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Intermediate Reserve Determination Study for the Integrated Vaal River System:

Lower Vaal Water Management Area Groundwater Component: Progress Report No. 2

Prepared for:

DWAF

October 2008
Compiled by
CJDeW Raath

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Intermediate Reserve Determination Study for the Integrated Vaal River System:
Lower Vaal Water Management Area.

21 October 2008

Conducted on behalf of:
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Notations and terms

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

Anisotropic 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potentiometric surface that has the shape of an inverted cone and develops around a borehole from which water is being withdrawn.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 L^2. Hydraulic conductivity is therefore used in all the calculations.

Piezometric head (ϕ) 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 (S_0), 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

Abbreviation	Description
BPEO	Best Practicable Environmental Option
DWAF	Department of Water Affairs and Forestry
Ec	Electrical Conductivity
EIA	Environmental Impact Assessment
EMPR	Environmental Management Programme Report
MAMSL	Meter Above Mean Sea Level
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MBGL	Meter Below Ground Level
MBGL	Meter Below Ground Level (i.e. depth)
NEMA	National Environmental Management Act
NWA	National Water Act
TDS	Total Dissolved Solids
tpm	Tons per month
TWQR	Target Water Quality Range

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2 INTRODUCTION

AGES was appointed by the Department of Water Affairs and Forestry to conduct a intermediate groundwater reserve determination study of the Lower Vaal WMA.

This report summarises the progress made up to 30 October 2008 in terms of the project implementation as laid out in the Terms of Reference, DWAF document WP8829/8, September 2007, paragraph 2.5.

The Vaal River system is the most important water resource system in South Africa as it provides water to more than 40 % of the country's inhabitants. There are numerous industries and mines in the supply area, which supports the production of more than 50 % of the country's gross domestic product.

Due to extensive development in the Vaal River System the local surface water resources in all three the Vaal WMAs have been fully exploited. It was therefore necessary to augment the supply by developing various water schemes importing water from the Thukela and Usutu to Mhlathuze WMAs, as well as from Lesotho through the Lesotho Highlands Water Project. Groundwater is of major importance in the Lower Vaal WMA and constitutes the only source of water over much of the WMA. Development of surface water naturally occurring in the WMA has reached its potential and all the water is being fully utilised. (*1999, MJ Tukker)*.

2.1 Terms of reference

2.1.1 Objectives

The purpose of the study is to provide the client with the following:

1. Resource Unit delineation; an updated resource unit classification taking cognisance of surface water quaternary catchment boundaries and the aquifers present in these catchments
2. Water balance and conceptual aquifer model, using the GRDM tool
3. Rapid reserve determinations to verify and validate the reserve determination by the GRDM method

4. Intermediate level reserve determinations
5. Management and strategy development

2.1.2 Scope of work

Phase 1: Inception phase that includes a literature review and inception report (Completed)

Phase 2: Study implementation phase that includes the following tasks

- Introduction
- Background information
- Physiography and climate
- Geohydrology
- Delineating resource units
- Water Resource classification
- Quantification of the Groundwater Reserve, groundwater flow balance modelling on quaternary catchment scale
- Setting of Resource Quality Objectives

2.1.3 Study area and location

The main groundwater unit is the Lower Vaal WMA No 10 (DWAF, 2004) (Figure 2-1).

The Lower Vaal WMA lies between the Middle Vaal and Lower Orange WMA's, with the Upper Orange WMA to the south of the Lower Vaal WMA and Botswana to the north.

Major rivers in the Lower Vaal Water Management Area include the Molopo, Harts, Dry Harts, Kuruman and Vaal rivers. The tertiary drainage areas in the Lower Vaal WMA comprises C31, C32, C33, C91, C92, D41, D42, and D73. The Lower Vaal WMA covers approximately 136146 km^2 (13 614 652 ha). The Lower Vaal WMA consists of 34 quaternary catchments as shown in Figure 2-1.

The Lower Vaal WMA is located downstream of Bloemhof Dam and upstream of Douglas

Weir. It extends to the headwaters of the Harts, Molopo and Kuruman River in the north and the Vaal River Downstream of Bloemhof in the south. It lies in the North West and Northern Cape Provinces, with the south-eastern corner in the Free State, and borders on Botswana in the north, as well as on the Crocodile (West) and Marico, Middle Vaal, Upper Orange and Lower Orange water management areas.

Figure 2-1 Lower Vaal Regional locality map

3 METHODOLOGY

The study consists of two phases:

- **Phase 1**: Regional assessment - desktop study, review of existing information data evaluation and aquifer delineation and
- **Phase 2**: Groundwater flow balance modelling on quaternary catchment scale.

4 PHASE 2

4.1 Site description of Lower Vaal WMA

4.1.1 Topography

The water in the Lower Vaal WMA flows from the Upper Vaal, across the Middle Vaal, Lower Vaal and Lower Orange WMAs before reaching the Atlantic Ocean near the town of Alexander Bay in the western corner of the country. There are no distinct topographic features in the WMA with most of the terrain being relatively flat except for low hills west of Kuruman and around Postmasburg (Figure 4-1). As a result of the generally arid climate, vegetation over the water management area is sparse, consisting mainly of grassland and some thorn trees (DWAF, 2004).

The elevation of the WMA decline from east to west from approximately 1374 m above mean sea level in the east in the Sannieshof area to 936 m above mean sea level in the west in the Vanzylsrus area. The highest peak is south of Kuruman at 1854 m above mean sea level.

4.1.2 Surface water and drainage

Several rivers drain the Lower Vaal WMA as shown in Figure 4-2. The main river systems are the Molopo, Harts, Dry Harts, Kuruman and Vaal rivers. The rivers mentioned above are all perennial, but many of the smaller tributaries are not and as such can not be used as a sustainable water supply by the communities.

There are several dams in the Lower Vaal WMA, Wentzel, Taung, Spitskop, Vaalharts Weir, West End, Cashel and Taus. Several of these dams are used as water supply.

The Harts River drains a catchment area of approximately 31 000 km_2 and has one major tributary, the Dry Harts which joins the Harts just downstream of Taung. The topography of the catchment is generally flat (the average slope of the Harts River is one in a thousand) and this

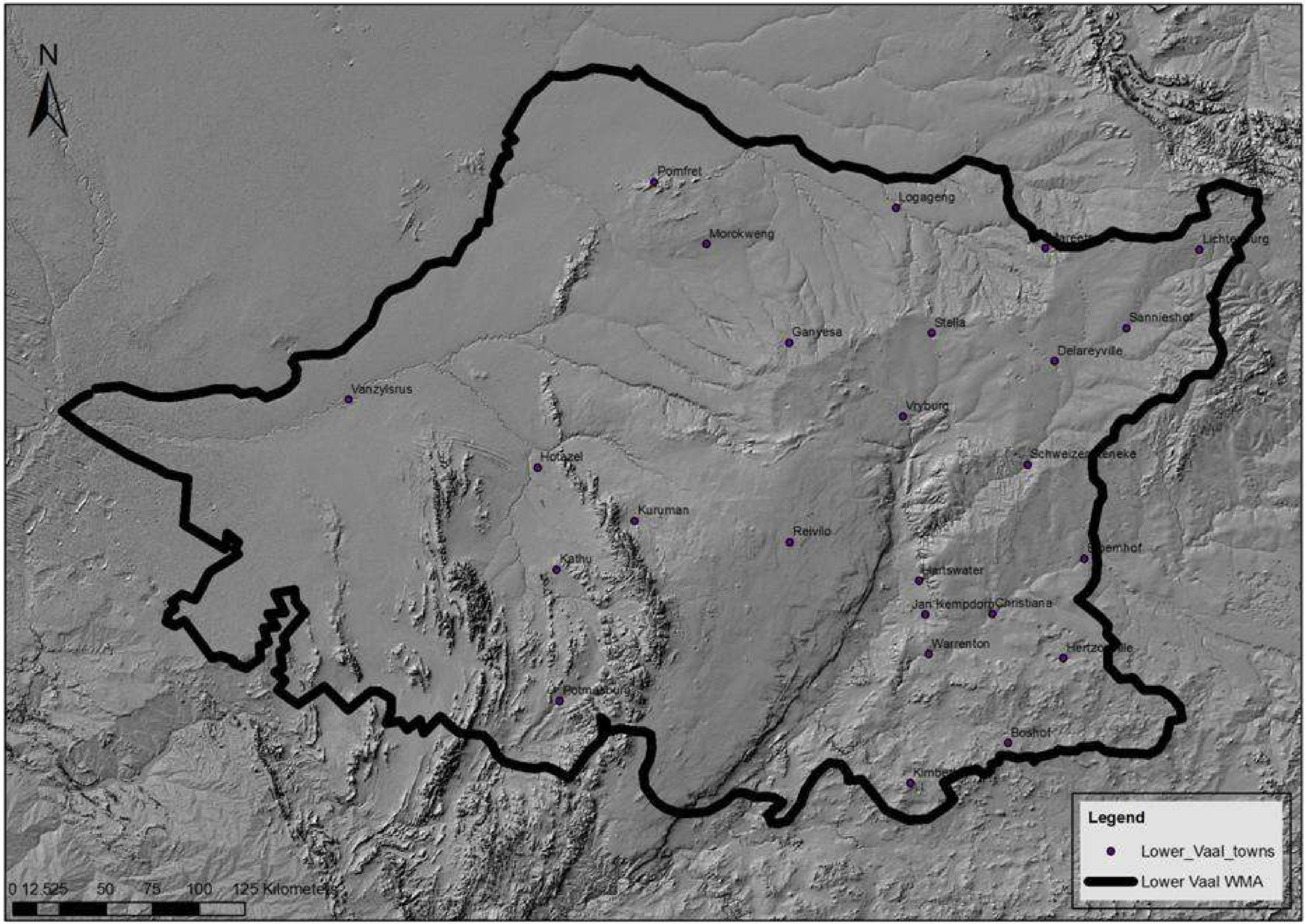

Figure 4-1 Lower Vaal WMA Topography (CSIR data)

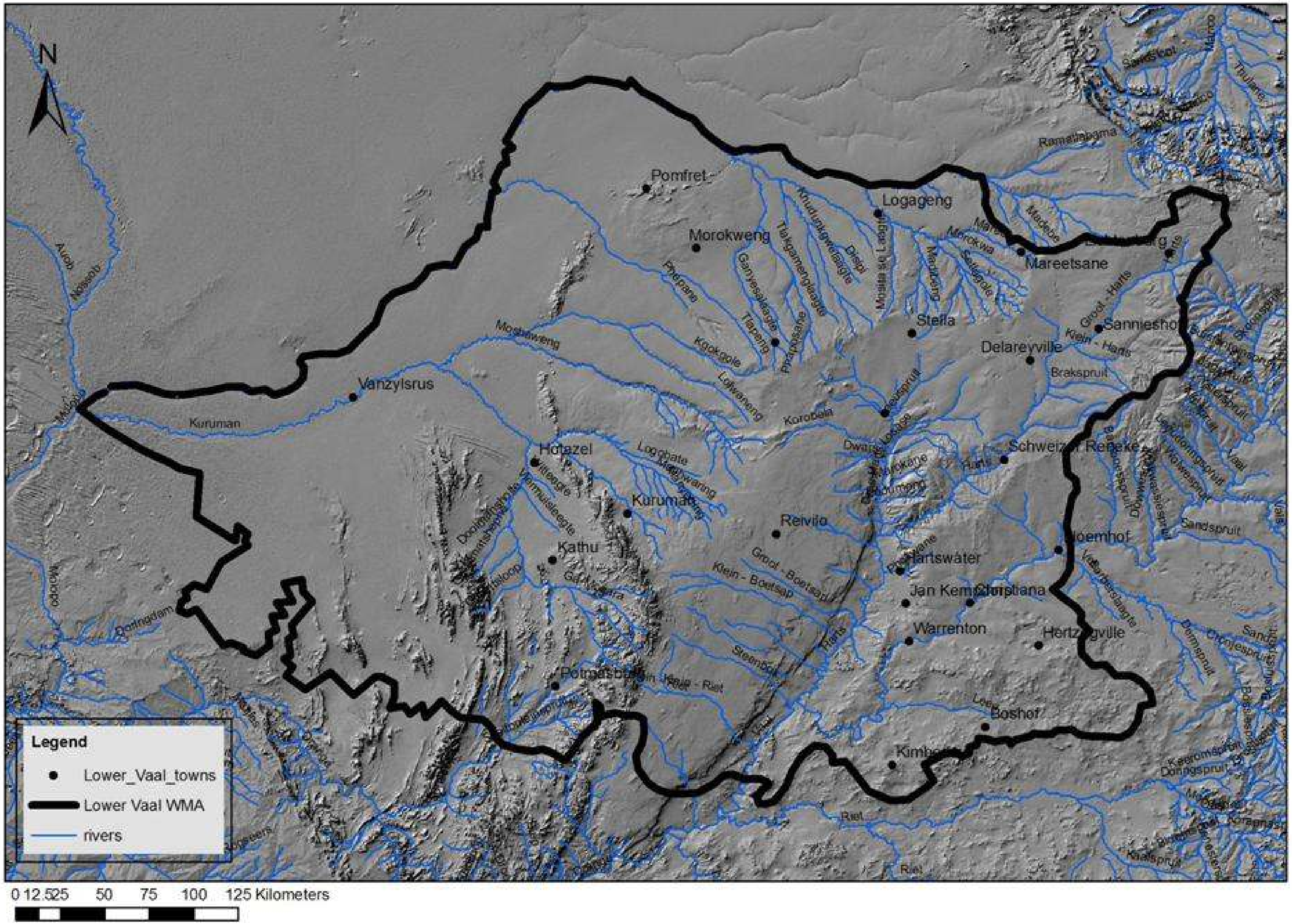

Figure 4-2 Lower Vaal WMA rivers

results in a very low drainage density and an ill-defined watershed. To the west of the Dry Harts and the lower Harts, the geology consists predominantly of dolomite and limestone whereas extrusive igneous rocks underlie the rest of the catchment. The catchment consists of moderate to deep soils, clayey in the western region, sandy loams along the middle band running north to south and clayey loams in the north east region. Most of the western sector is Kalahari thornveld and scrub bushveld covers merging into grassland in the north east. The MAP for the region ranges between 600 and 400 mm. The MAE is relatively high and varies between 1 800 mm in the north east to 2 600 mm in the far south west. A combination of the flat topography, low rainfall and high potential evaporation result in very low MAR (Mean annual run off) from this region, between just 5 and 10 mm (Tukker 1999).

There are a number of significant water usage features in this region. Barberspan is a natural off-channel storage system in the upper reaches of the Harts. Further downstream Wentzel Dam was constructed and relies totally on the natural flow of the Harts River. A very recent construction is the Taung Dam further downstream on the Harts River which at present does not supply irrigation or urban demands. The most important water usage feature adjacent to the Harts River is the Vaalharts Irrigation Scheme. Water for irrigation is abstracted and transferred, via a complex system of canals, from the Vaalharts Weir on the Vaal River to the irrigators between the lower Harts River and the Vaal River. Spitskop Dam was constructed on the lower Harts River to supply the irrigators in the region and stores the significant return flows from the Vaalharts Scheme (Tukker 1999).

The stretch of the Vaal River considered in this study is the reach between Bloemhof Dam and the Orange and Vaal River confluence in quaternary catchment C92B. The total catchment area is almost 22 500 km_2. The vegetation is predominantly Kalahari thornveld with areas of grassland in the east and small zones of Karoo in the south and west. The geology is comprised of three distinct groups. In the far west the geology is predominantly dolomite with extrusive igneous rocks north of the Vaal and argillaceous strata south of the river. There is a broad centre band running north to south of moderate to deep sandy loam soils. The rest of the catchment has moderate to deep clayey loam soils. The catchment is flat becoming undulating in the far south. The MAP of the region is 414 mm diminishing to under 400 mm in the lower reaches at the confluence with the Orange River. The MAE is 2 070 mm and ranges from 1 800 mm in the east to 2 600 mm in the west. Of the total catchment area only 35 % contributes directly to the river network. The remainder drains into the many pans and enclosed drainage basins and is evaporated. As a result of these endoreic areas, the low rainfall and high potential evaporation, the MAR (Mean annual run off) from the catchment is only between 0 and 5 mm. Bloemhof Dam is at the head of this catchment, water is released from Bloemhof Dam to support downstream riparian irrigators and is diverted at the Vaalharts Weir to the Vaalharts Irrigation Scheme.(Tukker 1999)

4.1.3 Climate

Climatic conditions are fairly uniform from east to west across the study area. The mean annual temperature ranges between 18.3ºC in the east to 17.4ºC in the west. Maximum temperatures are experienced in January and minimum temperatures usually occur in July. Frost occurs throughout the study area in winter, typically over the period mid-May to late August.

Precipitation is strongly seasonal with most rain occurring mainly in the summer months (October to April) with the peak of the rainy season in December and January. Rainfall occurs generally as convective thunderstorms, therefore rainfall events are of short. Maximum development of the storms occurs in the afternoon and early evenings (DWAF 2004 and South African Weather Service, 2008).

The overall range of the MAP for the entire WMA is 100 mm to 500 mm. Humidity is generally highest in February (the daily mean over the study area ranges from 66 % in the east to 62 % in the west) and lowest in August (the daily mean over the study area ranges from 53 % in the east to 57 % in the west). Average gross potential mean annual evaporation (as measured by Class A-pan) ranges from 1800 mm to 2 690 mm in the Lower Vaal WMA. The highest A-pan evaporation occurs in December and ranges between 300 mm and 380 mm.

In the southern and south eastern regions, the average rainfall per year is 414 mm, the average daily summer temperature is 32°C and the average daily winter temperature is 7°C. The MAE (mean annual evaporation) is 2070 mm and ranges from 1 800 mm in the east to 2600 mm in the west

In the north eastern and eastern regions the average rainfall per year is 460 mm and the average daily summer temperature is 30°C and the average daily winter temperature is 7°C. The MAP ranges between 500 and 600 mm in the upper reaches of the Harts River decreasing gradually to just below 400 mm at the confluence with the Vaal.

therefore rainfall events of short duration and a flooding nature can be expected. Maximum development of the storms occurs in the afternoon and early evenings (South African Weather Service, 2008).

4.1.4 Land use

The total urban and rural population in this WMA is approximately 1,282,000, of which about 718,000 live in urban centres. The largest concentration of urban population is in Kimberley, with an estimated population of 204,000. There are large rural populations in the Lower Vaal, especially in the areas west of Mafikeng, around Kuruman, Pampierstad and Lichtenberg. Land use within the Lower Vaal WMA is dominated by stock farming. The largest irrigation scheme is the Vaalharts Water Scheme, which is supplied from Bloemhof Dam. The scheduled area of this scheme is 39147 ha with quotas of 9 140 m$_3$/ha/annum. Including losses, the water use by this scheme is in the order of 500 million m$_3$/annnum. The following table shows land use and population per sub-catchment.

Table 1 Land use and population (DWAF 2004)

Sub Catchment	Irrigation (km^2)	Alien Vegetation (km^2)	Urban (km^2)	Total	Population Urban	Population Rural	Population Total
Molopo River	0	384	30.2	414.6	79250	361947	441197
Dry Harts	35.7	25.5	21	82.2	44500	78160	122660
Harts	1	12.5	19	32.5	111100	121000	232100
Vaalharts	336	0.3	36	373.2	51700	89110	140810
Vaal d/s Bloemhof	118	27.9	171	317.2	286900	58930	345830
TOTAL IN WMA	492	496	277	1265	573450	718647	1282597

In addition to the controlled irrigation there is a significant amount of diffuse irrigation which is supported by farm dams and river and groundwater abstractions. The reliability of supply for this type of irrigation is considerably lower than that of the controlled irrigation where it is dependant on farm dams and rivers as it is supported by little or no storage. Irrigation schemes making use of groundwater from the dolomite and fault zones are numerous and the water supply is very reliable if well managed.

There are no significant forestry activities in the Lower Vaal WMA.

There are several mines in operation in the Lower Vaal WMA. Large diamond mines are concentrated in the Kimberley area but numerous alluvial diamond operations can be found along many of the rivers or along paleo-river channels filed with diamondiferous gravels.

The largest open cast mine in South Africa, the Sishen iron ore mine is situated near Kathu where large volumes of water are pumped from the pit each day. The water pumped from the pit comes from the dolomitic aquifer in which the mine is situated.

4.1.5 Geological and geohydrological setting

From west to east the Lower Vaal WMA is underlain by the following geological lithologies as can be seen in Figure 4-3:

- Kalahari group: Sand, calcareous sandstone, clay, gravel
- Ecca Group: Shale; intruded by dolerite dykes and sheets
- Dwyka formation: Tillite with subordinate sandstone, mudstone, shale; intruded by dolerite dykes and sheets
- Granite gneiss
- Groblershoop group: Schist, meta-quartzite, metalava
- Volop group: Subgreywacke, quartzite, conglomerate, shale
- Mapedi, Lucknow and Hartley formations: Andesite, tuff, conglomerate, shale, quartzite, limestone
- Ongeluk Formation together with overlying Voëlwater and underlying Makganyeni and Gamagara Formation: Andesite, dolomite, jaspilite, lava, diamictite, sandstone, quartzite, conglomerate
- Campbell Group and Vryburg Formation: Dolomite, dolomitic limestone, chert, shale, siltstone, quartzite, andesite; diabase / dolerite dykes
- Giquatown Group: Mudstone, iron formation, riebeckite, jaspilite; diabase / dolerite dykes
- Nelspruit, Dalmein, Hebron, Halfway House, Goudplaats and intrusives: Granite, granodiorite, tonalite, gneiss, migmatite
- Ventersdorp Supergroup, Klipriviersberg, Zoetlief, Amalia, Hartswater and Sodium Groups: Andesite, quartz porphyry, dacite, rhyolite, trachyte, ignimbrite, tuff, agglomerate, volcaniclastics, conglomerate, sandstone, arkose, quartzite, shale, chert
- Mashashane and Mashishimale Suites; Baderouke, Hugomond, Lekkersmaak, Matlala, Matok, Moletsi, Palmi: Granite, biotite-muscovite granite; diabase / dolerite dykes

- Ecca Group: Shale, sandstone; intruded by dolerite dykes and sheets
- Dominion Group and Witwatersrand Supergroup: Andesite, quartz porhyry, quartzite, shale, conglomerate
- Kameeldoorns Formation: Conglomerate and shale
- Malmani Subgroup, Assen and Black Reef Formations: Dolomite, chert, subordinate quartzite, conglomerate, shale; diabase and syenite dykes and sills.

A comparison of the geology and the borehole distribution indicates the boreholes are not concentrated along the dolomite that is normally expected except in the Reivilo, Vryburg and Kathu areas(Figure 4-4).

4.1.6 Groundwater use

The National Groundwater Database was consulted to obtain hydrocensus information for the Lower Vaal. The information was compiled on the GIS and the results are presented in Figure 4-5. From the NGDB data 17124 boreholes were obtained with water use data (Figure 4-6). The main groundwater use is the following, 22% of the boreholes are used for agricultural and domestic purposes simultaneously, 6% are used for irrigation only, 44% are used for stock watering only and 25 % are used for domestic purposes. The remaining 3 % are divided into domestic garden use (1.85%), nature conservation (0.07%), public (1.26%), industrial commercial (0.09%), industrial (0.02%), industrial mining (0.4%) and power generation (1 borehole).

4.1.7 Water levels

The depth to water level in an aquifer is dependant on the groundwater inflows and outflows. Recharge from rainfall varies from one aquifer type to another and is dependant on the intensity, duration and frequency of rainfall. During a drought period, some aquifers have the ability to supply water to both surface streams and groundwater users. This use or volume must be released from the aquifer’s storage volume during low or no recharge periods.

In the Lower Vaal WMA, the average water level is 23 m below ground level and 1158m above mean sea level (Figure 4-7).

Groundwater flow mirrors the topography with a >90% correlation between topographic and piezometric head elevations. This correlation can be used to predict groundwater flow with confidence over most of the catchment. It also supports the approach of the study to make use of surface water catchments to evaluate and manage the groundwater component (Figure 4-8)

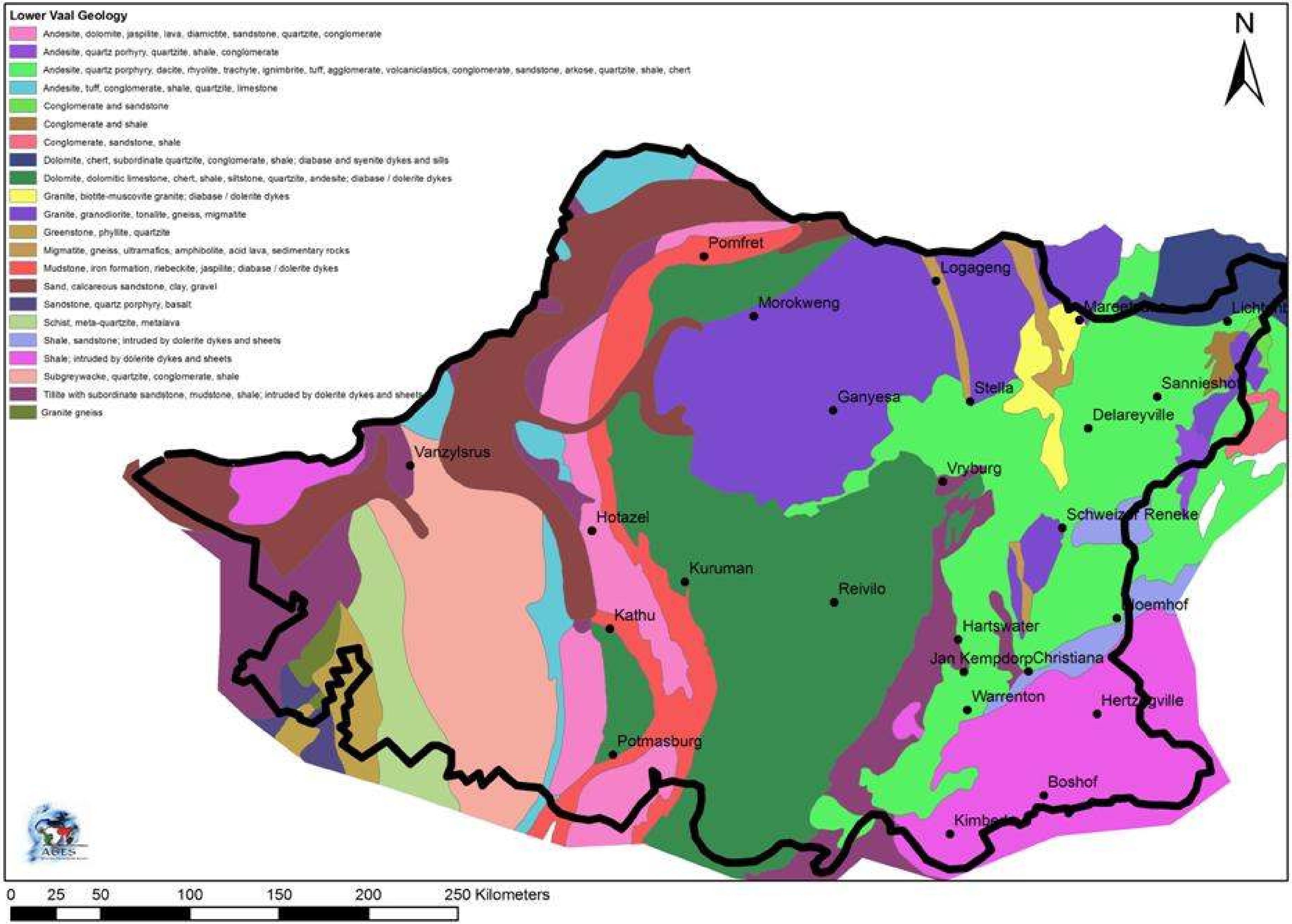

Figure 4-3 Lower Vaal WMA simplified geology

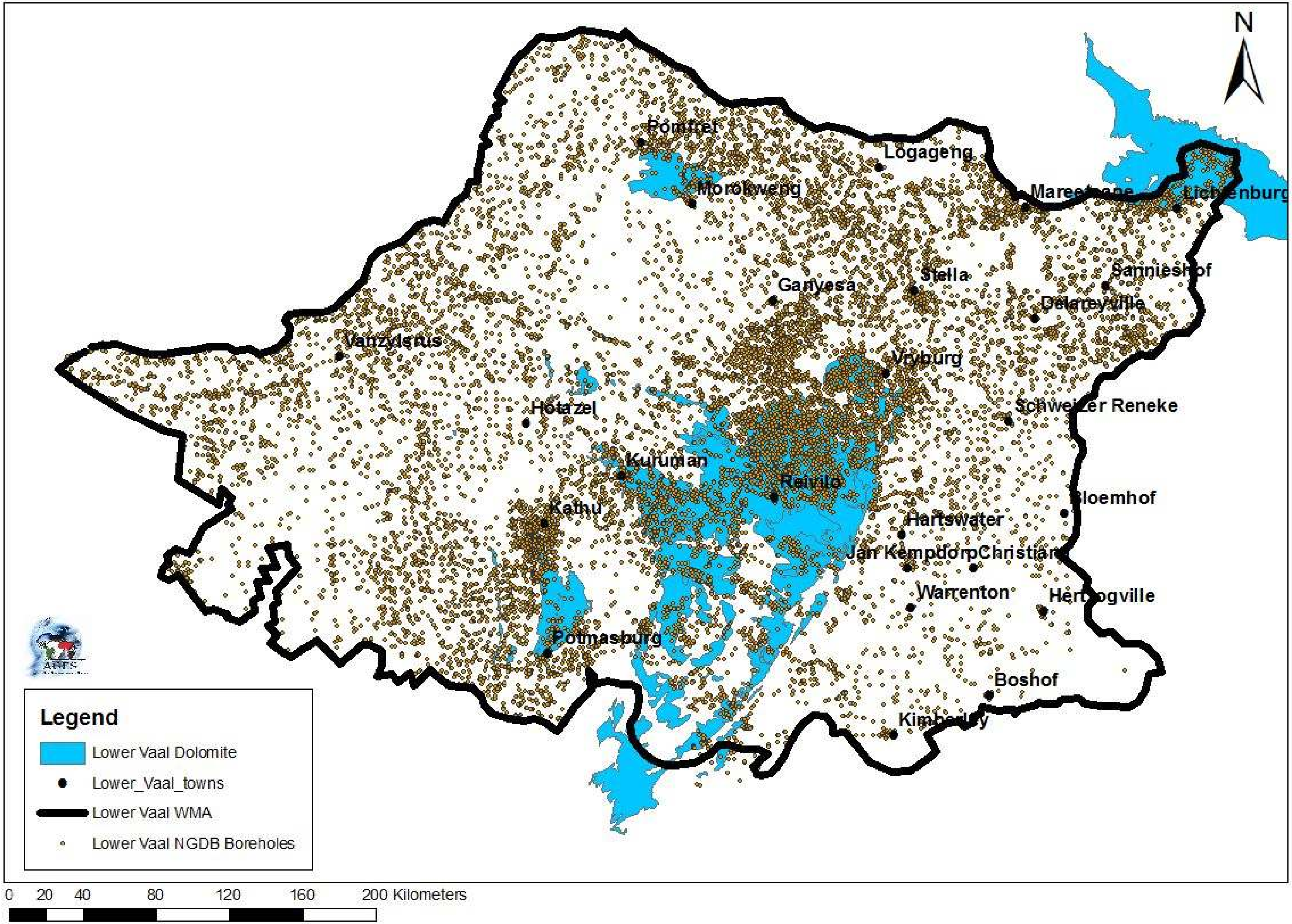

Figure 4-4 Lower Vaal WMA NGDB borehole distribution

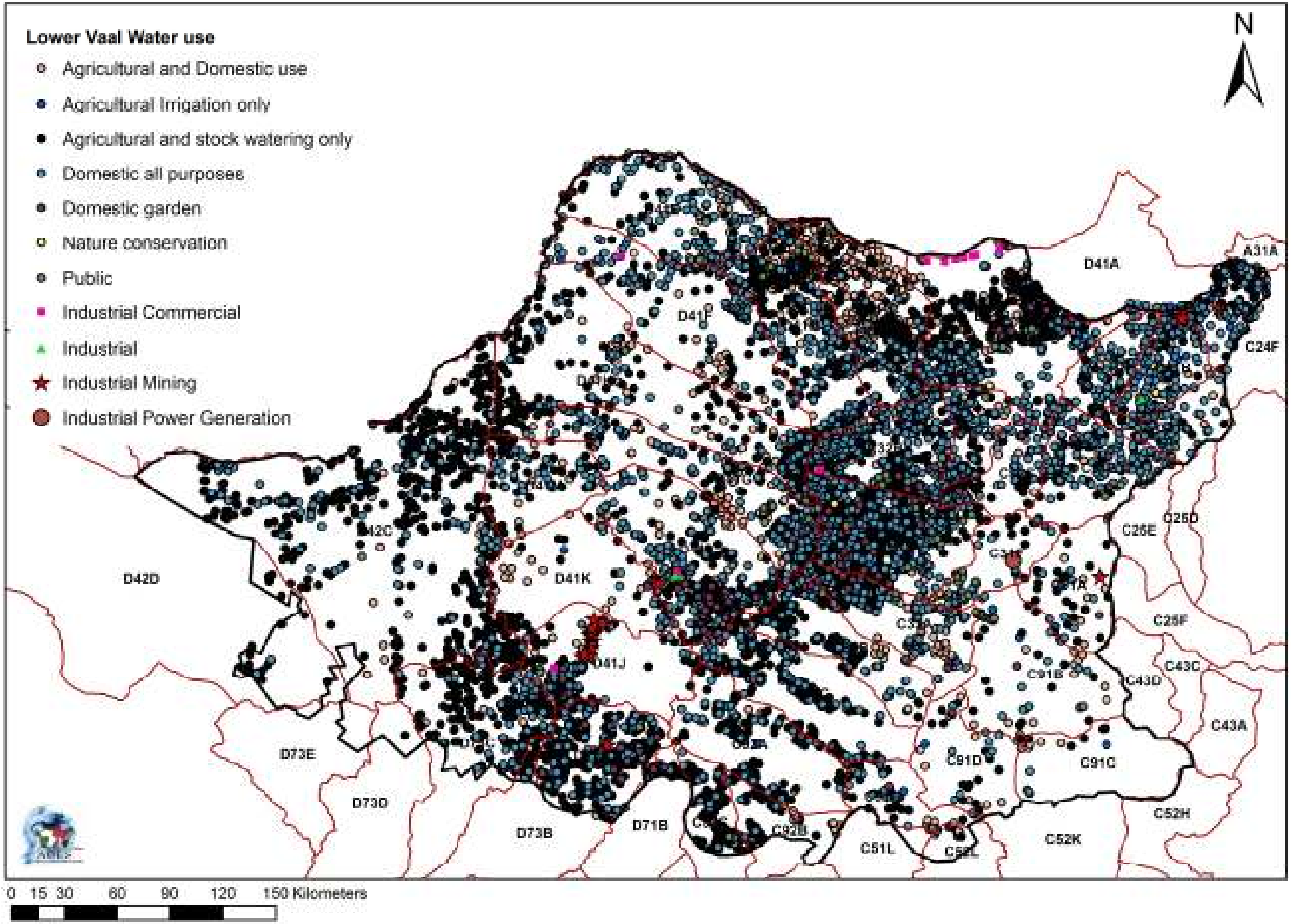

Figure 4-5 Lower Vaal WMA groundwater use

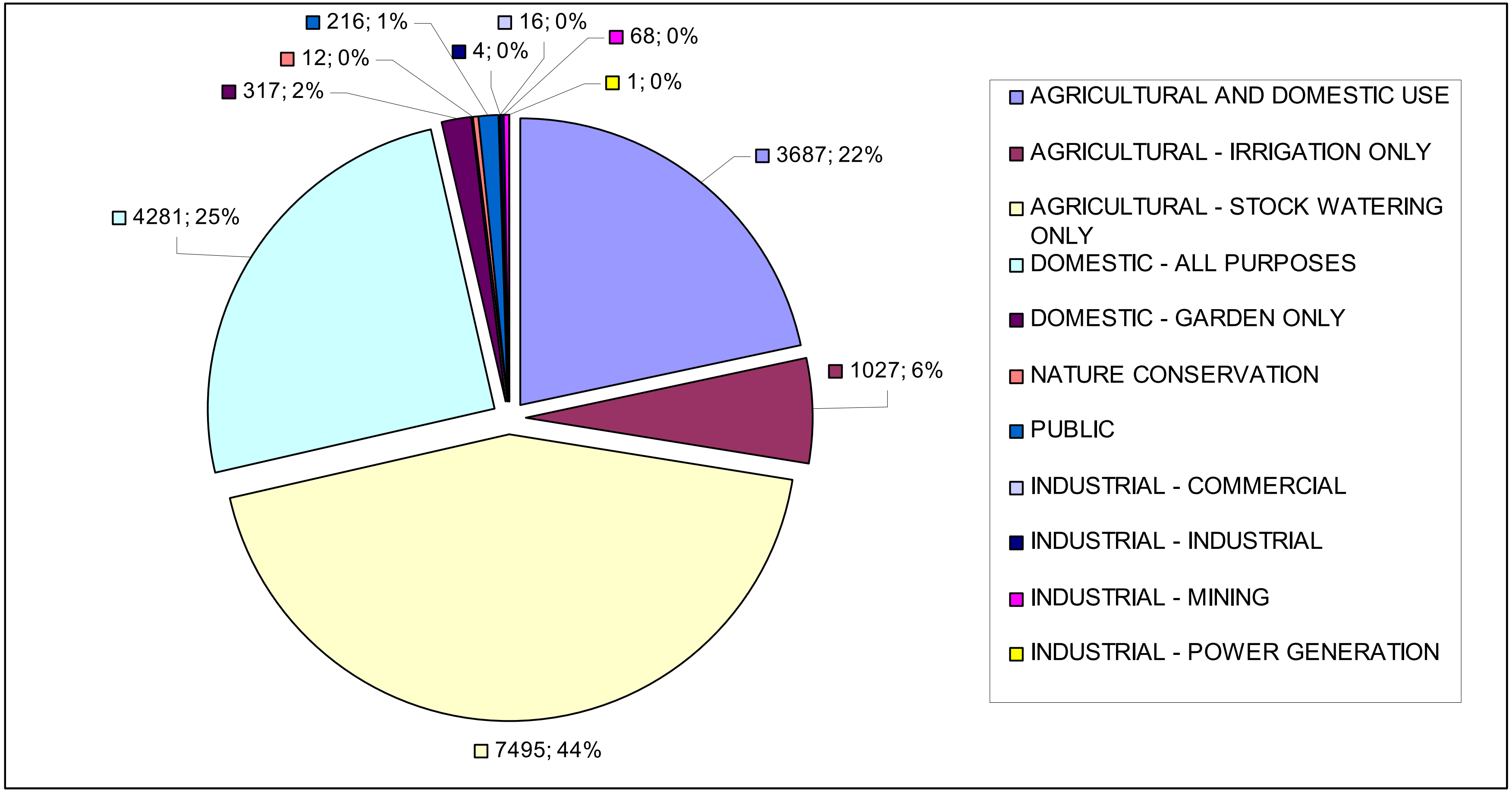

Figure 4-6 Pie chart of Lower Vaal WMA groundwater use

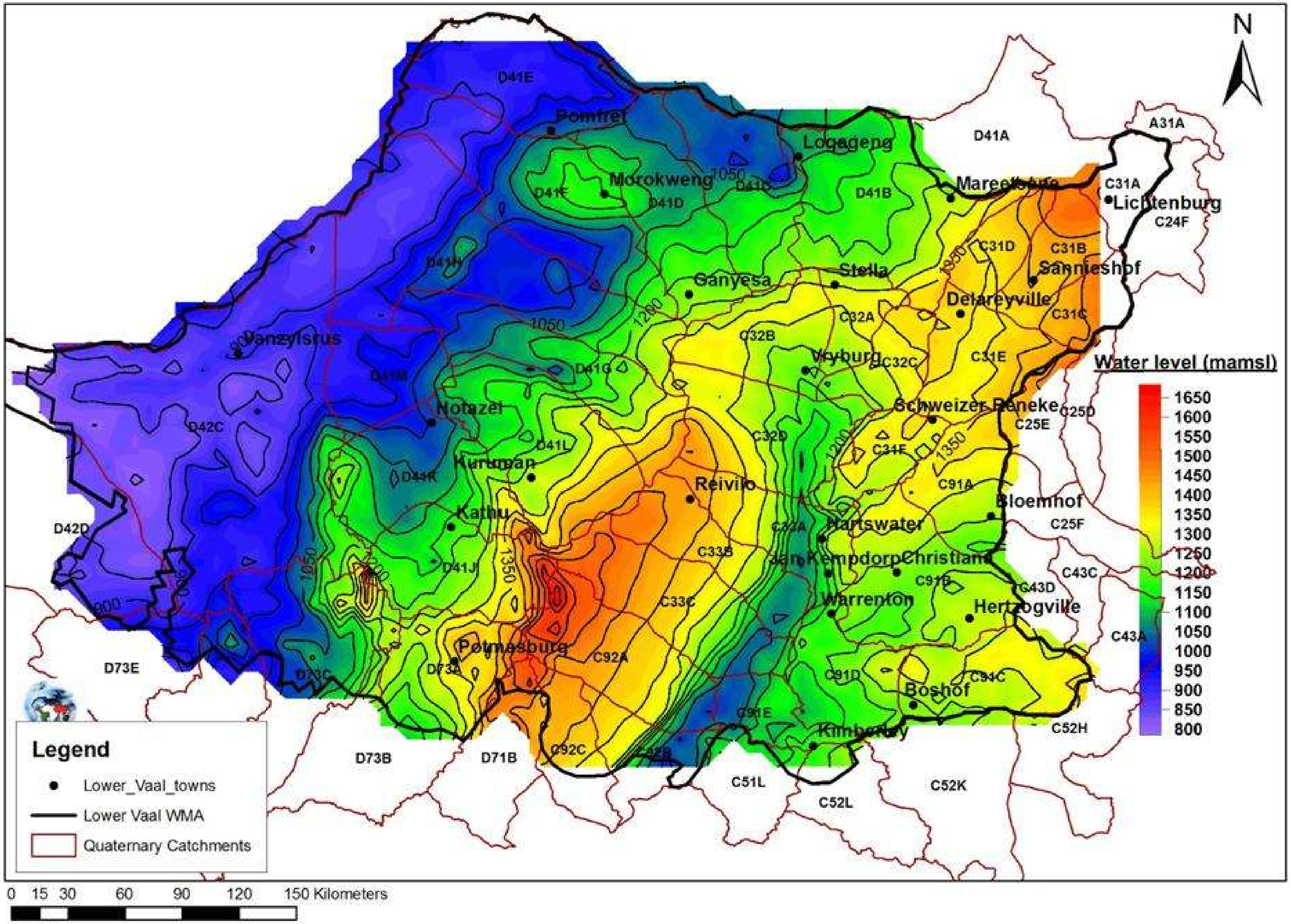

Figure 4-7 Lower Vaal WMA groundwater level contour map, meters above mean sea level (mamsl)

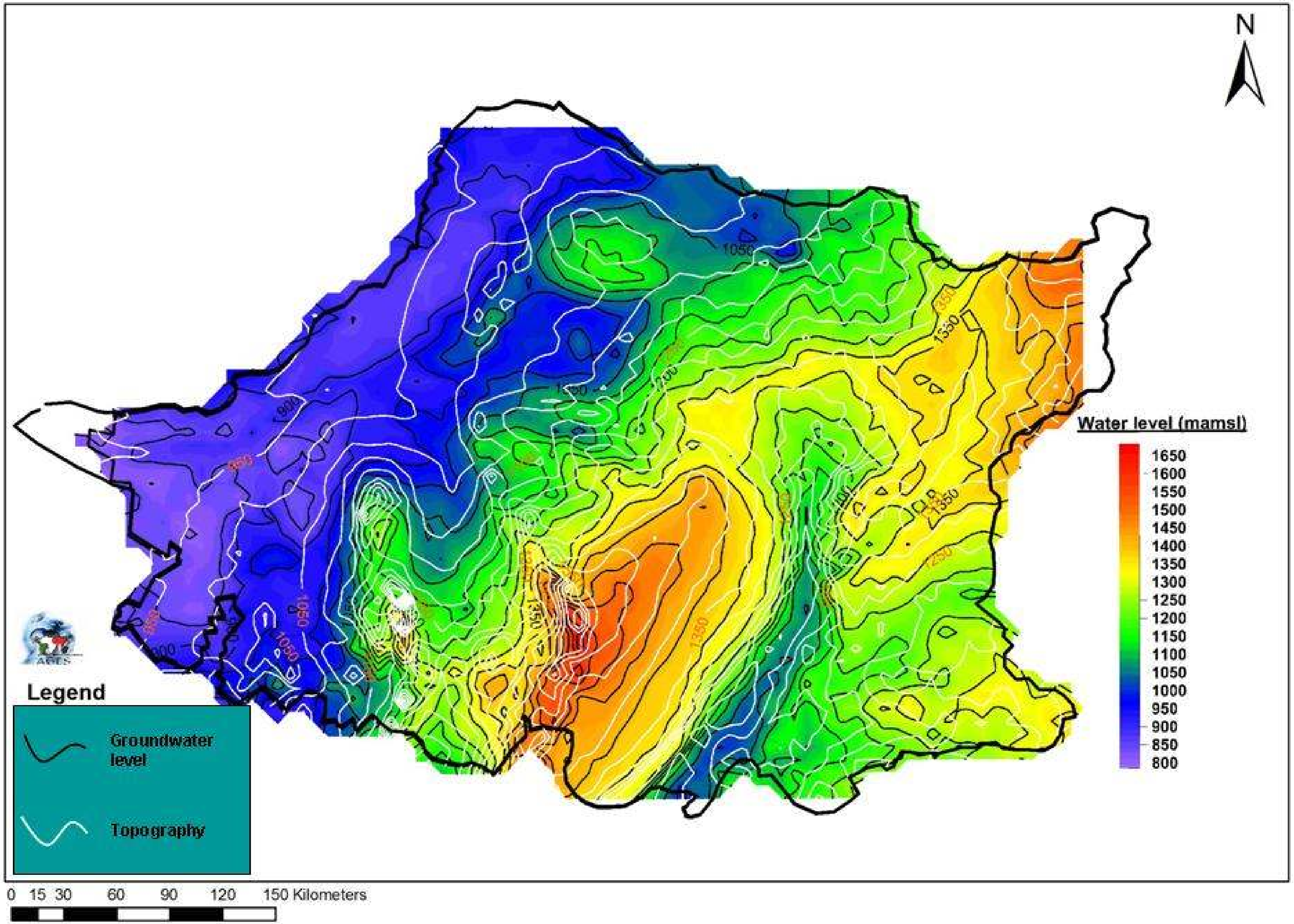

Figure 4-8 Topography contours (mamsl) overlying groundwater level contours (mamsl)

4.1.8 Water quality

The NGDB water quality data, samples collected from 2000 to present was used to compile pie charts of each monitoring point in a specific quaternary catchment. The aim is to identify representative monitoring points in each quaternary catchment to get an even spread of water quality data over the WMA.

The following pie charts are examples of water quality data in Quaternary catchment C31A of monitoring points on the farms Klipbankfontein, Roodepan and Rooipan.

The DWAF water quality guidelines for drinking water was used to class the different parameters measured of each sample.

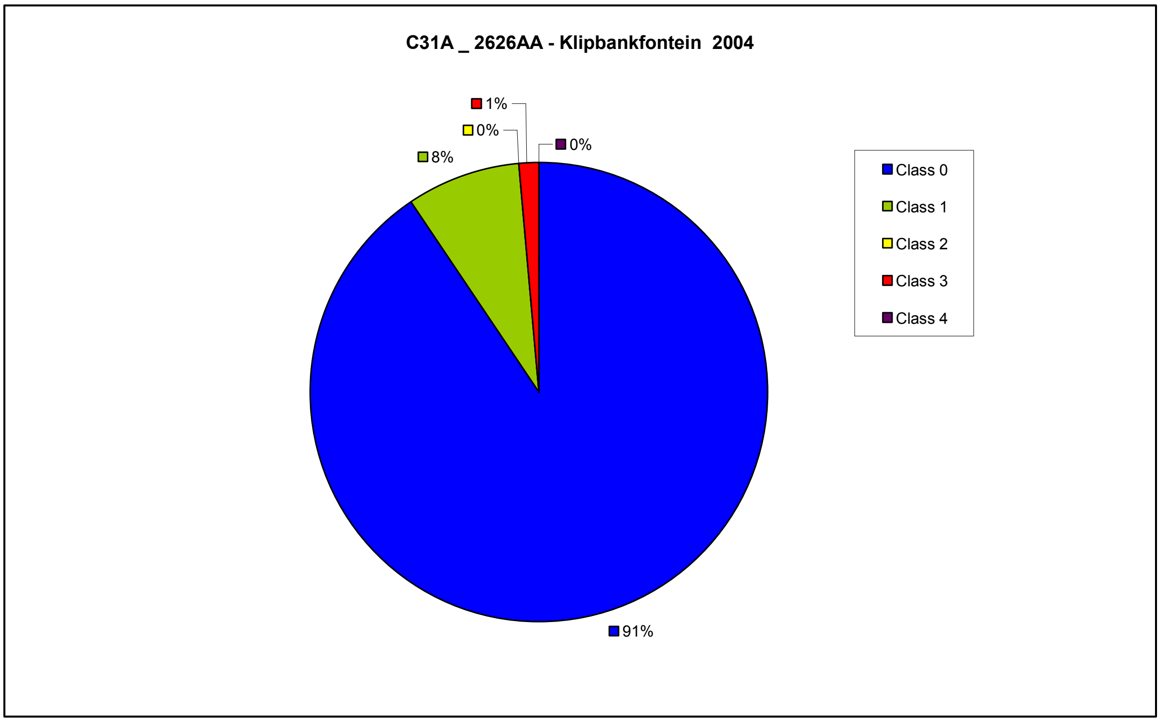

Figure 4-9 Water class chart of monitoring points on Klipbankfontein

Class 1 results were due to:

High levels of calcium, EC and nitrate reflected at monitoring point KLIPBANKFONTEIN - KM217 during February 2004.

High level of EC observed at monitoring point KLIPBANKFONTEIN - KM223 during February

2004.

High nitrate levels reflected in monitoring point KLIPBANKFONTEIN - KM151 during January 2004.

Class 3 results were due to:

High nitrate levels observed in monitoring point KLIPBANKFONTEIN - KM200 during January 2004.

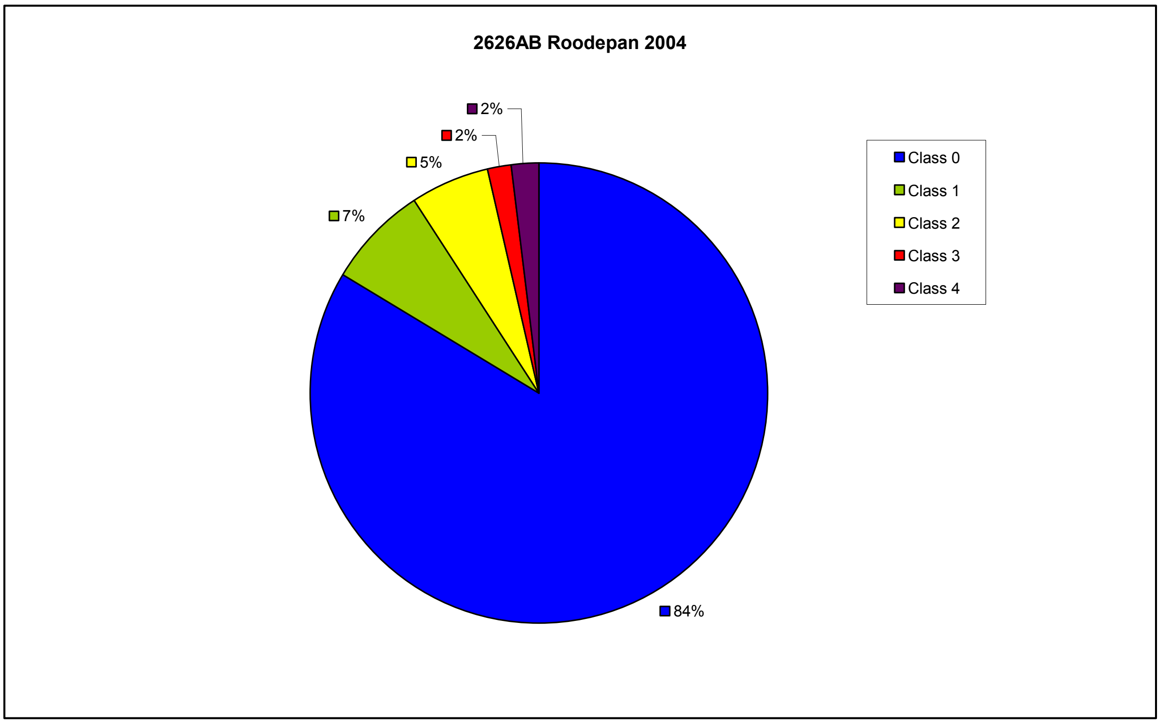

Figure 4-10 Water class chart of monitoring points on Roodepan

Class 1 results were due to:

High levels of EC reflected in monitoring point's ROODEPAN - RO4 and ROODEPAN - RO37 during January 2004.

High levels of calcium reflected in monitoring point's ROODEPAN - RO37 and ROODEPAN - RO6.

Class 2 results were due to:

High levels of nitrate and nitrite as nitrogen in monitoring points ROODEPAN - RO2, ROODEPAN - RO6 and ROODEPAN - RP1 during January 2004

Class 3 results were due to:

High levels of nitrate and nitrite as nitrogen in monitoring point ROODEPAN - RO4 during January 2004

Class 4 results were due to:

High levels of nitrate and nitrite as nitrogen in monitoring point ROODEPAN - RO37 during January 2004. This will cause possible chronic risk to some babies

The samples were analysed for the macro chemistry and the results are displayed Figure 4-11

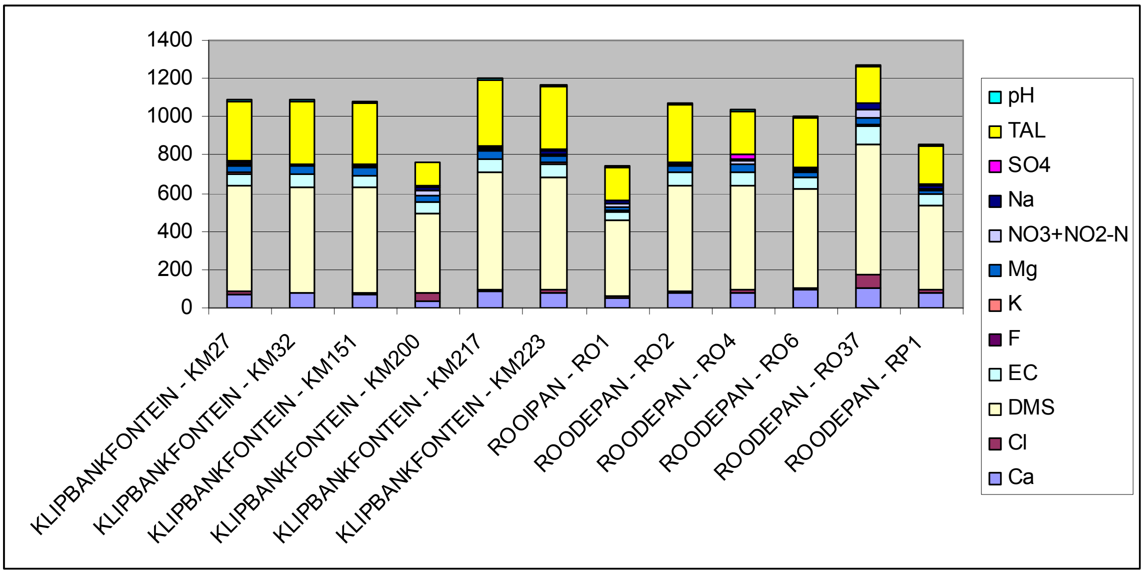

Figure 4-11 Macro chemistry of sample KM27 on Klipbankfontein

DMS and TAL dominated the most in the macro chemistry, whereas sulphate, fluorite and potassium were the least dominant.

4.2 Potentially stressed areas (Focus Areas)

The stressed areas were identified as quaternary catchments and aquifers where the outflow may exceed 80% of the recharge. From existing data the following areas are identified as potentially stressed and will require additional management strategies. These areas are also termed Focus areas and are described below.

4.2.1 Dolomite Aquifers

The dolomitic aquifers have a strategic importance in South Africa. Unregistered and uncontrolled abstraction is the main threat to this type of aquifer. The surface water component that is derived from dolomite outflows must be appropriately managed. Quaternary catchments in the Lower Vaal WMA which are partially or fully underlain by dolomite are D41F, D41D, C31A, D41G, D41C, C32B, C32D, C32C, C33A, C33B, C33C, C92A,C92B, C92C, D73A and D41J(Figure 4-12). A groundwater yield model will be done for the dolomitic aquifers as a unit since the dolomitic aquifers does not comply to the normal quaternary catchment scenarios because water move freely between quaternary catchments in the dolomite and is not restricted to a specific quaternary catchment.

What will complicate the groundwater reserve determination of the dolomite is the compartmentalisation by the dolerite dykes. During a recent fly over of the WMA as part of the field verification the many dykes intersecting at right angles in the dolomite were obvious as shown in Figure 4-13.

4.2.2 Springs

According to the NGDB data base there are a limited number of springs in the WMA, from the air many springs were visible that are not in any data base or on the topographic maps. Springs are very vulnerable to groundwater abstraction and as shown in Figure 4-14, 9 of the 10 springs mentioned in the NGDB data for the Lower Vaal WMA are located on dolomite. The spring flow of the major springs will play an important role in the groundwater reserve determination using the GYM model.

The Kuruman eye in Kuruman is currently flowing at a rate of 20000 m^3/day. Several of the springs mentioned in the NGDB data need to be field verified.

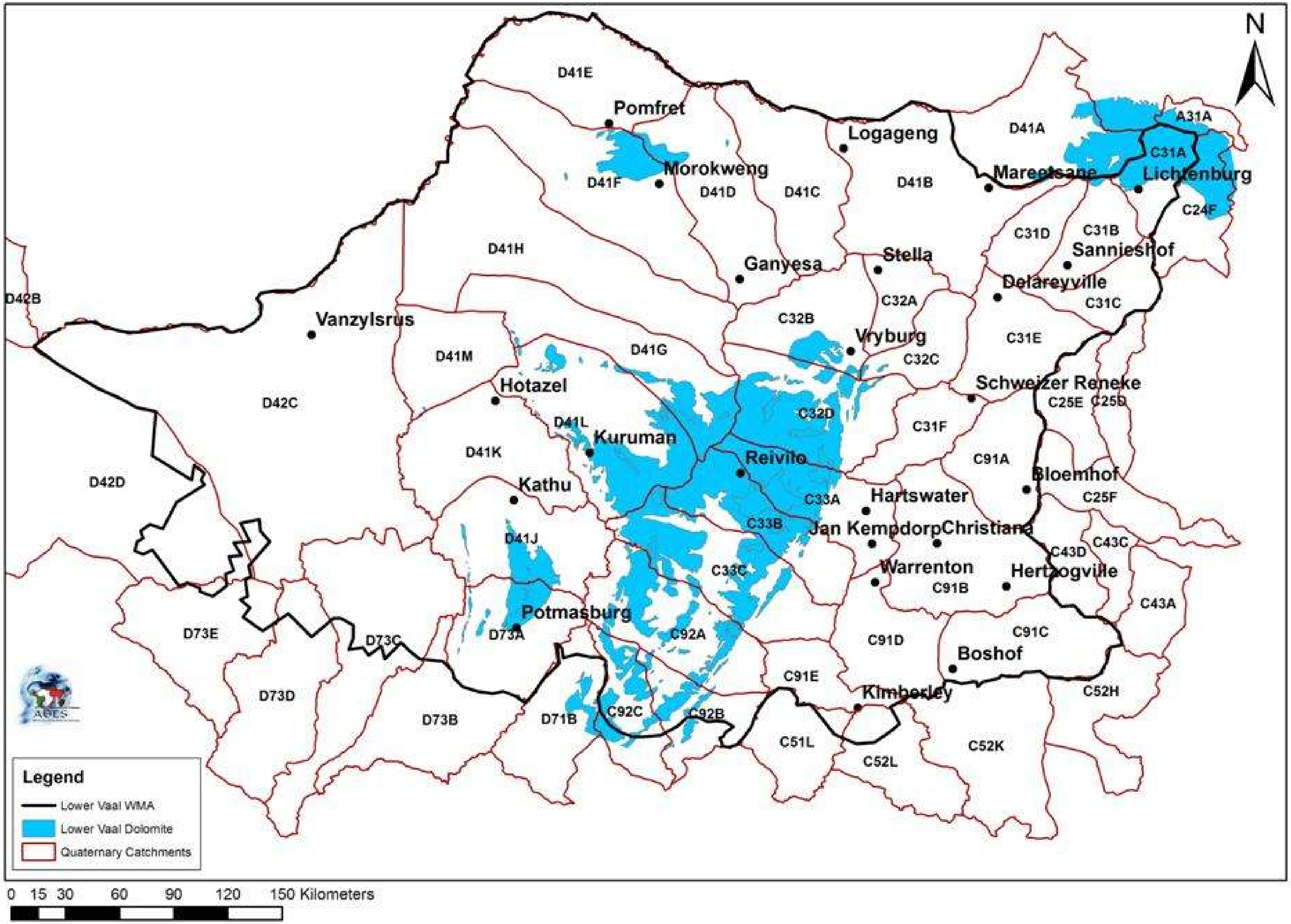

Figure 4-12 Lower Vaal WMA dolomite

Figure 4-13 Compartmentalisation of dolomitic aquifer by dolerite dykes

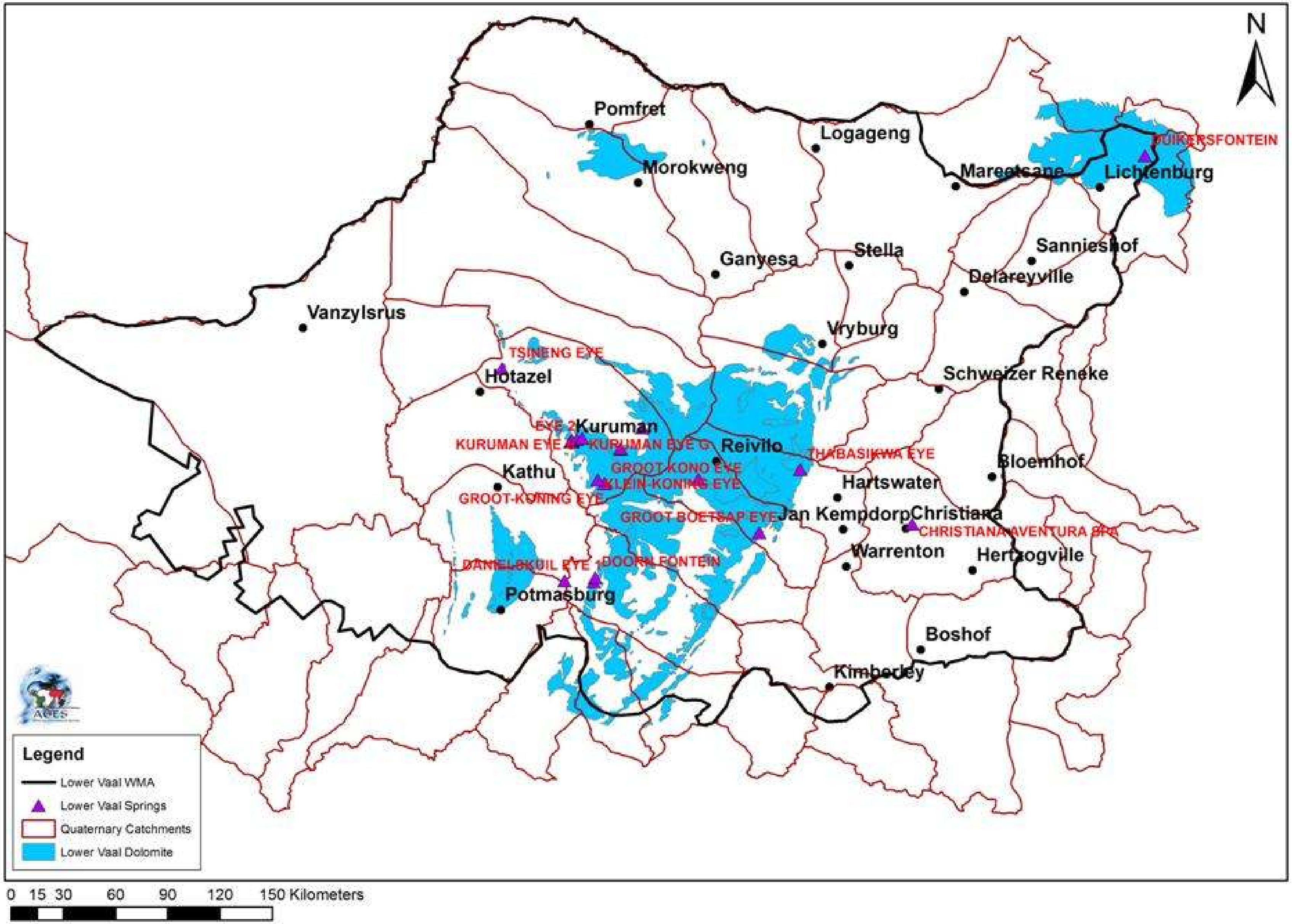

Figure 4-14 Lower Vaal WMA spring localities

4.2.3 Mining

Groundwater reserves may be influenced in catchments where mining is taking place on a large scale. Due to the nature of alluvial diamond mining it is impossible to take every small mining operation into account with the groundwater reserve determination. Several areas with large active mines were identified and special attention will be given to these catchments. The mining areas identified are the alluvial diamond mines around Barkley West, the open cast diamond mining in the kimberlite at Finch mine, mining operations around Kimberley, planned dewatering of an open cast mine at Reivilo and the extremely large open cast mine at Sishen. Information regarding several of the mines are still outstanding but will be incorporated in the model as soon as it is received.

4.2.4 Wetlands

The only major wetland in the Lower Vaal WMA is the Barberspan bird sanctuary halfway between Sannieshof and Delareyville (Figure 4-15) in quaternary catchment C31D. Many smaller wetlands or vlei areas are visible on the topographic maps and will also be incorporated in the groundwater yield model.

4.2.5 Agriculture

The agriculture and irrigation in the Hartswater, Jan Kempdorp area are of major importance, although the irrigation schemes make use of water coming from the Bloemhof dam via a canal system the recharge from the irrigation schemes will have an influence on the groundwater that must be taken into account. Although agriculture or irrigation schemes in the Lower Vaal WMA were thought to be of lesser importance except for the Hartswater scheme in the initial stages of the project it will have to be brought into consideration across the WMA specifically in the dolomitic areas since numerous centre pivots were seen in the dolomitic areas as well as off the dolomite during the fly over that are not recorded on any maps. A detailed study was made of catchment C31A to illustrate the importance of irrigation in a groundwater reserve determination.

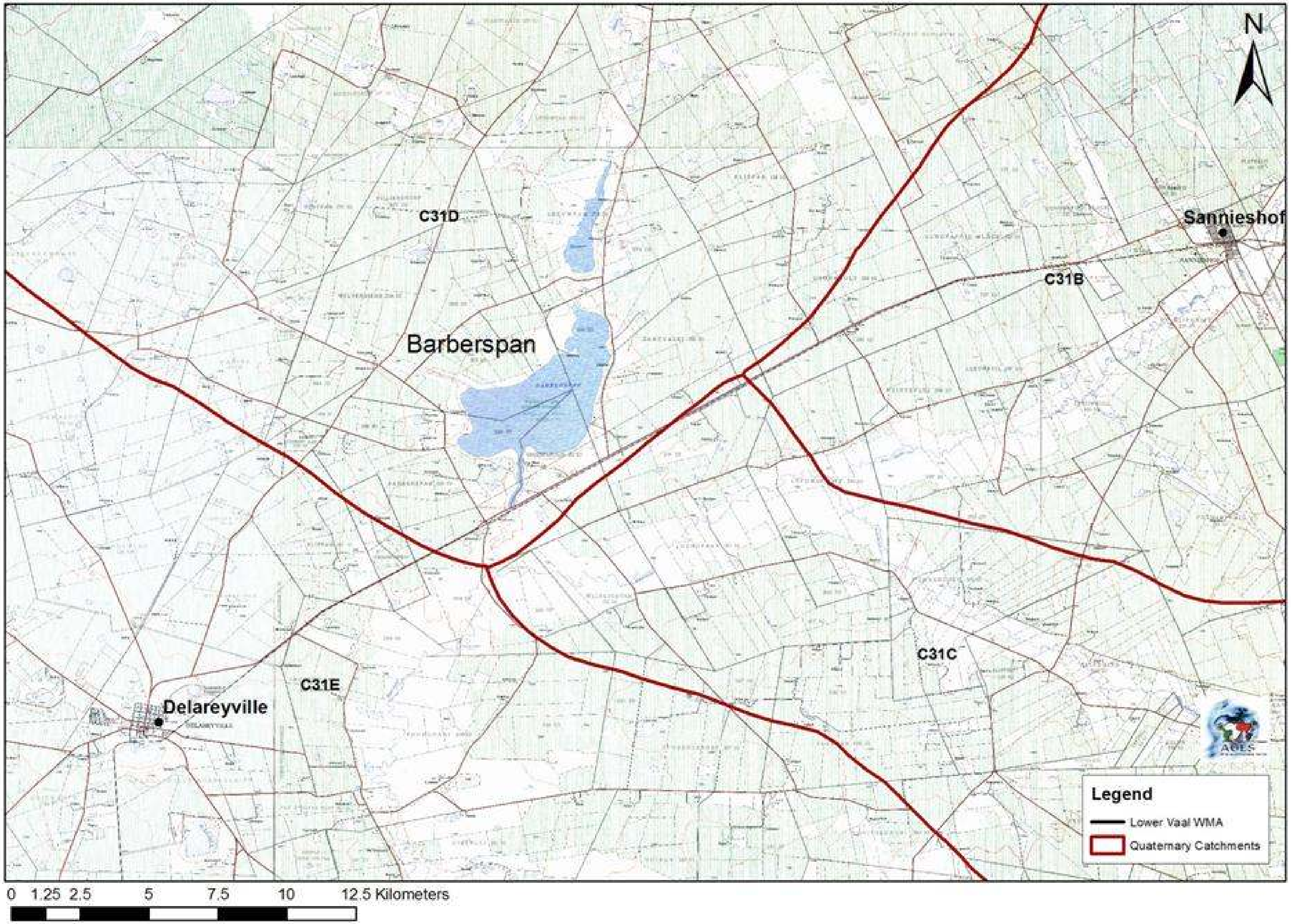

Figure 4-15 Barberspan wetland locality map

5 GROUNDWATER YIELD MODEL

The Groundwater Yield Model (GYM) has been developed by AGES and aims to quantify the groundwater balance on quaternary catchment scale based on assurance levels. In the steady state system, the inputs to the groundwater from recharge will equate the outputs from the groundwater to the surface water system in the form of base flow and losses to evapo-transpiration.

The general approach for assessments of water balances on a regional or local scale is to develop either numerical groundwater flow models[1] or analytical water balance models. Both these approaches have limitations as it cannot provide assurance levels.

The aim of the investigation was to provide assurance levels for the groundwater that is available[2]. Given the available resources and project scope, the scale of the area is too large for the application of numerical models. Analytical models could be applied on this scale but would not yield assurance levels

5.1 Data Sources

The input data was generated with Geographical Information Systems (GIS) from the National Groundwater Database (NGDB). For the study area, the following digital shape file information was consulted:

- population information from Stats SA from the 2001 population census;
- NGDB data containing water level, water quality, water use and yield records;
- land use including irrigation and national parks from the Environmental Potential and Tourism Atlas (ENPAT,2001);
- mining information from the DWAF digital dataset and internet research;
- dams, pans and wetlands in the DWAF digital dataset as well as measured on the 1:50 000 topographic maps and Google images;
- quaternary catchment and rainfall information from the GRDM, GRAII, SAGDT, NGDB and Weather SA datasets

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[1] Numerical models have the advantage that it can yield detailed spatial and temporal information but it is not feasible to develop e.g. 94 numerical models for the Inkomati WMA quaternary catchments. If numerical models has to be run stochastically to determine assurance levels, it will take even longer. Hence the approach was followed with the GYM that simulates each quaternary catchment as a single cell. Stressed catchments can be identified in this way for further assessment using numerical models.

[2] The assumption was made that if groundwater is abstracted, base flow is reduced. In reality, there will be lag times. Numerical models would be required to determine lag times, which can be done for selected stressed aquifers (focus areas). This assumption is conservative and was made as a precautionary approach..

- Communities and settlements from DWAF digital dataset (2005) for municipalities, local districts and settlements.

5.2 Validity / Data quality

The data quality of the NGDB borehole data set is expected to be poor to moderate, as a result of its age and the lack of field validation. Due to the model usage for planning purposes, a conservative approach was followed, where it was assumed that all boreholes are in use and abstract water according to its purpose. Boreholes for farm use (domestic and livestock) were assumed to use 0.5 ℓ/s for 24 hours per day. In reality, such boreholes would operate for 8 to 12 hours per day. The model would therefore allocate more water where uncertainties occur.

5.3 Data capture method

For each quaternary catchment, the following data was collected and the reasons for assumptions made are detailed below:

Table 2 Data input logic

Aquifer parameter	Comment
Aquifer surface area	This is the quaternary catchment area obtained from the Quaternary catchment data
Aquifer thickness	Average water level for catchment if dataset has more than 20 WL measurements that are trustworthy; if not, aquifer thickness = 40m
Aquifer storage co efficient	0.1% used by default, 0.1% = 0.001 storage.
Aquifer porosity	Default to 1%
Catchment surface water run off coefficient	Default is 0 (not applicable)
Aquifer dead storage level	This is 10% to 20% of aquifer thickness

Abstraction	Comment
Number of boreholes	NGDB and GRIP data. Boreholes not used for livestock farming purposes e.g. mining or water supply wellfields for irrigation
Average usage per year (m^3)	Abstraction amount
Total usage	Calculated

Farming	Comment
Number of Farms	Include all farms within the catchment. Select by location and use number of cadastral farms (ENPAT data)
Average usage per year (m^3)	Use 0.5 L/s or 15 800 m^3/a per farm
Total usage	Calculated

Alien Vegetation (in riparian zone)	Comment
Area (m²)	Land use data
Usage mm/a	600mm/a
Total usage	Calculated

Mean annual evaporation	Comment
Area (m²)	Quaternary catchment area
Evaporation mm/a	Dependant on climate zone
Total usage	Calculated

Wetlands	Comment
Area (m²)	Land use data
Area %	Calculated
Usage mm/a	1500 mm/a use by wetland
Total usage	Calculated

Mining	Comment
Number of mines	These are mines which dewater and thereby reduce the aquifer supply volume; only "active" mines from the mine dataset from CGS
Average usage m^3/mine/year	1 200m^3/d (43 2000 m^3/a) for PGE, Cr, Fe and Au mines. 200m^3/d (72 000 m^3/a) for the rest.
Total usage	Calculated

Community water supply	Comment
No of communities	GIS data. Extra communities/water use will be accounted for in the farms section
People/community	Population data used from 2001 census, this into the area of the municipality multiplied by the area of the catchment (people/km² * area) . This is the BHN amount.
Water use (Litres/person/day)	25 L/person/day is the norm; 60 L/person/day is used where population <10 000
Total usage	Calculated

Recharge	Comment
Aquifer recharge	Recharge dependant on geology.
	Dolomite <50% area - 4%
	Dolomite >50% area - 6%
	Dolomite <50% area + major regional structure - 8%
	Dolomite >50% area + major regional structure - 10%
	Quartzites, shales, volcanics - 2%
	Quartzites + alluvium / recharge zone (e.g. mountain range) - 3%

Irrigation	Comment

Area (m²)	Land use data
Usage mm/a	1200 mm/a
Total usage	Calculated

Dam Seepage	Comment
No of dams	Use the dams on the DWAF Dams shape file and calculate the total area
Average seepage (mm/y)	120 mm/a continues seepage
Average dam seepage size	Size of dam as average
Total usage	Calculated

5.4 The groundwater reserve

The determination of the reserve volume or protection volume entails the calculation of the groundwater contribution to base flow and thus the Instream Flow Requirements (IFR) as well as the portion of groundwater which must be allocated for basic human need requirements (BHN). The latter is relatively simple to determine as population data is readily available. The determination of the IFR, is the forte of surface water scientists and hydrologists. It is generally not determined on a quaternary catchment scale, but for a river section which may have multiple ecological, topographical and flow patterns and therefore different minimum flow requirements for the preservation of the environment.

The determination of the groundwater reserve for an aquifer unit or management unit is required before licensing of groundwater use can occur. The portion of the recharge which must be put aside for the protection of the aquifer and the surface water ecosystems which are reliant on groundwater base flow is the priority of the National Water Act (1998).

In the context of the groundwater yield model, an *indication* of the reserve is given as a proportion of recharge. This *indication* is dependant upon the accuracy of the recharge estimation and the estimation of the required base flow volume. The aquifers, where a detailed groundwater model was done are the same ones that require accurate reserve estimation for management purposes. The groundwater in storage is expected to comprise 60% of the aquifer thickness.

In drought conditions, groundwater abstraction uses the storage component of the aquifer. This should however not continue indefinitely. For the purpose of this study, the point to which the storage can and is utilised in the natural system, and from which it can recover, is termed the dead storage level.

In the current groundwater yield model, the dead storage level is given at 10% of aquifer thickness. Aquifer thickness default parameter was set at 38m in this model for all aquifers where the aquifer thickness was not yet determined in the catchment and therefore the dead storage level will be 3.8 m below the current, rest water level in the aquifer. The groundwater reserve portion should be allocated from this 10% or 3.8 m and can then be represented as a percentage of recharge.

In the current study a transient groundwater yield model was also done for 2 of the catchments as an example of the long term effects of drought and rain cycles on the groundwater level of an aquifer. The 2 catchments were C31A and C91C. C31A

5.5 Results of the Groundwater Yield Model

5.5.1 Surface water and groundwater base flow comparisons

It is important to note that the GYM results do not display actual values. Due to conservatism that was included based on the precautionary principle, it reflects groundwater volumes allocated to water uses. The actual water availability will be higher than what the model indicates as volumes were allocated e.g. the basic human need component.

The model still needs to be refined to be able to compare the GYM base flow volumes with the Vegter, DWAF volumes.

The differences that may occur in volumes can be attributed to the fact that groundwater evapo-transpiration losses and the basic human need component was not taken into consideration by Vegter.

Evaporation plays a critical role in the groundwater reserve determination studies as was seen during the fly over of the WMA. An example of evaporation is shown in Figure 5-1 as white salt deposits along the river edge.

The difference in these base flow volumes can partially be explained by uptake from riparian vegetation. Riparian vegetation often accounts for large reductions in groundwater volumes by intercepting seepage in the riparian zone.

It should be noted that GYM has a 95% assurance level for recharge determination using variable rainfall (see next section).

Figure 5-1 Lower Vaal evaporation along river

5.5.2 Groundwater balance results

According to the preliminary Groundwater Yield Model and interpretations from the results obtained, the regional groundwater balance calculations of the Lower Vaal WMA indicate that overall there is a surplus of groundwater in the WMA due to inflow[3] exceeding outflow[4]. The total volume of groundwater recharge is in the order of 1543 Mm^3/a.

Apart from groundwater evapo-transpiration losses, which account for up to 70% of the groundwater flow losses, the biggest water users are community water supply and irrigation and mining in certain catchments. The model input need to be refined because several parameters are still outstanding and default values were used and many of the parameters used need to be verified and cross checked where possible with other data sources.

In Figure 5-2 are the water balances for the 34 quaternary catchments (Preliminary results that will change with more and better data).

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[3] Inflow is defined as the total volume of water entering the groundwater system by rainfall recharge and inflow from dam seepage.

[4] Outflow is defined as the total volume of water leaving the aquifer unit through base flow to rivers, spring flow, evapo-transpiration and borehole abstraction.

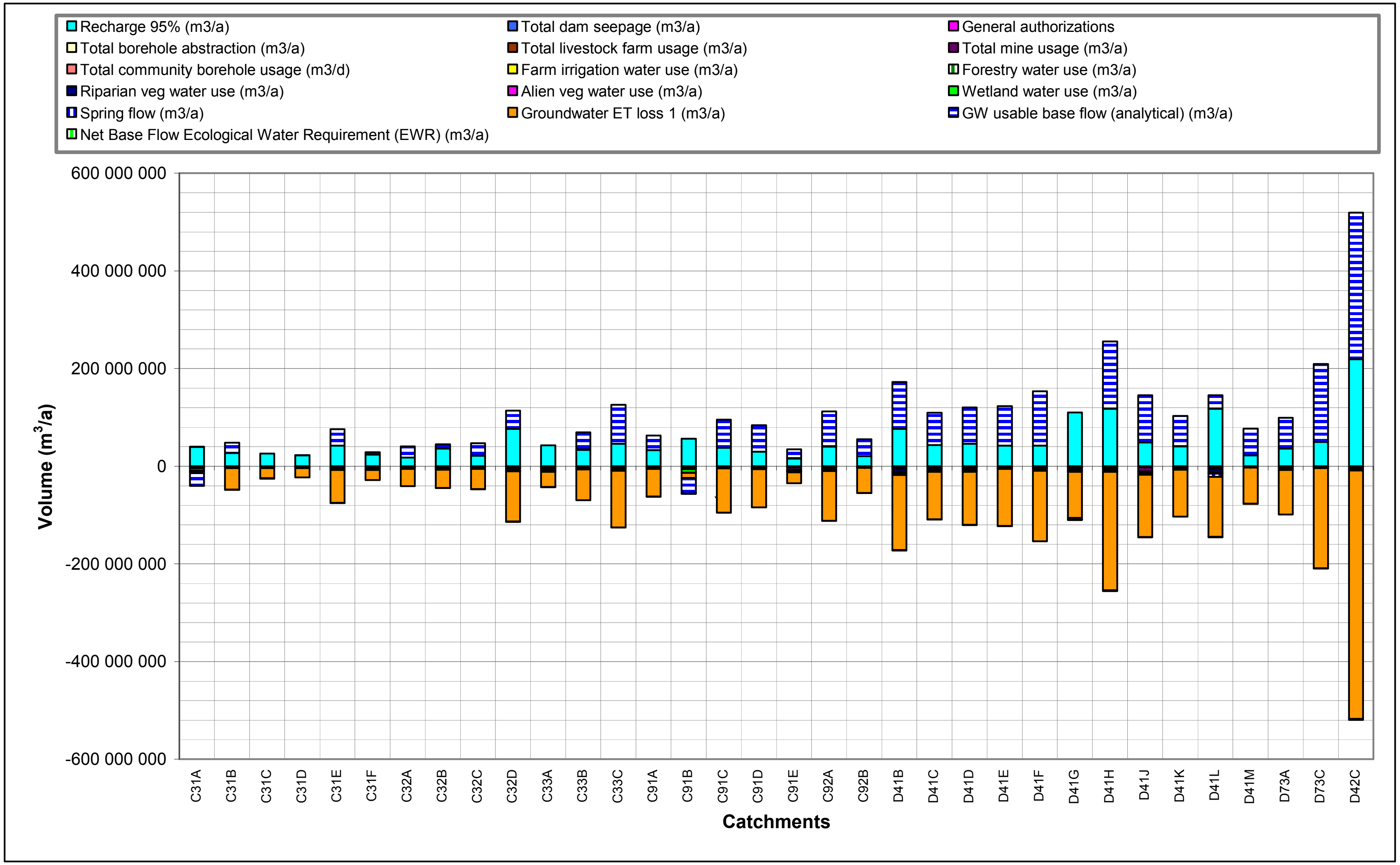

Figure 5-2 **Preliminary water balance for the Lower Vaal WMA**

5.5.3 Stressed quaternary catchments

Based on the groundwater flow balance assessment, the quaternary catchments were classified (Table 3) based on the ratio of outflow/inflow, before groundwater evapo-transpiration losses or actual base flow takes place (refer to Appendix A on the sequence of flow terms).

From the assessment, the groundwater component in the Lower Vaal WMA is mostly unstressed[5] . There are 4 (12 %) stressed catchments with classification as follows (Table 4, Figure 5-3)[6]:

- Class 1: High stress level = 1;
- Class 2: Medium stress level = 0;
- Class 3: Low stress level = 3;

Table 3 Groundwater stress level classification for quaternary catchments

Class1	High	80%	100%
Class2	Medium	60%	79%
Class3	Low	40%	59%
Not stressed		0%	39%

Table 4 Lower Vaal WMA quaternary catchment stress status

Quaternary catchment	C31A	C31B	C31C	C31D	C31E	C31F	C32A	C32B	C32C
Stressed status Net + EWR Base flow as % of inflow	25%	15%	14%	18%	18%	31%	32%	19%	25%

Quaternary catchment	C32D	C33A	C33B	C33C	C91A	C91B	C91C	C91D	C91E
Stressed status Net + EWR Base flow as % of inflow	13%	26%	19%	20%	17%	24%	11%	20%	76%

Quaternary catchment	C92A	C92B	D41B	D41C	D41D	D41E	D41F	D41G	D41H
Stressed status Net + EWR Base flow as % of inflow	25%	16%	23%	26%	24%	13%	23%	10%	10%

Quaternary catchment	D41J	D41K	D41L	D41M	D73A	D73C	D42C
Stressed status Net + EWR Base flow as % of inflow	35%	18%	19%	13%	22%	8%	4%

Quaternary catchment C31F is medium stressed possibly because of large areas under irrigation. Quaternary catchment C31A is also medium stressed possibly because of large areas under irrigation and centre pivots using groundwater from the fractured aquifer. Quaternary catchment D41J is most probably under medium stress because of the dewatering

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[5] Note that due to the high groundwater evapo-transpiration losses driven by evapo-transpiration, an aquifer may be unstressed and yet no or low base flows can be measured in the surface streams.

[6] There are some aquifers that are highly stressed on a local scale, which would not appear or are masked on the regional quaternary scale groundwater balances. Based on site specific information, these catchments are added in this section.

of the mine at Sishen. Quaternary catchment C91E is highly stressed because of the large population in the catchment which includes Kimberley, Barkly West and Delportshoop as well asmany mines around Kimberley and Barkly West.

5.5.4 Quaternary catchments – not stressed

There are 30 (88%) quaternary catchments in which the groundwater resource is not stressed. Additional development of groundwater resources is still possible in these catchments.

5.6 Transient model

A transient model was developed to illustrate the aquifer behaviour over long periods of time making use of variable rainfall and evaporation figures. Only the water level and baseflow fluctuations for Quaternary catchment C31A are illustrated below. The rainfall and evaporation figures for the past 100 years were used to predict the change in aquifer water levels (Figure 5-4) and the fluctuations in baseflow and baseflow requirement (Figure 5-5). The transient model is discussed in detail in Appendix A.

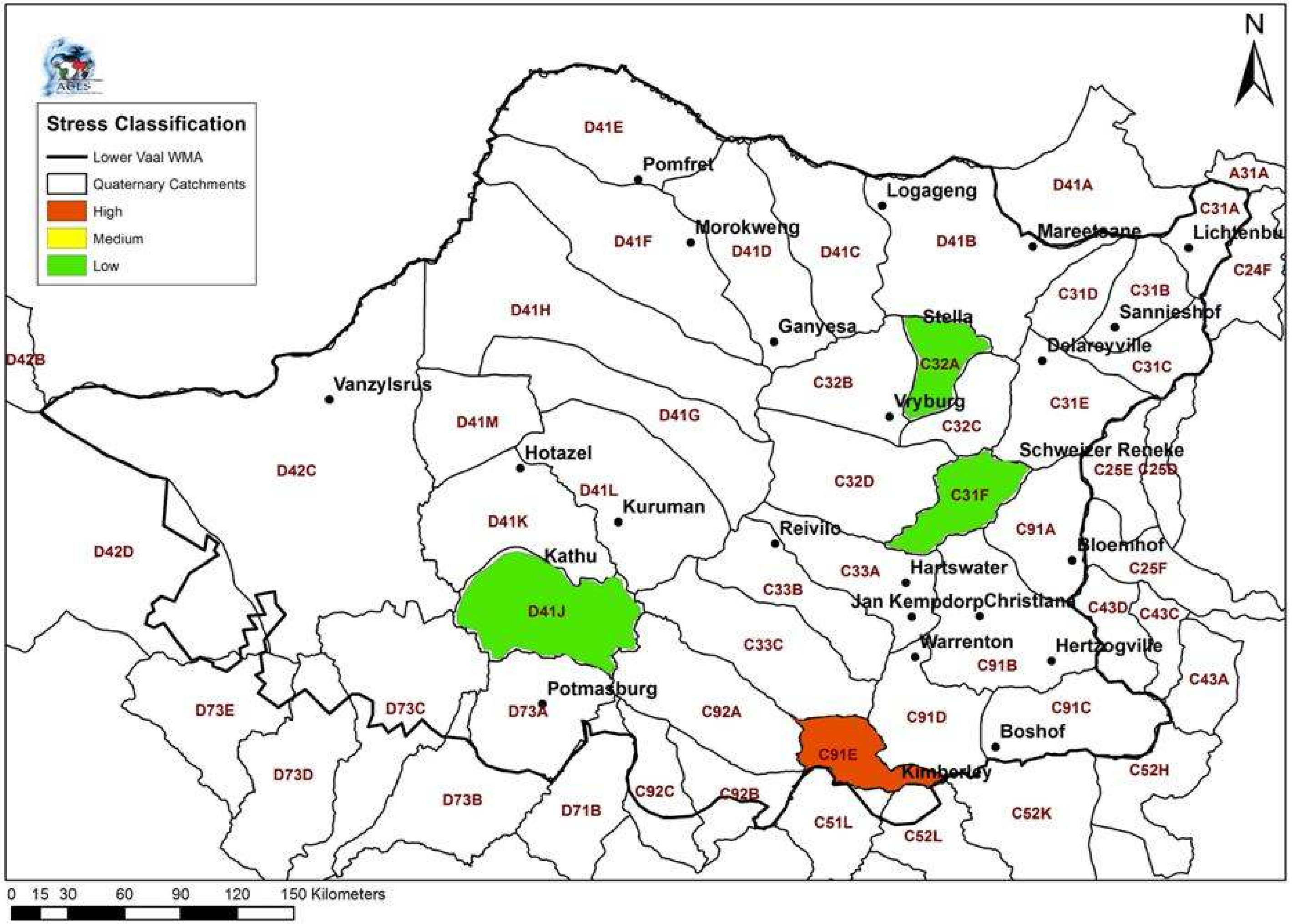

Figure 5-3 Lower Vaal WMA stressed catchments

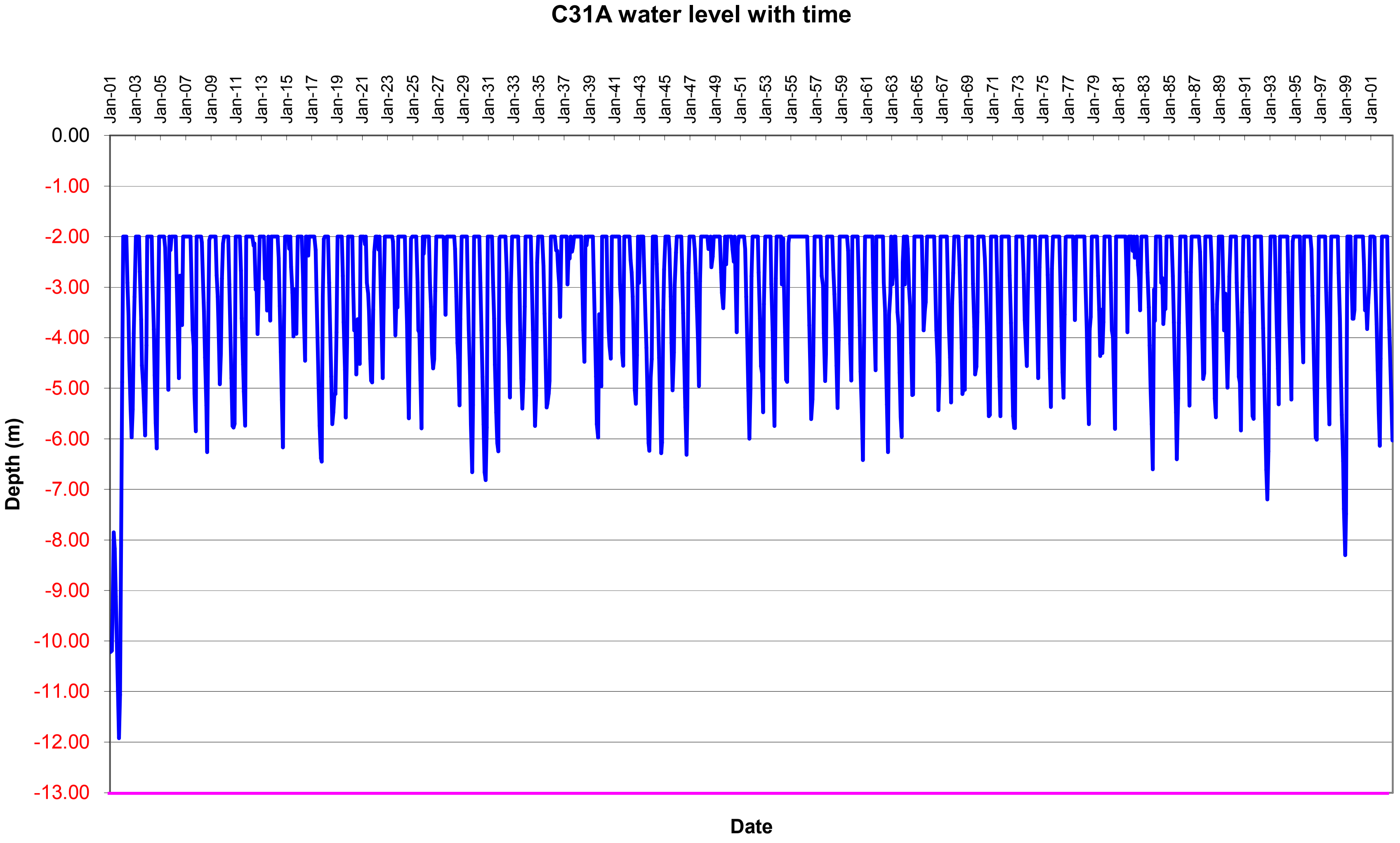

Figure 5-4 Quaternary catchment C31A water level fluctuations over time

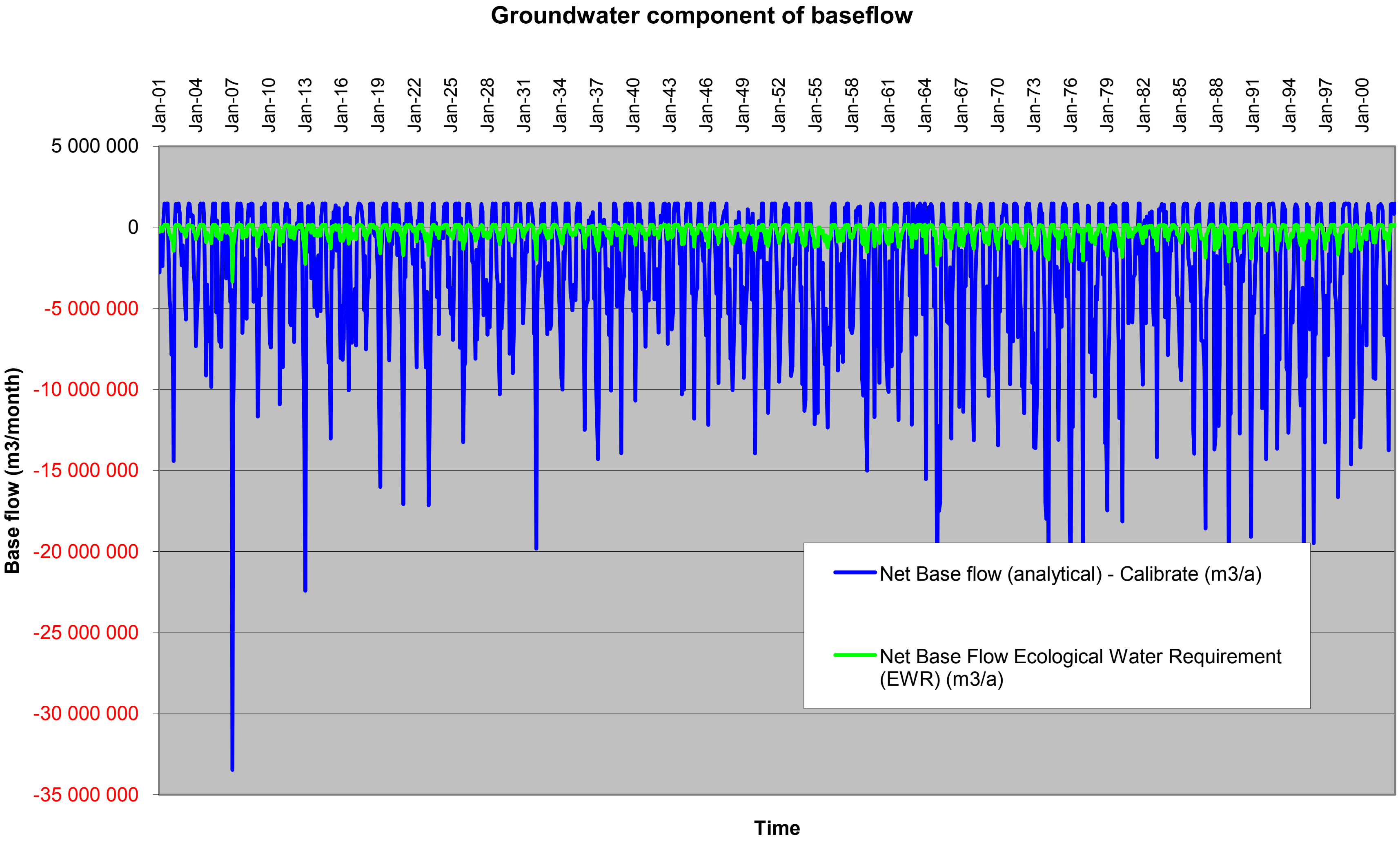

Figure 5-5 Quaternary catchment C31A fluctuations in base flow over time

5.7 Discussion

The Groundwater Yield Model is limited by the quality of the input data on a quaternary catchment scale. Due to the constraints imposed on data, a conservative approach was followed based on the precautionary principle. This means that more water would be available and some of the stressed quaternary catchments could be in a lower stress state than indicated. The groundwater component in the Lower Vaal WMA is considered good given that only 4 of the quaternary catchments are in a stressed state of which only 1 is highly stressed. These assessments need to be verified and checked. The assessments of the unstressed catchments need to be checked and verified as well but if correct, groundwater development is possible.

More focus should be put on stressed catchments with more detailed evaluations using numerical models.

The fact that the potential evapo-transpiration is more than 50 times the recharge means that the entire groundwater recharge volume can be evaporated on 2% to 5% of the catchment areas. In the Lower Vaal WMA, groundwater evapo-transpiration losses could account for 70% to 80% of the groundwater sinks as approximately 70% of the WMA is semi arid to arid. More groundwater may be available than was expected if it can be economically utilised before it is lost to evapo-transpiration.

The similarity between the pre-identified stressed areas and the water balance categorised stressed areas indicates that aquifers can be managed at this scale. The inclusion of a minimum base flow required for each quaternary, based on the groundwater component of the reserve, would enable the study team to classify the stressed status more accurately. The water allocations to each user i.e. irrigation, abstraction from boreholes and mining abstraction and dewatering would then be required to make provisions for this minimum base flow. The minimum base flow requirement is a product of surface water measurements and modelling and is also termed the IFR.

The next phase in the model development requires the inclusion of improved datasets for population, agricultural water use (as opposed to a broad assumption that all cadastral farms will use a given volume), wetlands, forestry, aquifer thickness and riparian vegetation.

Recharge is the most important controlling parameter. Aquifer thickness represented by the water level and a 10% depth to dead storage level influencing the assessment of the current level of the aquifers is also an important controlling factor for the assessment.

6 CONCLUSIONS AND RECOMMENDATIONS

At this stage in the project no conclusions or recommendations can be made as input parameters are still outstanding and data used need to be verified and checked. The model will be updated with improved data sets.

7 REFERENCES

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5. Vivier, J.J.P Gouws, WJ and Wydeman, R. (2005) Olifants River Water Resources Development Project: Groundwater Study Task (ORWRDP). AS-R-2005-05-24 Olifants River Water Management Area: Groundwater Assessment, April 2008, AGES Technical report: AG-R-2008-04-23

1. APPENDIX A: GROUNDWATER YIELD MODEL (GYM)

a. Background

The basics of the model applied on the Lower Vaal WMA groundwater reserve determination were developed during the Olifants River Water Resources Development Project: Groundwater Study Task (ORWRDP) (Vivier, et.al. 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 is impractical to e.g. develop 34 numerical models for the Lower Vaal WMA and obtain groundwater flow balances with assurance levels.

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 identify potentially stressed or sensitive catchments for which more detailed numerical models should be developed to refine the groundwater flow balance and identify e.g. detailed surface water and groundwater interactions.

b. Objective

The aim of the investigation is to develop a model that could be used to determine the groundwater flow balance and volume of groundwater available for use in aquifers on a quaternary sub-catchment scale at a chosen assurance level.

c. Methodology

A model was developed termed the Groundwater Yield Model (GYM) that could be used to determine the groundwater balances on a number of quaternary. The variability in rainfall-recharge and evapo-transpiration potential was identified as one of the factors that influence sustainability of groundwater supply, that cannot be managed.

The purpose of the model is to simulate groundwater flow balances on a quaternary sub-catchment scale. The output should provide statistical changes in groundwater volume based on rainfall recharge variations, which yields assurance levels for groundwater volume calculations.

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

i. The groundwater flow balance under steady-state conditions

Surface water drainages or rivers act as linear drains for groundwater seepage (). The volume of groundwater contributing to the flow in rivers is termed 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 evapo-transpiration losses
$-Q_{BF}$ = Base and spring flow

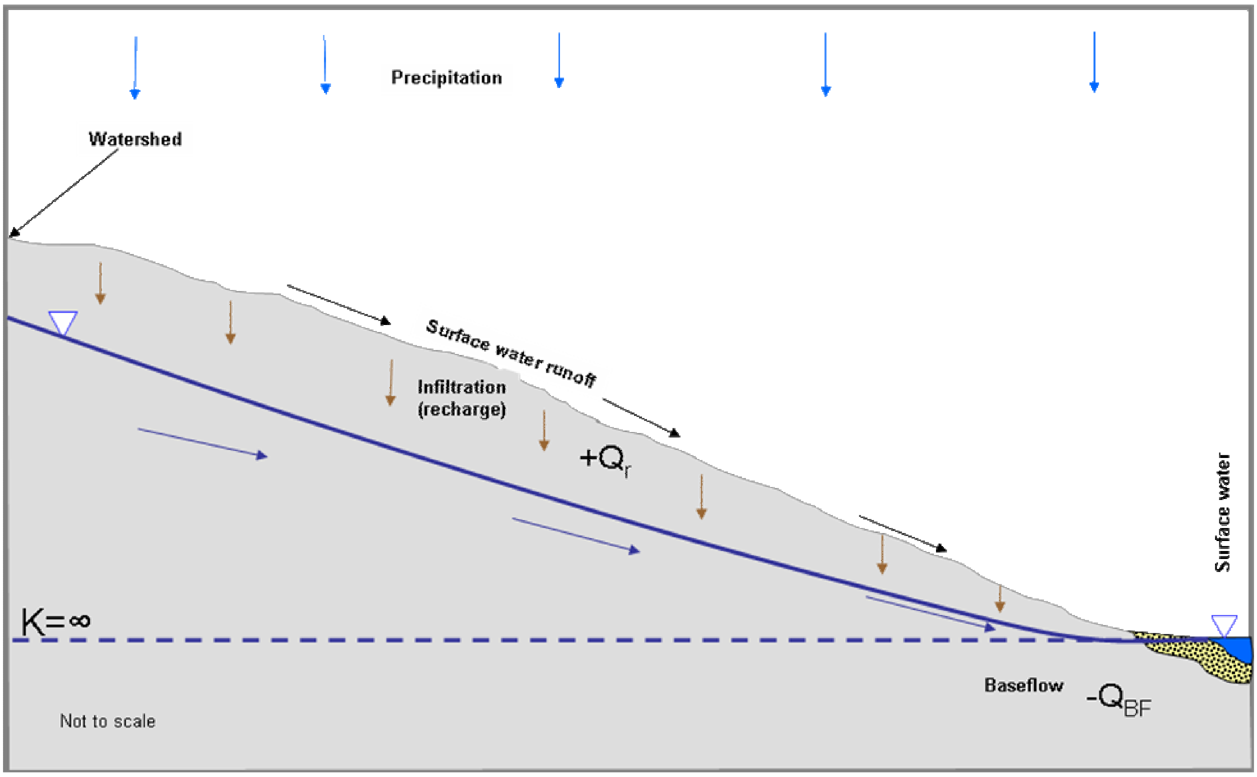

Figure 1-1 Geohydrological steady state conditions.

Spring flow and in some cases base flow are associated with evaporation and transpiration losses that will be discussed later.

ii. Transient flow and evaluation of groundwater volume buffering capacity during dry periods

The groundwater flow balance described in the pervious section can be differentiated in additional basic inflow and outflow components.

The regional, quaternary catchment scale Groundwater Yield Model (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 1-2). 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 (±1.96 standard deviations).

iii. 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 dam below that level is not considered as available for supply.

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 DSL 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 1-3).

In practice, there should be a relationship between the saturated thickness or GMC of an aquifer and the variability in rainfall-recharge (Figure 1-2 and Figure 1-3).

iv. Assumptions

The following assumptions were made:

- In natural steady-state conditions, the recharge equals base flow minus losses (e.g. evapo-transpiration).

- Any abstraction would result in immediate reductions in 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 defendable.
- Interaction with surface streams (i.e. base flow) was considered as a net outflow. Inflow from surface water streams was neglected. This assumption is conservative and requires smaller scale models to be able to evaluate these effects on a sub-quaternary catchment scale.

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.

v. Conceptual model

The conceptual groundwater flow model on which the analytical model was based, is shown in Figure 1-4. The inflow from groundwater recharge is balanced by outflow to springs, wetlands and 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 1-5).

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

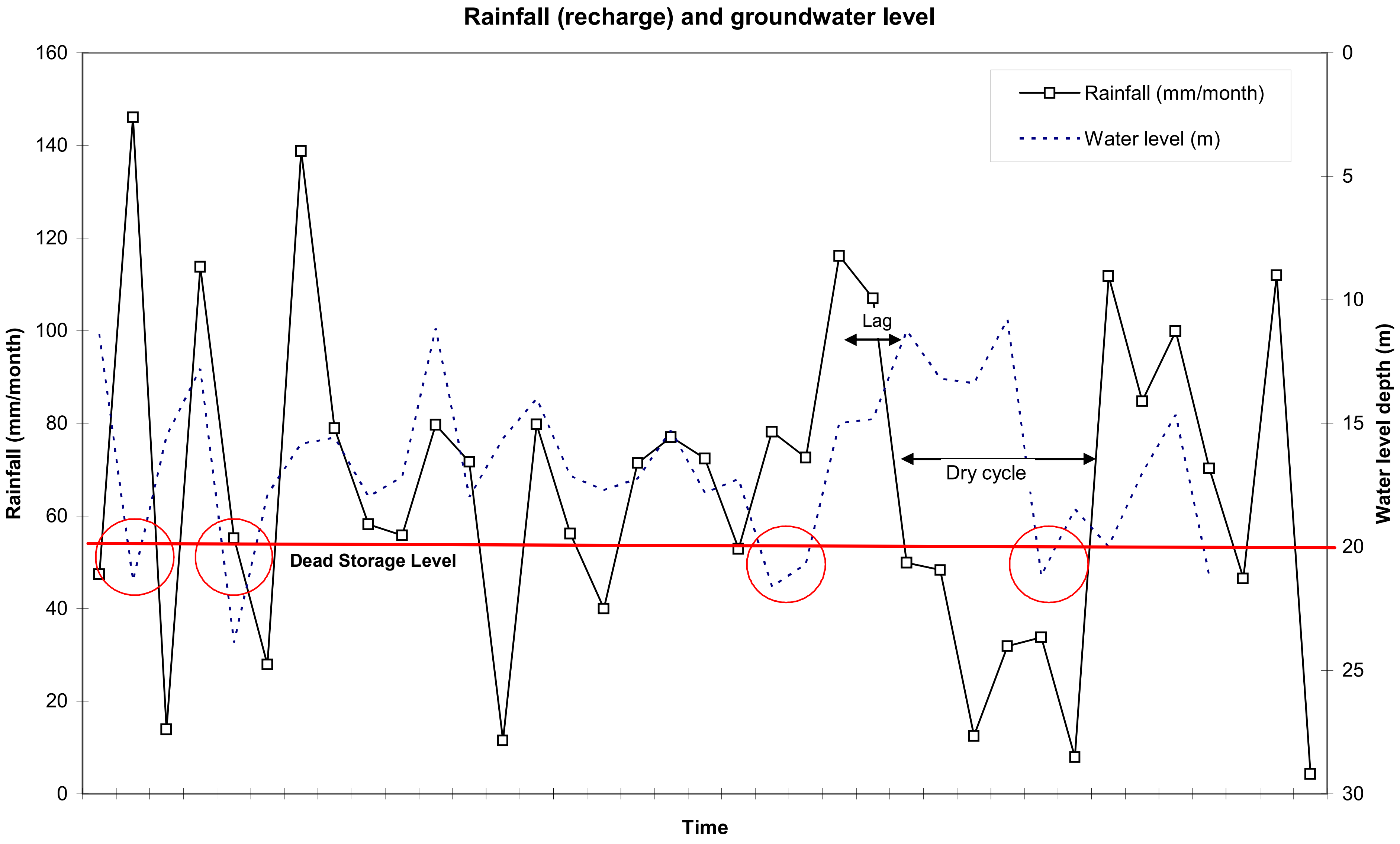

Figure 1-2 Time varying rainfall-recharge conditions showing system failure during dry cycles.

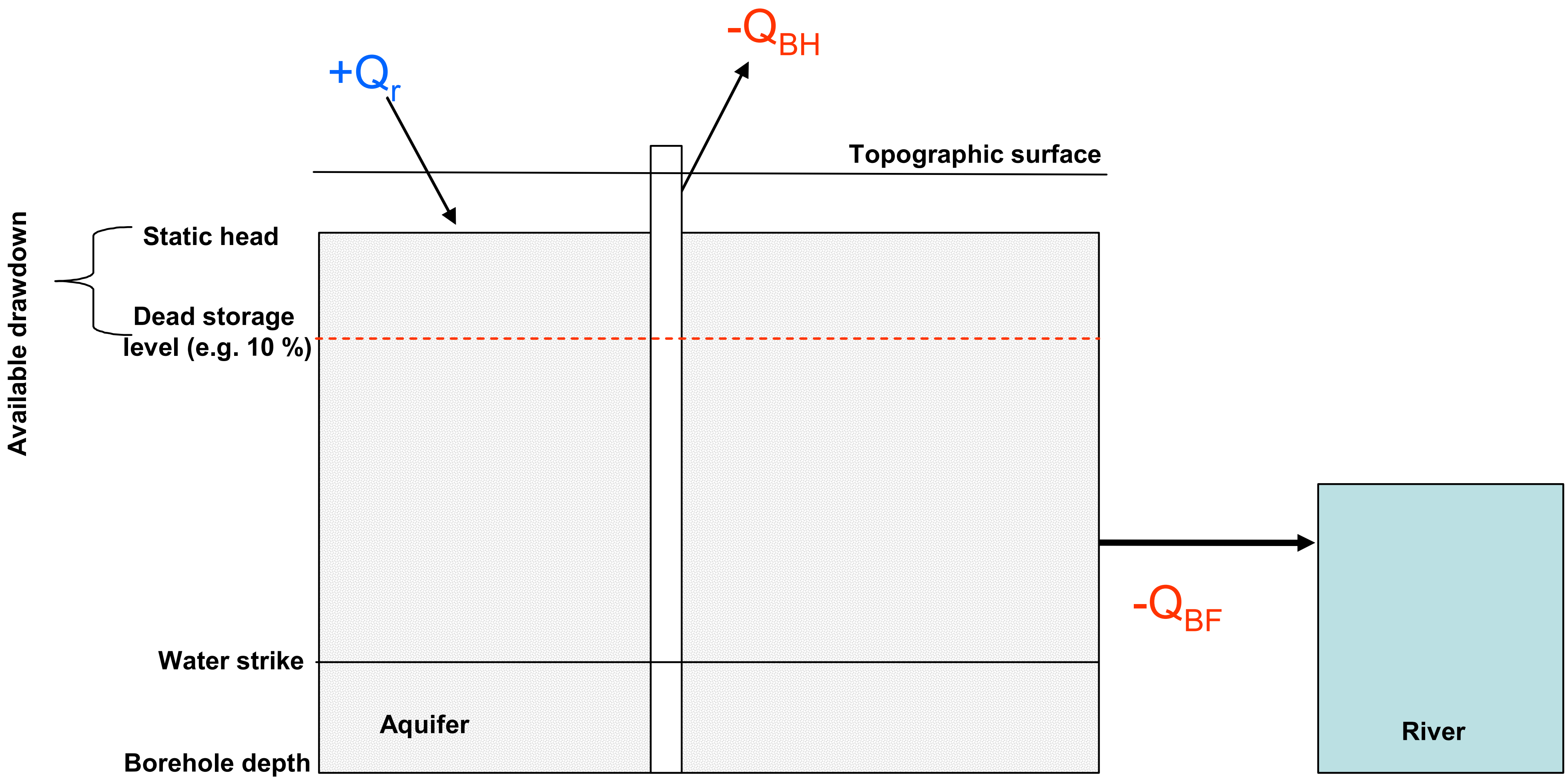

Figure 1-3 Schematic representation of the GYM conceptual model – dead storage level.

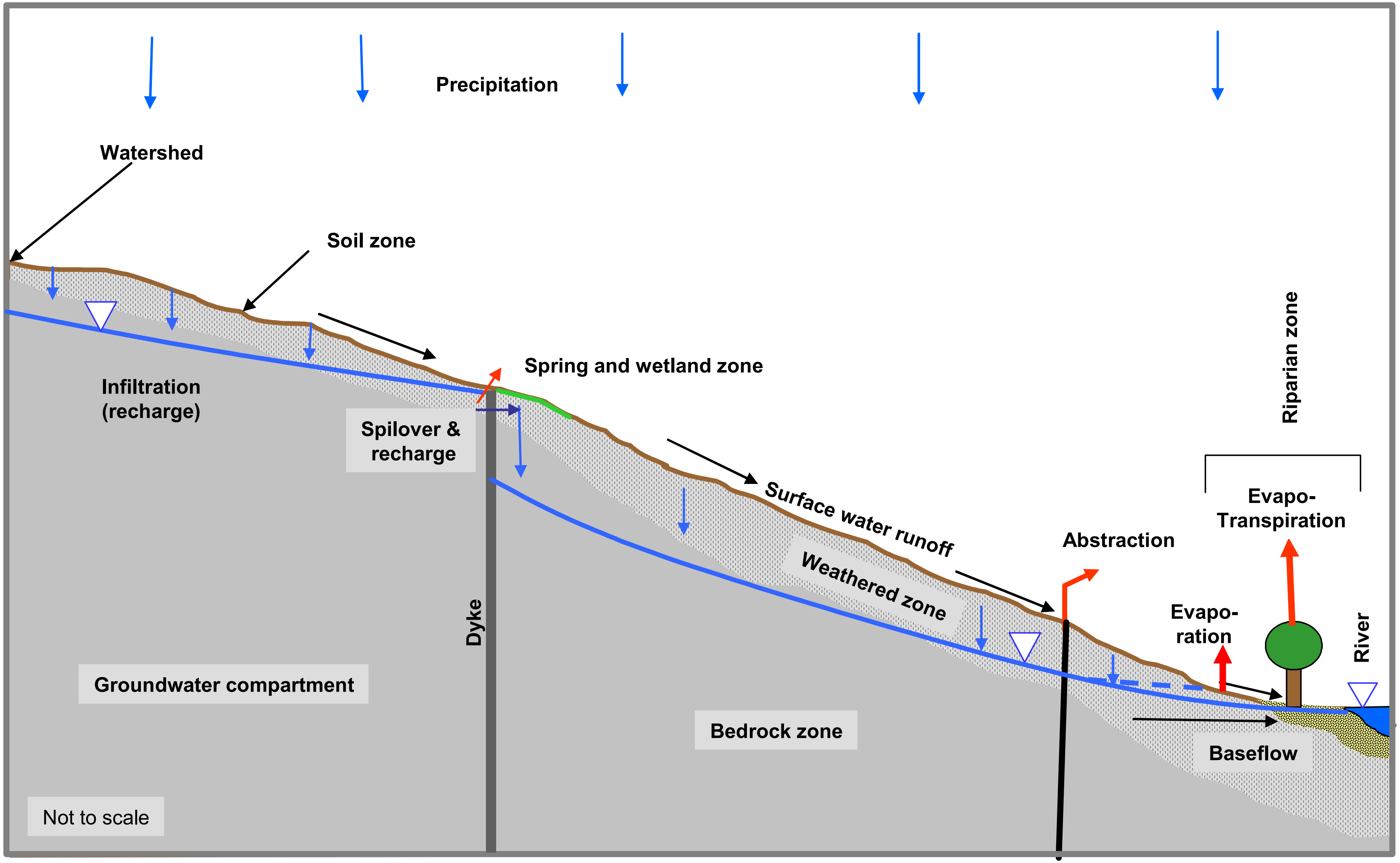

Figure 1-4 Schematic representation of the GYM conceptual model – field conditions (low base flow loss case).

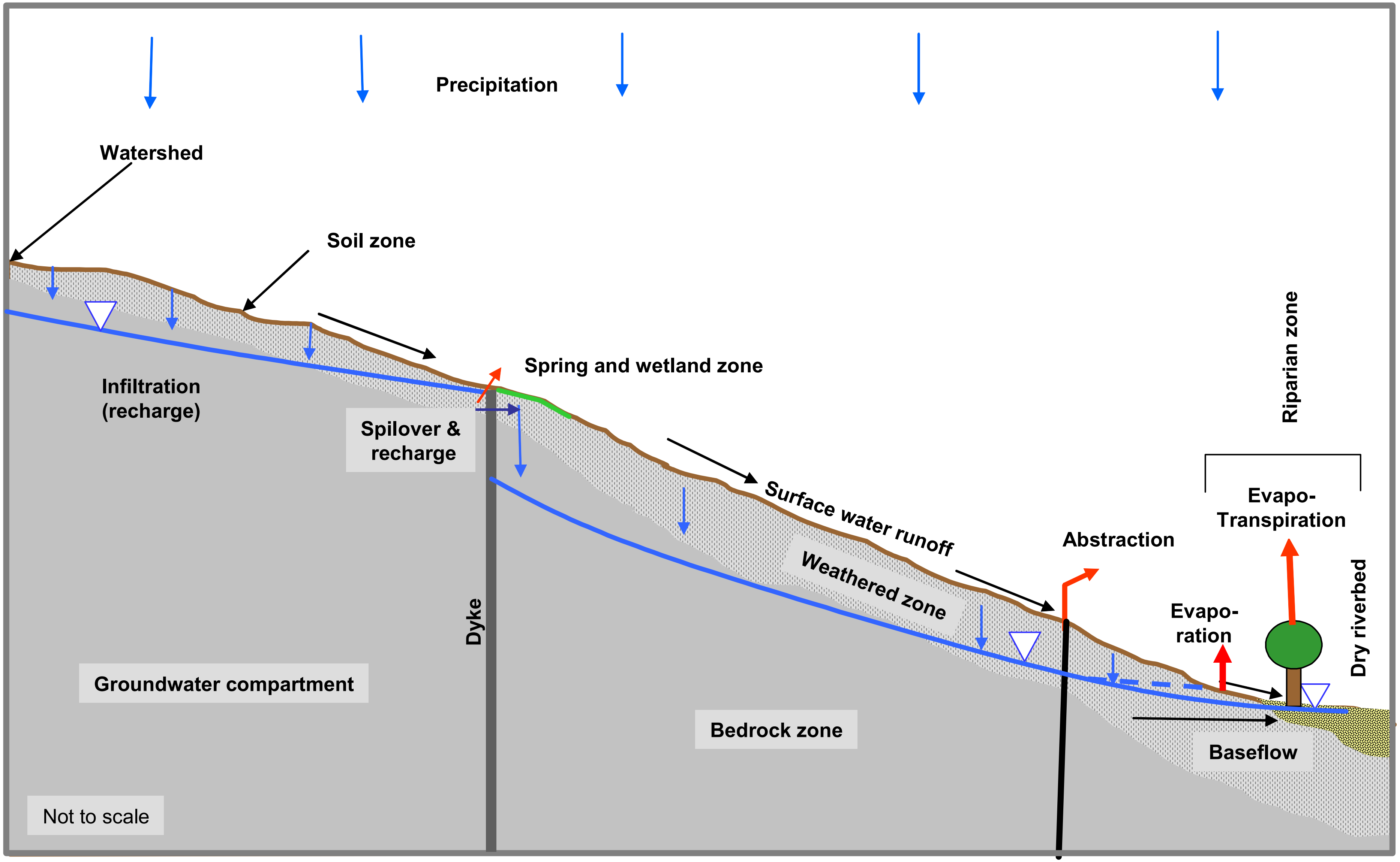

Figure 1-5 Schematic representation of the GYM conceptual model – field conditions (high base flow loss case).

vi. Analytical model

The model is a differentiation of the steady-state, basic case discussed in section i. 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:

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

$+Q_R$ = Recharge from rainfall $[L.T^{-1}]$[7]

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

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

3. Groundwater loss components ($-Q_{GLC}$).

$-Q_{AVEG}$ = Alien vegetation $[L.T^{-1}]$
$-Q_{ETP}$ = Evapo-transpirationration losses $[L.T^{-1}]$
$-Q_{MDW}$ = Mine dewatering $[L.T^{-1}]$

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

$-Q_{SF}$ = Spring flow $[L.T^{-1}]$
$-Q_{BF}$ = Base flow $[L.T^{-1}]$
$-Q_{WLD}$ = Wetland fed by groundwater $[L.T^{-1}]$
$-Q_{RVEG}$ = Riparian vegetation $[L.T^{-1}]$

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

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[7] $[L.T^{-1}]$ where L = length and T = time

$-Q_{BH}$ = Abstraction from boreholes $[L.T^{-1}]$

$-Q_{BHN}$ = Allocation for basic human needs and communities $[L.T^{-1}]$

$-Q_{IR}$ = Abstraction for irrigation $[L.T^{-1}]$

6. Volume of groundwater in storage (GV_{ST})

$+GV_{ST}$ = Volume of groundwater in storage $[L^3]$

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

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

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

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

It is evident that the groundwater used by natural systems (spring flow and 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 take water before it has the opportunity to flow to a natural system. The flow sequence is therefore important. Base flow is the last component to receive groundwater. When outflow exceeds inflow in any given time step, water would be taken firstly from storage, then from spring flow and then from base flow. A supplementary conservative assumption that can be made, is to allocate a minimum volume to base flow, so that it is constant (i.e. a minimum base flow component is allocated) 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 become positive (i.e. inflow into the groundwater system) and have a flow reduction effect on the river.

The groundwater balance from (4) is calculated for monthly time steps (Δt) to yield a monthly groundwater balance at a 95 % (or any 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.

1. 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} = 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 (i.e. dead storage level).

2. Variable recharge (+Q_R)

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, see example in Figure 1-6. The (e.g. 1.96 X) standard deviation for a 95 % assurance level is then used to obtain a range within which the monthly rainfall-recharge is sampled (Figure 1-7). 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 set range.

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.

3. Dam seepage (+Q_{DS})

Seepage from dams is determined by:

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

K_C = Hydraulic conductivity of 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.

4. Abstraction from boreholes for livestock farming (-Q_{BH})

Abstraction from boreholes that are used for farming is used as an outflow component. This information is obtained from hydrocensus data or the National Groundwater Data Base (NGDB). If data from the above sources is scarce, the number of farms in the quaternary sub-catchment is determined from spatial cadastral data on a Geographic Information System (GIS). Conservative assumptions are then made on the water use per livestock farm (e.g. 0.5ℓ/s per farm or 0.5 m^3/ha/day).

5. Allocation for basic human need (-Q_{BHN})

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 25 L/person/day to 60 L/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.

6. Borehole abstraction for irrigation (-Q_{IR})

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 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.

7. Return recharge from irrigation (+Q_{IRR})

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.

8. Mine dewatering ($-Q_{MDW}$)

When mines operate below the groundwater level, it will induce inflow and a 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:

$$Q_{MDW} = K\frac{dh}{dl} \times A_{MS} \qquad (7)$$

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

The information from (8) is generally too detailed to obtain for a quaternary catchment scale model. Actual 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.

9. Alien vegetation ($-Q_{AVEG}$)

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;

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

Q_P	=	Mean Annual Precipitation	$[L\ T^{-1}]$
Q_{ET}	=	Mean Annual Evapotranspiration 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 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 10 m, because deeper groundwater is unlikely to experience losses due to alien vegetation.

10. Wetlands fed by groundwater ($-Q_{WLD}$)

Wetlands that are sustained by groundwater would use water equal to the net evapotranspiration;

$$Q_{WLD} = (Q_P - Q_{ET}) \times A_{WLD} \tag{9}$$

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

The information is obtained from GIS coverages 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.

11. Riparian vegetation ($-Q_{RVEG}$)

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 eco-systems. The groundwater use by natural riparian vegetation systems are determined by:

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

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

12. Spring flow (-Q_{SF})

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.

13. Groundwater evapo-transpiration losses (-Q_{GETL})

Groundwater evapo-transpiration losses occur 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 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 determine from:

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

Q_{GETL} = Groundwater evapo-transpiration loss [L T^{-1}]
MAE = Potential Mean Annual Evapo-transpiration [L]

14. Base flow (-Q_{BF})

Base flow is a function of the groundwater recharge minus losses in the aquifer system. 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.

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 base flow occurs [L]

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

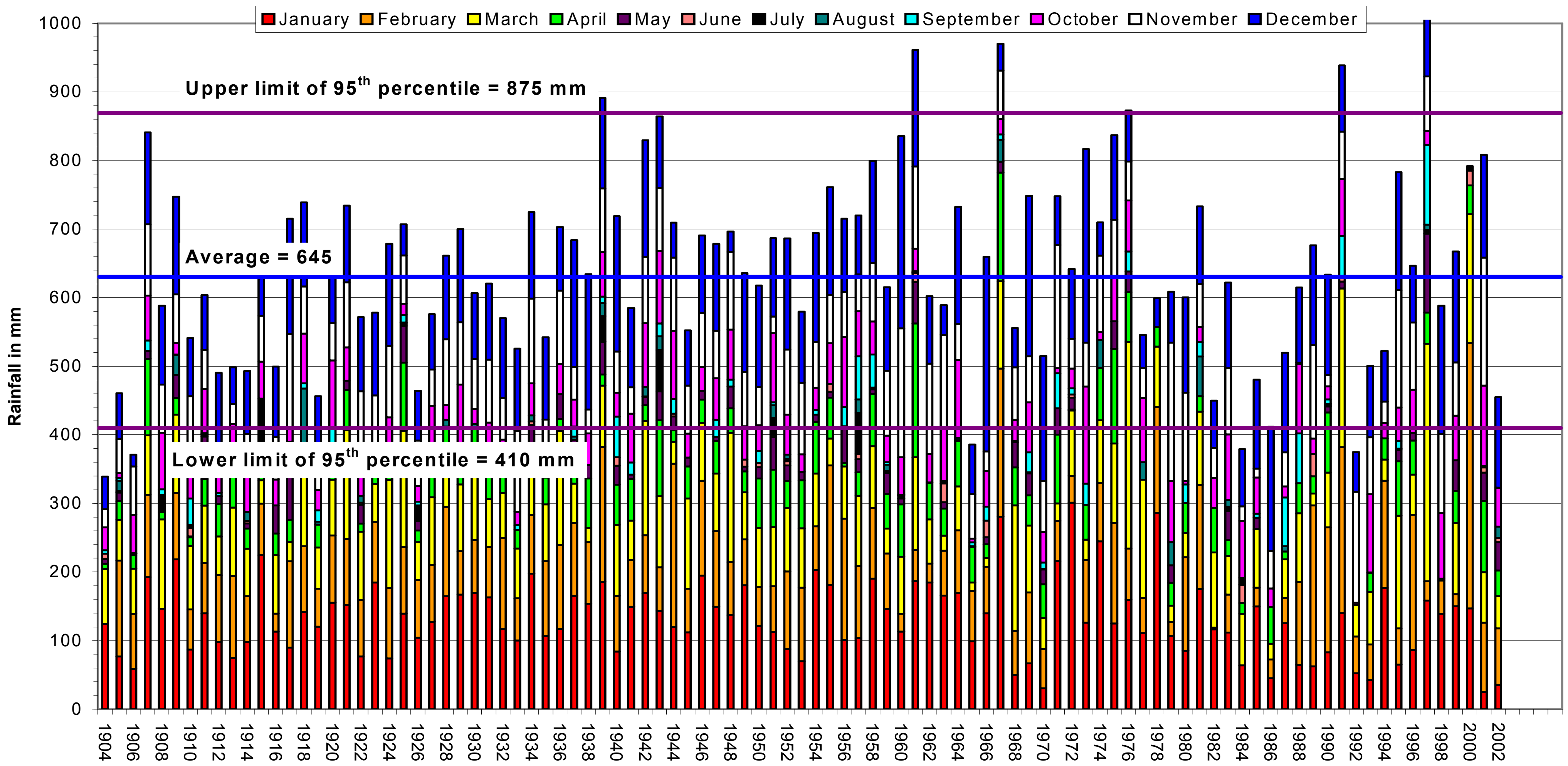

Figure 1-6 Monthly and annual rainfall data from 1904 to 2002.

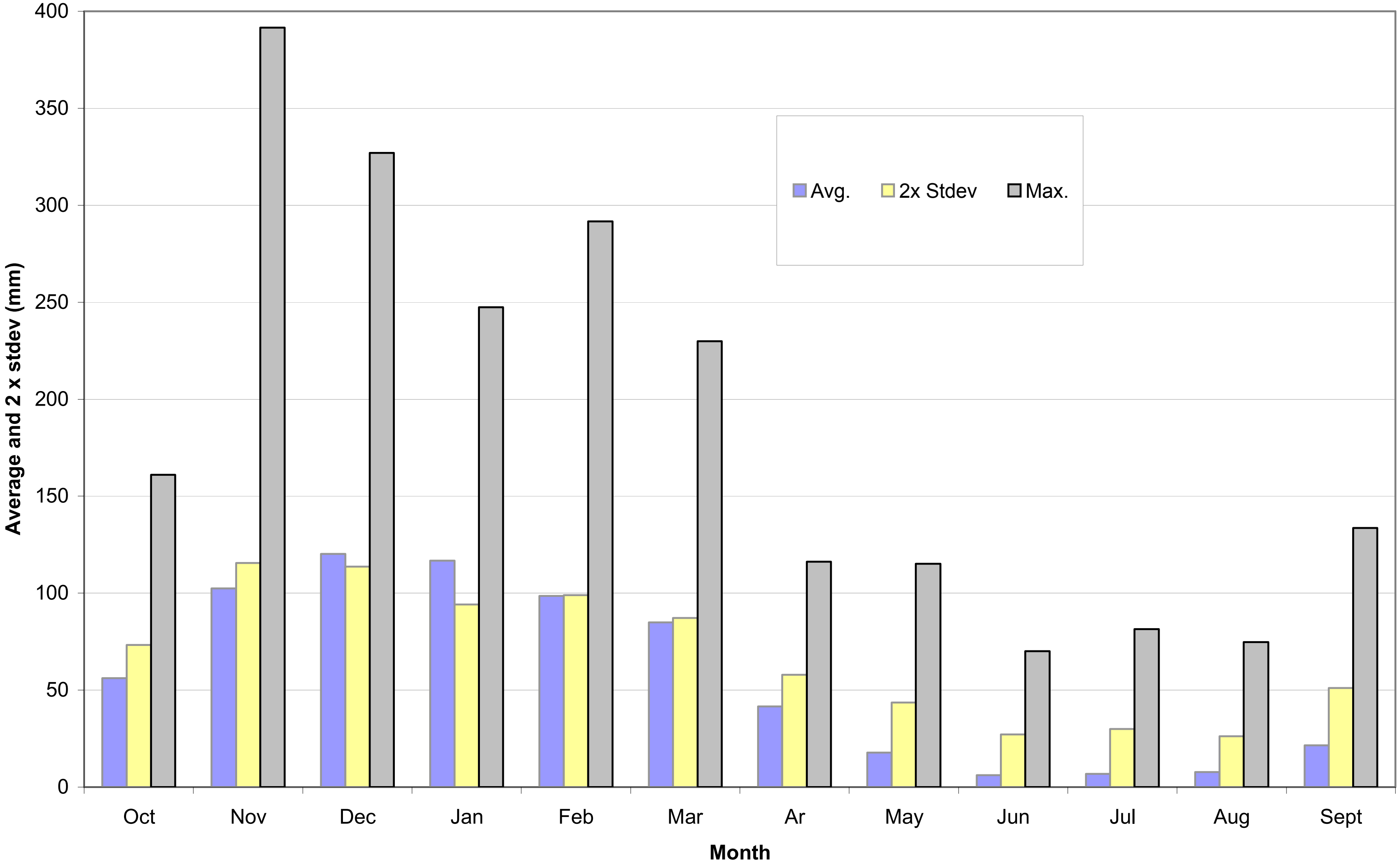

Figure 1-7 **Average monthly rainfall and standard deviations – showing the variability.**

15. Groundwater use vs base flow and time lags

In steady-state, all natural groundwater losses reduce base flow. There is however a time lag that is determined by the aquifer's transmissivity and. The time lag is only of significance if groundwater use is far from the surface water drainage line or if the aquifer's storativity is large enough to buffer the effects of abstraction between wet cycles.

In some cases it may be beneficial to abstract groundwater before other losses like alien vegetation and evaporation along the drainage courses occurs. In other cases, the groundwater contribution to base flow could be important to sustain eco systems in rivers. This aspect must be determined for site specific cases before management decisions can be made.

For the purpose of this assessment and because each quaternary aquifer was considered as a single cell in the model, it was conservatively assumed that any groundwater use reduces base flow immediately. It is often difficult or impossible to determine and prove the effects that buffering of losses could have on the lag of base flow effects with time.

Time lags are only calculated for catchments in which there are negative groundwater balances (i.e. where the outflow exceeds the inflow). These catchments are flagged and require regulatory intervention to reduce firstly losses to unnatural systems and then specific groundwater uses as determined by the strategy of the catchment.

d. Model input and output

The model input requires the information available to calculate the volume of groundwater in storage that is available for use.

The output is a spreadsheet with the groundwater balances of all the catchments showing the inflow vs outflow components. At catchments with a negative groundwater balance, the base flow component is indicated as zero.