. Johannesburg: Geological Society of South Africa/ Pretoria: Council for Geoscience. 501 – 520 p.

GEOTERRAIMAGE. 2010. 2008 KZN Province Land-cover mapping: Data users and metadata report for Ezemvelo KZN Wildlife (Biodiversity Research). 31 p.

KING, G. M. 2002. An explanation of the 1: 500 000 general Hydrogeological map: Durban 2928. Pretoria: Department of Water Affairs and Forestry. 37 p.

WOODFORD, A. C., ed., CHEVALLIER, L., ed., BOTHA, J. F., COLE, D., JOHNSON, M. R., MEYER, R., SIMONIC, M., VAN TONDER, G. J. & VERHAGEN, B. TH. 2002. *Hydrogeology of the Main Karoo Basin: Current Knowledge and Future Research Needs.* WRC report, TT 179/02. Gezina: WRC Printer. 466 p.

Appendix A

Groundwater Yield Model for the Reserve (GYMR) methodology

1. Introduction

This section was taken from report no. RDM/K000/02/CON/0507, Reserve determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua catchment: Technical Component – Knysna and Swartvlei, K. Vivier, 2009

The basic approach and model were developed since the Olifants River Water Resources Development Project: Groundwater Study Task (ORWRDP) (AGES, 2005). It was required to evaluate the groundwater potential of selected regional aquifers on a quaternary catchment scale. The normal approach to these assessments is to develop either numerical groundwater flow models or analytical water balance models. It was found that it is impractical to e.g. develop 114 numerical models for the Olifants River Water management Area (WMA) and obtain groundwater flow balances with assurance levels. A methodology and quantification model was developed that could address the groundwater management problem.

The outcome of the investigation was to provide assurance levels for the groundwater that is available on a quaternary catchment scale. In catchments where the inflow far exceeds the outflow (if losses are accounted for), the regional scale groundwater flow balance model provides sufficient information to allocate groundwater quantities. The model output is used to classify potentially (and not actual) stressed or sensitive catchments by accounting for all important inflow and outflow components, which includes losses. Through this process, catchments are identified, for which more detailed studies are required.

2. Methodology

A model was developed termed the GYM that could be used to determine the groundwater balances on a number of quaternary catchments while accounting for variable recharge from rainfall. The variability in rainfall-recharge, aquifer storage and evapo-transpiration potential was identified as one of the factors that influence sustainability of groundwater supply.

The purpose of the model is based on given assumptions, to simulate groundwater flow balances on a regional (primary) catchment scale with quaternary sub-catchment scale resolution, on annual or monthly time steps. The output provide statistical changes in groundwater volume based on rainfall recharge variations, which yields assurance levels for groundwater volumes.

The model was developed to simulate each catchment as a cell. Inflow and outflow components are calculated that must balance between time steps.

3. The groundwater flow balance under steady-state conditions

In a groundwater system that is used as a management unit, surface water drainages or rivers act as linear drains for groundwater seepage (**Figure 10.1**). The volume of groundwater contributing to the flow in rivers is termed the groundwater component of base flow. Base flow consists of both the groundwater component of base flow and a surface water component. The groundwater component of base flow can therefore not be more than base flow. Base flow is important to streams during low flow conditions, during which groundwater acts as a store and release mechanism.

In natural steady-state conditions, the net groundwater inflow from recharge is balanced by base flow (including spring flow if springs exist). In areas where springs exist, it usually supports downstream wetlands that are of environmental significance.

In its basic form, the groundwater flow balance is given by $+Q_r - Q_{GETL} - Q_{BF} = 0$, where;

$+Q_r$ = Recharge from rainfall
Q_{GETL} = Groundwater flow (evapo-transpiration) losses
$-Q_{BF}$ = Base and spring flow

Spring flow and the groundwater component of base flow are associated with evaporation and transpiration losses that will be discussed later.

The piezometric gradient, which can be measured from site characterization and monitoring boreholes are usually known. Boreholes can be pump tested to determine the transmissivity and hydraulic conductivity (**Figure 10.1**).

The outflow per unit length (L) of aquifer is given by Darcy’s law as,

$q = (K\ ^{dh}/_{dl}) \times D$, (1) where

q is the Darcy flux in m/d (or $m^3/m^2/d$), K is the hydraulic conductivity, D the aquifer thickness and $^{dh}/_{dl}$ the piezometric gradient.

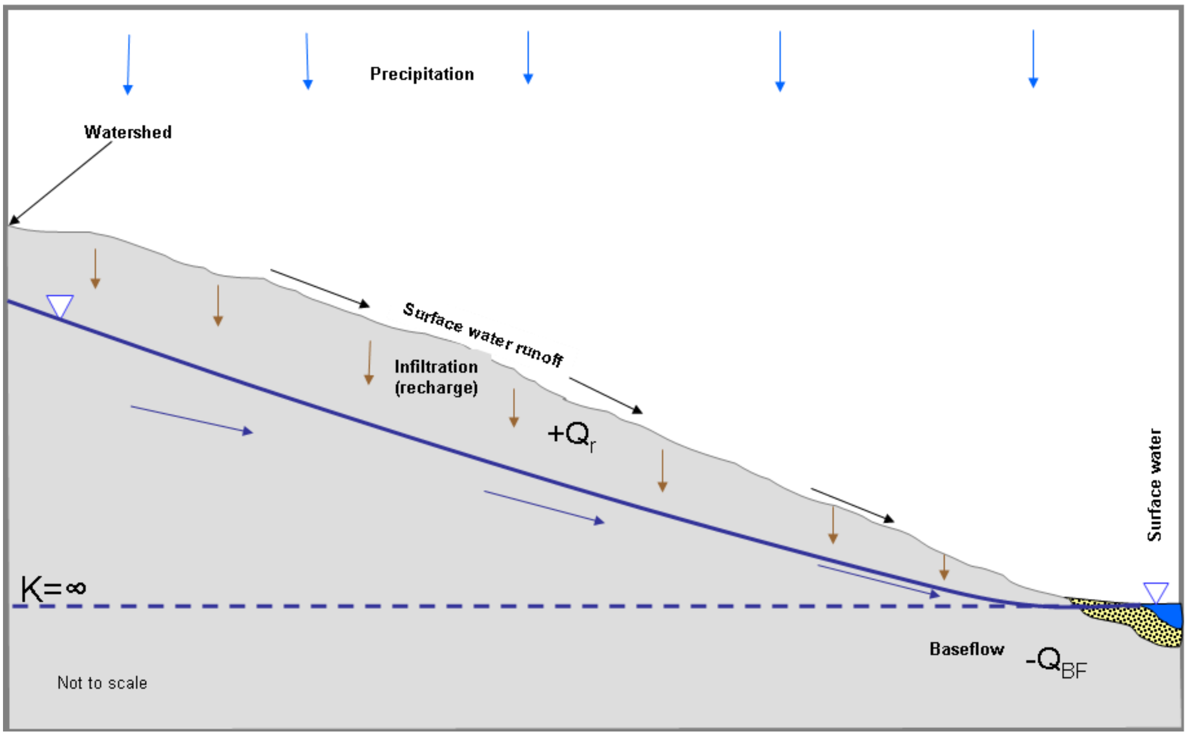

Figure 10.1: Geohydrological steady-state conditions

Since K, D and the head gradient can be measured, a steady-state model can be calibrated by changing the recharge value until the measured and simulated head gradients have a small (or acceptable) error. An acceptable error is usually considered as less than 10 % of the aquifer thickness. If the aquifer is for example 40 m thick, then an error of less than 4 m between the measured and simulated head elevations would be considered as acceptable.

A perfectly flat natural head gradient of 0, would imply an infinite hydraulic conductivity (**Figure 10.1**).

4. Transient flow and evaluation of groundwater storage volume buffering capacity during dry periods to provide assurance levels

The groundwater flow balance described in the previous section, can be differentiated in additional basic inflow and outflow components and into e.g. annual or monthly time steps.

The regional, quaternary catchment scale GYM was developed on this basis. The purpose is that it must be able to simulate groundwater volume availability based on assurance levels (typically 95%) through a large number of the sub-catchments. In the model, an aquifer was defined as its surface water quaternary catchment equivalent, which would form one cell in the system.

The output of the model should be able to account for the duration of variable rainfall-recharge periods obtained from statistical simulations based on historical rainfall records. It is therefore important to be able to evaluate the ability of the groundwater reservoir to buffer low recharge periods that are characterized by dry cycles (**Figure 10.2**). Stochastic generations of the monthly average rainfall-recharge and the standard deviation were used to determine inflow and accounting for outflow, it was used to evaluate the aquifer’s ability to sustain supply. The output was then used to calculate the water balance of each quaternary catchment at a 95 % assurance level.

The GYM model was adapted in 2007 and 2008 to account for the components that would be required for the groundwater reserve. The adapted version is known as the Groundwater Yield Model for the Reserve (GYMR).

4.1. Groundwater management constraint

The concept of a groundwater management constraint (GMC), which is similar to the surface water concept of a Dead Storage Level (DSL) was obtained from the management of surface water dams. The GMC is defined as the minimum level or management constraint to sustain the environment. The volume of the aquifer below that level, is not considered as available for supply. This constraint is often selected by the groundwater specialist performing the assessment.

This concept was applied on all aquifers as a minimum level management constraint. As a guideline, 10% to 20% of the saturated thickness of the aquifer was used as the GMC level. If an aquifer is for example 50 m thick, then 5 m to 10 m available drawdown over the entire area was used as the GMC level (**Figure 10.3**).

In practice, there should be a relationship between the volume in storage (equated to the saturated thickness) of an aquifer and the variability in rainfall-recharge (**Figure 10.2 – Figure 10.3**).

4.2. Assumptions

The following assumptions were made:

- In natural steady-state conditions, the recharge equals groundwater base flow minus losses (e.g. evapo-transpiration).
- Any abstraction would result in eventual reductions in groundwater base flow. This approach is conservative, since in reality there would be a time lag, which is longer for distances further away from the base flow or decant point. Under the approach that the model outcomes should be sustainable and to be used in Water Use License applications, this assumption is considered defendable.
- Interaction with surface streams (i.e. base flow) was considered as a net outflow. Inflow from surface water streams was shown as positive groundwater base flow, which indicates a severe depletion in groundwater storage.
- The model considers shallow aquifers (0-100 m). Deep groundwater inflow or outflow is not considered as information or evidence of these processes is not available or readily understood. It is assumed that inflow and outflow from deep groundwater balances.

The conservative assumptions used in the model will yield less water than in the actual case. This approach is in line with the environmental precautionary principle. The aim is not to determine actual groundwater flow balances as it is today, but rather to determine management scenarios that can be used for regulatory requirements and decision making.

4.3. Conceptual model

The conceptual groundwater flow model on which the analytical model was based, is shown in **Figure 10.5**. The inflow from groundwater recharge is balanced by outflow to springs, wetlands and groundwater base flow to rivers or streams under natural conditions. In areas where the recharge to evapo-transpiration ratio is low, most or all of the groundwater could be lost with the result that the streambed is dry (**Figure 10.5**).

Where anthropogenic influences occur, other losses occur such as boreholes, riparian vegetation and mine dewatering were included.

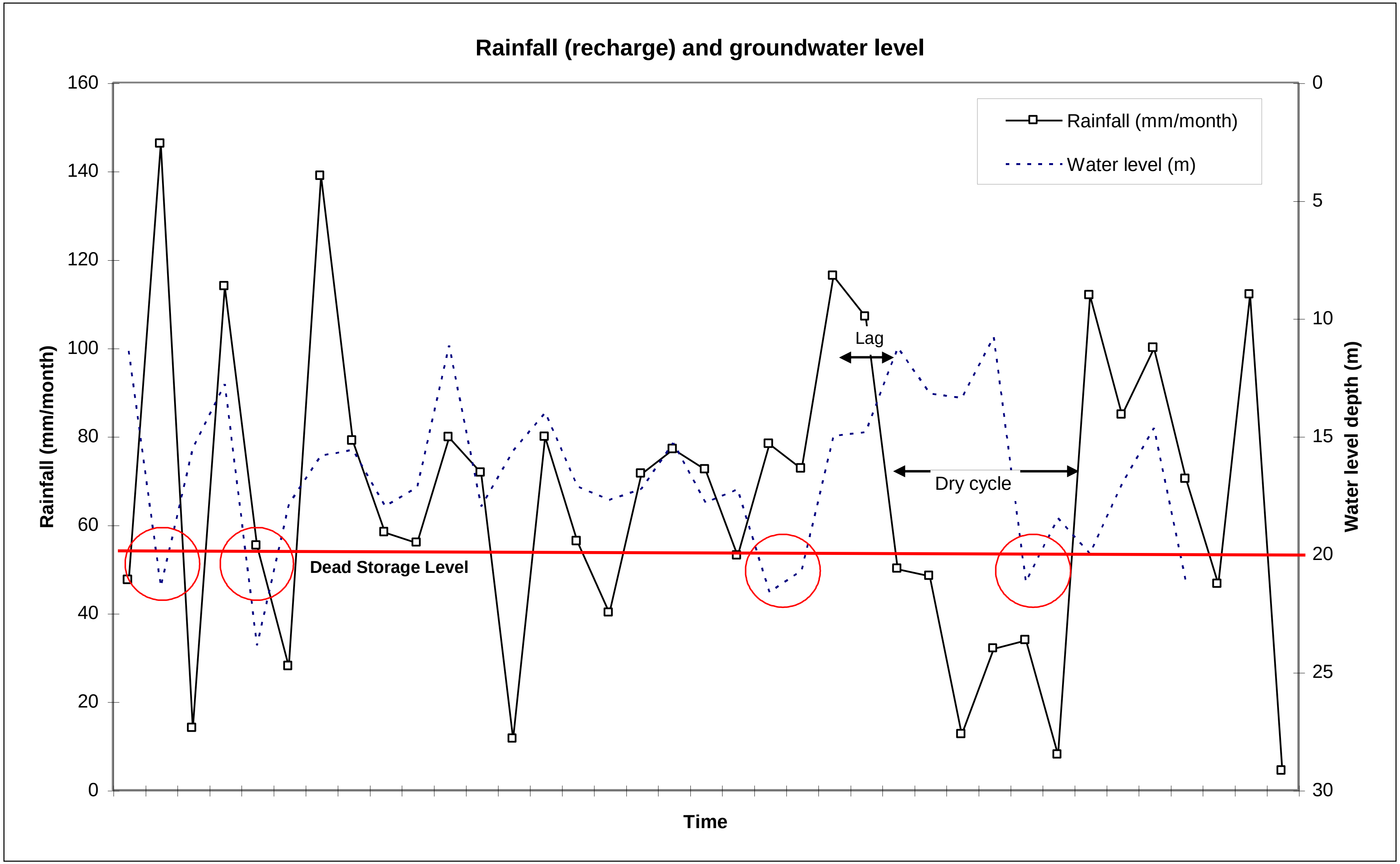

Figure 10.2: Time varying rainfall-recharge conditions showing system failure during dry cycles

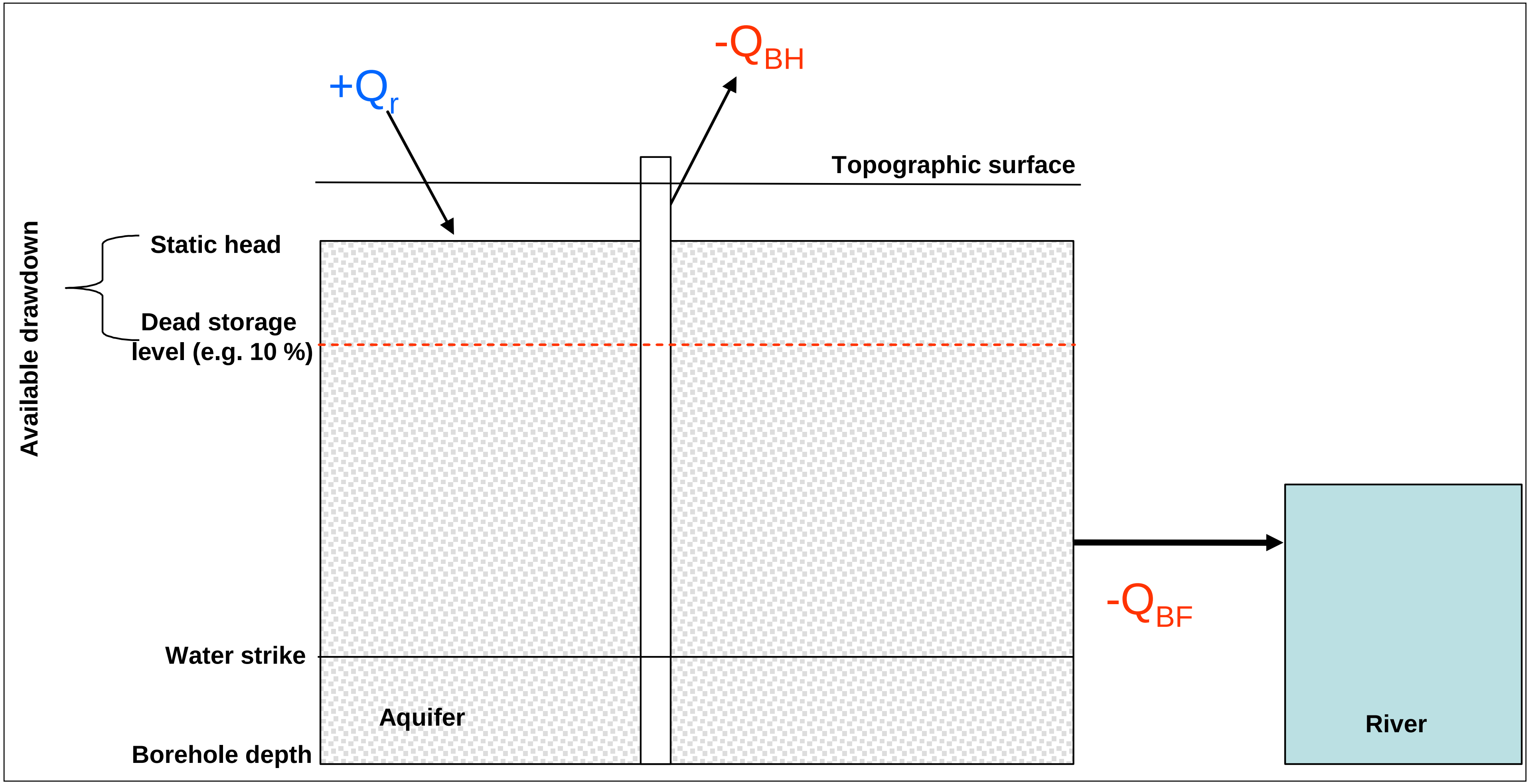

Figure 10.3: Schematic representation of the GYM conceptual model – dead storage level

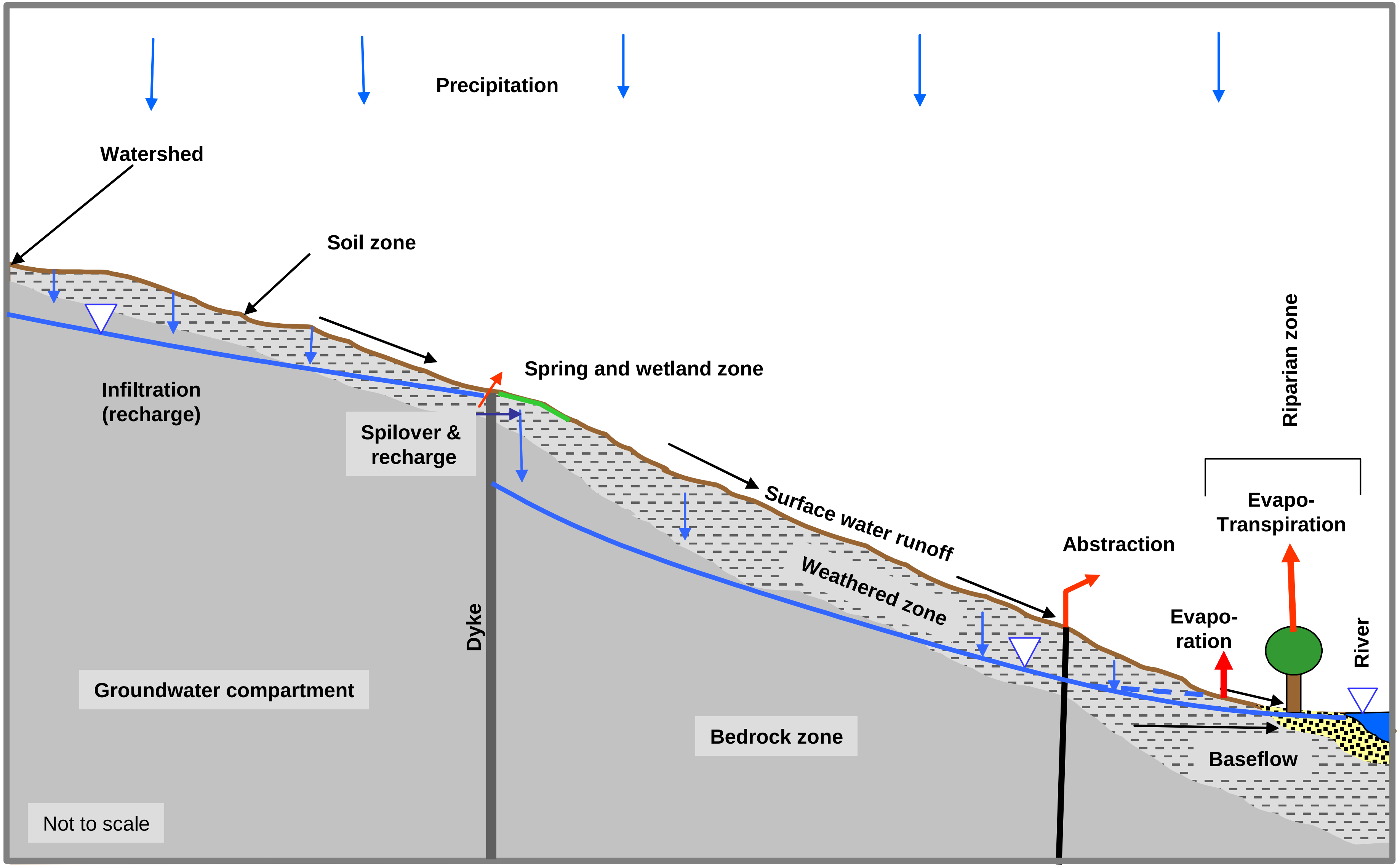

Figure 10.4: Schematic representation of the GYM conceptual model – field conditions (low baseflow loss case)

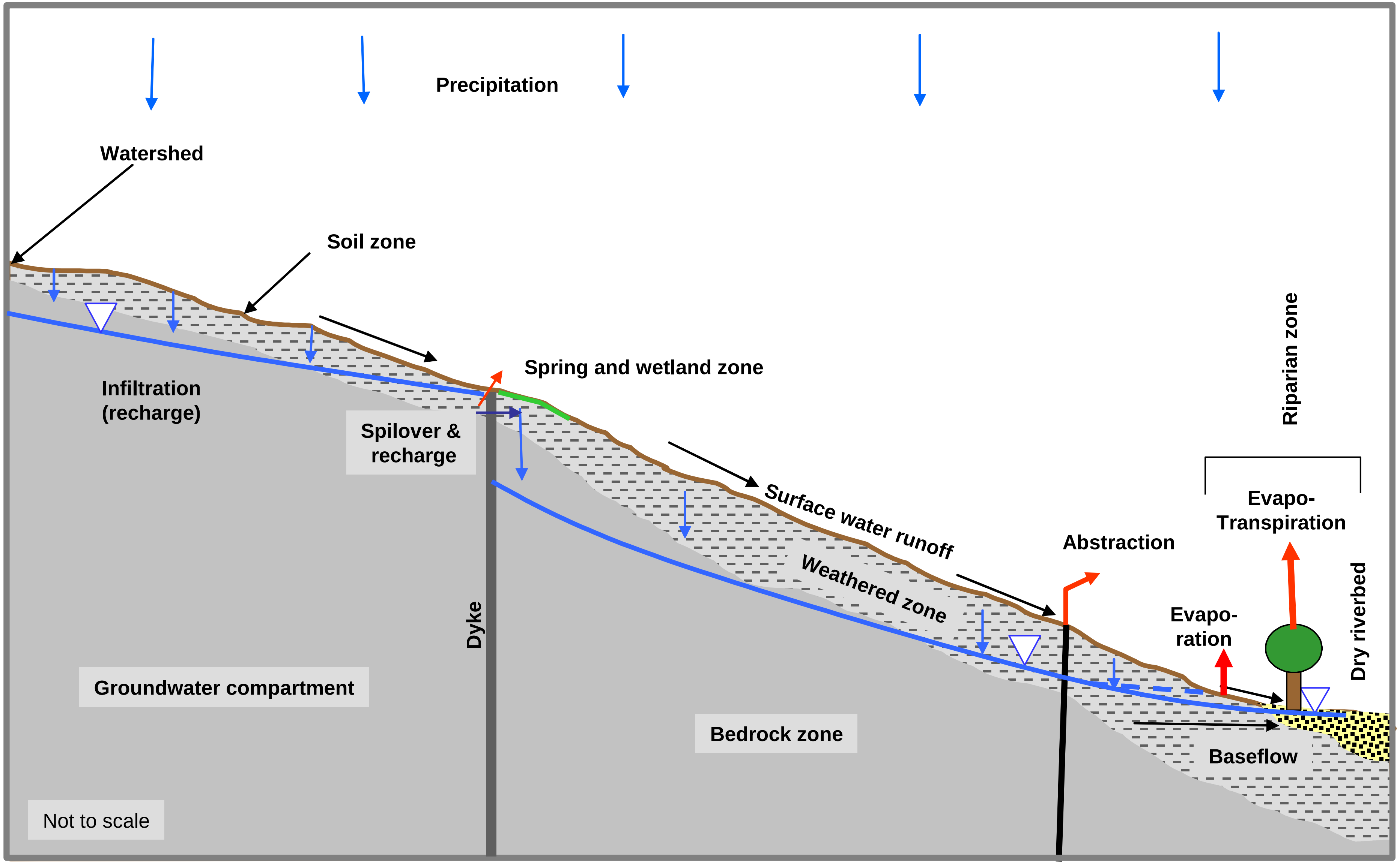

Figure 10.5: Schematic representation of the GYM conceptual model – field conditions (high baseflow loss case)

5. Analytical model

The transient model is a differentiation of the steady-state, basic case discussed in section 1. Distinction is made between natural and unnatural inflow and outflow components. Also between outflow components that are lost (e.g. evapo-transpiration especially by alien vegetation) and outflow components where groundwater is used (e.g. Basic Human Need Reserve). Groundwater Loss Components (GLC) is less valuable than Groundwater Use Components (GUC). This is due to the fact that it is more sensible to use groundwater for basic human need purposes than to lose it to alien vegetation. Hence if one has the option to prioritise outflow, all outflow components are not considered of the same importance level.

It is the purpose of the model to calculate the volume of groundwater in storage given that the volume of water required by natural systems is allocated for.

The various groundwater flow components are described by the following:

The groundwater inflow from natural systems (+Q_{GINS}).

+Q_R = Recharge from rainfall [L.T-1][2]

The groundwater inflow from unnatural systems (+Q_{GIUNS}).

+Q_{DS} = Inflow from Dam Seepages [L.T-1]
+Q_{IRR} = Return recharge from irrigation [L.T-1]

Groundwater loss components (-Q_{GLC}).

-Q_{AVEG} = Alien vegetation [L.T-1]
-Q_{ETPL} = Evapo-transpiration losses [L.T-1]
-Q_{MDW} = Mine dewatering [L.T-1]

Groundwater use by natural systems (-Q_{GUNS})

-Q_{SF} = Spring flow [L.T^{-1}]
-Q_{GBF} = Groundwater base flow [L.T^{-1}]
-Q_{WLD} = Wetland fed by groundwater [L.T^{-1}]
-Q_{RVEG} = Riparian vegetation [L.T^{-1}]
-Q_{EWR} = Ecological Water Requirement (component of groundwater base flow) [L.T^{-1}]

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[2] *[L.T^{-1}] where L = length and T = time*

Groundwater use by unnatural systems ($+Q_{GUUNS}$)

$-Q_{BH}$ = Abstraction from boreholes e.g. well fields for water supply [L.T-1]

$-Q_{LSF}$ = Abstraction from boreholes for livestock farming [L.T-1]
$-Q_{BHN}$ = Allocation for basic human needs and communities [L.T-1]
$-Q_{IR}$ = Abstraction for irrigation [L.T-1]
$-Q_{F}$ = Forestry groundwater use [L.T-1]

Volume of groundwater in storage (GV_{ST})

$+GV_{ST}$ = Volume of groundwater in storage [L3]

In a natural, steady-state situation, the groundwater balance equation for the model is given by;

$$\Delta GV_{ST} = Q_R - Q_{GETL} - Q_{GBF} \qquad (2)$$

In an unnatural groundwater system, the groundwater flow balance per time step is given by:

$$\Delta GV_{ST} = Q_R + Q_{DS} – Q_{BH} - Q_{LSF} – Q_{BHN} – Q_{IR} + Q_{IRR} – Q_{MDW} – Q_F - Q_{AVEG} – Q_{WLD} – Q_{RVEG} – Q_{SF} – Q_{GETL} – Q_{GBF} - Q_{EWR} \qquad (3)$$

It is evident that the groundwater used by natural systems (spring flow and groundwater base flow) is last in the flow sequence. This is because in the physical flow system, unnatural groundwater use such as from boreholes and mine shafts can utilise water before it has the opportunity to flow to a natural system. The flow sequence is therefore important. Groundwater base flow of which the Ecological Water Requirement (EWR) is a component, is the last component to receive groundwater. When outflow exceeds inflow in any given time step, water would be taken firstly from storage and then from base flow. A supplementary conservative assumption that can be made, is to allocate a minimum volume to groundwater base flow in the model. If outflow exceeds inflow, water would be taken mainly from storage until the head declines to the defined management constraint. Once the volume in storage is used, it is possible for base flow to reverse (i.e. inflow into the groundwater system, which is implemented as positive base flow in the model, which must be activated in the model) and have a flow reduction effect on the river. A maximum volume was implemented as a constraint in the model as the user need to determine whether the specific surface water resource has a flow constraint prior to activation of the possibility of reverse base flow. This is because most surface water streams in South Africa is dry for most of the times of the year, which would not allow reverse base flow from the stream to the aquifer.

The groundwater balance from (3) is calculated for monthly time steps (Δt) to yield an annual or monthly groundwater balance at a chosen assurance level.

The model output is put into perspective for the groundwater component of the reserve. The various flow components are discussed in more detail in the following section.

Groundwater volume in storage (GV_{ST})

The volume of groundwater in storage is determined from:

$$GV_{ST} = A \times D \times S_0 \qquad (4)$$

A	=	Surface area of the aquifer	$[L^2]$
D_{GMC}	=	Saturated thickness of the groundwater management constraint (GMC)	[L]
S_0	=	Specific Storativity	[1]

The volume in storage is calculated for each time step (Δt) and from which an average change in groundwater head is determined by:

$$\Delta h = \frac{V}{S_0} \qquad (5)$$

Δh	=	Change in head during time step	[L]
V	=	Net volume of water during time step	$[L^3]$

The model output graphs are given in terms of average depth to groundwater level based on available volume within the management constraint.

5.1. Variable recharge (+QR)

The groundwater recharge is calculated as a percentage of rainfall that is assumed to reach the aquifer, on a monthly basis. Data from the historical rainfall records is used to determine the monthly average rainfall (**Figure 10.6**). The standard deviation for a 95 % assurance level is then used to obtain a range within which the monthly rainfall-recharge is sampled (**Figure 10.7**). It is important to note that the 95% assurance level is much lower than the average rainfall, which is typical for semi-arid and arid conditions, which is prevalent in South Africa.

The sampling is done on a random basis within the statistical rainfall distribution.

When the aquifer is full, no additional recharge is accepted in the model. In reality, piezometric levels could rise above the static levels during wet periods. Provision could be made to allow e.g. a 10 % over saturation of the aquifer, which would increase the available volume of water.

5.2. Dam seepage (+QDS)

Seepage from dams is determined by:

$$Q_{DS} = K_C \frac{dh}{dl} \times A_D \qquad (6)$$

K_C	=	Hydraulic conductivity of the colmation layer formed by dam sediments	$[L\ T^{-1}]$
$^{dh}/_{dl}$	=	Head gradient (assumed to be 1 for vertical seepage)	[1]
A_D	=	Surface area of dam/s	$[L^2]$

This component is used conservatively with known dams and parameters, otherwise it is considered to be zero to prevent an overestimation of the groundwater volumes. Provision is made to allow dam seepage for only the wet seasons or e.g. 30% of the hydrological year when it will have a positive head.

5.3. Abstraction from boreholes for livestock farming (-QBH)

Abstraction from boreholes that are used for farming is used as an outflow component. For the Lower Vaal reserve determination an average of one head of cattle per 20 ha was used and a consumption of 60L/ 24 hr per head.

5.4. Allocation for basic human need (-QBHN)

Groundwater is an important source of water supply for basic human needs, especially for communities in rural areas. For areas that rely on groundwater as a source of supply, the allocation is made on between 25ℓ/person/day to 60ℓ/person/day. The population in the area is obtained from census and spatial GIS data bases, which is then used to calculate the basic human need allocation.

5.5. Borehole abstraction for irrigation (-QIR)

Water use for irrigation is obtained from the total surface area that is used for irrigation. The water use is determined by using 1ℓ/s/ha/day (80 m^3/ha/day) in the growing season. The irrigation areas are determined from GIS and remote sensing spatial data (satellite or aerial photographs).

In cases where Water Use Licensing information for sub-catchments is available, it will be considered as backup check. The licensed or registered volumes are usually higher than the actual use. In the Lower Vaal Study the WARMS registered data was used.

5.6. Return recharge from irrigation (+QIRR)

The return flows from irrigation acts as a source of groundwater recharge. In some cases, surface water is abstracted which is then used to irrigate on aquifers located further away from the surface water sources. If irrigation is optimal, no through flow to the aquifer should occur. However lower water quality (especially Na and Cl) and certain soil types (clay) pose risks of soil salinization. In these cases, over-irrigation is required to flush the salt load from the soils, which then contaminates the aquifer over time.

The default assumption is made that e.g. 10% to 20 % of the volume used for irrigation, recharges the aquifer.

5.7. Mine dewatering (-QMDW)

When mines operate below the groundwater level, it will induce inflow and cone of depression develops around it. Standard practice is to grout (i.e. seal) groundwater inflows, which is effective where the rock mass is competent and inflow occurs from isolated discrete fracture zones. Where the inflow occurs from homogeneously fractured or weathered rock units, sealing is in most cases ineffective or costly. High groundwater head pressure behind mine stopes could also cause failures. In these cases, the aquifer is dewatered to create a safe working environment.

The mine dewatering volume is determined by:

$$Q_{MDW} = K \frac{dh}{dl} \times A_{MS} \tag{7}$$

K	=	Hydraulic conductivity of mine workings	$[L\ T^{-1}]$
$^{dh}/_{dl}$	=	Head gradient (assumed to be 1 for vertical seepage)	[1]
A_{MS}	=	Surface area of mine stopes and shafts	$[L^2]$

The information from (7) is generally too detailed to obtain for a quaternary catchment scale model. Direct information on the volumes dewatered could be obtained from mines, as it is essential data to collect and could be included directly into the model as a flow volume and not a calculated parameter.

5.8. Alien vegetation (-QAVEG)

Alien vegetation often accounts for large reductions in groundwater volumes by intercepting seepage along springs and in the riparian zone. The groundwater use by alien vegetation systems are determined by;

$$Q_{AVEG} = (Q_P - Q_{ET}) \times A_{AVEG} \tag{8}$$

Q_P = Mean Annual Precipitation [L T^{-1}]

Q_{ET} = Mean Annual evapo-transpiration (MAE) rate of alien vegetation [L T^{-1}]

A_{AVEG} = Surface area covered by alien vegetation [L^2]

The areas covered by alien vegetation are determined from GIS and remote sensing and/or field mapping. It is important to determine the depth to groundwater in areas covered by alien vegetation, because the areas used in this component must use groundwater directly. The depth to groundwater in this case should not be greater than e.g. 10 m, because deeper groundwater is unlikely to experience losses due to alien vegetation.

5.9. Forestry (-QF)

Forests that intersect the groundwater zone would have a similar effect on groundwater reduction than alien vegetation. The groundwater use by forests are determined in a similar way from:

$$Q_F = (Q_P - Q_{ET}) \times A_F \tag{9}$$

Q_P = Mean Annual Precipitation [L T^{-1}]

Q_{ET} = Mean Annual evapo-transpiration (MAE) rate of alien vegetation [L T^{-1}]

A_F = Surface area covered by alien forests [L^2]

5.10. Wetlands fed by groundwater (-QWLD)

Permanent wetlands that are sustained by groundwater would use water equal to the net evapo-transpiration;

$$Q_{WLD} = (Q_P - Q_{ET}) \times A_{WLD} \tag{10}$$

Q_P = Mean Annual Precipitation [$L^3\ T^{-1}$]
Q_{ET} = MAE rate of wetland and wetland vegetation [$L^3\ T^{-1}$]
A_{WLD} = Surface area of wetland [L^2]

The information is obtained from GIS coverage and field mapping of the total surface area covered by wetlands that are supported by groundwater. Wetlands within 1 km from a river are assumed to be supported by surface water. Only those wetlands located away from surface water features are included in the groundwater assessment.

5.11. Riparian vegetation (-QRVEG)

Riparian vegetation also accounts for reductions in groundwater volumes by intercepting seepage along springs and in the riparian zone. Riparian vegetation is indigenous and in general does not use as much water as alien vegetation. Riparian vegetation has environmental importance because it supports ecosystems. The groundwater use by natural riparian vegetation systems are determined by:

$$Q_{RVEG} = \left(Q_P - Q_{ET}\right) \times A_{RVEG} \tag{11}$$

Q_P = Mean Annual Precipitation [$L^3\ T^{-1}$]
Q_{ET} = Potential MAE rate of riparian vegetation [$L^3\ T^{-1}$]
A_{RVEG} = Surface area covered by riparian vegetation [L^2]

5.12. Spring flow (-QSF)

The outflow to springs is directly determined by measuring the cumulative flow of springs (-Q_{SF}) in the catchment. It is assumed that there would be losses between the aquifer and the spring if e.g. groundwater seeps out in a zone around the actual spring eye and opportunity exists for evapo-transpiration losses.

5.13. Groundwater evapo-transpiration losses (-QGETL)

Groundwater evapo-transpiration losses occur in the groundwater-surface water interaction zone, where the groundwater level is shallow, along drainages and streams, springs and at seepage zones. It was found that in the Olifants Catchment, the MAP is e.g. 600 mm, while the MAE is in the order of 1400-1800 mm. The MAE is more than double the MAP. Groundwater recharge is in the order of 2 - 4% (except dolomites, where it is much higher at 8 - 15 %) of the MAP. The potential groundwater evapo-transpiration losses are therefore 50-70 times higher than the recharge. It means that the total groundwater recharge could be lost over a groundwater evapo-transpiration loss area of 1 - 2% of the catchment area.

The groundwater evapo-transpiration loss is determined from:

$$Q_{GETL} = MAE\ x\ A_{ET} \qquad (11)$$

Q_{GETL}	=	Groundwater evapo-transpiration loss	$[L\ T^{-1}]$
MAE	=	Potential MAE	[L]

5.14. Groundwater base flow (-QGBF)

Groundwater base flow is a function of the groundwater recharge minus losses in the aquifer system. Groundwater base flow is often the last component in the flow sequence to receive water. It is influenced by recharge and the hydraulic parameters of the aquifer.

Groundwater base flow can be determined from:

$$Q_{BF} = K\frac{dh}{dl} \times D \times L \qquad (12)$$

K	=	Hydraulic conductivity of the general aquifer	$[L\ T^{-1}]$
$^{dh}/_{dl}$	=	Head gradient (assumed to be correlated to topography)	[1]
D	=	Saturated thickness	[L]
L	=	Length of drainage system along which groundwater base flow occurs	[L]

If the recharge, aquifer losses, aquifer thickness (D) and length of outflow (L) is known, the minimum transmissivity (or hydraulic conductivity) of the aquifer to allow groundwater base flow can be determined.

5.15. Groundwater base flow, Ecological Water Requirement (-QEWR)

The component of base flow that is required for the ecological reserve is determined by ecological water specialists. If this value is provided, it can and should be included in the model to determine whether it can be sustained by groundwater alone or which percentage of e.g. the drought low flow component could be sustained by groundwater. More research on the model implementation is required on this section.

The component of groundwater that could be utilised in a catchment, would typically be the groundwater base flow minus the ecological water requirement. It is for now assumed that the flow loss component is fixed. In practice alien vegetation could be reduced to reduce the flow losses or groundwater could be used before it is allowed to undergo flow losses. This would be a management decision taken for each catchment based on the flow and environmental character.

5.16. Deep groundwater inflow and outflow

There are possibilities for inflow from or outflow to deep seated aquifers, which stretches beyond the quaternary boundary. Provision is made for deep groundwater inflow and outflow as a flow component $+Q_{DGW}$ and $–Q_{DGW}$. Unless data from e.g. shallow and deep boreholes with piezometric head elevations can be provided to prove that deep groundwater flows into or out of the system, the assumption is made that these two components are zero. The assumption could also be made that outflow to and inflow from deep aquifers balance with a zero effect.

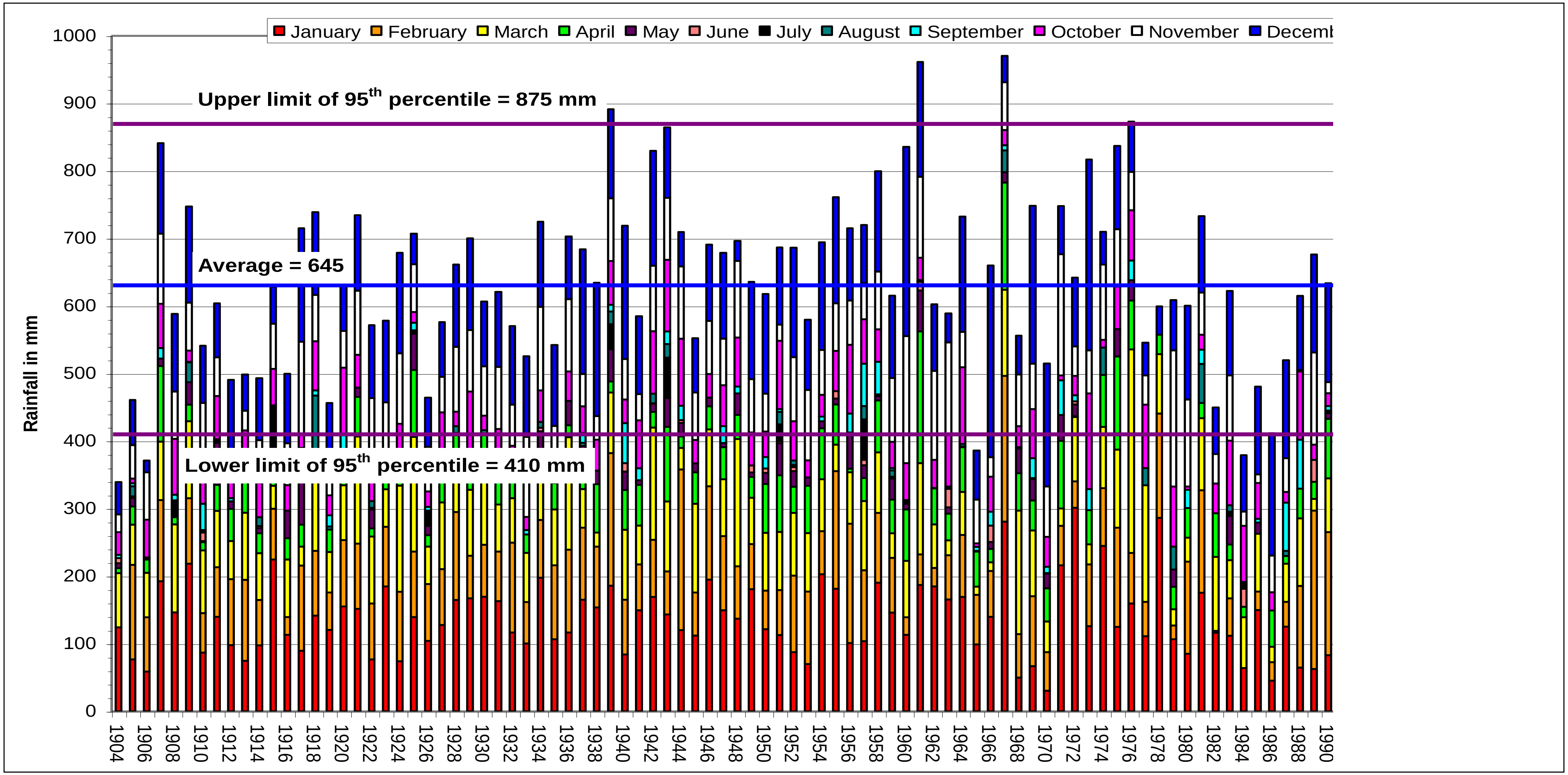

Figure 10.6: Monthly and annual rainfall data for station 0548280 (Saulspoort Hospital) from 1904 to 2002

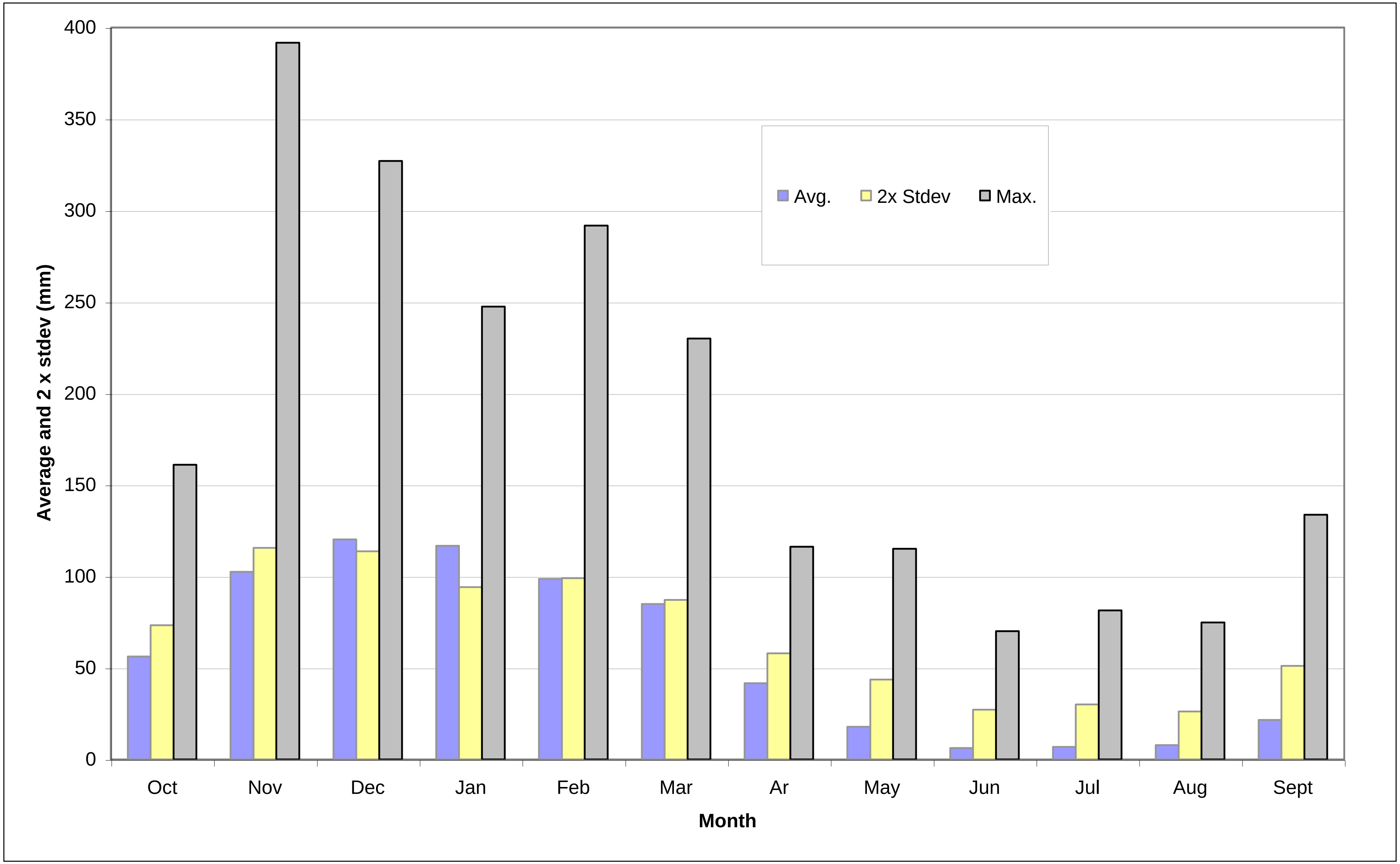

Figure 10.7: Average monthly rainfall and standard deviations – showing the variability

6. References

Van Tonder GJ, Usher, B and Hughes D. (2007) *Groundwater/surface water interaction: A new perspective. In proceedings of the Groundwater Conference.* 8-9 October 2007. Bloemfontein. South Africa.

Vivier JJP, Gouws, WJ and Wydeman R. (2005) *Olifants River Water Resources Development Project: Groundwater Study Task (ORWRDP).* AS-R-2005-05-24