Groundwater Resource Directed Measures for Maloney's Eye Catchment

Report to the

Water Research Commission

by

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1 INTRODUCTION

1.1 Preamble

The Department of Water Affairs (DWA) is mandated through the National Water Act (NWA; Act36 of 1998) to ensure that the nation’s water resources are protected; used; developed; conserved; managed and controlled in a sustainable manner for the benefit of all persons. The act states “*the quantity, quality and reliability of water, required to maintain the ecological functions of which humans depend, shall be reserved so that human use does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems*”. This amount and quality of water that must remain for ecosystems to remain healthy and to be able to provide for the basic needs is called the Reserve.

It is currently the responsibility of the Chief Directorate: Resource Directed measures within DWA to determine the Reserves of the country’s water resources such as rivers, groundwater, wetlands and estuaries. Methods for Groundwater Resource Directed Measures (GRDM) assessments are new and still under development and review. As a general principle, an effort has to be made to keep methods simple and efficient, while clear and accepted terminology needs to be used. In developing and refining the GRDM methods, cognisance needs to be taken of the outcomes of GRDM assessments:

- How much groundwater can be abstracted without impacting the Reserve and resource Classification requirements?
- How should the groundwater resource be managed to ensure the resource is used sustainably?

Water management in South Africa is based on three key principles:

- Sustainability – water use must promote social and economic development, but not at the expense of sustaining the environment (technical component)
- Equity – every citizen of the country must have access to water and the benefit of using water (social component)
- Efficiency – water must not be wasted and must be used to the best possible social and economic advantage (economic component)

The DWA has entered into a memorandum of understanding (MoA) with the Water Research Commission (WRC) to conduct research programs on behalf of the Chief Directorate: Resource Directed Measures.

The groundwater component of the Reserve was done on a rapid (quaternary catchment) level for the Crocodile (West) and Marico Water Management Area (WMA). The Present Status Category (PSC) classification of the groundwater resource in catchment A21F is E with a resource category as being Poor.

In view of the very high water use / demand for agricultural irrigation in the **Steenkoppies Dolomite Compartment, a sub-portion of the quaternary catchment A21F** and currently with reduced flows discharging from the Maloney's Eye, there is a need to carry out an intermediate / comprehensive level of the groundwater Reserve. The latter will depend on the geohydrological data available.

Increasing quantities of effluent return flow from urban and industrial areas offer considerable potential for re-use, but at the same time a major concern of pollution in some areas. Return flows also originate from irrigation, estimated at 10% of annual water use.

As the implementing, agent the WRC is required to engage groundwater specialists who have worked on the Crocodile (West) and Marico WMA, so that they are able to use the data at their disposal efficiently and effectively. Golder Associates Africa (Pty) Ltd was appointed by the WRC as Professional Service Provider (PSP) to conduct a comprehensive groundwater Reserve determination of the Steenkoppies Dolomite Compartment (DC) (Figure 1-1).

1.2 Implementation (GRDM Assessment)

To date the most commonly applied manual to address the methods and procedures needed to implement the Groundwater Resource Directed Measures (GRDM) was based on Parsons and Wentzel (2007). This manual was updated in 2011 by the Institute for Groundwater Studies, University of the Free State, which included some new methods which can be applied to assess Groundwater Resource Directed Measures. More importantly the GRDM manual is aligned to that of the gazetted Regulations for the Establishment of the Classification System (2010) (Dennis, 2011). As a result, it is important to incorporate the updated methodology and more specifically the classification (categorisation) of water resources as outlined by the 2011 manual.

In addition, for the high level (Intermediate/comprehensive) GRDM assessment of the Maloney's Eye certain data gaps identified by recent studies (e.g. Barnard, 1997; Holland et al., 2009). The identified data gaps were largely addressed by the following pre-required site investigations:

- Additional gravity surveys. Extension of existing gravity coverage in the direction to Maloney's Eye, mapping major high transmissivity zones that act as conduits for preferential groundwater flow. One thousand and seventy gravity stations were surveyed along selected profiles at 100 metre station interval. Approximate 1400 existing gravity data points (hardcopy DWA data) in the compartment area were captured electronically and incorporated in a common gravity data set.

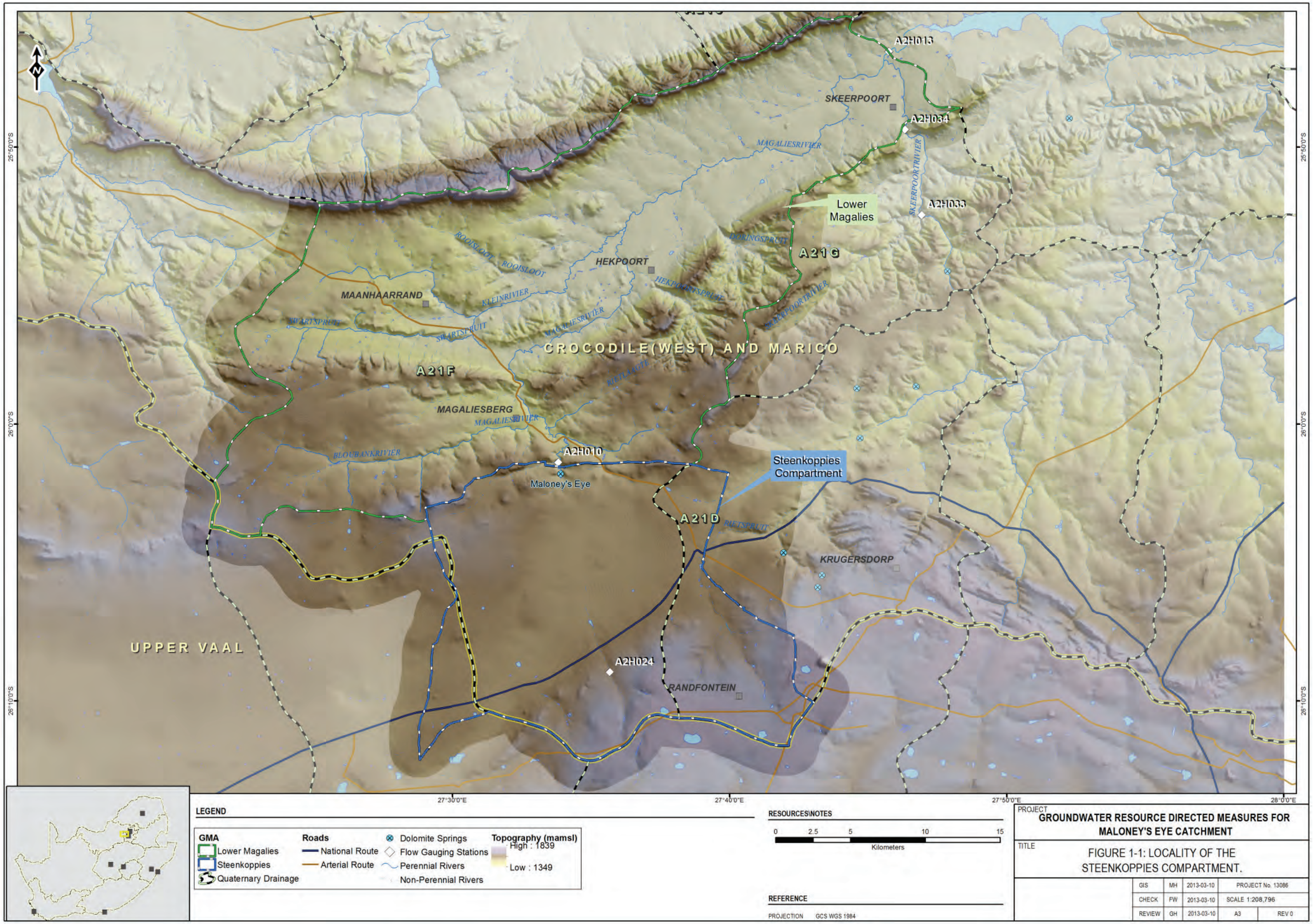

Figure 1-1 Location of the study area

- Tarlton water use borehole information. Collation of production boreholes and water use information, from the Tarlton Users Association's data base.
- Steenkoppies dolomite compartment hydrocensus survey. Survey was conducted to ground truth production boreholes, measure water levels in all accessible boreholes with previous water level measurements to obtain a snapshot of current water levels (April 2011). Water level measurements were focussed at boreholes located close to possible compartment sub-boundaries. The survey included water sampling from higher yielding boreholes and Maloney's Eye for chemical analysis of macro elements aimed at obtaining reliable chloride concentrations in groundwater. Historic chloride values are very low (1 to 2 mg/l) of which the reliability is uncertain.
- Magalies River hydrocensus survey. Survey of boreholes in proximity of the Magalies River was conducted down-stream of Maloney's Eye to obtain information to assist in assessing the interaction between surface and groundwater source.

In correspondence with the proposal submitted to the WRC and in terms of the appointment the GRDM assessment entailed three main phases (Initiation, Implementation and Termination), each phase comprising a number of tasks.

1.2.1 Phase 1: Project Inception

This phase comprises five tasks:

- Task 1.1. Literature review
- Task 1.2. Collation of project borehole database (spatial, depth and time dependant) and GIS information layers.
- Task 1.3. Initiation workshop to identify draft approaches to conduct GRDM on the delineation of various aquifer units (quantity and quality considerations) taking cognisance of Integrated Unit of Analysis (IUA) as per the National Water Resource Classification regulations.
- Task 1.4. Approach / methodology to be used in delineation and quantification of groundwater and surface water interactions, occurring near rivers and wetlands.
- Task 1.5. Compile inception report detailing preliminary methods statement for iterative GRDM study and update costing of study.

1.2.2 Phase 2: Study Implementation

This phase formed the essence of the study and comprised of discrete tasks (each with defined deliverables according to the GRDM methodology) as listed below:

- Task 2.1: Preparation and Pre-required Site Investigations. This task overlaps with Phase 1, details the ToR, set required level of GRDM confidence, capture and incorporate existing data into study, define study area. Conduct pre-required site investigations (includes verification of existing data) and incorporate data into study. The pre-required site investigations included:
  - Additional gravity surveys (1070 gravity data points)

  - Tarlton water use borehole information
  - Steenkoppies DC hydrocensus survey
  - Magalies River hydrocensus survey
- Task 2.2. Description of Study Area. This task entailed the physical and geohydrological description of the study area to required GRDM level. Deliverables are:
  - Geohydrological description of aquifer systems, recharge sources and conceptual model. This included preliminary/existing delineation of aquifer systems up to secondary delineation (Refer Task 2.3 below)
  - Description of the status of identified water resources with reference to:
    - Identifying ambient/reference conditions
    - Observed impacts (quantity and quality)
- Task 2.3. Delineation of Resource Units (Groundwater Unit of Analysis). A three-tier system of delineation from primary delineation (quaternary catchment level), then secondary delineation (based on aquifer type and significant eco region) and last tertiary delineation (based on conceptual model with delineations of single sub-dolomite compartments or sub-aquifer units) will be used. Deliverables are:
  - Delineation and description of Groundwater Unit of Analysis (GUA).
  - Map showing extent of delineated units.

Delineations to tertiary level are required prior to commencement of 3D numerical modelling to firstly quantify and simulate natural conditions.

  - Consideration of groundwater interaction with wetlands, rivers, etc.
  - GRDM determinations for each GUA to include:
    - Resource Classification
    - Preliminary Reserve Quantification
    - Preliminary Resource Quality Objectives (RQO's)
- Task 2.4. Water Resource Classification. This task entails defining the current impact (quantity and quality) on the resource for each GUA, and will be informed by numerical modelling. Deliverables are:
  - Assigned Water Resource Category
  - GRDM assessment data sheet for all GUA
- Task 2.5. Quantification of the Groundwater Reserve. This task quantifies the groundwater volume (both quantity and quality) that can be abstracted from a water resource (Allocation) without impacting the ability to contribute to the Reserve (BHN and Ecological Reserve), and will be informed by numerical modelling.
  - o Deliverables for all GUA are:
  - Quantification of recharge.
  - Quantification of groundwater contribution to base-flow and groundwater dependant ecosystems

  - Quantification of the groundwater basic Human Needs (BHN)
  - Quantification of groundwater allocation
  - Compile standard GRDM assessment sheet
  - Scale results to appropriate units according to the management and administrative needs of DWA.
  - Delineation of aquifer protection zones from which groundwater use is limited or not allowed.
- Task 2.6. Setting of Preliminary Resource Quality Objectives (RQO's). This task dealt with technical considerations to preliminary setting of practical, implementable and measurable goals that balance the need to protect and sustain a water resource with the need to develop and use the resource. This task will be informed by transient aquifer modelling. Deliverables are:
  - List of preliminary RQO's, either numeric or descriptive, to set aquifer management criteria and/or limits of acceptable impact to protect groundwater dependant ecosystems, etc.
- Task 2.7. Monitoring Programme for post GRDM. Task entails defining monitoring protocols to generate data to assess whether the RQO's are being met for each GUA.
  - The design of the monitoring programme is guided by information requirements related to resource management and protection as specified for the GRDM determination process. The established 3D numerical aquifer model will be available as a reliable tool for future aquifer management and will be used to inform this task.

On completion of tasks 1 to 7 of the phase 2 study component a comprehensive draft technical report was compiled and presented to the steering committee for approval and external review. The report includes recommendations on improving future Reserve determination studies and report back on capacity building of HDI's during the current study.

1.2.3 Phase 3: Project Termination

On approval of the draft technical report by the client the PSP was requested to terminate the study by compiling a comprehensive final technical report. This report contributes to and builds on the evolving practice of GRDM assessment studies and includes recommendations on improving future Reserve determination studies and capacity building of HDI's during the technical studies

1.3 Assumptions related to GRDM assessments

To be able to undertake GRDM assessments and quantify the volume of groundwater required to meet Classification requirements and sustain the Reserve, a number of assumptions are made:

- Groundwater systems are generally resilient and can normally recover from most perturbations. However, it is accepted that groundwater contamination can persist over decades and centuries.

- Groundwater resources can be developed and used up to a point without significantly impacting the ability of groundwater resources to sustain the Reserve or meet the RQOs.
- The ability of a geohydrological system to satisfy basic human needs, RQOs and the ecological Reserve is not impacted if regional groundwater levels do not decline significantly over the long term, and ambient groundwater quality remains within natural limits.
- The sustainable rate at which groundwater can be abstracted is a function of the average long-term annual recharge, while the volume of groundwater held in storage acts as a buffer during dry periods.
- It is assumed that recharge and groundwater abstraction are distributed relatively evenly throughout significant water resources.
- The validity of each GRDM assessment will be reviewed at least every five years using monitored data from the study area.

1.4 Sources of Information

The following datasets were collated as part of the inception phase:

- The 1:250 000 scale geological maps 2526 Rustenburg and 2626 West Rand.
- Water level monitoring data (HYDSTRA) extracted from the National Groundwater Database (NGDB) managed by DWA.
- Water level logger data (part of the SAMA WUA monitoring program).
- Groundwater quality data extracted from the NGDB and relevant reports.
- Effluent discharge volumes from the Randfontein WWTW.
- Long term monthly rainfall records for all stations within the study area.
    - Numerous rainfall station data (part of the SAMA WUA monitoring program).
- Long term flow records of the Maloney’s Eye (A2H010) in addition to the Brandvlei (A2H024) and Magalies River at Scheerpoort (A2H013).
- Water level measurements from Greenway farms -since 2004.
- Aeromagnetic data for the dolomite outcrop and map sheet 2527DD.
- Gravity survey data conducted in 1985 (digital).
- Water use validation data and registered water use as per WARMS dataset.
    - Validation data obtained from Schoeman & Associates aimed to determine existing lawful water use in the area prior to 1998 was conducted in the late 2000s.

2 LITERATURE REVIEW (THE MALONEY'S EYE CONCERN)

2.1 Setting

The Steenkoppies DC is located in the upper reaches of the Magalies River catchment (A21F) which comprises a total drainage area of approximately 1 000 km^2. The Maloney's Eye catchment (the Steenkoppies DC) comprises an area of approximately 332 km^2 and is underlain by the Malmani dolomite formations of the Chuniespoort Group. It is within this Group that karst formation has occurred. Dykes that form boundaries to groundwater flow cross the dolomites, creating isolated hydrogeological compartments.

2.2 Reduction of spring discharge

The Steenkoppies DC has received great attention since the naturally discharging spring of the Steenkoppies DC (known as "Maloney's Eye") reached the lowest flow on record. During March 2007 eight of the nine springs constituting the Maloney's Eye stopped flowing and flow was measured at 0.05 m^3/s (or 1.58 Mm^3/a). This had major consequences for downstream water users as flow from the spring forms a portion of the flow of the Magalies River. At the time of this study, flow measured at the Maloney's Eye gauging station was 0.338 m^3/s (or 10.66 Mm^3/a) compared to a long term average of 14.13 Mm^3/a (since 1908). The Steenkoppies DC has been exploited through the abstraction of groundwater primarily for agricultural irrigation since the early 1980s and recent studies have indicated declines in groundwater levels in the Steenkoppies DC, suggesting over abstraction which could lead to a decline in discharges to the Eye (Barnard, 1997; Holland et al., 2009). In 2007 the Magalies River Crisis Committee (MRCC) made a submission to the South African Presidency regarding the low flows at Maloney's Eye and the possible impact on the Magalies River, seeking amongst other things a temporary cessation of all groundwater abstractions from the Steenkoppies DC to allow the flow at the eye to recover. However, the value of agricultural activities in the Steenkoppies DC is very large, both in terms of money flowing into the area and in terms of employment. The Tarlton Farmers estimate that the activities are worth more than three quarters of a billion rand and employ 3500 people directly, as well as supporting large numbers of people and economic activities indirectly. Obviously any major reduction in farming activities could have severe economic and social consequences for the area. In 2007 the 'Tarlton" farmers started negotiations aimed at the establishment of a Water User Association (WUA) for the area, to be known as the Steenkoppies Aquifer Management Association (SAMA), with the assistance of the Danish government aid organisation DANIDA. The WUA is essentially aimed at furthering the joint interests of users of groundwater from the Steenkoppies DC, and a constitution for the WUA has been submitted and awaits final response from DWA.

2.3 Hydrogeological studies

Hydrogeological investigations conducted on the Steenkoppies DC in the early 1980s, were mainly to determine the groundwater supply potential for emergency utilisation (Foster, 1984; Kuhn, 1986; Bredenkamp et al., 1986). During the late 1990s a decrease in the flow of the Maloney's Eye caused great concern amongst downstream users who blamed irrigation activities and the sub-sequent over exploitation of the groundwater resources in the Steenkoppies DC, for the decrease in flow. Barnard's (1997) investigation focussed firstly to determine the catchment boundaries for Maloney's Eye, and secondly to draw up a water balance for the catchment with special reference for reasons for the reduced flow. This study included a simulation of the Steenkoppies DC by means of a numerical flow model mainly to quantify hydraulic parameters and establish a balance between them. Barnard (1997) concluded that a general decline in water levels will occur over the aquifer resulting in a decline the flow of the Maloney's Eye for below average or average rainfall seasons.

During the mid-2000s the Tarlton farmers dispute that irrigation is to blame for the low flows at Maloney's Eye, although they agree that water resources in the greater Magalies area are under stress. They state that "No credible evidence has been put forward to show that the water difficulties in the Tarlton and Magalies River area is attributable to the existing lawful use of water by the Tarlton Farmers". As a result, the Tarlton farmers commissioned and paid for a groundwater study by the environmental consultancy ERM (Pty) Ltd which supports their views (ERM, 2007). In particular, the ERM report states that changing rainfall patterns, changing sewage inputs to the compartment, changing water uses downstream of Maloney's Eye, alien vegetation along the banks of the Magalies River, mining activities and other factors are also to blame for the decline in flow at the eye and in the Magalies River (ERM, 2007).

Under increasing pressure from both the Tarlton farmers and downstream users, the DWA Water Resource Planning directorate initiated a study as part of the Dolomitic Guideline Development in 2009. During this investigation carried out by Holland et al. (2009), the conceptual understanding of the Steenkoppies DC was reviewed and updated. The study also proposed specific interventions with regard to management and concluded that the flow at Maloney's Eye correlates very well with rainfall over most of the record length, but that in the last fifteen or so years, the flow has declined further than rainfall records would suggest. Further, the groundwater levels in the compartment have declined in recent years, to levels below what would be expected from rainfall decreases alone. Despite these resulting conclusions, the interaction of the Maloney's Eye with the larger Magalies River catchment wasn't assessed. The need for an intermediate / comprehensive level of the groundwater Reserve was proposed by a number of investigations and should provide insight into the relationship between declining flows at the eye and declining flows further downstream in the Magalies River.

3 DESCRIPTION OF STUDY AREA

3.1 Drainage region

The Steenkoppies DC drains towards the north and forms part of the upper catchment of the Magalies river (quaternary catchment A21F) (Figure 1-1). This Magalies River catchment is part of the upper Crocodile River sub-system and are located within the Crocodile (West) and Marico Water Management Area as described by the DWA. These surface catchments are immediately north of the sub-continental surface water divide (Witwatersrand watershed) between the Vaal River basin to the south and the Limpopo River basin to the north. Believe is that the perennial Maloney's Eye forms a large portion of the flow contributing to the Magalies River system which sustains irrigation activities along the river.

3.1.1 Surface water flows

The low density of runoff drainage over the Steenkoppies DC suggests high recharge and a predominance of water flow underground, which eventually drains into surface streams at topographic lows or emanates as springs next to diabase dykes or formation contacts (e.g. Maloney's Eye). Although the Upper Rietspruit forms part of the adjacent quaternary catchment it does form a vital part of the Steenkopies DC groundwater system. The Upper Rietspruit drains storm water and surface run-off from the town of Randfontein in addition to treated sewage effluent from the Randfontein Sewage Works facility. For some distance, stream flow remains constant, but irrigation dams and the leakage from the river bed into the underground network reduces the flow to virtually zero at the Tarlton intersection[1]. A summary of the effluent inflows and discharges of the Randfontein WWTW is given in Table 3.1.

Table 3.1 Randfontein effluent inflows and discharges into the Upper Rietspruit

Year	Raw Inflows Mm^3/a	Effluent outflow Mm^3/a		
		River	Irrigation	TOTAL:
2004	**3.60**	1.34	0.94	**2.28**
2005	**3.45**	1.48	1.34	**2.82**
2006	**4.75**	1.52	1.45	**2.97**
2007	**4.95**	0.84	2.07	**2.91**
2008	**5.19**	0.54	2.73	**3.28**
2009	**2.7***	0.5	1.7	**2.2**
2010	**5.4**	1.59	2.7	**4.29**

** - Data incomplete*

Based on the information obtained from the Randfontein WWTW average effluent discharge for the past five years amount to 2.95 Mm^3/a of which approximately 1.15 Mm^3/a is discharged into the Upper Rietspruit and 1.8 Mm^3/a is used for irrigation purposes. A small component is also used by the adjoining mine dumps for dust suppression and also for irrigation of newly planted vegetation for

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[1] E-mail Communication (7 September 2011). Mr. Richard Magwanya of the Randfontein Municipality.

rehabilitation. Therefore it is fair to assume that very little or any of these effluent discharge components reaches the Steenkoppies DC.

The monthly discharge values are plotted in Figure 3-1 together with monthly rainfall data from the Randfontein rainfall station. Although, no relationship between rainfall and effluent inflow or discharges is evident, an increase in the effluent discharge for irrigation purposes is seen from January 2007 with a slight decrease in discharges to the Rietspruit.

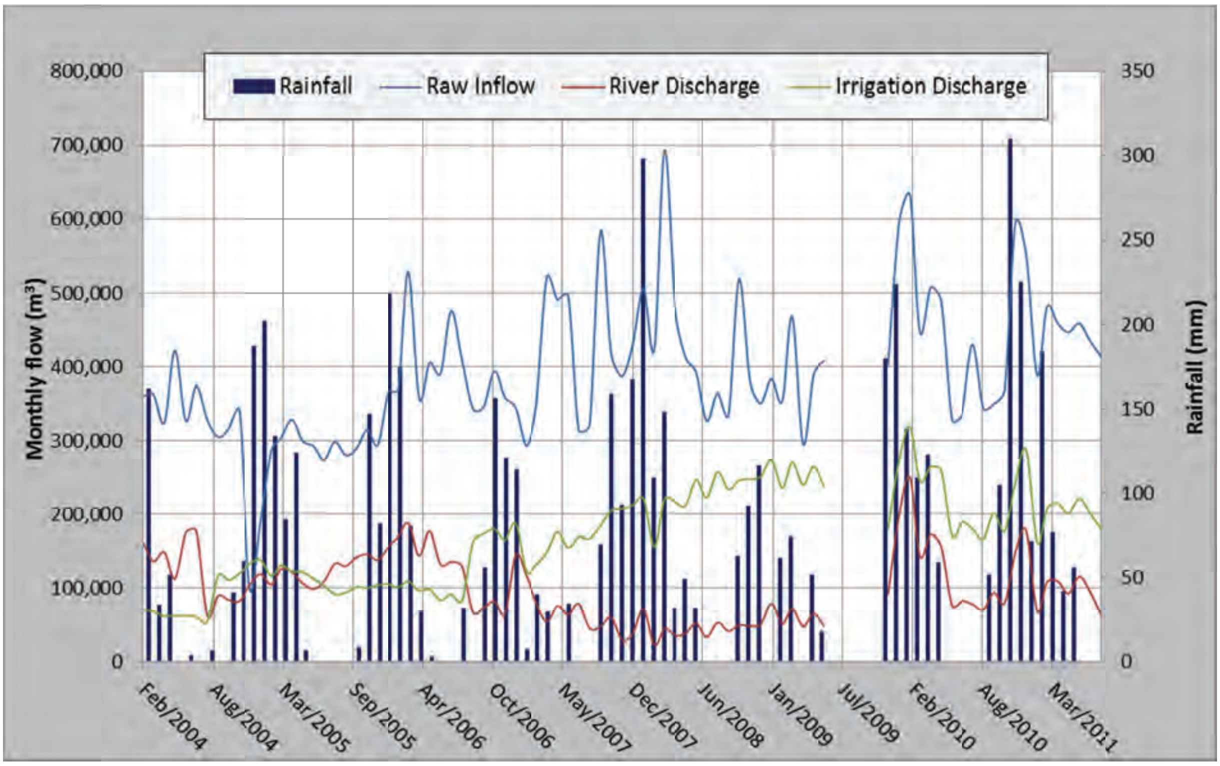


Figure 3-1 Randfontein effluent discharges and raw inflows

Gauging stations

The most important DWA hydrological gauging stations near the Steenkopies DC are the Maloney's Eye (A2H010) and Brandvlei (A2H024) stations. The Magalies River gauging station (A2H013) is approximately 34km downstream of the Maloney's Eye. The monthly flow hydrograph of both A2H010 and A2H024 are illustrated in Figure 3-2. The peaks of the surface run-off hydrograph correspond well with the peaks of the Maloney's Eye flow. The extend run-off recession period is also substantially longer compared to the river system. The information illustrated in Table 3.2 was obtained from the 100-year flow record of the downstream weir of the Maloney's Eye (A2H010).

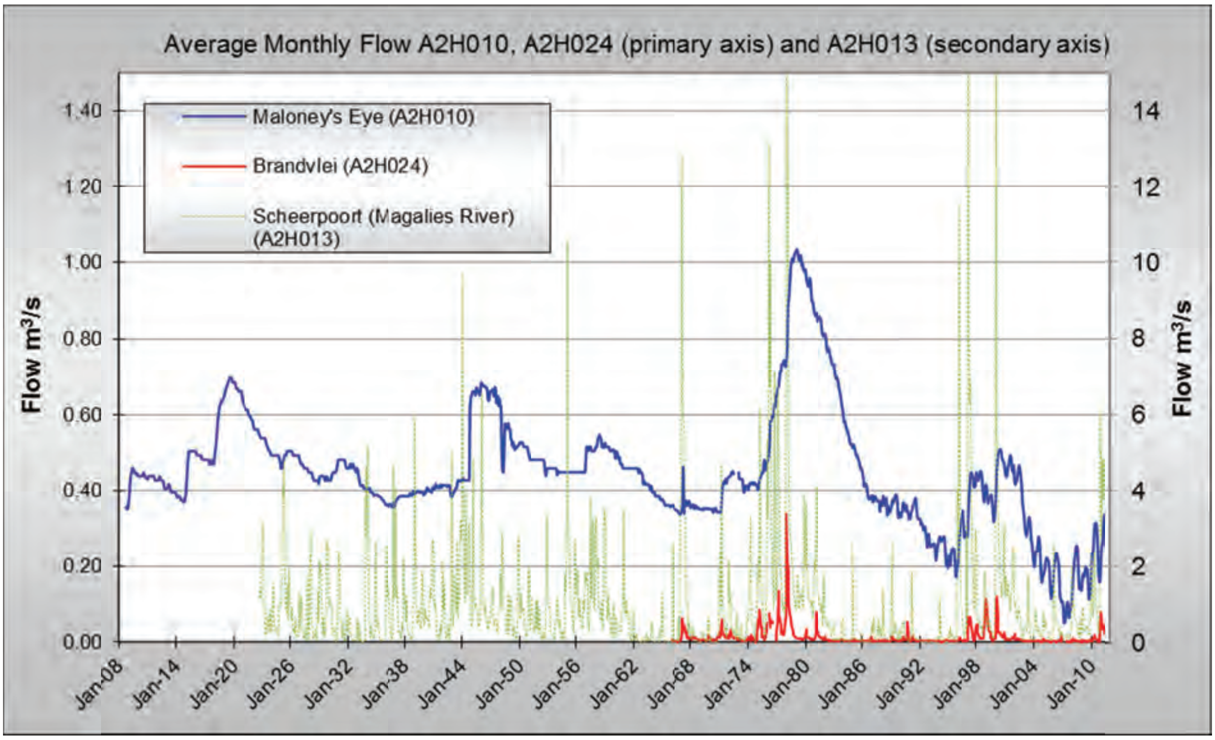


Figure 3-2 Flow hydrographs of DWAF gauging stations A2H010, A2H024 and A2H013

Table 3.2 Maloney's Eye flow summary table (October 1908 to June 2010)

Year (Record)	Min (Mm^3/a)	Max (Mm^3/a)	10 Percentile (Mm^3/a)	90 Percentile (Mm^3/a)	Median (Mm^3/a)	Average (Mm^3/a)
Pre 1985	10.63	32.64	11.67	21.26	14.48	15.72
Post 1985	1.58	16.43	5.32	14.22	10.25	9.79
Last Decade	1.58	15.52	3.47	14.03	7.08	7.76
Complete Record	1.58	32.64	8.68	20.76	13.78	14.19

Over the last decade the average flow of the Maloney's Eye is significant less compared to the long term and pre-1985 flow records. It is also evident that short term flow fluctuations (variations) have increased over the last few years.

3.2 Topography

The Steenkoppies DC is typified by an almost flat undulating plain bounded by between the scarp slopes of the Witwatersrand Supergroup to the south and the Pretoria Group in the north (Photo 1). The altitude along the Witwatersrand watershed and the Magaliesberg mountain range is approximately 1700 metres above mean sea level (mamsl), while the flood plain of the Magalies River ranges between 1400 mamsl to 1200 mamsl from west to east (Figure 1-1).

Photo 1 Looking north towards the Magalies River (south of Magaliesburg)

3.3 Climate and rainfall

The climate in the area is typical of the South African “Highveld”, characterised by warm summers, while 80% of the rainfall is experienced as thunderstorms, and cool dry winters with cold nights. Climatic data of six meteorological stations closest to the study area is summarised in Table 3.3 and spatially presented in Figure 3-4.

Table 3.3 Meteorological stations in the study area

Station Name	Station ID	Rainfall Record		Elevation (mamsl)	Mean Annual Rainfall MAP (mm)	Distance from Maloney’s Eye (Km)
		Start	End/Current			
Vlakfontein*	474751	1934	1989	1,531	693.4	13.5
Steenkoppies*	475121	1907	1952	1,502	664.4	3.7
Randfontein*	475338	1954	2009	1,705	662.0	19.3
Randfontein GM*	475370	1914	1995	1,722	708.5	22.7
Randfontein Jamespark*	475370	1980	2000	1,722	709.1	22.7
Krugersdorp Kroningspark*	475456	1965	2011	1,695	716.5	23.1
Magaliesburg*	512090	1969	2011	1,429	613.8	3.2
Deodar#	30619	1982	2011	1,625	639.9	12.9

**- Data obtained from the South African Weather Services (Pretoria)*
 # - Data obtained from the Agricultural Research Council (Pretoria).

The monthly rainfall time series of different meteorological stations in the wider area of interest were screened with regard to their recorded mean annual precipitation. Only four stations (Vlakfontein, Steenkoppies, Randfontein and Deodar) showed a similar mean annual precipitation (MAP), where, the maximum deviation of mean annual precipitation was below 10%. These stations were considered for the compilation of a single, representative time series from 1908 to 2011. The time series was compiled by calculating a weighting average (using a squared inverse distance weighting method) of all monthly rainfall records available for a given time period:

$$h_{n,x} = \left(\sum_{i=1}^{4} h_{n,i} \frac{1}{d_i^2}\right) \bigg/ \left(\sum_{i=1}^{4} \frac{1}{d_i}\right)$$

Where,

$h_{n,x}$	estimated representative monthly precipitation for area of interest
$h_{n,i}$	monthly precipitation of neighbouring stations
d_i	distance of stations to area of interest (Maloney's Eye)

If a rainfall station did not have any records for a given time period, the station was omitted from the calculations above (Figure 3-3). The chosen approach ensured the compilation of a continuous 100 year time series of rainfall records; though several time periods rely solely on a single operational station (e.g. only Steenkopjes (475121) was operational prior to 1934).

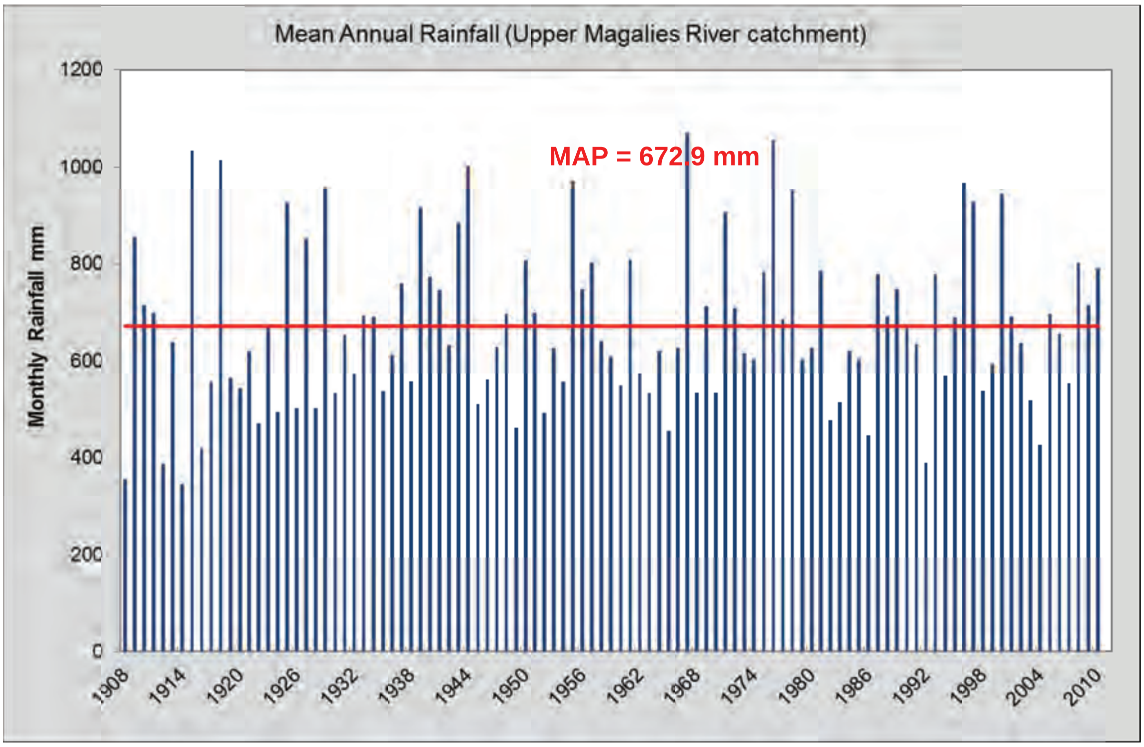


Figure 3-3 Mean annual precipitation for the upper Magalies River catchment

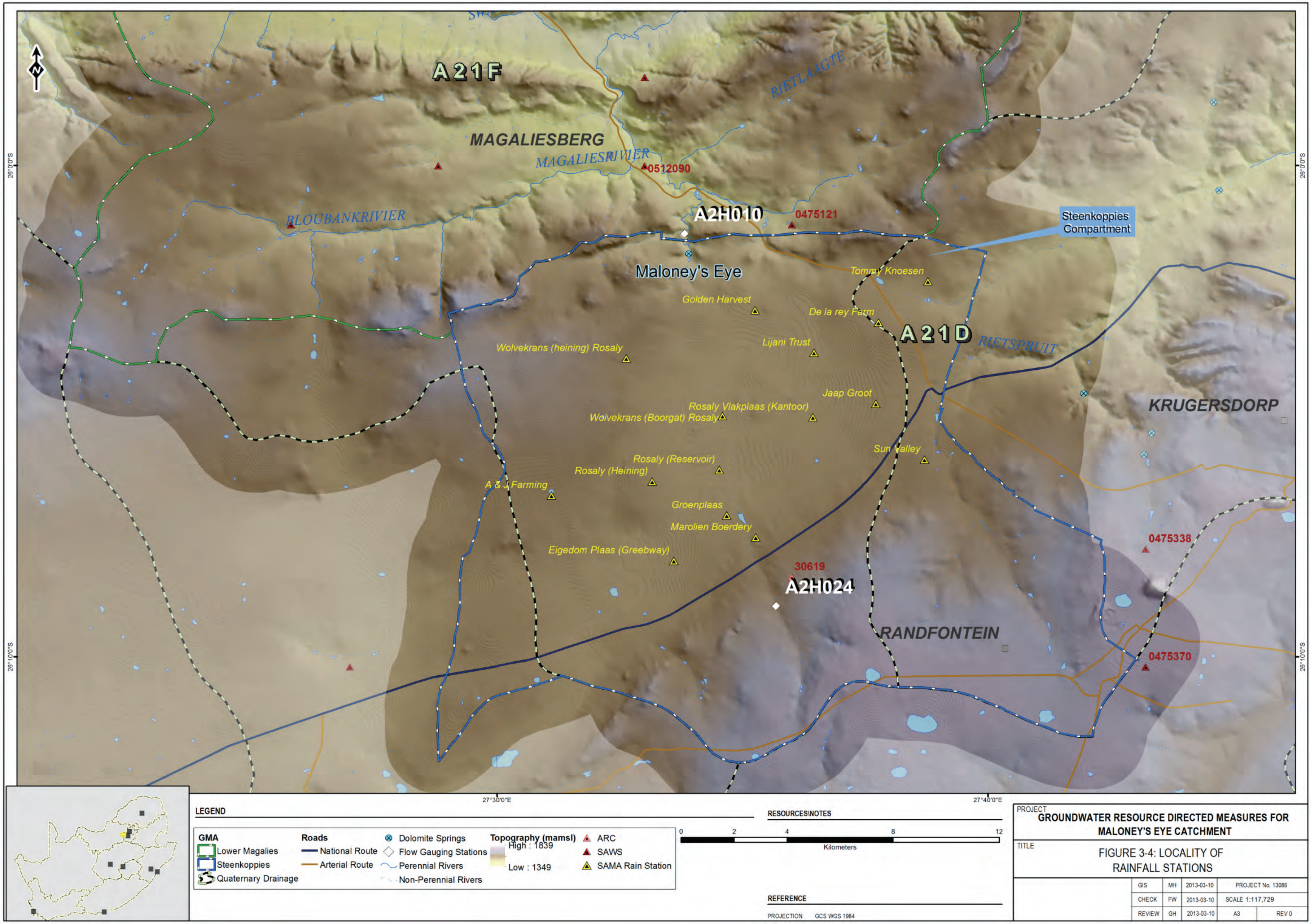


Figure 3-4 Locality of rainfall stations

3.4 Geology

The northern boundary of the Steenkoppies DC runs along the base of the up-tilted Pretoria Group strata, comprising of the Timeball Hill and Rooihoogte Formations (Table 3.4 and Photo 2). The strata dip northwards 20-30°. The southern boundary along a number of rock types ranging from igneous basement rocks to the sedimentary succession of the gold bearing Witwatersrand formations forming the faulted rim of the Witwatersrand basin. Dipping off the western flank of the Johannesburg Dome with a disconformable contact is the basal formation of the Transvaal Supergroup consisting of the Black Reef Quartzite Formation underlying the Malmani subgroup dolomites of the Chuniespoort Group Steenkoppies DC. Based on the abundance of chert, the Malmani subgroup has been subdivided into five dolomitic formations (table), however due to the geological complexity and lack of outcrop, the Steenkoppies DC is undifferentiated (Figure 3-5).

Table 3.4 General stratigraphy of the study area (SACS, 1980:205; Foster, 1984; Obbes, 2001)

Super Group	Group	Formation	Thickness (in m)	Lithology
TRANSVAAL	PRETORIA	Rayton	120	Shale, quartzite.
		Magaliesburg	300	Quartzite.
		Silverton	600	Shale.
		Daspoort	80-95	Quartzite.
		Strubenkop	105-120	Slate.
		Hekpoort	340-550	Andesite.
		Timeball Hill	270-660	Shale, Diamictite, Klapperkop Quartzite and ferruginous quartzite.
		Rooihoogte	10-150	Quartzite, Shale, Bevets Conglomerate Member and Breccia.
	CHUNIESPOORT	Frisco	30-158	Chert-free dolomite with some primary limestone and carbonaceous shale at the base.
		Eccles	490	Chert-rich dark dolomite with stromatolitic and oolitic bands. Chert increases to the top.
		Lyttelton	220-290	Chert-free dark dolomite with large stromatolites and sometimes with wad.
		Monte Christo	740	Alternate layers of chert-rich and chert-poor light coloured dolomite with stromatolites and oolites.
		Oaktree	190-330	Chert-poor dark dolomite with interbedded layers of carbonaceous shale at the base
		Black Reef	11-30	Shale and Quartzite. Arkosic Grit
WITWATERSRAND	CENTRAL RAND	-	2 880	Aranaceous, rudaceous rocks.
	WEST RAND		5 150	Quartzite, reddish and ferruginous magnetic shales.
	DOMINION		?	Quartzite, conglomerate, shale, interbedded lava.
BASEMENT COMPLEX				

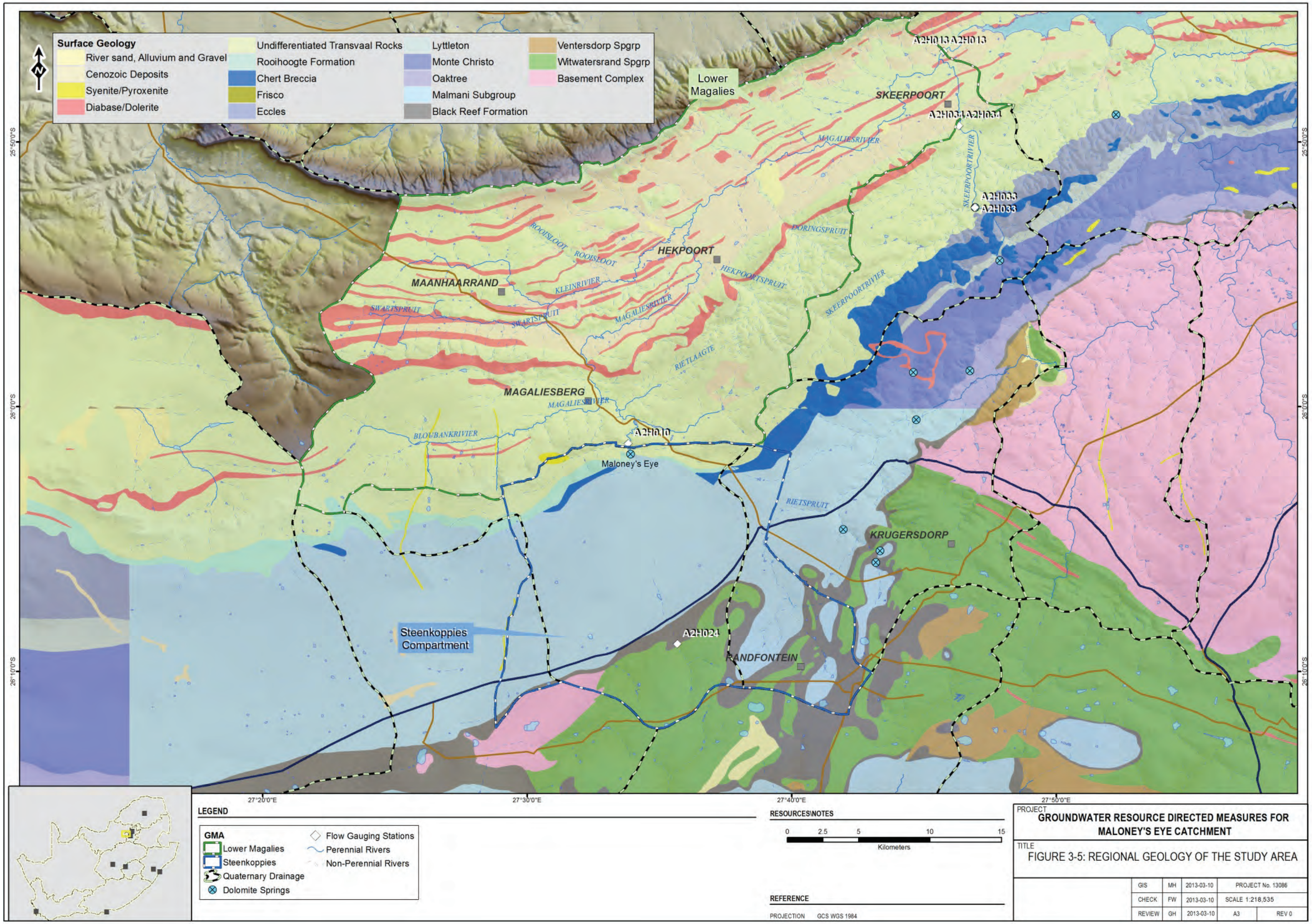


Figure 3-5 Geology of the study area

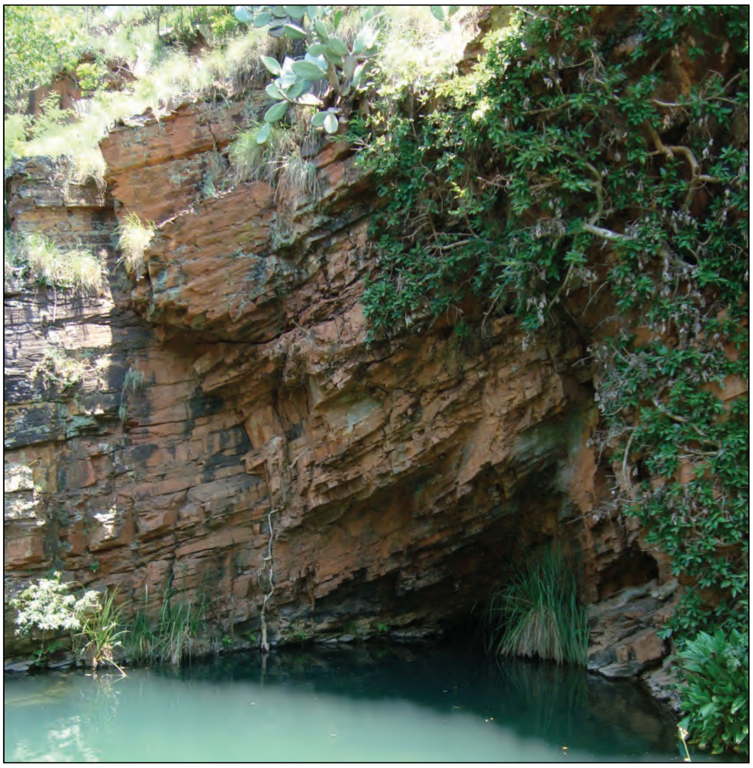


Photo 2 Pretoria Group outcrop downstream of the Maloney's Eye

3.4.1 Karstification

The present karst forms and geomorphology have been created by the interplay of ancient and recent erosion cycles on lithologies that have undergone many episodes of deformation. The dolomite is frequently concealed under a thick blanket of residual material that is derived from recent dolomite dissolution and the weathering of older karst regoliths.

3.4.2 Dykes and lineaments

A number of intrusive dykes occur in the area, subdividing the dolomite into compartments and smaller sub-units. The magnetic nature of the dykes makes aeromagnetic data ideal for mapping these features. The total magnetic field (TMF) map together with interpreted linear anomalies is presented in Figure 3-6. These linear anomalies interpreted as dykes' forms the basis for the delineation of compartments and groundwater management and hydrogeological response units.

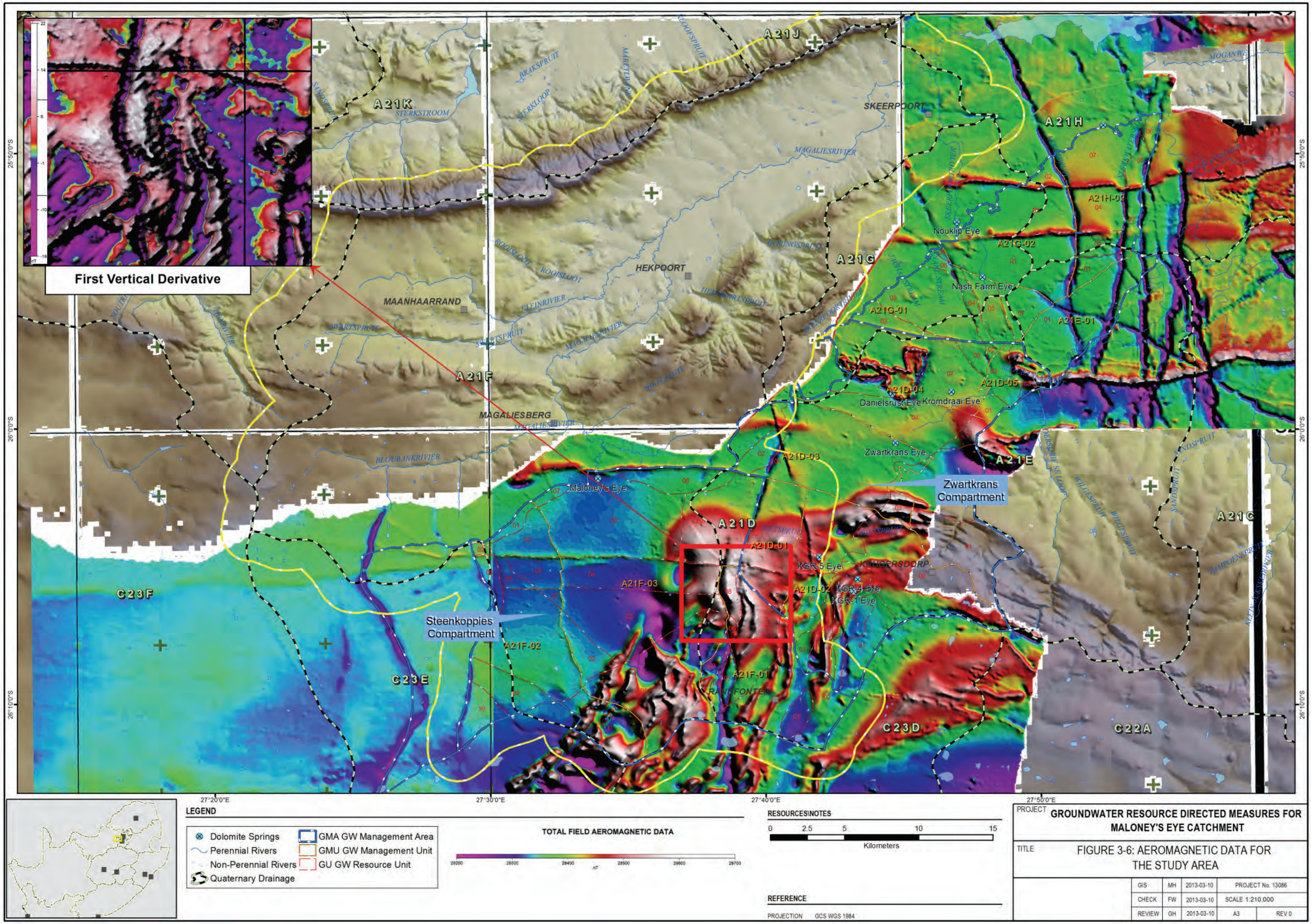


Figure 3-6 Aeromagnetic data for the study area

4 Hydrogeological setting

The data gathered during the desk study and data evaluation phase of the study has been used to develop a hydrogeological conceptual model for the area, which forms the basis for the numerical modelling. In a typical hydrogeological setting groundwater flow and aquifer development are closely linked to the geology and structural geology of an area. There is no reason to believe that the area under investigation will not conform to this assumption and therefore the surface geology as depicted in Figure 3-5 forms the basis on which the conceptual hydrogeological model is based spatially. The nature and distribution of the geological units, and possibly geological structures and dykes control the hydrogeology of the study area.

The aquifer(s) underlying the study area consist(s) mainly of hard rock aquifers associated with the Witwatersrand Supergroup (quartzite), the Ventersdorp Supergroup (Lava), Chuniespoort Group (dolomite) and the Pretoria Group (quartzite and shale) and Karoo Sequence (Ecca Group) sandstone and shale. Post-Karoo dolerite dykes and diabase dykes traverses the study area to divide the dolomite into “compartments”. Historical aquifer test results obtained for these dolomitic “compartments” revealed that very large transmissivities and storativities are associated with the Steenkoppies dolomites (especially within the Monte Christo and Eccles Formations) (Bredenkamp et al., 1986). The dolomites are therefore capable to hold and transmit vast quantities of groundwater.

The overlying Pretoria group reveals very low primary permeabilities and signifies weakly developed secondary permeabilities along faults and fractures. Once the dolomite is exploited excessively it is expected that the Pretoria Group will contribute groundwater to the dolomite (Kuhn, 1989). The hydraulic connection between the dolomites and the underlying Witwatersrand and Basement rocks is considered poor due to the low permeability values of these rocks. Drilling and aquifer testing results obtained elsewhere have indicated that the quartzite and lava formations are very low yielding and very low in permeability (calculated transmissivity values vary between $10^{-2}m^2/d$ and $10^{-1}m^2/d$ as found on the MMC Krugersdorp and the Doornkop TSF Sites to the south of the study area. Karstified dolomites in contrast have orders of magnitude higher permeability and transmissivity values in the order $1\text{-}20x10^3m^2/d$ are not uncommon. Drilling in the area also indicated to a weathered profile down to 35-60 m and fractured to 140 m below surface. The permeability in the dolomitic aquifer is largely the result of extensive weathering and karstification (leaching) of the dolomite. The weathered part of the dolomite underlain with fractures and fissures is highly heterogeneous. These karst aquifers are often characterised by a dual or triple porosity, comprising of solutional voids, fractures and the rock matrix (intergranular pores). While the fractures and the rock matrix provides most of the storage potential (low permeability), the conduits act additionally as drains (high permeability).

4.1 Aquifers

The aquifers identified in the study area can be summarised as follows:

- Karst aquifer
    - Steenkoppies karst aquifer has exceptional groundwater potential with borehole yields often exceeding 5 l/s. Groundwater generally occurs along fault and shear zones associated with intense deformation resulting in the occurrence of fractures, joints and cavities subsequently enlarged by dissolution processes in the dolomites Large quantities of groundwater can be stored in these dissolution channels and cavities.
- Fractured aquifers
    - Of the Pretoria Group strata the formations comprising of predominantly quartzite (e.g. Klapperkop quartzites, Daspoort Formation) are regarded as fractured aquifers and owe its groundwater potential largely to fracturing. Expected borehole yields are low to moderate with expected yields ranging from 0.5 to 5 l/s.
    - The fractured aquifers associated with the Witwatersrand Supergroup rocks comprise of the quartzite, shales and conglomerate of the Hospital Hill and Government subgroups. Groundwater potential is generally low however, faulting and fracturing can enhance groundwater storage capacity considerably.
    - The groundwater potential of the Black Reef quartzite is regarded insignificant and in instances where the groundwater flow direction is towards the dolomite (such as the Steenkoppies DC), steep groundwater gradients are expected due to the poorer transmissive properties of the quartzite compared to those of the dolomite (Barnard, 1997).
- Intergranular and fractured aquifers
    - Of the Pretoria Group sediments the shale bearing formations (e.g. Timeball Hill) can be regarded as aquifers that develop weathering zones which are associated with fracturing. Shales are more susceptible to weathering than quartzites or chert, the weathered material providing intergranular space for water accumulation. Borehole yields are typically below 2 l/s.
    - The Basement complex towards the southeast of the Steenkoppies DC comprise of a deeper fractured (i.e. secondary) aquifer overlain by a weathered horizon of variable thickness. The groundwater yield potential is regarded as moderate with yields often exceeding 2 l/s.
- Intergranular alluvial aquifers (limited to the main Magalies River System)
    - Alluvial sediments along drainage channels form elongated aquifers (so called valley trains) with limited width and depth. Alluvial aquifers are recharged during periods of high stream-flows as well as during the rainfall season. It is an important local major aquifer and borehole yields are seldom less than 5 l/s.

4.2 Gravity survey and Dolomite Aquifer Zones

Gravity surveys are effectively used for delineating potential zones of leaching (karstification) and/or infilling by residual debris of cavities in dolomite strata.

This method is based on measuring minute variations in gravity, which relate to differences in the sub-surface distribution of mass of soil or rock. These density variations are usually produced by changes in rock type which are characterised by changes in porosity or grain density changes, varying thicknesses of unconsolidated deposits over bedrock, and solution cavities in dolomite bedrock.

Weathered or leached dolomite has a lower density (1.85 mg/cm^3) than dolomite bedrock (2.85 mg/cm^3) and this negative density contrast result in negative residual gravity anomalies. A water saturated cavity has a density of only 1.0 mg/cm^3. A gravity low anomaly represents low density bedrock and cannot distinguish between leached/weathered dolomite and a cavity.

In the 1980s the Department of Water Affairs and Forestry conducted a gravity survey on a 100 m grid spacing, known as the Tarlton gravity survey which covered an area of 90 km^2. The Tarlton extension surveys in 1985, conducted by Southern Geophysical Exploration, covered large portions of both the Steenkoppies and Zwartkrans Dolomite Compartments at 100 m station intervals along 250 m spaced traverses. The original gravity data from the 1980s was available as Bouguer anomalies (both absolute and relative) in the form of hard copy maps, with labelled data points. During the 2009 Steenkopies groundwater assessment these map plots were used to collate an electronic Bouguer gravity data set, totalling 9910 data points. (Holland et al., 2009).

As part of this groundwater reserve study the existing gravity survey was augmented by additional gravity surveys (totalling 1067 gravity stations) towards the Maloney’s Eye to assist in delineating major karst features within the highly heterogeneous dolomite aquifer. In addition to this regional DWA gravity survey data (2058 gravity stations) was located in hard copy format and captured electronically to compile a comprehensive data set for the Steenkoppies DC totalling 13,035 gravity stations.

The relative Bouguer gravity data was formerly compiled by DWAF applying standard gravity data corrections. A density factor of 2.67 g/cc was used for the surface elevation corrections. The relative Bouguer gravity data was tied into the national network and a constant value of -148.19 mgal should be added to obtain absolute gravity values based on the IGSN71 gravity base system.

Reduction of Bouguer to residual gravity

The relative Bouguer gravity data (anomalies) contains information of two gravity components:

- A regional gravity field reflecting deep density variations of the underlying bedrock.
- Residual gravity anomalies reflecting near surface (<200 m) and local density differences as a result of leached dolomites or overburden (e.g. Karoo sediments).

In the study of dolomite aquifers we need to remove the deep seated gravity effects. This is done by compiling a regular/smooth regional gravity field and subtracting it from the Bouguer data in such a way that zero gravity values represent solid dolomite at surface. The subsequent compiled residual gravity data represents only near surface density variations. Zero or slightly positive gravity values represent outcropping dolomite bedrock, and negative values leached dolomite zones. Pending the configuration of the underlying leached dolomite and fill material of paleo-channels a 40 to 50 meter factor per -1 mgal residual gravity value can be used to estimate the depth to bedrock.

The relative Bouguer anomaly map together with the regional gravity field, surface elevation and residual gravity map are presented as a mosaic in Appendix A.

A conceptual bedrock elevation map was compiled by multiplying negative residual gravity values by 50 to obtain a bedrock depth estimate. A zero depth to bedrock value was used for positive residual values. These depth estimates were subtracted from the surface altitudes at each gravity station to obtain conceptual bedrock elevations. The bedrock elevations were combined with water level data to delineate zones of karst dolomite below the water table. The saturated leached dolomite zones represent highly transmissive aquifers and groundwater conduits feeding the Maloney’s Eye (Figure 4-1).

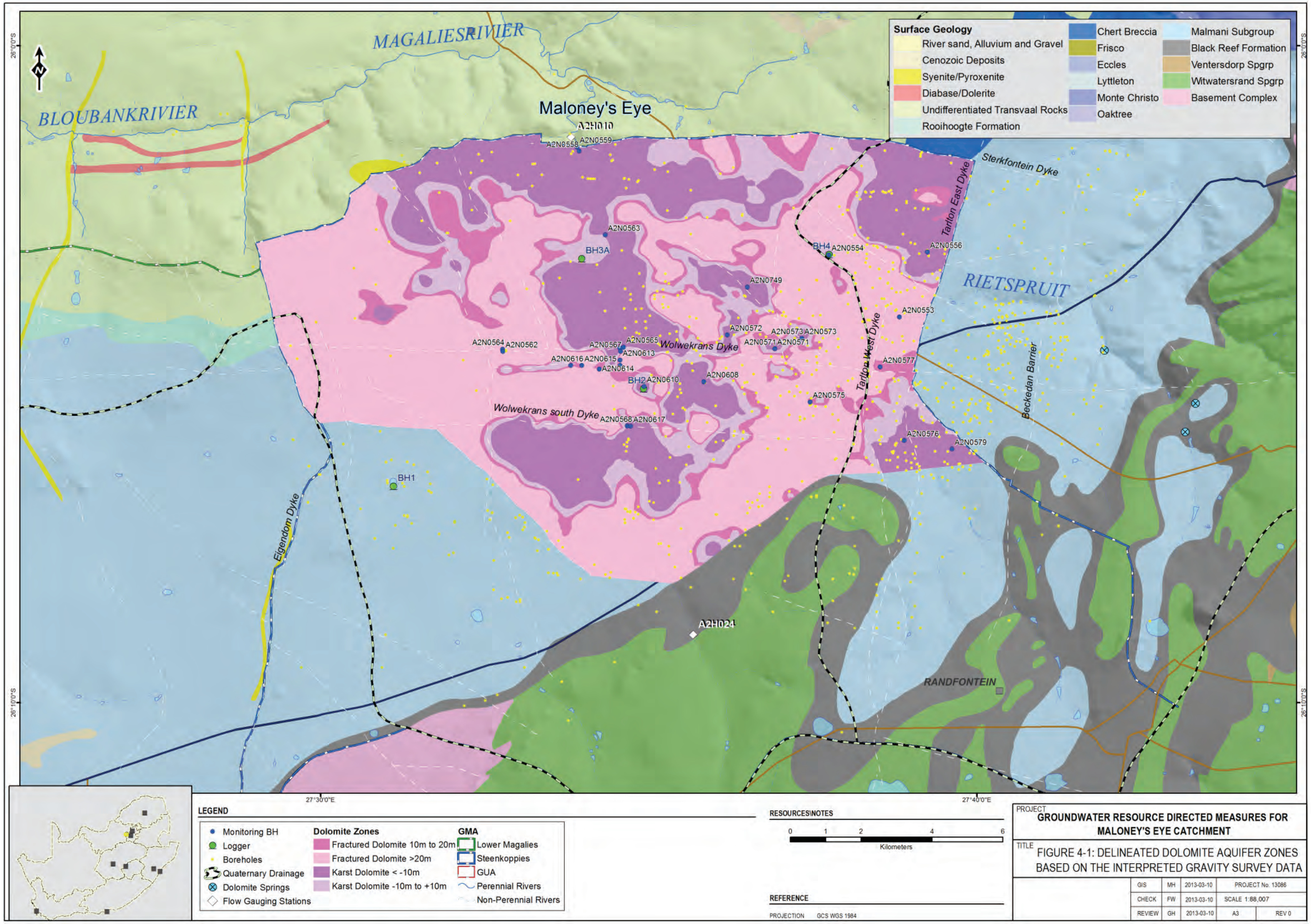


Figure 4-1 Delineated dolomite aquifer zones based on the interpreted gravity survey data

4.3 Delineation of groundwater units

The first step in the RDM Classification process as outlined under Chapter 3 of the NWA, is the demarcation of the units of analysis (UA), of which is to be classified, a Reserve assessment undertaken and Resource Quality Objectives (RQOs) set.

Groundwater Units of Analysis (GUA)

By definition, quaternary catchments are used as the primary delineation of water resource units in RDM assessments. When delineating a groundwater unit, it is worth remembering that a Class, Reserve and RQOs have to be set for each unit; linkages with other components have to be considered; and each unit will have to be managed. As a result setting resource unit boundaries will probably be an iterative process requiring modification until all component requirements have been accommodated. However, due to the nature of groundwater the resource units are often completely different to that of surface water systems. In addition many GRDM assessments precede surface water RDM assessments. In this regard the delineation of groundwater is preliminary and provides valuable input towards the final classification of the integrated water resource. Accordingly to align more closely to the gazette approach for classifying water resources, the term Groundwater Unit of Analysis (GUA) will be used. Similarly to Groundwater Resource Units (GRUs) the GUAs are decided based on geohydrological, hydrological and ecological criteria, while taking into consideration the significance of groundwater (Dennis, 2011). In most instances, it is assumed that the GUA is the quaternary catchment; however, this might not always be the case. In this case a second level of delineation is based on aquifer (e.g. primary aquifer, secondary aquifer, dolomitic aquifer). Though these aquifers may be linked, the nature of subsurface flow in them is so different that they warrant obvious delineation. In some cases, it may be desirable to regroup these aquifer types into a single GUA. This is considered and motivated during the third level of delineation. Although no formal methodology exists for delineating groundwater resource units beyond the second level of delineation, three criteria namely physical, management and functional, could be used as the basis for delineation.

It is a well-known fact that dolomites are effectively divided into “compartments” by dolerite or syenite dykes (Vegter, 1986). Other features such as brecciated faults and topographic divides may also form compartment boundaries. Groundwater conditions in each compartment may be relatively uniform and the water table surface fairly flat, whilst large differences in water level between compartments may be found. Flow does occur between compartments, but usually on a smaller scale compared to flow within a compartment. Compartment boundaries are also often associated with spring lines and seepages, as groundwater is forced to the surface (such as the Maloney’s Eye). Based on the high level delineation of the groundwater resources within the larger A21F quaternary catchment and the Steenkoppies DC, 14 groundwater management units (GMU) have been delineated (Figure 4-2). The Steenkoppies DC (the Maloney’s Eye catchment) consists of 6 GUA’s and represents an area of 332 km^2, while the lower Magalies river catchment have been delineated in 8 GUA’s totalling an area of 740 km^2.

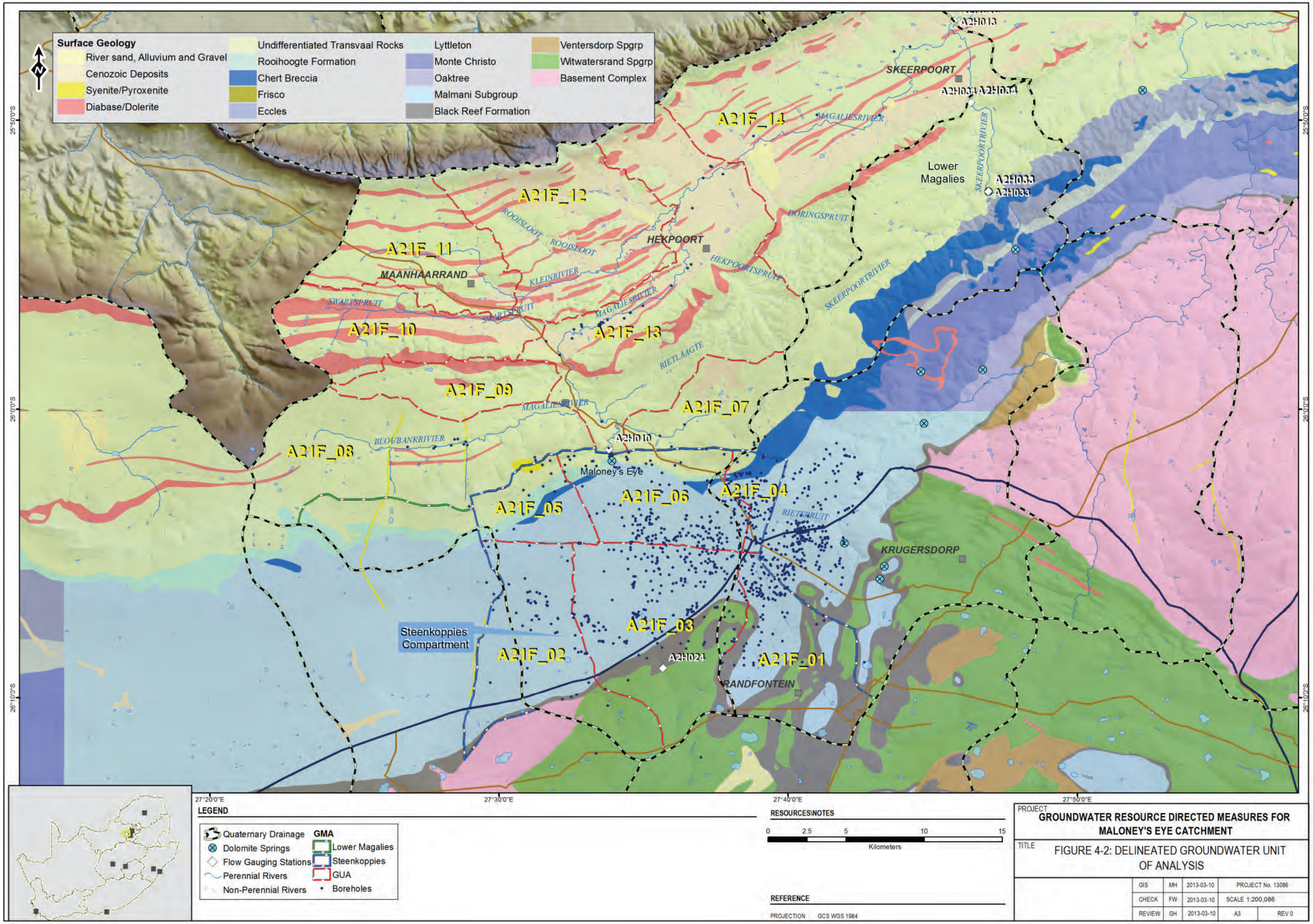


Figure 4-2 Delineated groundwater unit of analysis

4.4 Groundwater recharge

Groundwater recharge are normally also orders of magnitudes higher than on other hard rock aquifers as a result of the large permeability that the dolomites exhibit. The groundwater system within the study area is largely recharged via infiltration of precipitation. It is thought that most of the groundwater recharge occurring within the study area discharges via the Maloney's Eye (Photo 3) and discharge to the base of river drainage systems in the lower Magalies area.

Photo 3 Maloney's Eye

The annual recharge is estimated to be in the order of 2-4% of MAP across the hard rock aquifers. Across the dolomite areas the recharge is significantly higher (in the order of 84 mm/a or 12% of MAP) and in line with the much larger permeabilities for these aquifers.

Recharge to the aquifer is from precipitation during the rainy season. Monitoring data have indicated that there is a good relationship between the CRD and the water level fluctuations in the dolomite aquifer which indicates to dynamic recharge occurring. A good correlation between the flow of the Maloney's Eye and the CRD was also obtained indicating that rainfall is the driver behind the groundwater system's dynamics (Figure 4-3). The rainfall/recharge relationship is discussed in more detail under the transient calibration (in the appended model report Appendix B).

Based upon previous work conducted on dolomite terrain it was concluded that an exponential relationship between recharge and rainfall produced acceptable results. Such a relationship would entail that moderate recharge rates would occur at moderate rainfall events. However once rainfall gets higher the rate of recharge would increase disproportionately with rainfall. This would make sense since the soil moisture deficits would already have been overcome with large monthly rainfalls effecting saturated conditions in the soil zone close to surface causing development of maximum hydraulic conductivity values maximizing vertical infiltration rates into the aquifers.

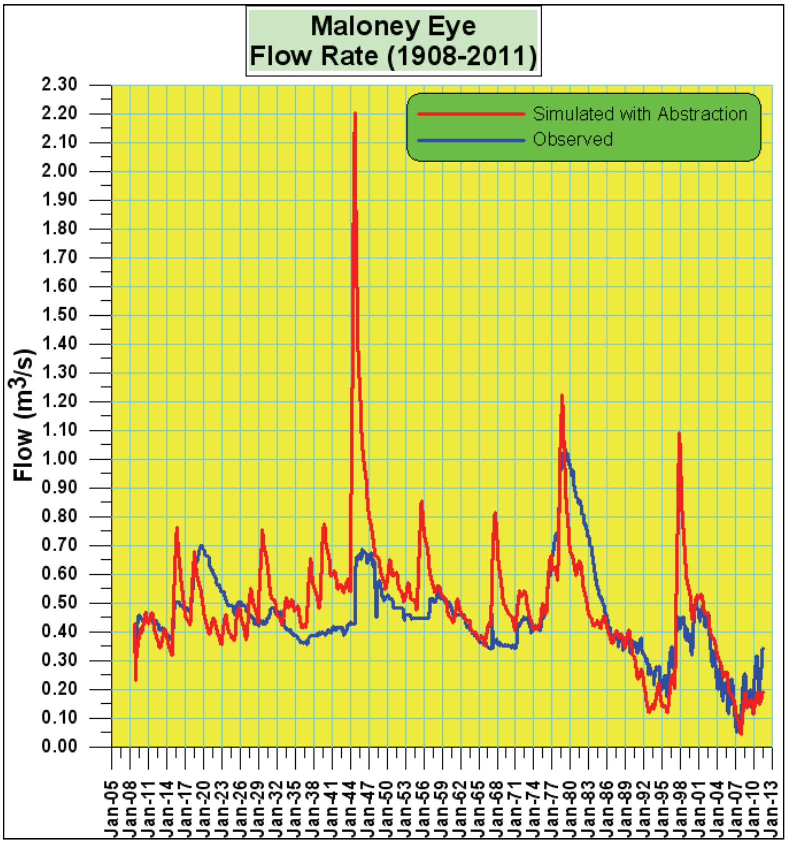


Figure 4-3 Simulated vs. observed flow rates at Maloney's Eye using an exponential relationship between rainfall and recharge

In the case of the Steenkoppies DC an additional (external) source of recharge was identified – since the hard rock area to the south the Steenkoppies DC has a well-developed steeper surface gradient it is thought that this would provide additional run-off to cause "flash flood" conditions onto the Steenkoppies DC. The Steenkoppies DC is riddled with sinkholes which would then provide the pathway for run-off water to recharge into the underground. Taking the above concepts into consideration, numerous simulation runs were performed over the historical period (2008-2011) and a recharge to rainfall relationship developed to represent the flow at the Maloney's Eye on a trial-and error approach.

Final calibration parameters include the following:

- A nine month moving average was applied on the recharge series.
- Recharge (mm/month) was derived as a fraction of rainfall.
    - The recharge fraction was obtained from the following formula:

Recharge Fraction = 1.0*[0.025e(0.011*Rainfall)]

The obtained recharge to rainfall relationship is depicted in Figure 4-4 or the three recharge zones modelled. The spatial zoning used for the assignment of recharge is as follows:

- Zone 1 (Steenkoppies DC)
- Zone 2 (Witwatersrand rocks to the south of Steenkoppies DC.
- Zone 3 (Pretoria Group to the north of the Steenkoppies DC.

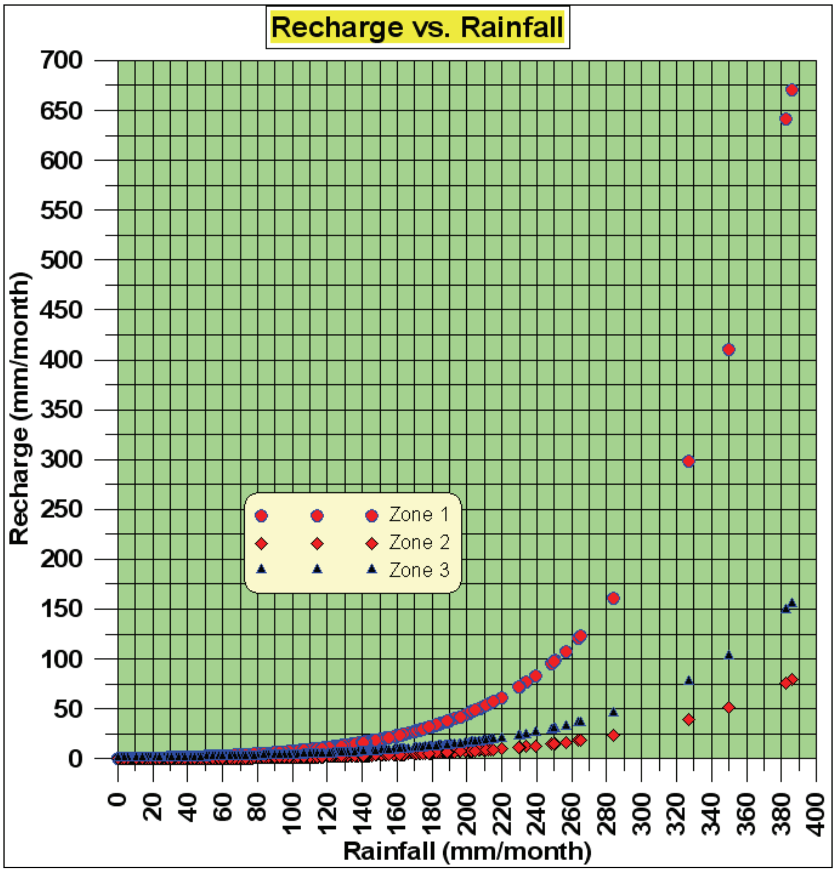


Figure 4-4 Recharge vs. Rainfall relationship obtained for all three zones modelled (linear Y-axis)

A breakdown of the statistics of the recharge rates for each of the GMU's are shown in Table 4.1

4.5 Groundwater levels

A total of 379 water levels were collated from historical reports and recent hydrocensus data. A summary of water level data within each groundwater unit is provided in Table 4.2.

Although DWAF has monitored groundwater levels since 1985, only 14 of the 37 stations within the Steenkoppies DC are still active. A number of monitoring boreholes has ceased only in the last couple of years. A summary of the long-term monitoring stations are provided in Table 4.3 and illustrated spatially in Figure 4-1.

Table 4.1 General statistics associated with the recharge on the GUA's in the study area

Groundwater Management Area	GUA	Area (Km^2)	N	Recharge (m^3/d)		Std. Dev
				Mean	Median	
Steenkoppies DC	A21F-01	62.6	1,233	8,837	6,472	9,967
	A21F-02	78.5		15,531	11,031	18,799
	A21F-03	94.5		16,817	12,085	19,874
	A21F-04	12.9		3,251	2,276	4,045
	A21F-05	27.5		6,802	4,763	8,459
	A21F-06	56.2		13,754	9,630	17,113
	Total	332		64,992	46,257	78,257
	In Mm^3/a			**23,7 Mm^3/a**	**16.9 Mm^3/a**	
Lower Magalies River	A21F-07	35.9	1,233	1,775	1,358	1,713
	A21F-08	106.6		4,844	3,723	4,602
	A21F-09	33.5		1,580	1,223	1,475
	A21F-10	61.4		2,760	2,137	2,577
	A21F-11	66.4		2,928	226	2,733
	A21F-12	95.1		4,187	3,241	3,908
	A21F-13	156.9		7,010	5,423	6,564
	A21F-14	183.7		7,818	6,052	7,298
	Total	740		32,902	23,383	30,870
	In Mm^3/a			**12 Mm^3/a**	**8.3 Mm^3/a**	

Table 4.2 Summary of water levels for each groundwater unit

Groundwater Management Area	GUA	Area (Km^2)	N	Water levels (m below surface)			Water elevation (mamsl)		
				min	max	mean	min	max	mean
Steenkoppies DC	A21F-01	62.6	45	1.9	75.6	32.4	1505.0	1655.5	1565.9
	A21F-02	78.5	37	11.3	107.9	63.1	1494.2	1603.1	1523.7
	A21F-03	94.5	77	6.1	98.2	64.8	1483.0	1707.2	1508.9
	A21F-04	12.9	50	3.5	84.9	54.5	1483.9	1576.6	1514.1
	A21F-05	27.5	15	7.2	126.5	52.8	1479.8	1580.1	1536.1
	A21F-06	56.2	107	3.8	178.9	63.4	1437.5	1571.3	1498.2
Lower Magalies River	A21F-07	35.9	5	2.0	80.0	21.5	1422.5	1526.2	1490.1
	A21F-08	106.6	10	2.6	90.0	16.4	1440.8	1617.1	1515.6
	A21F-09	33.5	-						
	A21F-10	61.4	-						
	A21F-11	66.4	-						
	A21F-12	95.1	1	8.8			1718.2		
	A21F-13	156.9	27	0.1	22.6	6.5	1243.6	1444.6	1333.8
	A21F-14	183.7	5	1.7	7.2	3.5	1184.7	1239.9	1212.8

Table 4.3 Summary of long-term water level monitoring data for the Steenkoppies DC

UNIT	BH_ID	Commence		Last WL	WL	Measured WL data					Ceased
		Date	WL	Date	WL	Count	Min	Mean	Max	Min-Max	
A21F-01	A2N0576	Mar-85	50.3	May-11	42.2	251	30.2	46.7	61.9	31.7	
	A2N0579	Mar-85	26.0	Feb-11	27.6	140	23.1	27.0	31.7	8.6	
A21F-03	A2N0562	Nov-85	80.0	Jun-10	78.2						Yes*
	A2N0566	Sep-85	58.2	May-11	59.0	194	56.9	59.0	61.7	4.8	
	A2N0567	Sep-85	58.0	May-07	58.5	236	57.8	59.3	61.8	4.0	
	A2N0568	Aug-85	62.0	Feb-07	65.6						Yes
	A2N0569	Mar-85	75.8	Jun-01	75.0						Yes
	A2N0570	Mar-85		Apr-02	71.3						Yes
	A2N0574	Mar-85		Mar-11	75.0						Yes*
	A2N0575	Mar-85	89.5	Mar-05	86.2						Yes
	A2N0608	May-87	70.6	Nov-10	72.5	166	67.1	71.0	72.6	5.5	Yes
	A2N0609	Apr-87	71.8	Mar-10	73.6						Yes*
	A2N0610	Apr-87	60.1	May-11	60.7	217	58.8	60.8	26.8	4.0	
	A2N0611	Jun-87		Aug-01	55.4						Yes
	A2N0612	Jul-87	55.1	May-11	55.8	182	54.2	56.0	58.3	4.2	
	A2N0613	Jun-87		Jul-96	53.4						Yes
	A2N0614	May-87	67.5	May-11	68.4	196	64.9	68.0	70.4	5.5	
	A2N0615	Jul-87	68.3	Feb-11	70.1	181	64.9	69.0	71.2	6.3	
	A2N0616	Jun-87	68.6	May-11	69.3	163	65.7	69.1	71.3	5.5	
	A2N0617	Apr-87		Mar-10	63.6						Yes*
	A2N0618	Jun-87	74.3	Nov-99	74.7						Yes
	A2N0619	Jul-87	74.5	Jun-01	74.0						Yes
A21F-04	A2N0553	Apr-85	66.4	May-11	60.0	257	58.3	64.3	71.3	13.0	
	A2N0555	Mar-85	50.6	Jan-90	56.1						Yes
	A2N0556	Mar-85	42.3	Apr-11	46.3	242	44.0	49.4	58.3	14.3	
	A2N0577	Apr-85	61.1	May-10	57.7						Yes*
A21F-05	A2N0564	Nov-85	75.9	Nov-09	79.6						Yes*
A21F-06	A2N0554	Mar-85	81.0	May-11	3.5#						
	A2N0558	May-85	8.7	Sep-10	8.6	614	7.3	8.6	9.7	2.4	
	A2N0559	May-85	8.1	Sep-10	7.8	245	5.8	7.9	8.9	3.1	
	A2N0560	Dec-85	58.8	Jun-93	59.7						Yes*
	A2N0561	Nov-85		Mar-10	63.6						Yes*
	A2N0563	Aug-85	100.6	Aug-09	65.3						Yes*
	A2N0565	Sep-85	54.0	Aug-01	57.5						Yes
	A2N0571	Apr-85	72.2	Nov-10	72.9	115	71.4	73.5	80.3	8.8	Yes*
	A2N0572	Mar-85	68.8	May-11	69.5	257	67.9	69.6	71.2	3.2	
	A2N0573	Apr-85	72.2	Nov-99	72.5						Yes

* - Data missing
\# - Faulty levels

4.5.1 Groundwater hydrographs

The distribution of monitoring boreholes is presented in Figure 4-1. Generally, groundwater levels fluctuate according to the characteristics of precipitation events (i.e. amount, duration, and intensity) and various hydrogeological variables (i.e. topography, thickness of the unsaturated zone, and matrix composition of saturated and unsaturated materials). Groundwater level fluctuations from the observed hydrographs vary between 2.4 and 9 m. a well-identified seasonal water-level fluctuation is observed for most monitoring boreholes. Except for the mid to late 1980s the CRD (a short moving term average of 9 months and a long term moving average of 60 months) fits the observed water level trends reasonably well, especially towards the edges of the Steenkoppies DC (e.g. A21F-04) (Figure 4-5).

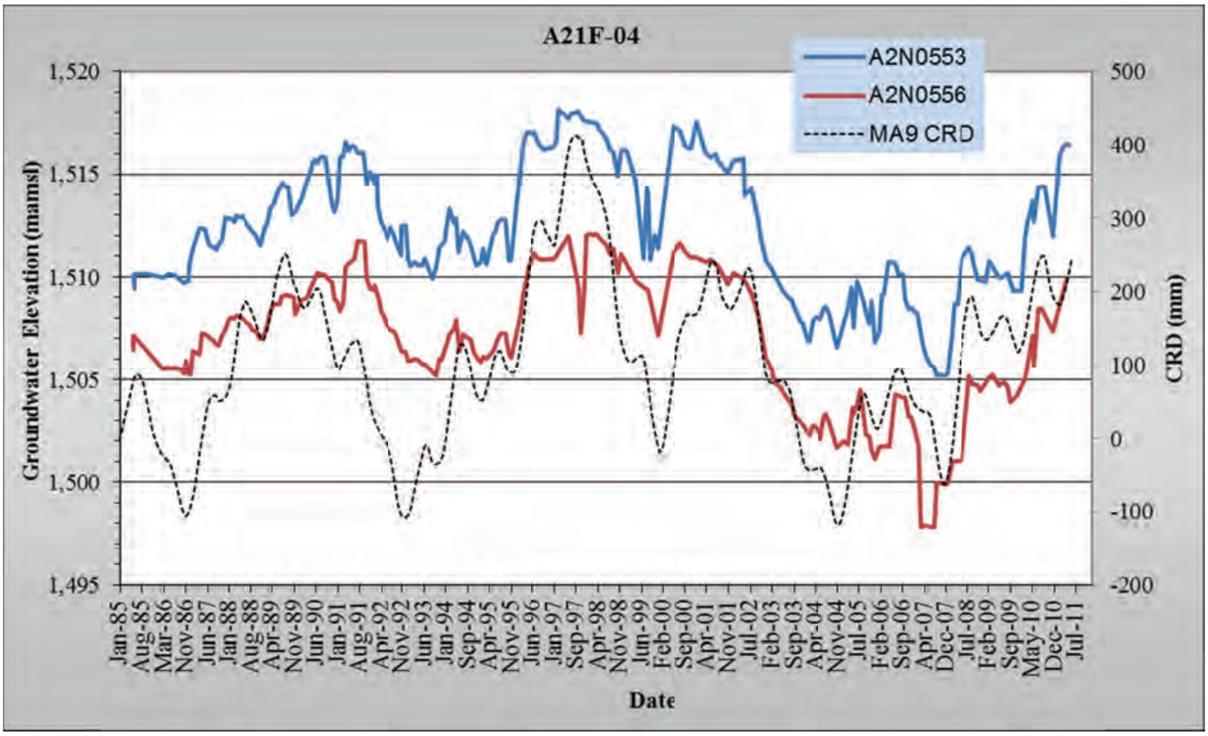


Figure 4-5 Borehole water levels within GUA A21F-04

Towards the centre of the Steenkoppies DC south of the Wolwekrans dyke most monitoring boreholes shows similar trends (Figure 4-6 and Figure 4-7) in GUA A21F-03. The CRD graph seems to have a similar trend compared to the water levels towards the end of the 1990 and continuous throughout the last two decades.

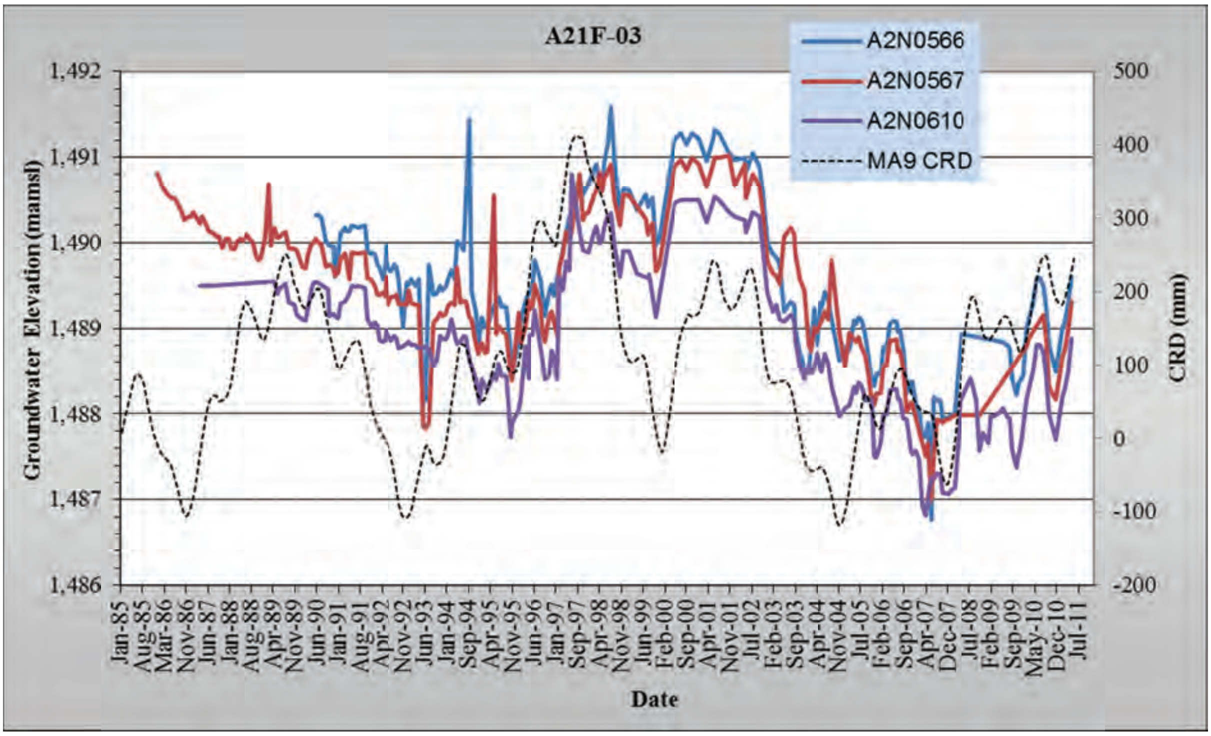


Figure 4-6 Borehole water levels within GUA A21F-03

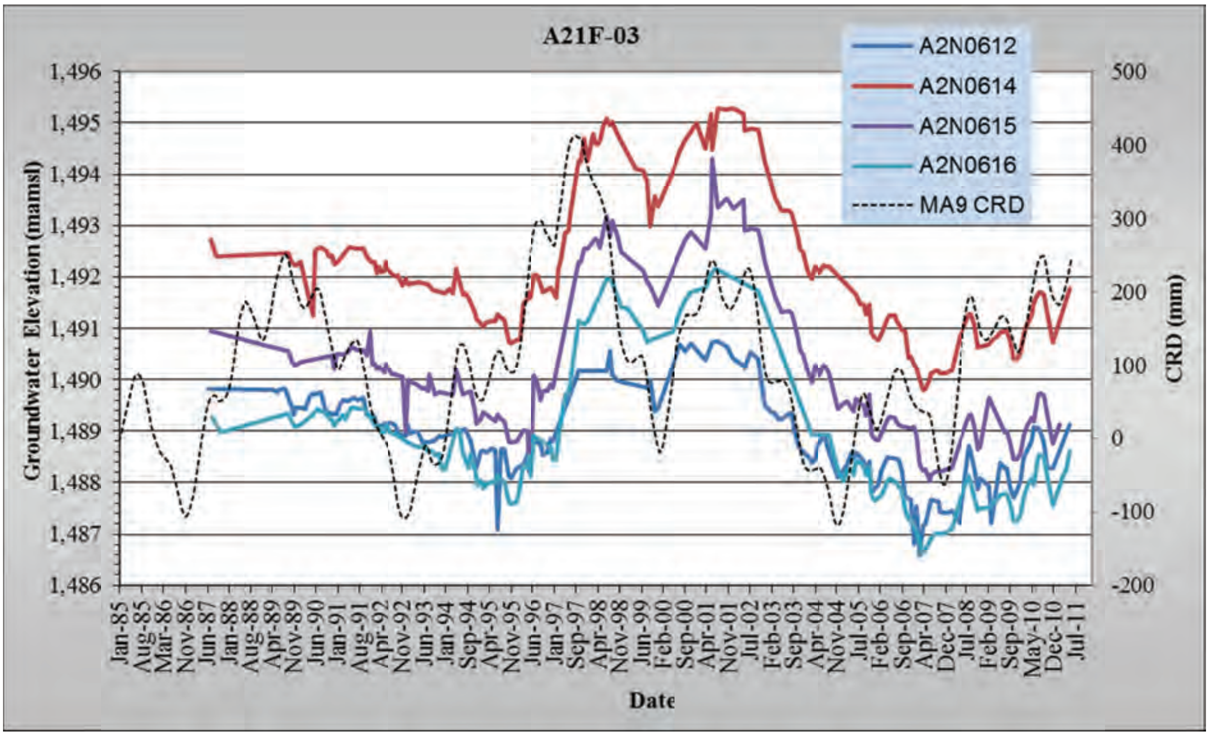


Figure 4-7 Borehole water levels within GUA A21F-03

Water levels within the upper Rietspruit catchment (A21F-01) shows similar trends and an increase in water levels is observed in the last 4 years (Figure 4-8).

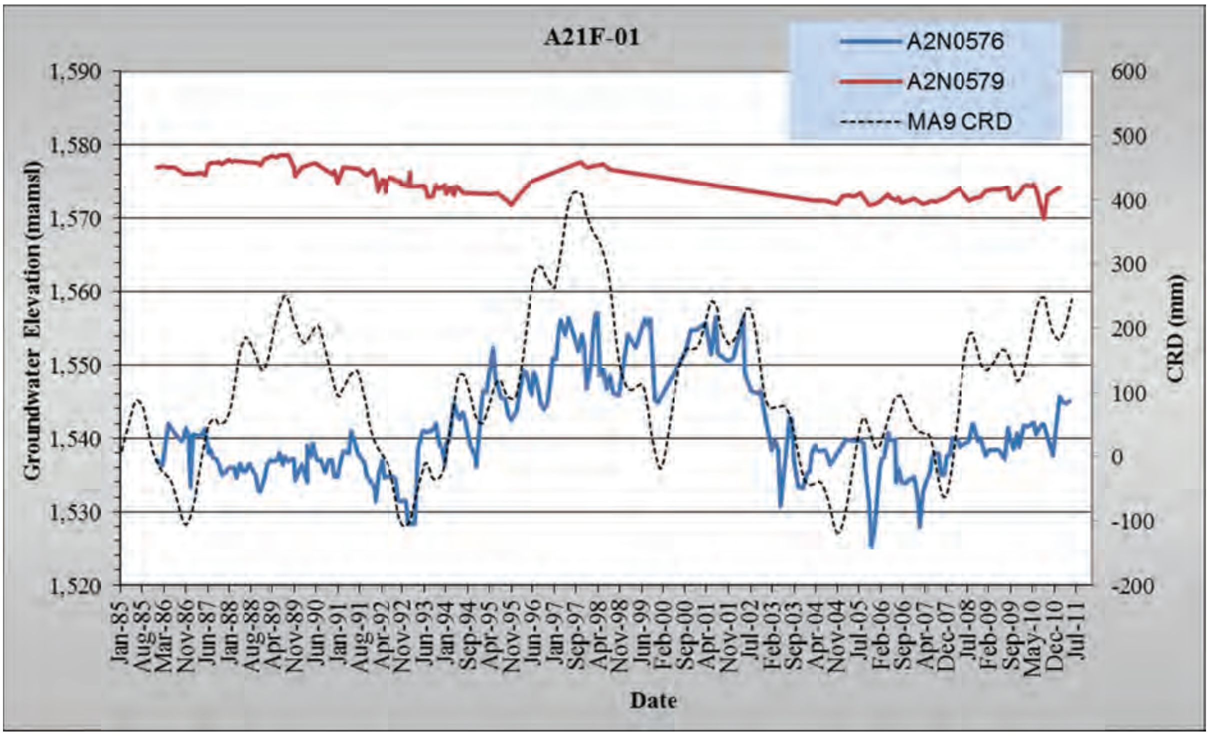


Figure 4-8 Borehole water levels within GUA A21F-01

Towards the Maloney's Eye the main discharging groundwater unit, a more subtle water level fluctuation is observed (Figure 4-9).

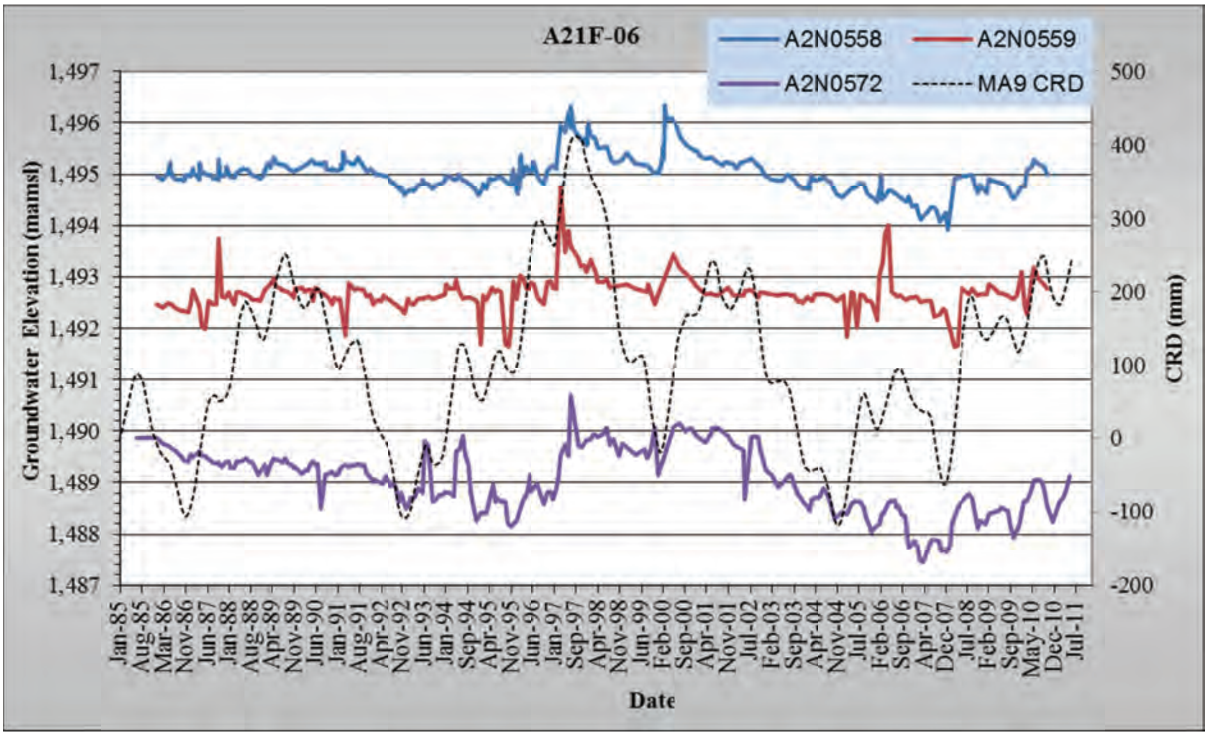


Figure 4-9 Borehole water levels within GUA A21F-06

4.5.2 Borehole loggers (SAMA)

The distribution of the four borehole loggers installed in March 2011 by the Steenkoppies Aquifer Management Association (SAMA) is illustrated in Figure 4-1 and listed in Table 4.4.

Table 4.4 Borehole logger summary

ID	Latitude	Longitude	Serial nr. data	WL (m below surface)	Comment
Borehole 1	27.51854	-26.1118	1053462	73.36	Josie
Borehole 2	27.58199	-26.0871	1053500	61.48	A2N0610
Borehole 3	27.56632	-26.0541	1054695	79.59	Roberto
Borehole 4	27.62917	-26.053	1054706	3.94#	A2N0554
Barro 5	27.62917	-26.053	1054705		Barro Logger

- Water levels are 70 m different compared to historical data.

All boreholes show similar trends with a distinct recharge period during the summer period (which constitutes up to 80% of the annual precipitation) and a recession period that starts more or less in July (Figure 4-10 and Figure 4-11).

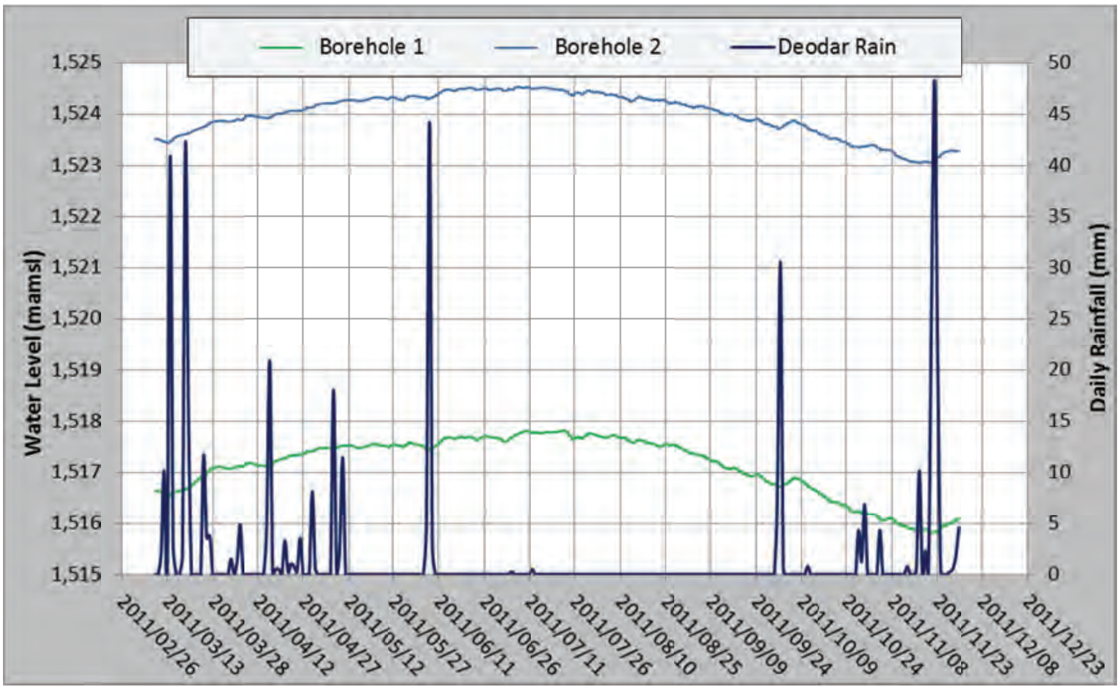


Figure 4-10 Continuous water level measurements for Borehole 1 and 2

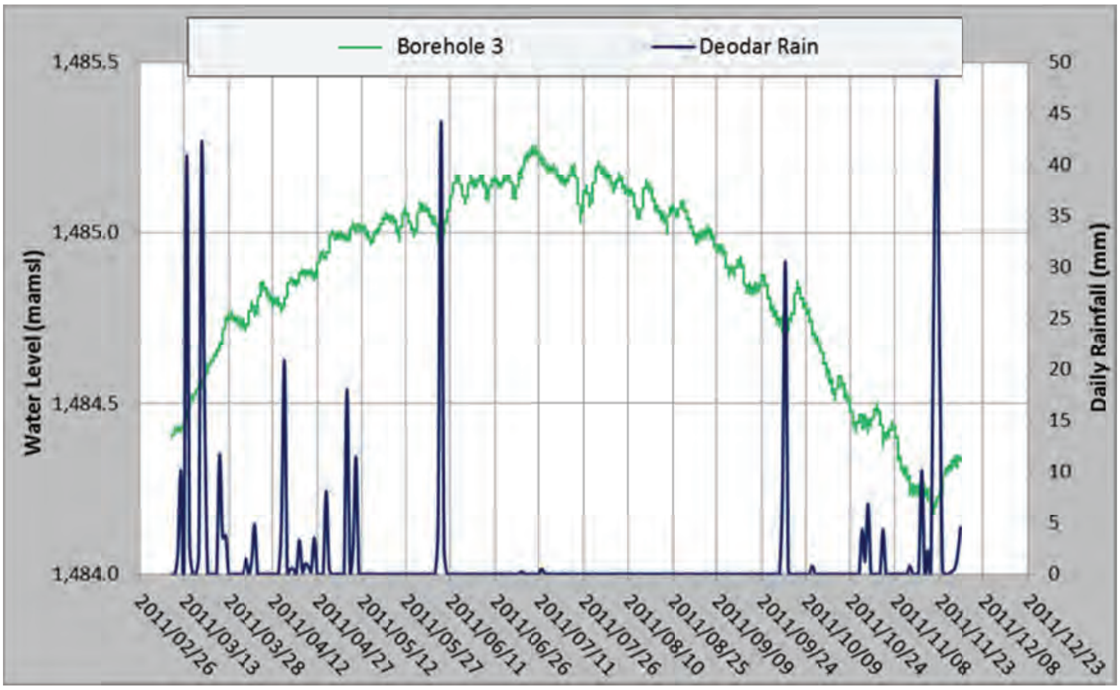


Figure 4-11 Continuous water level measurements for Borehole 3

4.5.3 Groundwater gradient

Groundwater flow is from areas of higher piezometric elevations to lower elevations. Groundwater flow directions mimic the surface topography. This is confirmed by the fair correlations between groundwater levels and the surface topography (see Figure 4-12).

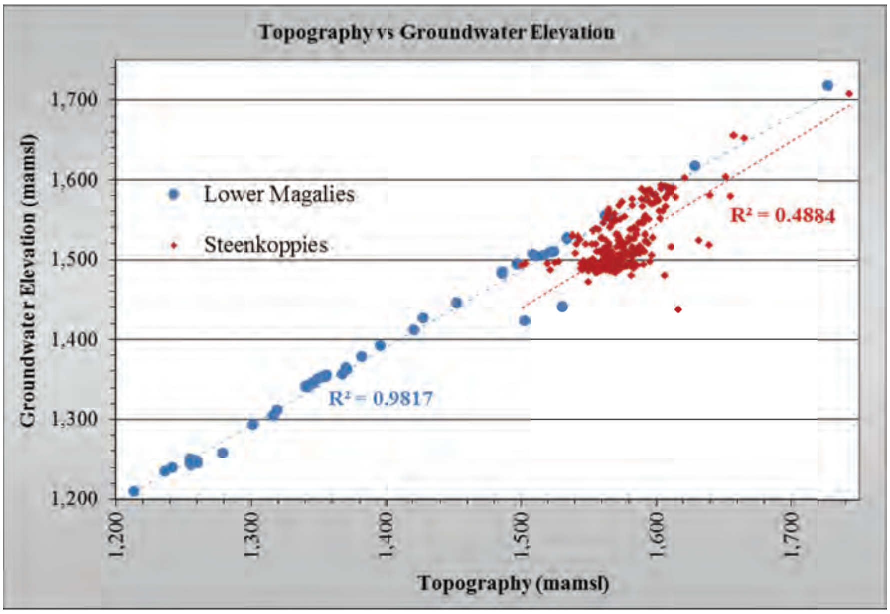


Figure 4-12 Plot of groundwater levels vs. topography

From this figure it is evident that the dolomite water levels vs. topography are following a different relationship than that of the hard rock water levels vs. topography. Dolomite water levels are in general deeper than that of the hard rock aquifers. The dolomite water levels however still mimic the topography to a large extent. Figure 4-13 show the simulated steady state groundwater elevations and groundwater flow directions for the steady state calibration. There are insufficient boreholes with groundwater level data to create an observed water table map for the entire model area. Therefore, the model output has been evaluated in a qualitative manner by observing the shape of the water table contours near known hydraulic boundaries, divides and drainages. The calibrated model water table is similar to what would be expected at the location of internal watersheds divides and major drainages. The simulated water levels are discussed in more detail under the steady state calibration (in the appended model report Appendix B).

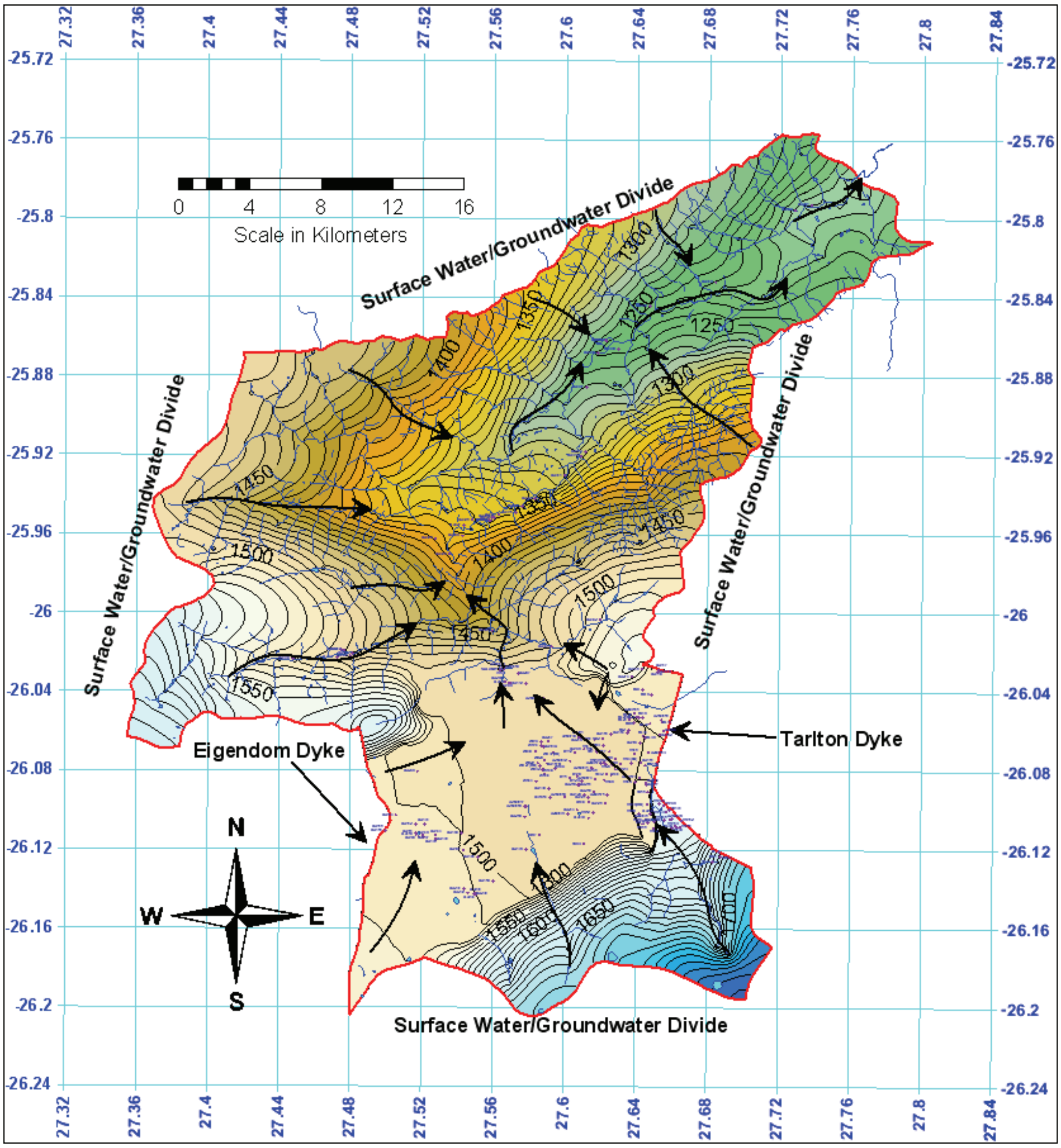


Figure 4-13 Simulated water levels based on the steady state mode calibration

4.6 Surface-groundwater interaction (Baseflow)

4.6.1 Magalies River baseflow

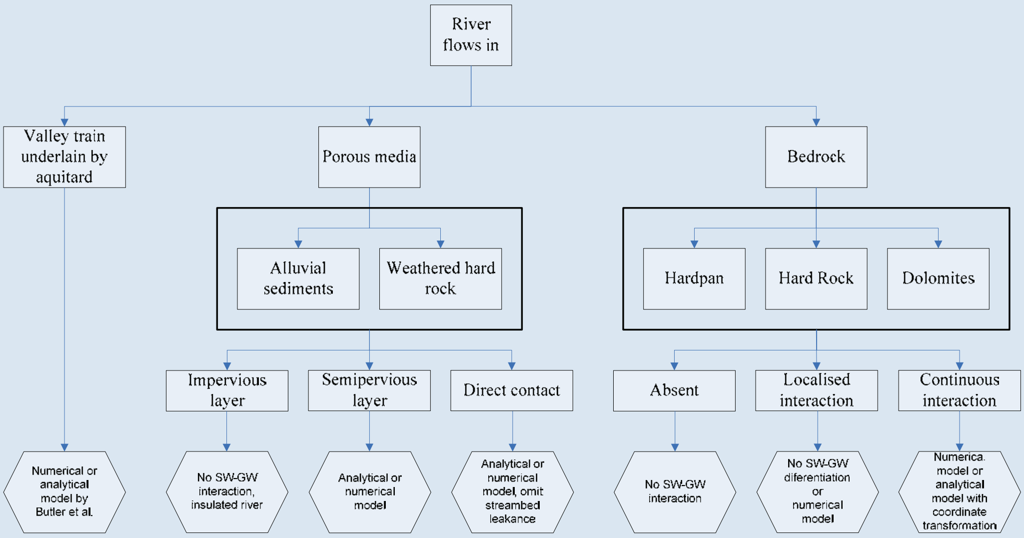
The first step in establishing the potential for surface-groundwater interaction is to classify the river system along its drainage course. The following characteristics of rivers can be regarded important for the understanding of surface–groundwater interaction:

- Gradient between piezometric surface and river stage (either side).
- Occurrence and characterisation of clogging layers in the riverbed.
- Hydrogeological characteristics of the strata along the river stretch.
- Regional groundwater gradients.

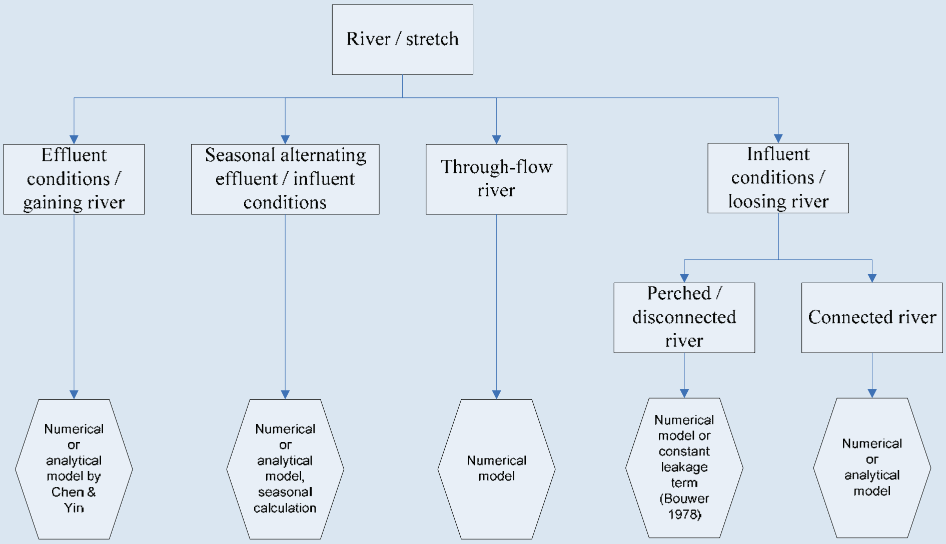
The only flow gauging stations potentially available for the recession analysis is the Maloney's Eye (A2H010) and Scheerpoort (A2H013). In the absence of flow hydrographs within the study area the focus will be largely on the classification and characterisation of groundwater-surface interaction with the main aim to provide insight into the significance of the flow of the Maloney's Eye on the Magalies River catchment.

Groundwater – surface water interaction - classification.

A simple two tier classification scheme, with a geological classification of the river-aquifer setting followed by a brief hydraulic classification of the interaction is proposed.The primary geological classification differentiates between rivers flowing in porous media or over bedrock. A third class accounts for valley trains underlain by aquitards, a typical situation of an alluvial aquifer along a river stretch underlain by impervious hard rocks.



Following the conceptualisation of the geological setting the type of surface-groundwater interaction is classified based on the prevailing hydraulic gradient.



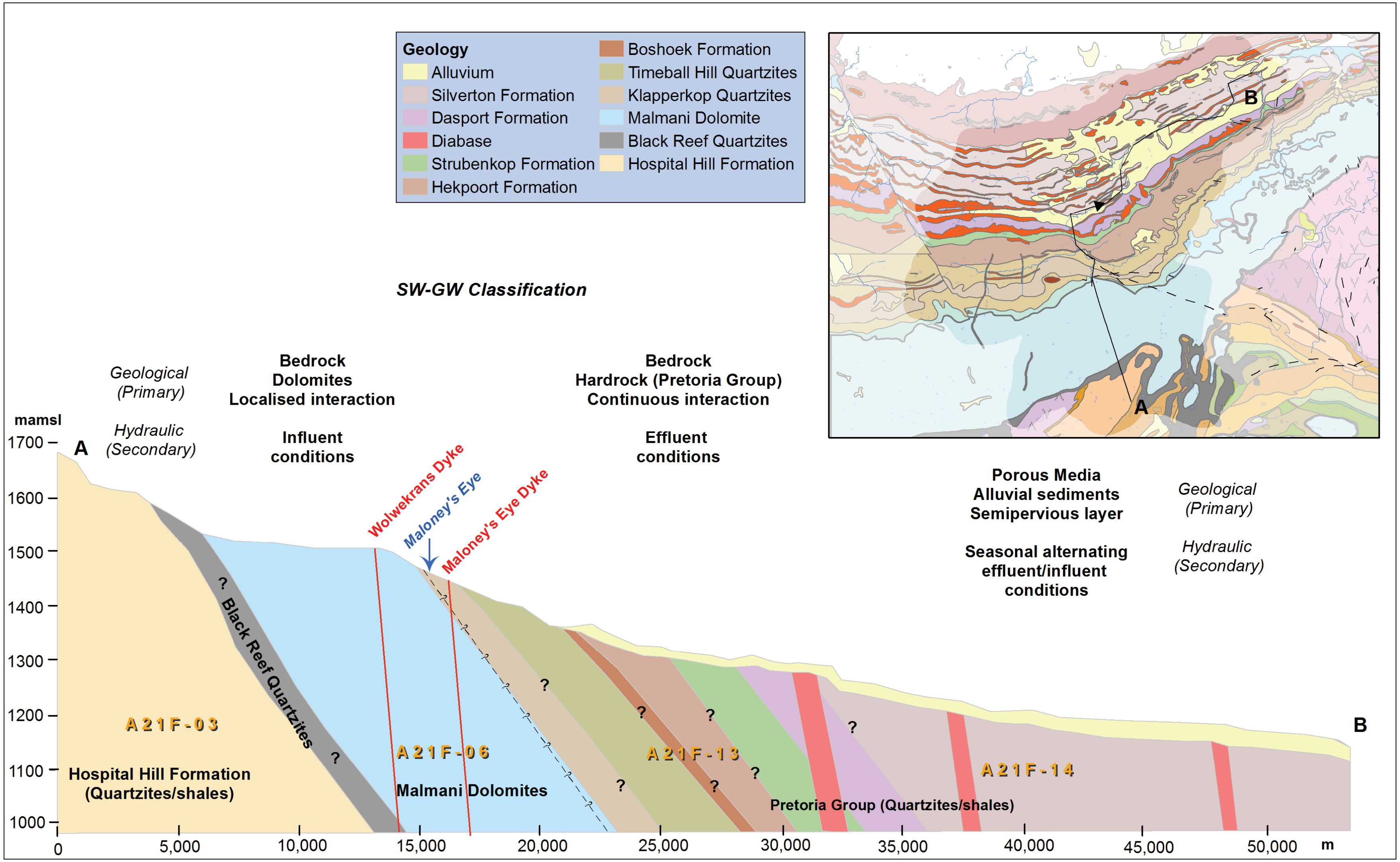


Figure 4-14 Simplified geological profile of the Magalies River Catchment

The Steenkoppies DC is devoid of surface drainages and run-off from the quartzites to the south disappears relatively quickly in swallow holes or sinking streams, which is characteristic of karst terrains. Groundwater contributes to baseflow throughout the lower Magalies River catchment via sub surface seepage and springs. The Magaliesberg Range and the southern belt of Pretoria Group strata are important areas for groundwater recharge and baseflow. In the upper reaches of the Magalies River (north of the Maloney's Eye) a higher gradient towards the River course is observed and where the alluvium is lacking the surface-groundwater exchange is directly from the regional aquifer to the River. Towards the lower reaches the Magalies River floodplain is characterised by a relatively thick alluvial layer. The surface-groundwater exchange between the alluvium and the Magalies River occurs on a far shorter time scale in comparison to the interaction between the regional and alluvial aquifers. Regional aquifers of the lower catchment show marginal gradients towards the River course and exchange water with the river only indirectly via the alluvial deposits. Surface-groundwater interaction is strongly seasonal as both effluent / influent conditions can occur depending on the recharge period of the alluvium.

Based on the GRA II dataset the Magalies River catchment (A21F) has a high probability of baseflow. A summary of the GRA II baseflow values is provided in Table 4.5.

Table 4.5 Groundwater contribution estimates

Quaternary	Area (Km^2)	MAR (Mm^3)	Recharge (Mm^3)	Hughes (Mm^3)	Shultz (Mm^3)	Pitmann (Mm^3)	GRA II (Mm^3)	Maintenance Low flow (Mm^3)	PESC
A21F	1001	25.1	33.9	12.1	7.3	10.2	3.9	3.1	C

* - In-stream Flow Requirements (IFR) maintenance low flows based on the SPATSIM (Spatial and Time Series Information Modelling) flow modelling system (Hughes and Palmer, 2005) simulation runs conducted during this study (based on the PESC).

Baseflow

The Schultz figures consider baseflow to be the portion of ground water which contributes to the low flow of streams originating from the regional groundwater body. The Herold and Hughes interpretations of baseflow include all water which migrates through the subsurface, hence it includes seepage from perched aquifers, high lying springs and interflow. A large fraction of this water never reaches the regional aquifer, hence does not form part of the available groundwater resources. To determine potential baseflow depletion resulting from pumping the regional aquifer the Schultz figures may be more appropriate. To determine the potential impact of induced recharge, or to set subsurface water contribution to the ecological reserve, the Hughes figure and the hydrograph separation method provides a volumetric total of available baseflow.

Various methods with which the groundwater contribution to baseflow can be calculated are provided in Parsons and Wentzel (2007) and Dennis (2011). One of the most common methods to determine baseflow is through river hydrograph separation and recession curves. A river hydrograph consists of three components: direct runoff, interflow through the unsaturated zone and groundwater discharge from the saturated zone (Figure 4-15). Although a baseflow is often defined as the groundwater discharge from the saturated zone in classic hydrogeological textbooks the word baseflow is generally known to many hydrologists as delayed flow components (mainly groundwater), as opposed to a quick, direct runoff. Thus, baseflow itself is not indicative of origins of water sources. The baseflow is normally separated by removing the direct runoff from a hydrograph. As a result, such a baseflow component may still contain some interflow component.

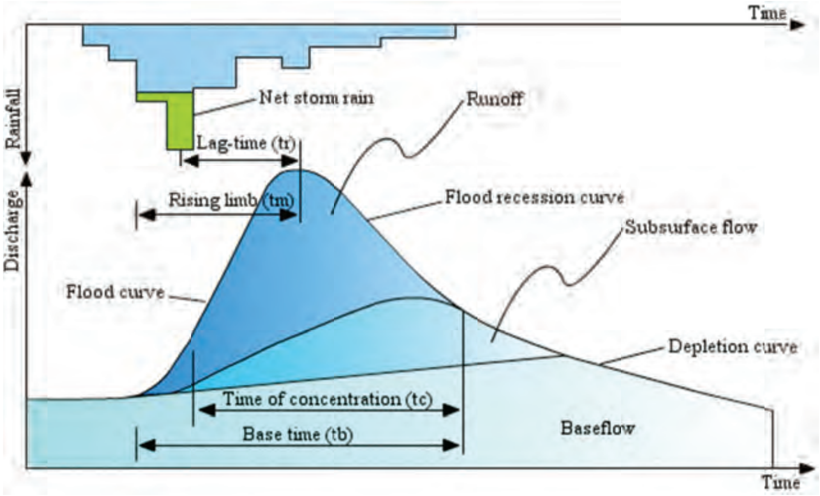


Figure 4-15 The flood hydrograph from a rainfall event (Musy, 2001)

A baseflow separation for the Magalies river downstream gauging station A2H013 for a 31 year period (Jan-1980 to Sep-2011) is illustrated in Figure 4-16 and summarised in Table 4.6. The mean annual baseflow obtained from the separation method is approximately 6.4 Mm^3/a.

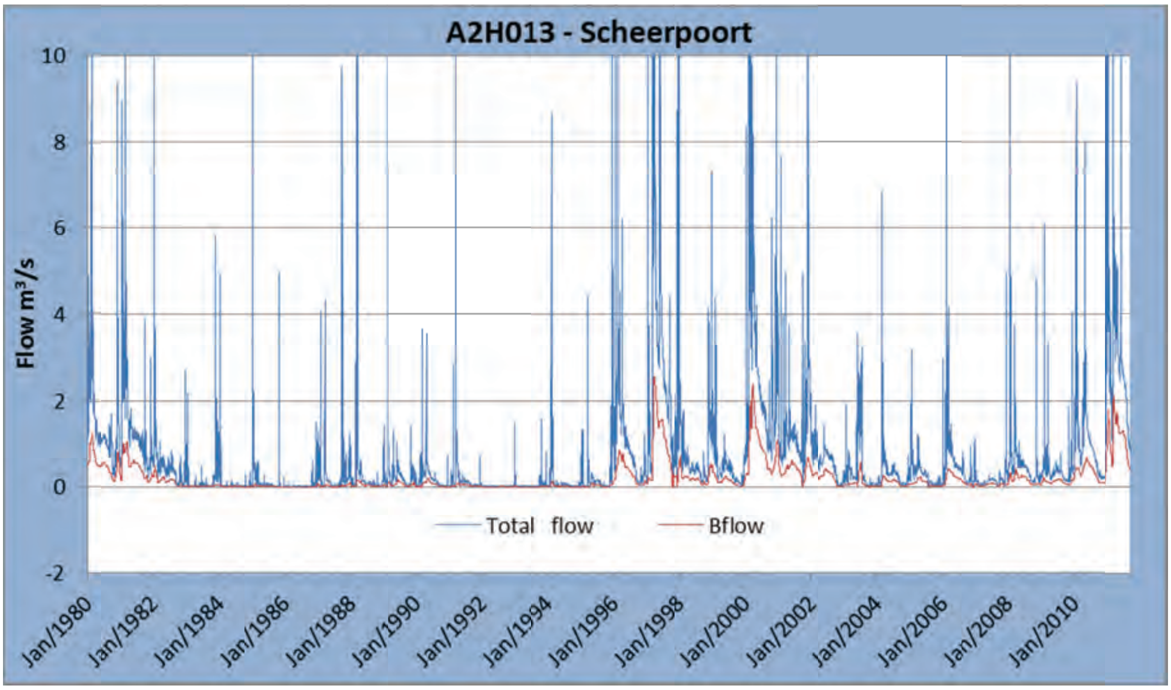


Figure 4-16 Baseflow separation for the Magalies River Scheerpoort station (A2H013)

Table 4.6 Baseflow separation results.

Months	Number of days of data	Mean flow (m^3/s)	Mean baseflow (m^3/s)	Mean baseflow (Mm^3/a)
January	992	1.15	0.25	7.32
February	904	1.91	0.57	14.87
March	992	1.56	0.55	16.06
April	960	0.90	0.31	9.63
May	992	0.83	0.25	7.70
June	960	0.72	0.22	6.64
July	992	0.59	0.15	4.88
August	992	0.43	0.08	2.63
September	950	0.34	0.04	1.15
October	961	0.26	0.02	0.53
November	930	0.37	0.03	0.96
December	961	0.90	0.15	3.92

4.6.2 Simulated baseflow (numerical model)

During the model development Constant head boundary conditions were therefore specified along the major surface drainages, which are known to receive base flow from groundwater as, indicated in Figure 4-17. A constant head boundary condition was also specified at the location of the Maloney's Eye. The constant head boundary condition allows groundwater to discharge, in this case, from the model area at a rate dependent on the hydraulic conductivity and hydraulic gradient across the boundary. The constant head boundaries were constrained so that water can only be removed from the system – a reversal of the hydraulic gradient back towards the aquifer from the surface system would therefore not allow water to enter the aquifer from the surface water system. This therefore represents a true “drain type” boundary condition.

A summary of the temporal baseflow statistics simulated across the six groundwater unit of analysis (GUA's) feeding to the Maloney's Eye and the eight GUA of the Lower Magalies is provided in
Table 4.7. The modeled baseflow volumes are higher compared to the baseflow separation values and more in range with the Hughes and Pitmann baseflow values (refer to the previous section). The model assumes that water leaves the model only via internal surface drainage and discharge to the base of river drainage.

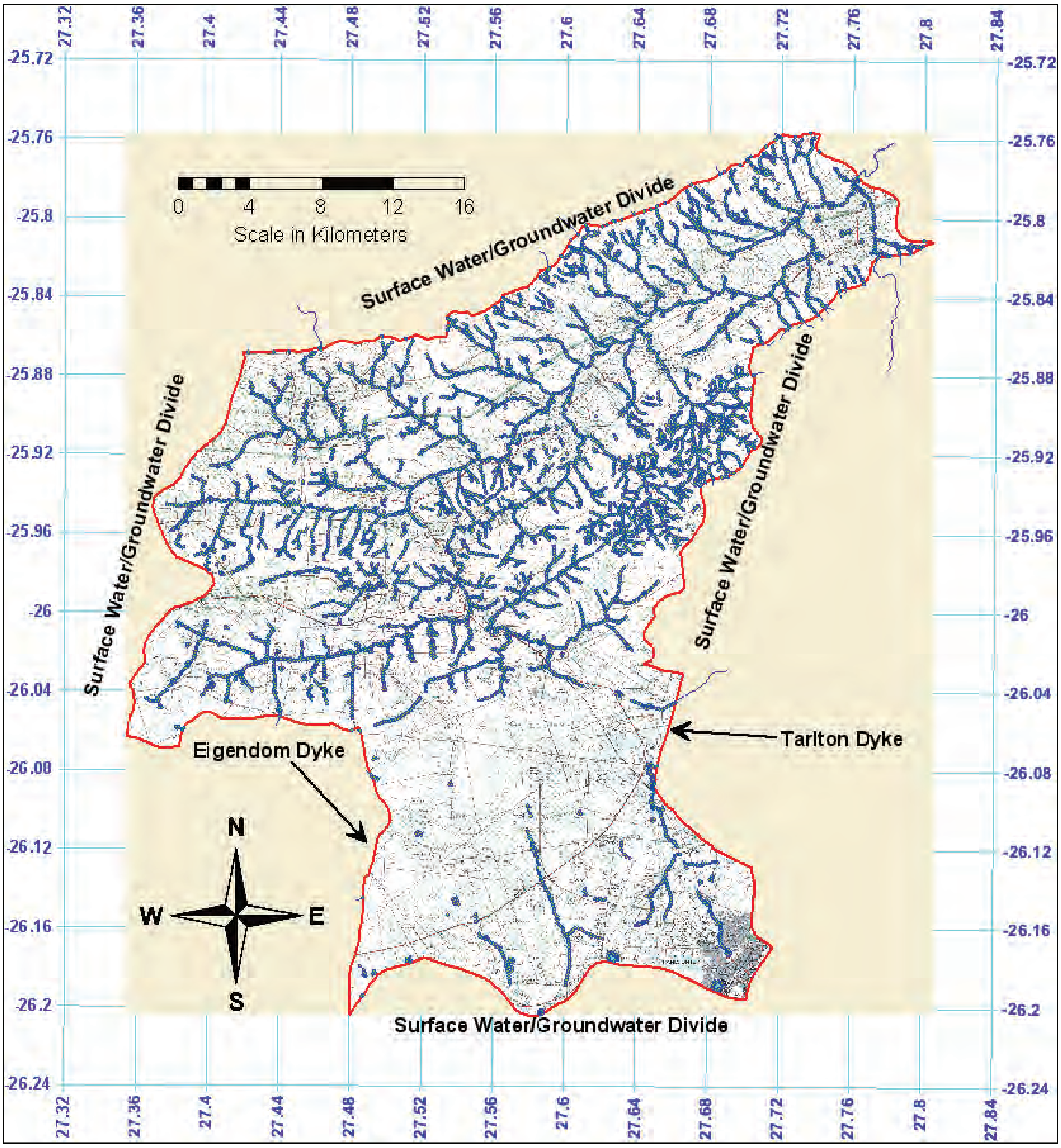


Figure 4-17 Internal modelling boundaries (Blue Circles) (Type I Dirichlet) representing drain nodes along rivers and streams

As a result, the baseflow component includes all subsurface flow such as seepage from perched aquifers and interflow. Predicted low flows (refer to Table 4.7) were determined and adjusted by utilising the IFR value (refer to Table 4.5) for the Lower Magalies River as target maintenance low flows. The Maloney's Eye predicted low flows is based on the minimum flows as the Eye outlet represents a 100% groundwater contribution to surface water.

Table 4.7 General statistics associated with the baseflow on the GUA's in the study area

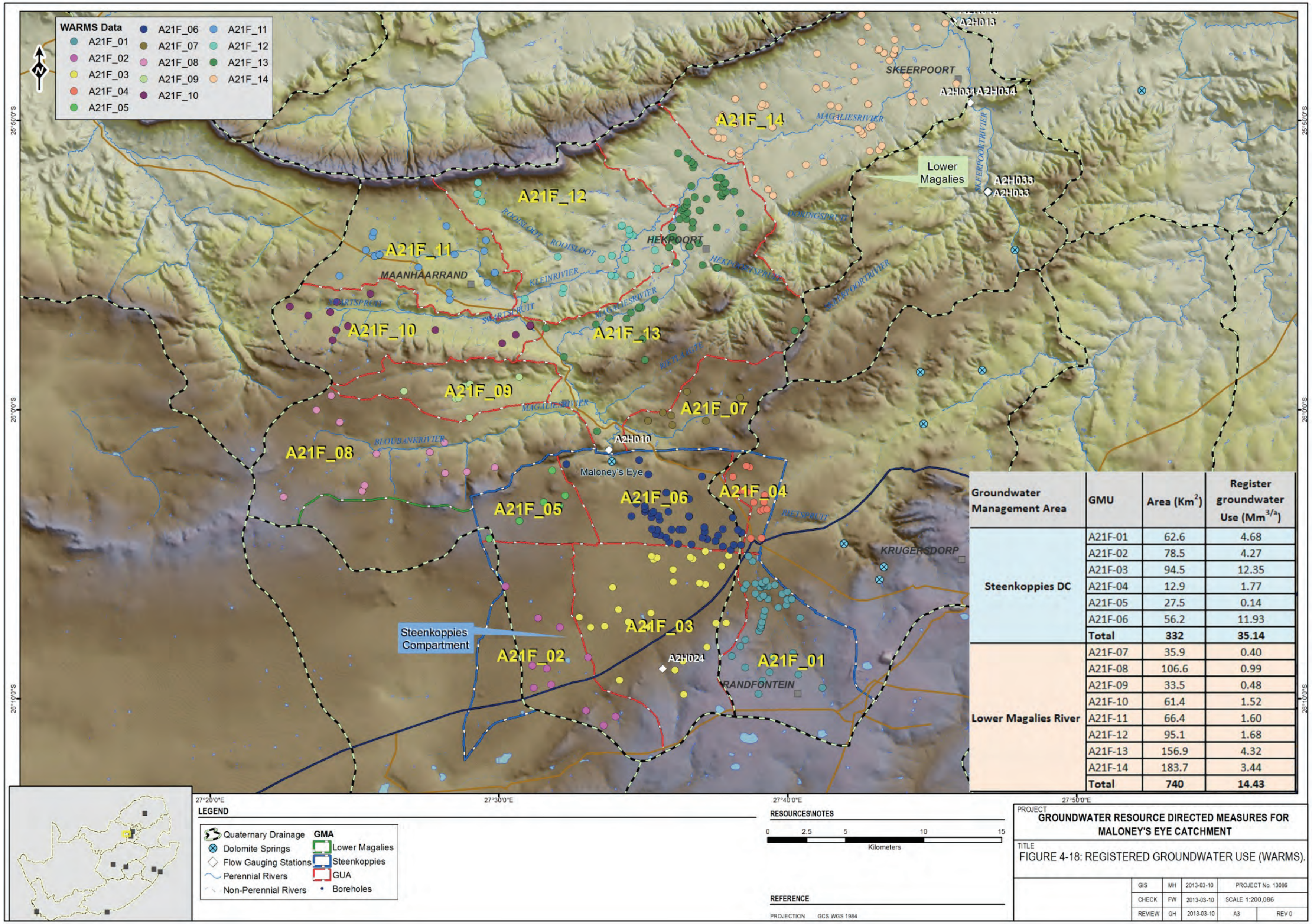
Groundwater Management Area	GUA	Area (Km^2)	N	Baseflow (m^3/d)				
				Mean	Median	Minimum	Predicted Low Flows*	Std. Dev.
Steenkoppies DC	A21F-01	62.6	1,233	4,482	3,676	2,542	2.542	2,732
	A21F-02	78.5		377	347	224	224	106
	A21F-03	94.5		532	479	296	296	185
	A21F-04	12.9		0	0	0	0	-
	A21F-05	27.5		0	0	0	0	-
	A21F-06	56.2		42,537	40,359	3,736	3.736	19,269
	Total	332		47,928	44,861	6,798	6.798	22,294
	In Mm^3/a			**17,5 Mm^3/a**	**16,4 Mm^3/a**	**2.4 Mm^3/a**	**2.4 Mm^3/a**	-
Lower Magalies River	A21F-07	35.9	1,233	777	721	530	175	205
	A21F-08	106.6		4,615	4,400	3,474	1,146	925
	A21F-09	33.5		537	478	271	89	223
	A21F-10	61.4		3,750	3,586	2,864	945	741
	A21F-11	66.4		2,336	2,190	1,569	518	618
	A21F-12	95.1		4,566	4,358	3,408	1,125	937
	A21F-13	156.9		16,718	15,815	7,549	2,491	5,342
	A21F-14	183.7		7,665	7,252	5,532	1,826	1,787
	Total	740		40,964	38,800	25,197	8,315	10,778
	In Mm^3/a			**14,9 Mm^3/a**	**14,2 Mm^3/a**	**9.2 Mm^3/a**	**3.1 Mm^3/a**	-

*- Considered as the maintenance low flow which contributes to the ecological water requirements.

4.7 Groundwater use (abstraction)

The exact time period when large scale groundwater abstraction commenced is unclear, although according to the biggest commercial farmers in the Tarlton area irrigation started about 35 years ago. No readily available groundwater abstraction data is available for the area. Two borehole surveys conducted by Bredenkamp *et al*. (1986) and Barnard (1997) are perhaps the earliest indication of the volume of groundwater abstracted for irrigation purposes. Other indications of groundwater use can be obtained in the Water User Authorisation and Management system (WARMS). This system contains information on water users which are registered with the DWAF. The spatial distribution and registered volumes per GUA is shown in Figure 4-18 and summarised in subsequent tables.

A recent water use verification project conducted by Schoeman & Associates on behalf of the DWAF aimed to determine existing lawful water use in the area prior to 1998. The two estimated water use datasets were produced for 1998 and 2004 with further verification and capturing of information during 2008/2009. Although some farmers have been consulted in the process, the assessment of existing lawful use prior to 1998 required the interpretation of satellite images of this era.



Groundwater Management Area	GMU	Area (Km^2)	Register groundwater Use (Mm$^{3/a}$)
Steenkoppies DC	A21F-01	62.6	4.68
	A21F-02	78.5	4.27
	A21F-03	94.5	12.35
	A21F-04	12.9	1.77
	A21F-05	27.5	0.14
	A21F-06	56.2	11.93
	Total	**332**	**35.14**
Lower Magalies River	A21F-07	35.9	0.40
	A21F-08	106.6	0.99
	A21F-09	33.5	0.48
	A21F-10	61.4	1.52
	A21F-11	66.4	1.60
	A21F-12	95.1	1.68
	A21F-13	156.9	4.32
	A21F-14	183.7	3.44
	Total	**740**	**14.43**

Figure 4-18 Registered groundwater use (WARMS)

The data was therefore produced by interpreting surface areas under irrigation and the respective types of crop irrigated.

Calculating groundwater use

WARMS (Water Use Authorisation & Registration Management System

The NWA makes registration with the National Register of Water Users mandatory. All water users, who do not receive their water from a service provider, local authority, water board, irrigation board, government water scheme or other bulk supplier need to register. This is with the exception of Schedule 1 users. It is important to note that the lawfulness of the registered water use still needs to be determined by the Department of Water Affairs. Validated data is available on quaternary catchment scale for the Limpopo WMA. WARMS is one of the only sources of data available that is based on actual current reporting. There are issues with under and over registration, but when these have been corrected it will be a fundamental functional dataset for the DWAF with a potentially long lifetime.

The approach adopted for this study was to compare abstraction rates from specialist reports with the WARMS database and the predicted abstraction based on irrigation requirements and simulated abstraction rates (from the numerical flow model). A final estimate is based on the most probable value taking into consideration the range of estimates and the knowledge of the region.

During this investigation the crop area was updated based on the latest satellite imagery. The irrigation requirement for each crop type and percentage crop distribution is based the preliminary results from Mr Theunis Vahrmeijer's PhD research[2]. The crop irrigation was linked to the digitised crop area and calculated for each groundwater unit of analysis of the Steenkoppies DC.

Figure 4-19 indicates the distribution of coupling and pivot irrigated fields. The initial crop distribution and irrigation requirement is presented in Table 4.9. The water use is presented in Table 4.10. A summary of the estimated water use from the Steenkoppies DC is provided in Table 4.8. Based on the results and other sources of information on groundwater use in the Steenkoppies DC it is evident that depending on mean annual rainfall, crop type and crop distribution the water use within the DC for irrigation purposes range from 20 to 30 Mm^3/a.

Table 4.8 Summary of groundwater use for the Steenkoppies DC (Values in Mm^3/a) (Holland et al., 2009)

	Bredenkamp *et al.* (1986)	**Barnard (1997)**	**Schoeman & Associates**	
Year	1986	1997	1998	2004
Irrigation	13.5	19.0		
Households	3.9	1.7		
Total	**17.4**	**20.7**	**34.9**	**33.6**

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[2] Personal Communication (14 April 2009). Mr. Theunis Vahrmeijer Steenkoppies Aquifer Management Association.(SAMA)

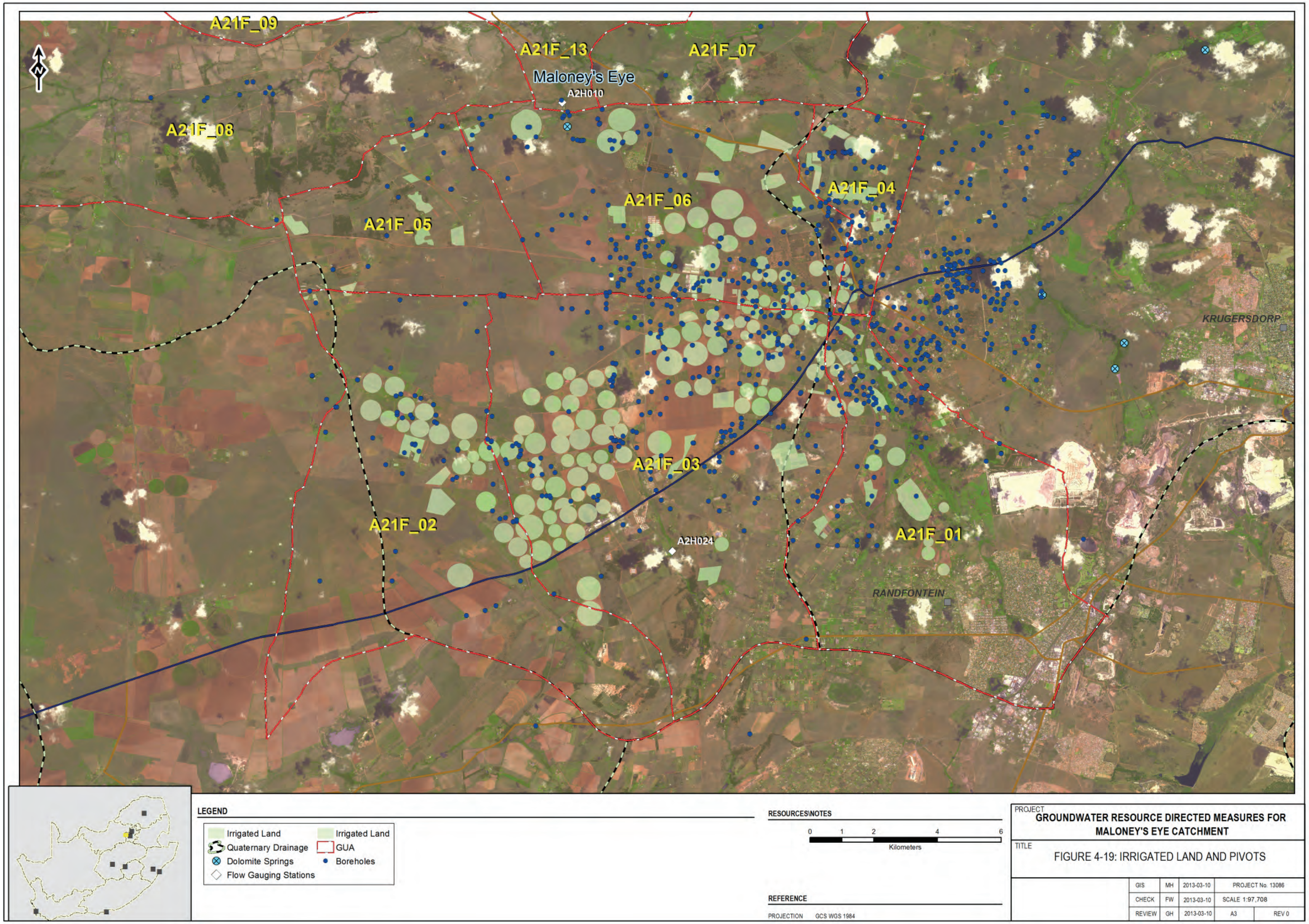


Figure 4-19 Irrigated land and pivots

Table 4.9 Crop irrigation distribution percentage and requirements

Crop type	Percentage	Irrigation requirement			
		Summer (mm/a)		Winter (mm/a)	
		Pivot	Coupling	Pivot	Coupling
Maize	21%	193	153	135	206
Wheat	20%	282	220	261	323
Broccoli	19%	148	148	194	457
Lettuce	15%	282	350	449	369
Carrots	9%	229	179	350	351
Potatoes	7%	300	300	396	396
Beetroot	5%	613	613	702	702
Cabbage	4%	193	153	135	206

Table 4.10 Estimated groundwater use based on irrigated crop requirements

Groundwater Management Area	GUA	Area (Km^2)	Water Use (m^3/a)		
			Pivot	Coupling	Combined
Steenkoppies DC	A21F-01	62.6	1,015,434	1,555,245	2,570,679
	A21F-02	78.5	3,860,639	756,709	4,617,348
	A21F-03	94.5	11,357,884	1,340,942	12,698,826
	A21F-04	12.9	411,081	1,133,053	1,544,134
	A21F-05	27.5	-	867,003	867,003
	A21F-06	56.2	4,050,549	1,912,692	5,963,241
TOTAL		332	20,695,587	7,565,644	**28,261,231**

4.7.1 Simulation of spring flow (impacted by abstraction)

To simulate the responses of the aquifers temporally and spatially, the specification of groundwater recharge (which obviously is a function of rainfall) and the specification of abstraction from the aquifers and is required. The objective then is to simulate as outputs the temporal observed water level and spring flow fluctuations. Due to the measureable effect abstraction has on the Maloney's Eye the temporal variation of abstraction was derived from the flow response of the spring to recharge over the entire catchment area. The simulation was based on similar modelling of springs in the Bo Molopo dolomite in relation to two components of recharge, generated in excess of 15 mm rainfall per month, in addition to:

1) Multiplying the recharge coefficient derived from a quadratic rainfall response, relative to the average rainfall over a characteristic period in excess of the threshold rainfall, and was multiplied by the average rainfall over a selected period. The latter was obtained by trial and error.
2) The second contribution from a rainfall-recharge coefficient that is multiplied by the ratio of the average rainfall over a second period relative to the long-term average rainfall.

3) Incorporating the pumping as an equivalent depth of precipitation.

Q_{spring} (i) = a*(Rf48/Rflt)*Rf60)*A + b*(Rf48/Rflt)*Rf36)*A – Q(i)

Where Q_{spring} = the flow of month (i) in cub m and A = the area of aquifer a and b = recharge coefficient applicable to the average rainfall over the preceding 48 months Rf 60 and Rf36 the average rainfall over 60 and 36 preceding months respectively Rflt = the average rainfall over the full time series of rainfall (Bredenkamp, 2012).

Abstraction rates were assigned according to seven different abstraction functions over time as depicted in Figure 4-20 and Table 4.11. The estimated abstraction was specified for each borehole position based on the potential yield of the borehole and boreholes used for irrigation purposes.

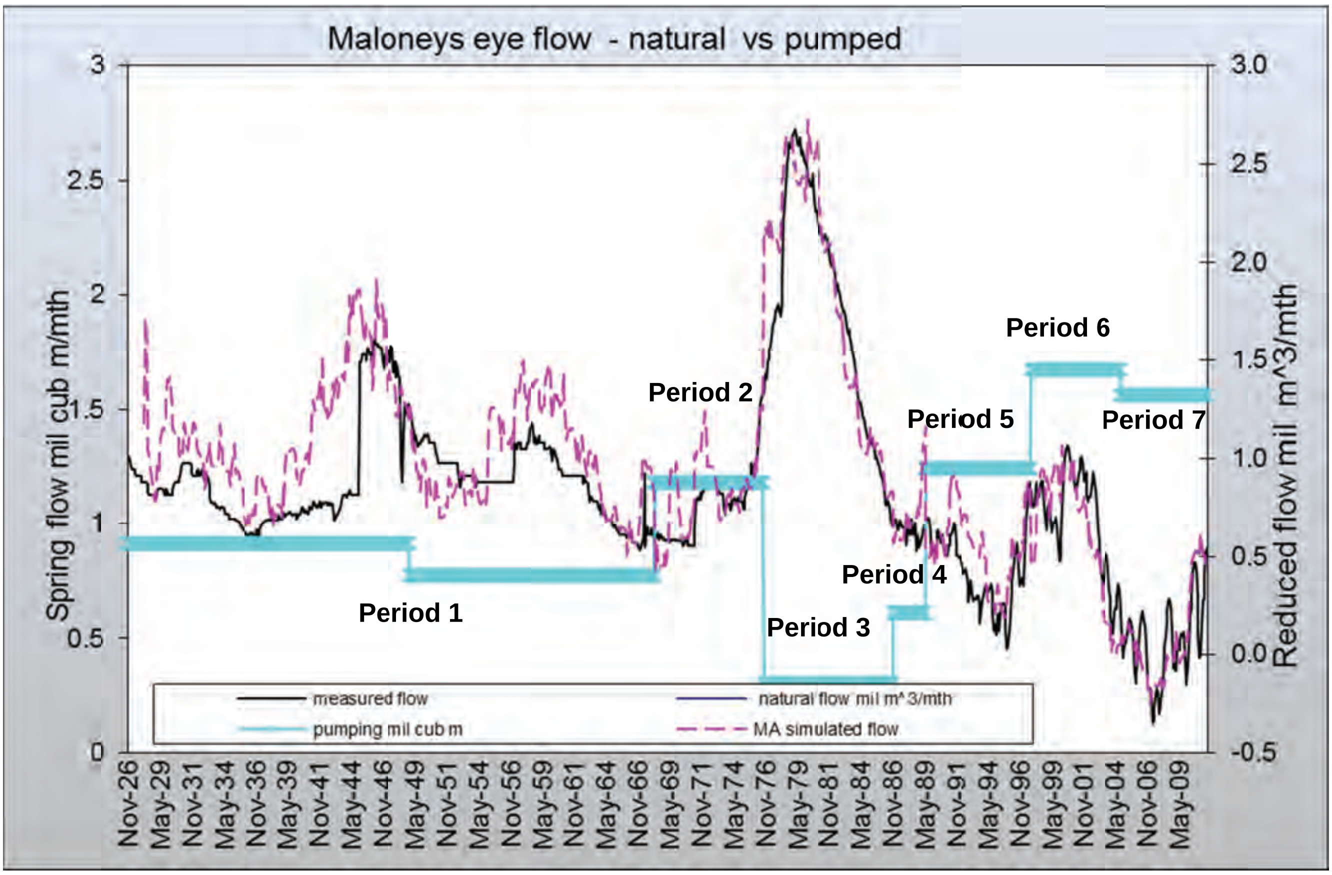


Figure 4-20 Simulation of the response of Maloney's eye with pumping incorporated over the period 1926 to 2001

Table 4.11 Estimated groundwater use based on irrigated crop requirements (compared with WARMS)

Groundwater Management Area	GUA	Water Use (Mm^3/a)		Simulated long term abstraction rates (Mm^3/a)					
		WARMS	Crop Requirements	Period1to3	Period4	Period5	Period6	Period7	Period8
Steenkoppies DC	A21F-01	4.68	2.57	0.93	0.22	0.60	1.21	0.57	1.55
	A21F-02	4.27	4.62	2.07	0.49	1.33	2.71	1.28	3.44
	A21F-03	12.35	12.70	5.47	1.30	3.52	7.16	3.39	9.12
	A21F-04	1.77	1.54	0.66	0.16	0.43	0.87	0.41	1.10
	A21F-05	0.14	0.87	0.00	0.00	0.00	0.00	0.00	0.00
	A21F-06	11.93	5.96	2.48	0.59	1.59	3.24	1.53	4.13
	Total	**35.14**	**28.26**	**11.60**	**2.76**	**7.46**	**15.19**	**7.18**	**19.34**
Lower Magalies River	A21F-07	0.40							
	A21F-08	0.99							
	A21F-09	0.48							
	A21F-10	1.52							
	A21F-11	1.60							
	A21F-12	1.68							
	A21F-13	4.32							
	A21F-14	3.44							
	Total	**14.43**							

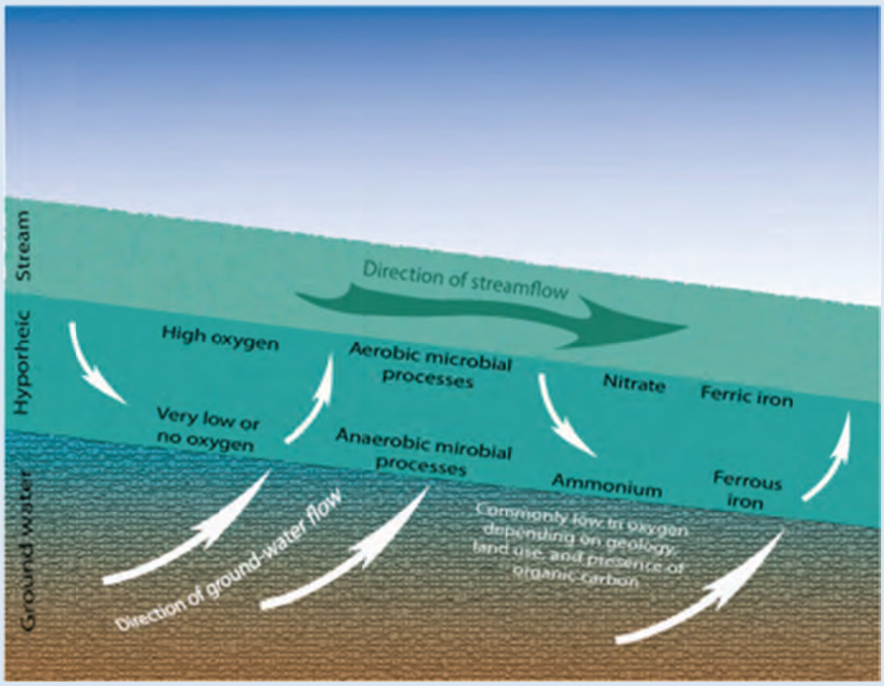
From the recharge/rainfall Figure 4-3 described in the previous section it is evident that the combination of temporal recharge, abstraction and boundary conditions assigned produced a reasonable resemblance between the observed and simulated flow of the Maloney’s Eye. This is especially valid since the late 1940s. The model still simulates however quite large peak flows during the high flow (high rainfall) events. This could be attributable to various factors; either the observed flow records did not capture all the flow during a high rainfall event or the modelled input of recharge still needs to be distributed further temporally.

4.8 Groundwater quality

The major ions with some trace elements based on groundwater management units (GUAs) are depicted in Table 4.12. Generally the groundwater in the Steenkoppies DC is within acceptable drinking quality limits. However, groundwater units and A21F-01 and A21F-01 which receives effluent discharge water from the Randfontein sewage works in the Upper Rietspruit have a slightly poorer water quality with elevated concentrations of sulphate and chloride compared to the rest of the Steenkoppies DC. The elevated manganese and iron concentrations observed within A21F-06 is attributed to a single sample collected in January 2009. The borehole may be impacted by local pollution sources as no other form of iron and manganese was found.

Groundwater quality

Domestic use (human consumption) is considered by the authors as the highest beneficial use, with the supposedly most stringent quality requirements. It is assumed that any water resource, which is deemed fit for human consumption, also meets the requirements of aquatic ecosystems. While the water quality requirements of aquatic ecosystems might differ and are in fact for several elements even more stringent than for domestic use (e.g. Cd), the chosen approach avoids the pitfall of equating groundwater quality in the sub-surface to water quality discharging into a surface water body. In other words, the methodology recognizes the processes occurring in discharge areas in general (e.g. evapotranspiration) and the enhanced microbiological and chemical reactions (e.g. Redox or cation exchange reactions) in the hyporheic zone specifically (Figure below), without trying to quantify them by setting only domestic use requirements for the groundwater resource itself.



It is therefore recommended to use the South African Water Quality Guidelines Vol. 1 – Domestic use (DWAF, 1996), or the national drinking water standard (SANS 241: 2011) for the present status category assessment of a water resource.

PRESENT CATEGORY	DESCRIPTION	COMPLIANCE (SPATIAL/TEMPORAL)
I	DWA class 0 or 1 or natural background	95%
II	DWA class 2 (95% compliance) or natural background (75% compliance)	75%
III	DWA class 3 or 4 or natural background (<75% compliance)	<75%

Groundwater quality of the available dataset for the GUA is of good quality and the present status category can be categorised as I with more than 90% of samples for all GUA apart from A21F-01 which is categories as Class II (75% compliance). A21F-01 shows elevated concentrations of Cl, SO_4 and NO_3, confirming the impact of the Randfontein WWTW on the groundwater system. The lack of water quality data in the Lower Magalies make it not possible for any categorisation at this stage.

Table 4.12 Groundwater quality for the study area (All units in mg/l, EC in mS/m)

GUA	Para-meter	pH	EC	Ca	Mg	Na	K	SO_4	Cl	NO_3 as N	Fe	Mn	PO_4
Lower Magalies	Nr	7	7	7	7	7	7	7	7	7			
	Mean	7.2	28.84	15.54	12.24	20.46	2.20	10.39	13.90	4.27			
A21F-01	Nr	54	54	54	54	54	53	53	52	53	10	10	51
	Mean	6.5	29.92	18.29	10.34	15.46	1.27	68.75	19.13	1.54	0.03	0.04	0.07
A21F-02	Nr	5	5	5	5	5	5	5	5	5	3	3	5
	Mean	8.0	161.7	44.52	26.42	4.36	1.52	3.04	2.92	2.03	0.05	0.05	0.49
A21F-03	Nr	60	60	60	60	60	60	60	60	59	7	7	54
	Mean	6.7	18.00	12.19	6.83	3.76	0.61	8.33	4.39	0.21	0.06	0.04	0.11
A21F-04	Nr	15	15	14	14	15	14	15	15	15	8	8	12
	Mean	7.9	76.44	29.91	20.02	24.42	1.54	40.85	25.72	1.71	0.06	0.03	0.15
A21F-05	Nr	1	1	1	1	1	1	1	1	1			1
	Mean	7.8	28.10	30.00	17.00	2.00	0.30	5.00	3.00	0.05			0.01
A21F-06	Nr	44	44	44	44	44	44	44	44	42	11	11	39
	Mean	7.4	51.87	22.83	16.43	6.32	0.91	9.84	6.87	0.46	0.31	0.11	0.14
Steenkoppies DC (all)	Nr	179	179	178	178	179	177	178	177	175	39	39	162
	Mean	7.0	38.89	19.07	11.91	9.66	0.98	29.27	11.09	0.85	0.12	0.06	0.12

Class I
Class II
Blue font – lowest mean and red font – highest mean (A21F-05 excluded).

4.8.1 Time series data

Long term water quality data for the Maloney's Eye (station 90163) was obtained from the DWAF. The location of this monitoring station is located at the Maloney's gauging station (A2H010) downstream of the Eye. This is also at the confluence of a stream draining the quartzites ridges towards the west of the Eye (Figure 3-5). The sampling location may have a distinct influence on the chemistry especially if the sample is taken after the confluence of the stream it will contain both a quartzite and dolomite water type signature. The quality of surface water entering the upper reaches of the Steenkoppies DC (station 90171) is mostly determined by the water quality from surface run-off from the quartzite hills of the Witwatersrand Supergroup. The quality of surface water leaving the Magalies River catchment is represented by station 90165 is mostly determined by the water quality from surface run-off from the Pretoria Group quartzites and shales. These station records contain major ions and selected trace elements since 1978.

A summary of the WQMS datasets are presented in Table 4.13 and a plot of the major anions and cations of the Maloney's Eye versus flow are illustrated Figure 4-21 to Figure 4-26 (units presented in mmol/L = mg/L/gram formula weight). The long term water quality of the surface water station is generally of good quality while no increasing or decreasing trend for any of the major ions could be established.

Table 4.13 Summary information of time series of surface water quality data (All units in mg/l)

ID	Station		pH	Ca	Mg	K	Na	Cl	NO_3 as N	SO_4	HCO_3	F	NH4-N	PO4-P
90171	A2H024 - Brandvlei	N	206	206	206	206	206	206	206	206	203	201	206	206
		min	5.0	0.5	0.5	0.1	0.2	1.5	<0.1	1.4	4.9	<0.1	<0.1	<0.1
		mean	6.5	3.2	2.0	0.7	2.7	4.4	0.1	5.4	18.2	0.1	0.1	0.1
		max	8.6	52.3	29.2	7.0	51.8	93.7	0.9	80.2	188.6	0.5	1.1	0.3
90163	A2H010 - Maloney's Eye	N	217	252	252	253	249	251	239	252	269	220	252	251
		min	7.0	3.0	2.2	0.2	0.2	1.5	0.0	0.4	0.0	<0.1	<0.1	<0.1
		mean	7.9	26.6	16.4	0.9	2.6	3.3	0.3	5.0	145.8	0.1	0.1	0.1
		max	9.9	111.7	59.1	5.8	65.9	18.6	4.1	207.2	358.4	1.3	1.9	1.4
90165	A2H013 - Scheerpoort	N	1395	1314	1314	1314	1309	1314	1375	1313	1322	1278	1366	1382
		min	4.7	8.0	3.7	0.1	0.2	0.5	<0.1	0.4	63.6	0.1	<0.1	<0.1
		mean	8.1	31.5	21.2	0.7	3.0	4.5	0.7	7.1	189.7	0.2	0.1	0.1
		max	8.8	39.3	30.9	7.4	41.8	36.8	4.0	53.3	241.5	3.9	1.4	0.7

Blue font – lowest mean and red font – highest mean (A21F-05 excluded).

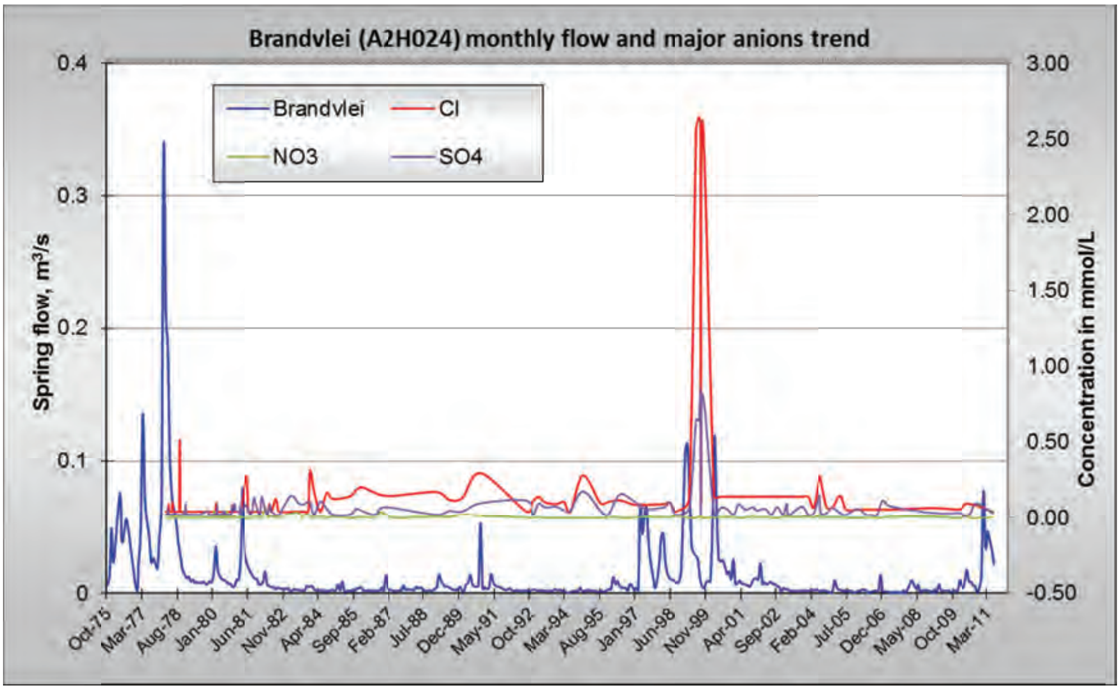


Figure 4-21 Chemical trend of major anions and flow (Brandvlei)

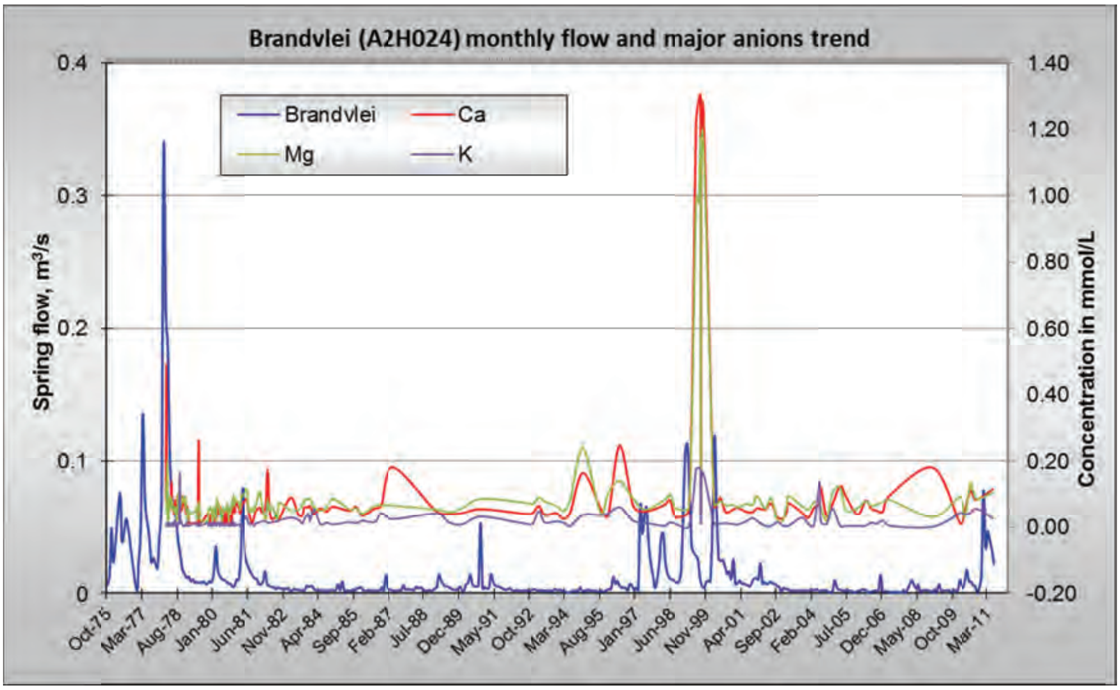


Figure 4-22 Chemical trend of major cations and flow (Brandvlei)

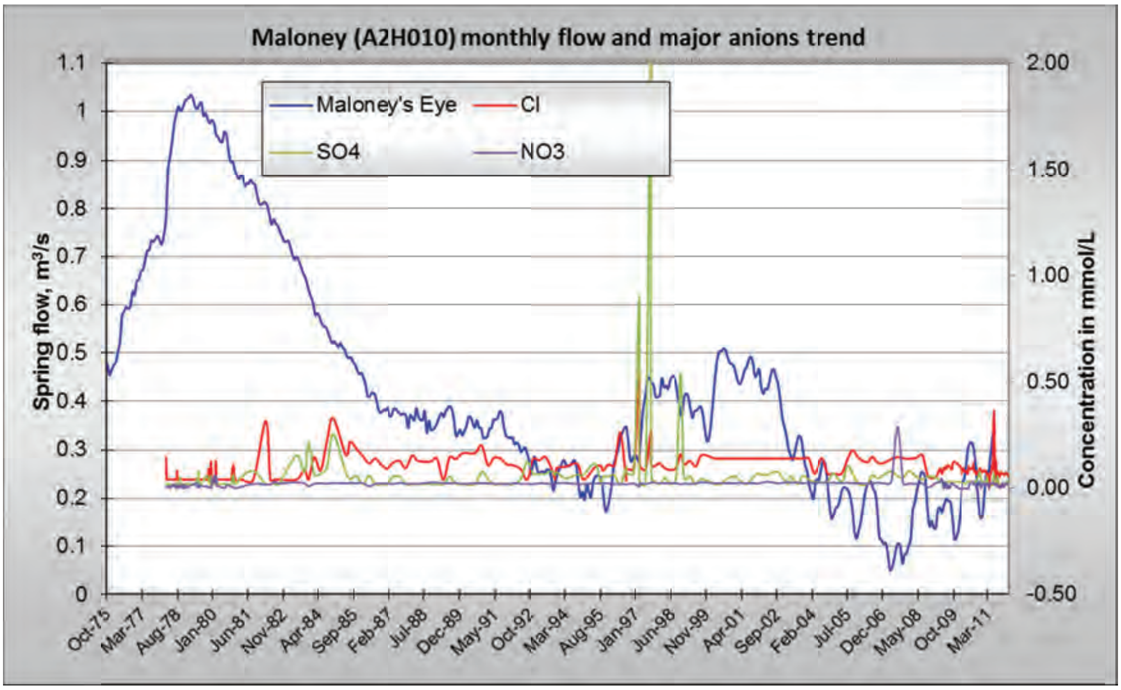


Figure 4-23 Chemical trend of major anions and flow (Maloney's Eye)

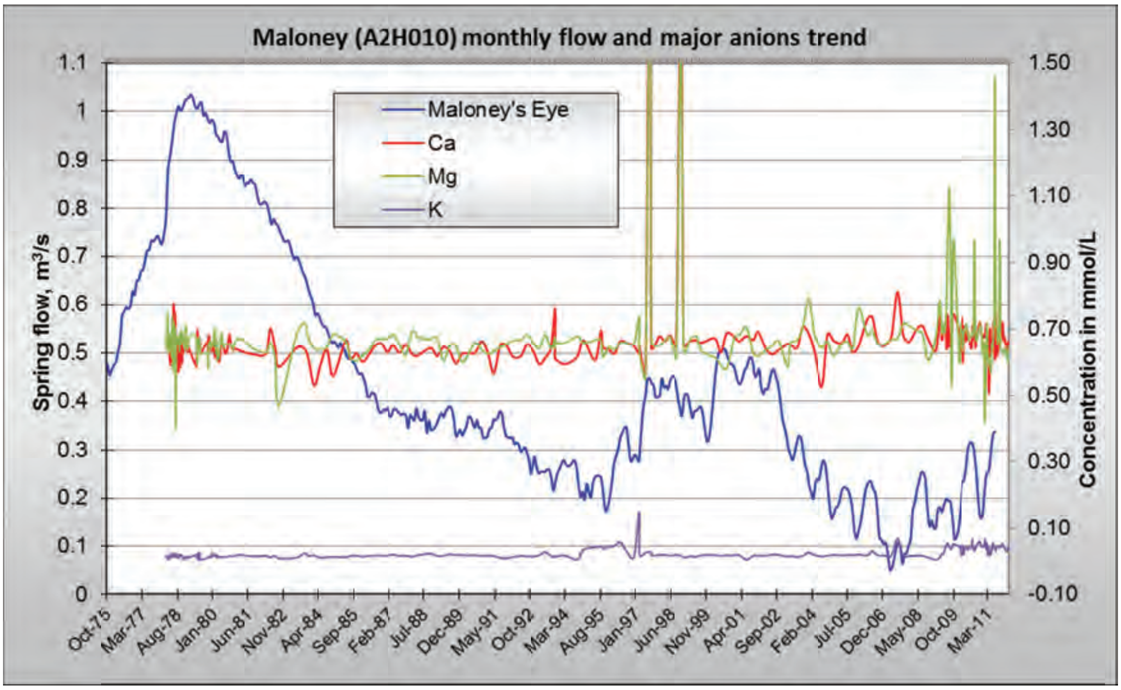


Figure 4-24 Chemical trend of major cations and flow (Maloney's Eye)

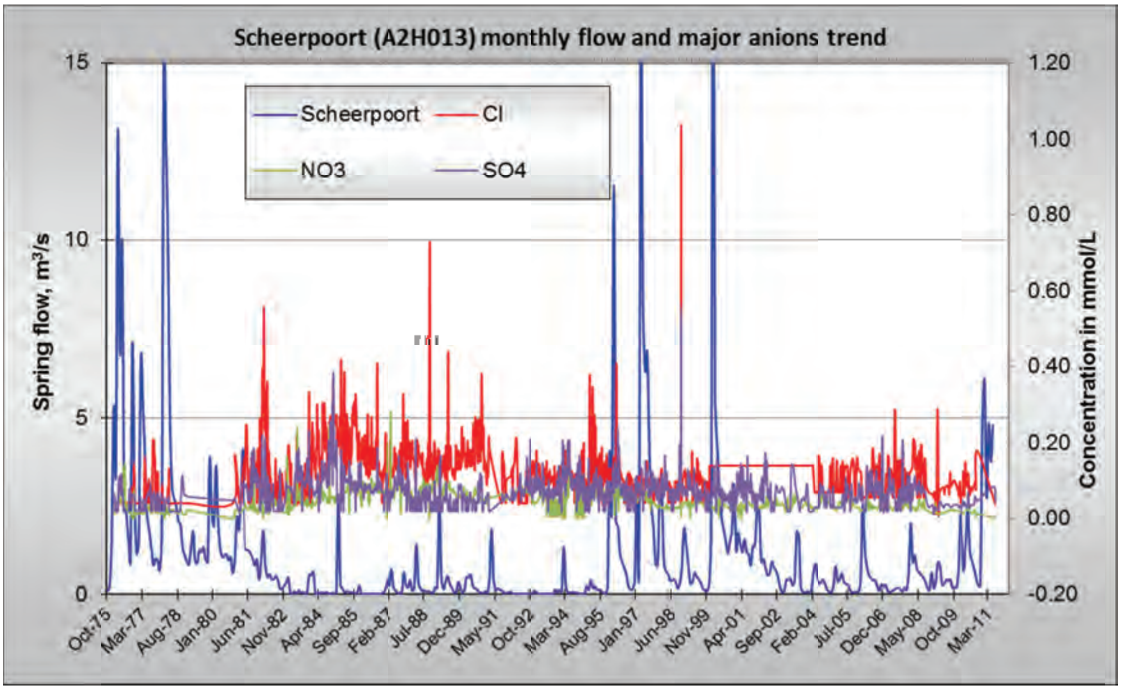


Figure 4-25 Chemical trend of major anions and flow (Magalies River)

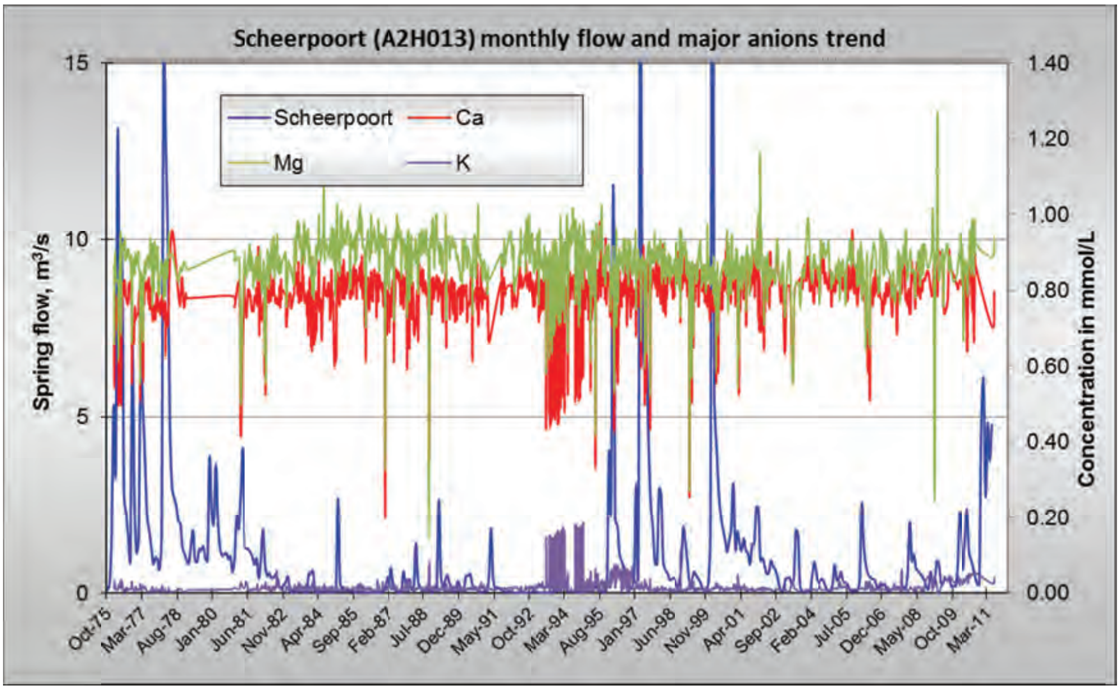


Figure 4-26 Chemical trend of major cations and flow (Magalies River)

5 RESERVE DETERMINATION AND CATEGORISATION

5.1 Groundwater reserve

Reserve determination

The groundwater component of the Reserve is the part of the groundwater resource that sustains basic human needs and in some instances contributes to EWR. To be able to quantify the groundwater component of the Reserve, the volume of groundwater needed for BHN and contributing to EWR needs to be quantified. The EWRs of the Resource in question must consider the following:

- Groundwater contribution to baseflow in rivers.
- Groundwater contribution to wetlands.
- Groundwater contribution to springs and other Groundwater Dependant Ecosystems.

The groundwater component of the Reserve is defined by the following relationship:

$$Reserve(\%) = \frac{EWRgw + BHNgw}{Re} \times 100$$

Where:

R*e* = recharge
BHN_{gw} = basic human needs derived from groundwater
EWR_{gw} = groundwater contribution to EWR

Groundwater should only be allocated to users and potential users once the volume of groundwater that contributes to sustaining the Reserve has been quantified and RQOs have been met.

Due to the scale of this assessment in addition to the difficulty in quantifying groundwater contributions to wetlands, springs and GDEs, the EWR_{gw} is mainly based on the groundwater contribution to baseflow. However, mentioning of potential GDEs, wetlands and springs occurring within each GUA will allow the RDM office to initiate more detailed studies to account for these contributions to the Reserve.

5.1.1 Basic Human Needs (BHN)

Currently, basic human needs (BHN) are set at 25 ℓ/p/d. Although normally quite small in comparison to other uses, it must be borne in mind that this is a right to water and must be legally protected. Although numerous sources of population data are available over the larger region no breakdown per GUA could be provided. The total population over the Magalies River catchment based on the GRA II dataset was used to determine the BHN. To cater for any uncertainty in the data and based on the premise that the data is outdated the total population figure was multiplied by three. The estimated BHN based on a population of 11636 (x3) is 0.3 Mm^3/a.

5.1.2 Reserve determination summary

The Reserve assessment is provided per groundwater unit analysis and is based on the recharge and baseflow estimated provided in subsequent sections (Table 5.1). The long term minimum baseflow requirements were based on the model simulation.

Table 5.1 Groundwater reserve summary

Groundwater Management Area	GUA	Area (Km^2)	Recharge Mm^3/a	Predicted Low Flows* Mm^3/a	BHN Mm^3/a	Reserve Mm^3/a	Reserve %
Steenkoppies DC	A21F-01	62.6	3.23	0.93	0.02	0.95	29%
	A21F-02	78.5	5.67	0.08	0.02	0.10	2%
	A21F-03	94.5	6.14	0.11	0.02	0.13	2%
	A21F-04	12.9	1.19	0.00	0.02	0.02	2%
	A21F-05	27.5	2.48	0.00	0.02	0.02	1%
	A21F-06	56.2	5.02	1.36	0.02	1.39	28%
	Total	**322**	**23.72**	**2.48**	**0.14**	**2.62**	**11%**
Lower Magalies River	A21F-07	35.9	0.65	0.06	0.02	0.09	13%
	A21F-08	106.6	1.77	0.42	0.02	0.44	25%
	A21F-09	33.5	0.58	0.03	0.02	0.06	10%
	A21F-10	61.4	1.01	0.34	0.02	0.37	37%
	A21F-11	66.4	1.07	0.19	0.02	0.21	20%
	A21F-12	95.1	1.53	0.41	0.02	0.43	28%
	A21F-13	156.9	2.56	0.91	0.02	0.93	36%
	A21F-14	183.7	2.85	0.67	0.02	0.69	24%
	Total	**740**	**12.01**	**3.03**	**0.18**	**3.22**	**27%**

*-Considered as the maintenance low flow which contributes to the ecological water requirement

5.1.3 Groundwater use and availability

Defining stress

The concept of stressed water resources is addressed by the NWA, but is not defined. Part 8 of the Act gives some guidance by providing the following qualitative examples of 'water stress':

- Where demands for water are approaching or exceed the available supply.
- Where water quality problems are imminent or already exist.
- Where water resource quality is under threat.

The groundwater stress index reflects water availability versus water used. Groundwater use should include water utilised by current water users, water required to sustain the Reserve as well as for BHN. The Stress Index for an assessment area is defined as follows:

$$SI(\%) = \frac{gwUse}{Recharge} \times 100$$

Where:
gwUse = Current groundwater use
Recharge = Recharge (as a volume)

In calculating the Stress Index, the variability of annual recharge is taken into account in the sense that not more than 65% of average annual recharge can be allocated on a catchment scale).

PRESENT CATEGORY	DESCRIPTION	COMPLIANCE (SPATIAL/TEMPORAL)
I	Minimally used	≤20%
II	Moderately used	20% – 65%
III	Heavily used	> 65%

A guide for quantifying groundwater use is documented below.

ACTIVITY	PERCENTAGE OF RECHARGE
Stock watering, farm domestic water supply, rural water supply	Use ranges between 5% and 20% of recharge
Small-scale irrigation, rural water supply, water supply for villages and small towns	Use ranges between 20% and 40% of recharge
Water supply for large rural communities, medium to large towns, large-scale irrigation	Use ranges between 40% and 65% of recharge

Groundwater use estimates vary between the WARMS, crop requirements and simulated abstraction based on the response to the Maloney's Eye flow (Table 4.11). The categorisation of stress was based on the simulated groundwater abstraction for the Steenkoppies DC (Period 8) and the WARMS dataset for the Lower Magalies River (Table 5.2). The registered WARMS dataset (June 2010) might be an overestimate of groundwater use and require verification. Based on the stress index shown in Table 5.2 the Lower Magalies River is under stress and any future groundwater abstraction should take existing water use into consideration within each GUA. Future abstraction should also be subject to licensing. The determination of groundwater use per GUA makes it possible to establish over-allocation and identify certain GUA for future development (while taking cognisance of the RQOs set).

Table 5.2 Groundwater use and associated stress

Groundwater Management Area	GUA	Area (Km^2)	Recharge Mm^3/a	GW Use Mm^3/a	Stress Index (GW Use as % of Recharge)	Present Category
Steenkoppies DC	A21F-01	62.6	3.23	1.55	48%	II
	A21F-02	78.5	5.67	3.44	61%	II
	A21F-03	94.5	6.14	9.12	> 100%	III
	A21F-04	12.9	1.19	1.10	93%	III
	A21F-05	27.5	2.48	0.00	0%	I
	A21F-06	56.2	5.02	4.13	82%	III
	Total	322	23.72	19.34	82%	III
Lower Magalies River	A21F-07	35.9	0.65	0.40	62%	III
	A21F-08	106.6	1.77	0.99	56%	III
	A21F-09	33.5	0.58	0.48	83%	III
	A21F-10	61.4	1.01	1.52	>100%	III
	A21F-11	66.4	1.07	1.60	>100%	III
	A21F-12	95.1	1.53	1.68	>100%	III
	A21F-13	156.9	2.56	4.32	>100%	III
	A21F-14	183.7	2.85	3.44	>100%	III
	Total	740	12.01	14.43	>100%	III

5.1.4 Groundwater quality component of the Reserve

While the groundwater quality category was presented in section 4.8 the quality component of the Reserve can be presented by using statistical parameters (e.g. median, 5 and 95 percentiles) for selected major ions and trace elements (Table 5.3). The ambient groundwater quality is based on the median values while the 5th and 95th Percentile provides an indication of the extreme upper and lower water quality ranges. The preliminary groundwater quality is often set at 10% of ambient groundwater quality.

Table 5.3 Groundwater quality component of the Reserve

GUA	Parameter	pH	EC	Ca	Mg	Na	K	SO_4	Cl	NO_3 as N	Fe	Mn	PO_4
Lower Magalies	Nr	7	7	7	7	7	7	7	7	7			
	Median	6.3	3.70	1.60	1.85	2.15	0.66	5.90	1.50	0.16			
	5th Percentile	6.4	3.20	1.01	1.00	1.00	0.55	2.00	1.50	0.05			
	95th Percentile	8.4	64.44	41.29	35.25	60.09	5.34	35.21	61.14	14.19			
A21F-01	Nr	54	54	54	54	54	53	53	52	53	10	10	51
	Median	6.5	9.55	8.50	5.00	2.00	0.60	9.00	3.00	0.26	0.03	0.03	0.01
	5th Percentile	5.9	3.07	1.00	1.00	2.00	0.30	7.00	3.00	0.04	0.01	0.03	0.01
	95th Percentile	7.5	100.8	85.85	47.70	68.80	3.72	374.4	90.50	6.00	0.08	0.08	0.47
A21F-02	Nr	5	5	5	5	5	5	5	5	5	3	3	5
	Median	8.0	195.0	43.90	26.40	4.00	1.34	1.86	3.00	1.26	0.05	0.05	0.80
	5th Percentile	7.8	39.22	30.72	19.00	3.14	0.83	1.15	2.10	0.34	0.05	0.05	0.01
	95th Percentile	8.1	267.8	61.66	36.04	5.87	2.64	6.40	3.81	5.19	0.05	0.05	0.80
A21F-03	Nr	60	60	60	60	60	60	60	60	59	7	7	54
	Median	6.7	7.95	6.00	3.50	2.00	0.50	8.00	3.00	0.13	0.05	0.05	0.01
	5th Percentile	5.8	2.90	1.00	1.00	2.00	0.30	1.14	0.99	0.04	0.04	0.02	0.01
	95th Percentile	8.1	65.00	34.00	20.53	7.05	1.32	21.00	5.10	0.62	0.11	0.05	0.80
A21F-04	Nr	15	15	14	14	15	14	15	15	15	8	8	12
	Median	7.8	37.50	32.00	22.00	17.00	1.45	40.00	24.00	0.70	0.04	0.03	0.03
	5th Percentile	7.6	14.57	13.65	10.65	5.10	0.57	5.70	4.00	0.19	0.03	0.03	0.00
	95th Percentile	8.4	327.1	44.35	27.35	56.05	2.47	86.37	45.40	5.23	0.15	0.05	0.80
A21F-05	Nr	1	1	1	1	1	1	1	1	1			1
	Median	7.8	28.10	30.00	17.00	2.00	0.30	5.00	3.00	0.05			0.01
A21F-06	Nr	44	44	44	44	44	44	44	44	42	11	11	39
	Median	7.4	24.85	23.00	17.00	3.00	0.60	6.00	3.00	0.17	0.05	0.05	0.01
	5th Percentile	6.6	11.68	8.30	6.30	2.00	0.30	2.00	1.00	0.04	0.03	0.03	0.01
	95th Percentile	8.2	252.2	35.70	26.96	22.76	2.87	32.42	34.50	1.96	1.49	0.43	0.80
Steen-koppies DC (all)	Nr	179	179	178	178	179	177	178	177	175	39	39	162
	Median	7.0	18.50	14.35	10.00	3.00	0.60	9.00	3.00	0.20	0.05	0.04	0.01
	5th Percentile	5.9	3.09	1.00	1.00	2.00	0.30	1.93	1.00	0.04	0.02	0.03	0.01
	95th Percentile	8.1	211.9	44.15	27.05	51.50	2.92	59.24	62.76	3.93	0.18	0.06	0.80

5.1.5 Categorisation and management options

Baseline class

Defining the point at which a resource is no longer being used in a sustainable manner is generally very difficult. The level of sustainability probably fluctuates through time, and impacts from over-use could manifest themselves sometime after the impact was caused. The change from sustainable use to over-use is gradational, and not necessarily marked by some distinct change. Indicators of quantitative unsustainable groundwater use include:

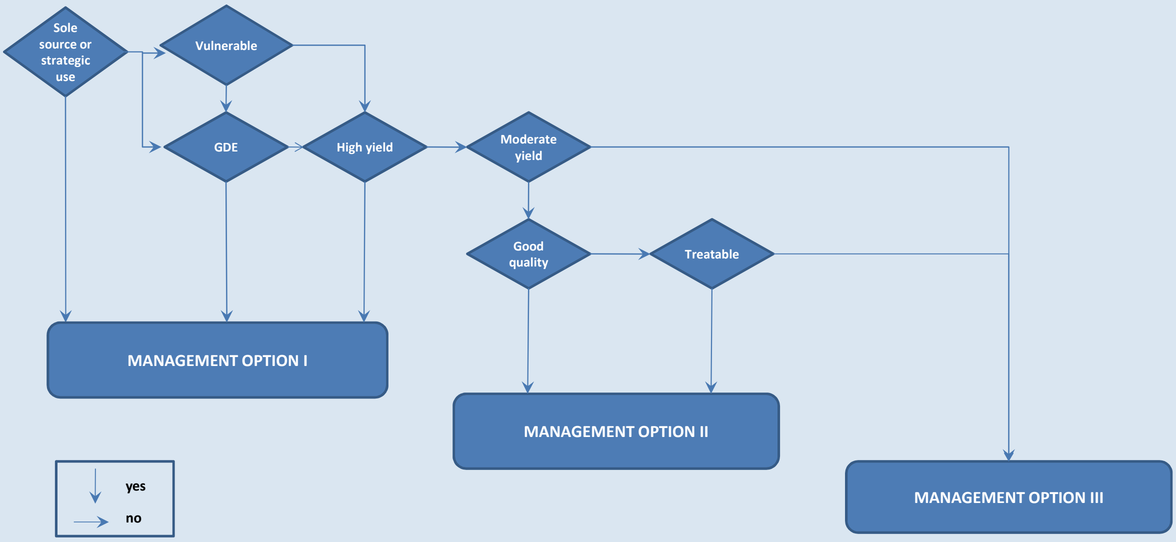
- Land subsidence or sinkhole formation.
- Long-term declining water levels on a regional level.
- Long-term declining water quality levels.

A guide for assessing the status of groundwater units based on observed impacts resulting from groundwater abstraction is presented below.

PRESENT CATEGORY	GENERIC DESCRIPTION	AFFECTED ENVIRONMENT
Minimally used (I)	The water resource is minimally altered from its pre-development condition	No sign of significant impacts observed
Moderately used (II)	Localised low level impacts, but no negative effects apparent	Temporal, but not long-term significant impact to: – spring flow – river flow – vegetation – land subsidence – sinkhole formation – groundwater quality
Heavily used (III)	The water resource is significantly altered from its pre-development condition	Moderate to significant impacts to: – spring flow – river flow – vegetation – land subsidence – sinkhole formation – groundwater quality

Management Options

Monitoring forms an essential part of what must be a seamless process of managing the country's water resources. Monitoring essentially falls outside the GRDM process, but is required to ensure that the Reserve and Resource Quality Objectives are both realistic and are adhered to. Groundwater monitoring has the simple goal of quantifying the behaviour and response of groundwater systems to various controls and stressors (recharge, discharge, abstraction, etc.). Extensive monitoring already takes place, but both surface and groundwater monitoring programmes need to be revised and updated on a regular basis. However it is costly and labour intensive to monitor extensively. Considering that also moderate yielding aquifers can have a significant contribution to water supply schemes, it is proposed to combine the actual or potential importance of an aquifer and the groundwater quality to arrive at a recommended monitoring class for all aquifers as shown below.



The management options are defined according to table below.

Management Option	Recommended Monitoring*
I	Monthly monitoring of groundwater levels and chemistry
II	Monitoring of groundwater levels and chemistry every 3 months.
III	Monitoring of groundwater levels and chemistry every 6 months

Water quality analysis should include the following parameters: pH, EC, Ca, Mg, Na, K, Palk, MAlk, F, Cl, Br, NO$_3$(N), PO$_4$, SO$_4$.

A summary of the final categorisation for the Steenkoppies DC and the Lower Magalies River provided in Table 5.4

Table 5.4 Final groundwater categorisation and management options for each GUA

Groundwater Management Area	GUA	Area (Km^2)	Present Category (Stress)	Present Category (Impact)	Present Category (Quality)	Final Present Category	Management Option
Steenkoppies DC	A21F-01	62.6	II	II	II	II	I
	A21F-02	78.5	II	I	I	II	I
	A21F-03	94.5	III	III	I	III	I
	A21F-04	12.9	III	II	I	III	I
	A21F-05	27.5	I	I	I	I	I
	A21F-06	56.2	III	III	I	III	I
Lower Magalies River	A21F-07	35.9	III	II	*	III	II
	A21F-08	106.6	III	II		III	II
	A21F-09	33.5	III	II		III	II
	A21F-10	61.4	III	II		III	II
	A21F-11	66.4	III	II		III	II
	A21F-12	95.1	III	II		III	II
	A21F-13	156.9	III	II		III	II
	A21F-14	183.7	III	II		III	II

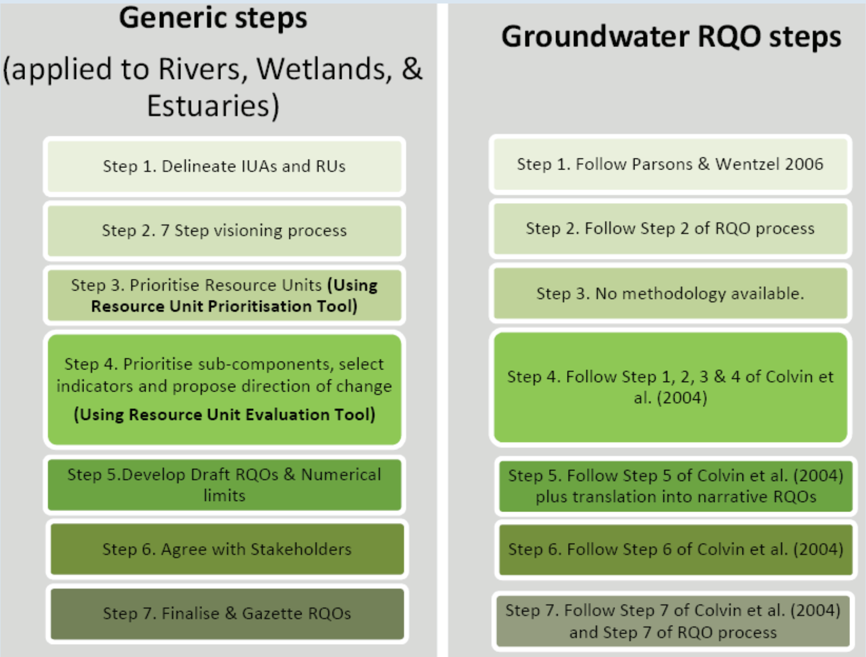
* - The amount of water quality data availability for the Lower Magalies does not justify categorisation at this stage.

6 RESOURCE QUALITY OBJECTIVES

RQOs must set objectives for the management of water resources in a catchment or other GUAs, (if applicable) and by its very nature be applicable on that scale. In general terms, RQOs establish clear goals relating to the quantity and quality of a water resource. They provide goals and objectives that frame the vision for sustainable use of a water resource, and hence form the basis for catchment decision-making and management. When setting RQOs, a balance must be found between the need to protect and sustain water resources on the one hand, and the need to develop and use them on the other.

Resource Quality Objectives (RQOs)

Although no formal methodologies exist with respect to setting RQOs for the groundwater component. Guidelines and methodologies are documented in Colvin et al. (2004) and Parsons and Wentzel (2007). A generic process to develop and implement RQOs has been developed in 2011 (DWA, 2011). In the process groundwater is dealt with separately as not only are the Resource Units completely different to the surface water systems, so are the variables of concern. These processes have been aligned with the above mentioned guidelines but the most notable difference is the description of RQOs as narrative and with attendant Numerical Limits.



According to the National Water Resources Strategy (DWAF, 2004) deals with RQOs for groundwater saying that “Resource Quality Objectives for groundwater resources are considered crucial for the effective protection of groundwater. Numeric or descriptive statements for a groundwater resource will be set in order to guide the use and management thereof, typically these will relate to - groundwater levels or gradients (time and locality specific); groundwater abstraction rates; groundwater quality; spring flow; and targets for the health and terrestrial ecosystems that are dependent on groundwater”.

6.1 Steenkoppies RQO's

- A21F-01 – The upper Rietspruit GUA receives approximately 1.5 Mm^3/a of treated effluent from the Randfontein WWTW. Long term groundwater quality data indicate the impact of sewage effluent flows on the surface stream with elevated sulphate, chloride, nitrate and bicarbonate values compared to the Brandvlei and Maloney's sampling stations. Most water sue is rom surface water abstraction and compared to the rest of the Steenkoppies DC groundwater use is marginal. Water levels appear to recover back to levels observed in the mid-1980s.
    - RQO's should include:
        - Continuous monitoring of water levels at DWA stations.
        - Compile database for the effluent discharges from the Randfontein WWTW.
        - Continuous monitoring of groundwater quality at DWA stations.
        - Compulsory licensing.
- A21F-02 – The most western GUA is devoid of any surface drainage and sub-surface flow dominates. No DWA monitoring station is within the GUA, however, the SAMA have installed a continuous logger as part of their management programme. An estimated 60% of recharge is being abstracted in the GUA. Compared to the rest of the Steenkoppies DC groundwater quality is poor but still within recommended drinking limits and at a present status category of I.
    - RQO's should include:
        - Establishment of monthly of water level monitoring stations (boreholes).
        - Establish groundwater quality monitoring programme at DWA stations.
- A21F-03 – One of two major GUAs contributing to the flow of the Maloney's Eye and is also the most utilised with groundwater use exceeding recharge by 50%. Although numerous DWA monitoring stations are located within the GUA, they are limited to the northern parts south of the Wolwekrans dyke. Groundwater quality is of great quality and has the lowest mean concentrations for most elements in the Steenkoppies DC. Groundwater levels appear to have recovered somewhat from the lowest recovered values in 2007.
    - RQO's should include:
        - Continuous monitoring of water levels at DWA stations.
        - Establishment of monthly of water level monitoring stations (boreholes) towards the south of the GUA.
        - Continuous monitoring of groundwater quality at DWA stations.
        - Motivate and implement monitoring of groundwater discharges for large scale irrigation activities.
        - Compulsory licensing.
- A21F-04 – The GUAs is immediately east of the Tarlton dyke and receives water discharging from A21F-01. As a result the signature of the Randfontein effluent return flows is evident in the water qualities. Water levels in this GUA show the highest seasonal fluctuations due to

lower permeabilities over the region. Water levels appear to have recovered to levels observed in the mid-1980s levels. However, groundwater use is almost 90% of recharge over the GUA.

  - RQO’s should include:
    - Continuous monitoring of water levels at DWA stations.
    - Continuous monitoring of groundwater quality at DWA stations.
    - Motivate and implement monitoring of groundwater discharges for large scale irrigation activities.
- A21F-05 – The GUAs has the least groundwater information and utilisation of the resource is minimal.
  - RQO’s should include:
    - Establishment of monthly of water level monitoring stations (boreholes).
    - Continuous monitoring of water levels at DWA stations.
    - Establish groundwater quality monitoring stations.
- A21F-06 – This GUA hosts the Maloney’s Eye and should receive management priority. Groundwater quality is good and well within recommended drinking water quality limits. Abstractions within the GUA are within 80% of the natural replenishment although water levels do show a slight increase over the couple of years, due to above average rainfall events. Although some DWA monitoring stations are located within the GUA, they are limited to either at the Maloney’s Eye or towards the south, north of the Wolwekrans dyke.
  - RQO’s should include:
    - Continuous monitoring of water levels at DWA stations.
    - Establishment of monthly of water level monitoring stations (boreholes) towards the central parts of the GUA.
    - Continuous monitoring of groundwater quality at DWA stations.
    - Motivate and implement monitoring of groundwater discharges for large scale irrigation activities.
    - Establishment of protection zones and management thereof accordingly (refer to next section).
    - Compulsory licensing.
- Lower Magalies River – Due to the general lack of data within the lower Magalies River groundwater management area, RQO’s is not specified based on individual GUA but rather generically proposed. According to the WARMS dataset groundwater is utilised extensively in the lower Magalies River and may have significant impacts on the groundwater contribution to baseflow of the Magalies River.
  - RQO’s should include:
    - Establish groundwater monitoring programme (water quality and water levels) throughout the Lower Magalies.

- Motivate and implement monitoring of groundwater discharges for large scale irrigation activities.
- Compulsory licensing for A21F-13 and A21F-14.

6.2 Maloney's Eye protection zone

The Maloney's Eye is groundwater driven and therefore need to be protected. One approach to protect the spring is by establishing protection zones which then managed to minimize the potential of groundwater contamination by human activities that occur on the land surface or in the subsurface. However, it must be noted that the Steenkoppies DC host numerous existing lawful water users and many of the land uses cannot be altered. Nevertheless establishment of the protection zones of the Maloney's catchment is a pro-active approach to the sustainable management of the Maloney's Eye.

6.2.1 Approach

In many countries there is no policy that directly addresses the protection of groundwater used for drinking water. In South Africa, feasibility studies towards the policy development on aquifer protection zoning have been conducted in 2008 (DWAF, 2008). The timeline for the implementation of the protection zone policy is not known at the time of this study. A wide variety of techniques can be used to determine protection zone, varying from simple non-analytical methods to complex numerical transport models (EPA, 1993). The size and shape of the spring protection zone depends on the hydrogeological characteristics of the aquifer system.

Numerical simulations of the groundwater system offer the best available analysis of the flow system and the best available delineation of the zone of contribution (ZOC) for a given well. In this study the developed numerical model was used to delineate protection zones according to the following guidelines:

Commonly, zones are delineated to achieve the following levels of protection (Jolly and Reynders, 1993; Chave et al., 2005):

- An *Operational Zone* immediately adjacent to the site of the spring to prevent rapid ingress of contaminants to the spring (also referred to as the '*Accident Prevention Zone*').
- An *Inner Protection Zone* based on the time expected to be needed for a reduction in pathogen presence to an acceptable level (often referred to as the '*Microbial Protection Area*').
- An *Outer Protection Zone* based on the expected time required for dilution and effective attenuation of slowly degrading substances to an acceptable level. A further consideration in the delineation of this zone is sometimes also the time needed to identify and implement remedial intervention for persistent contaminants.
- A further much larger zone, the *Total Capture Area*, sometimes covers the total catchment area of a particular abstraction where all water will eventually reach the abstraction point. This is designed to avoid long term degradation of quality.

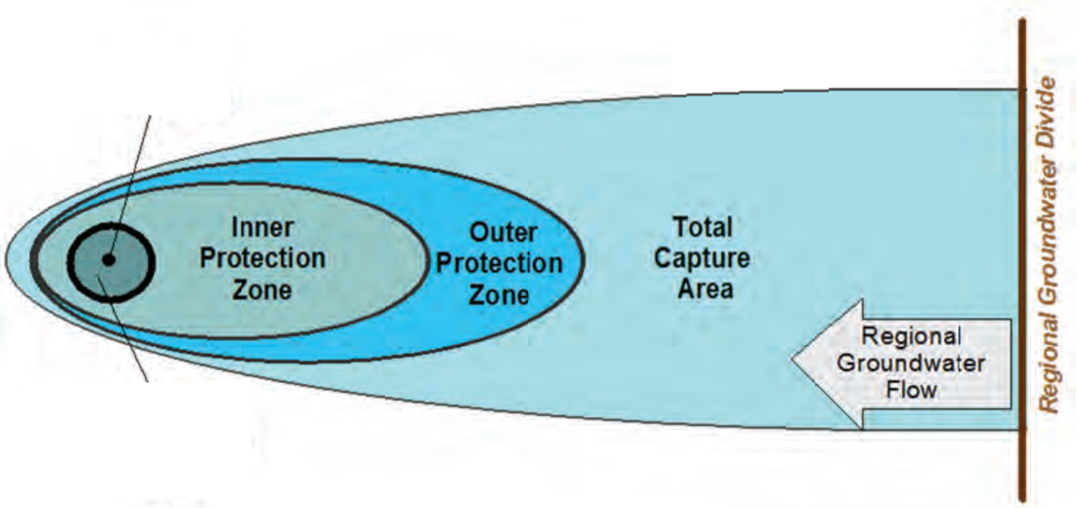


Figure 6-1 Common protection areas delineated around drinking water supplies (DWAF, 2008)

6.2.2 Results

The developed numerical model was used in combination of the reverse particle tracking method to delineate the time-of-travel based on the capture zone of the wells. The time-of-travel capture zones were used to rank the degree of risk based on the contaminant travel time to reach the water supply wells. For the Maloney's Eye the following criteria was used:

- Zone 1 – Immediate vicinity of the Maloney's Eye – 150 m (fixed radius).
- Zone 2 – Inner protection zone – 100 day time-of-travel *(Due to the extremely high conductivity of the dolomite the zone falls within the immediate vicinity of the Eye).*
    - Is based on the information that enteric viruses survive in water and water for an average 100 days.
    - This zone also includes the time required to ensure the natural or appreciable reduction in microbiological organisms, which is 50 days (EPA, 1993).
- Zone 3 – Outer protection zone – 5, 10 and 20 year time-of travel
    - In the case of severe pollution (e.g. hazardous spill) within the recharge area of the wellfields (A delay of groundwater within the aquifer of at least 10 years is needed (EPA, 1993)).
- Zone 4 – Capture zone – The entire Steenkoppies DC forms the catchment area of the Maloney's Eye and is therefore regarded as the capture zone based on the premise that all water within the zone will eventually reach the production wells (< 50 years).

Based on the simulated time-of-travel for the Maloney's Eye protection zones were captured (Figure 6-2). The end points of the simulated paths (Travel Lines) represent the origins in the groundwater system of particles that would eventually reach the Maloney's Eye within the identified period.

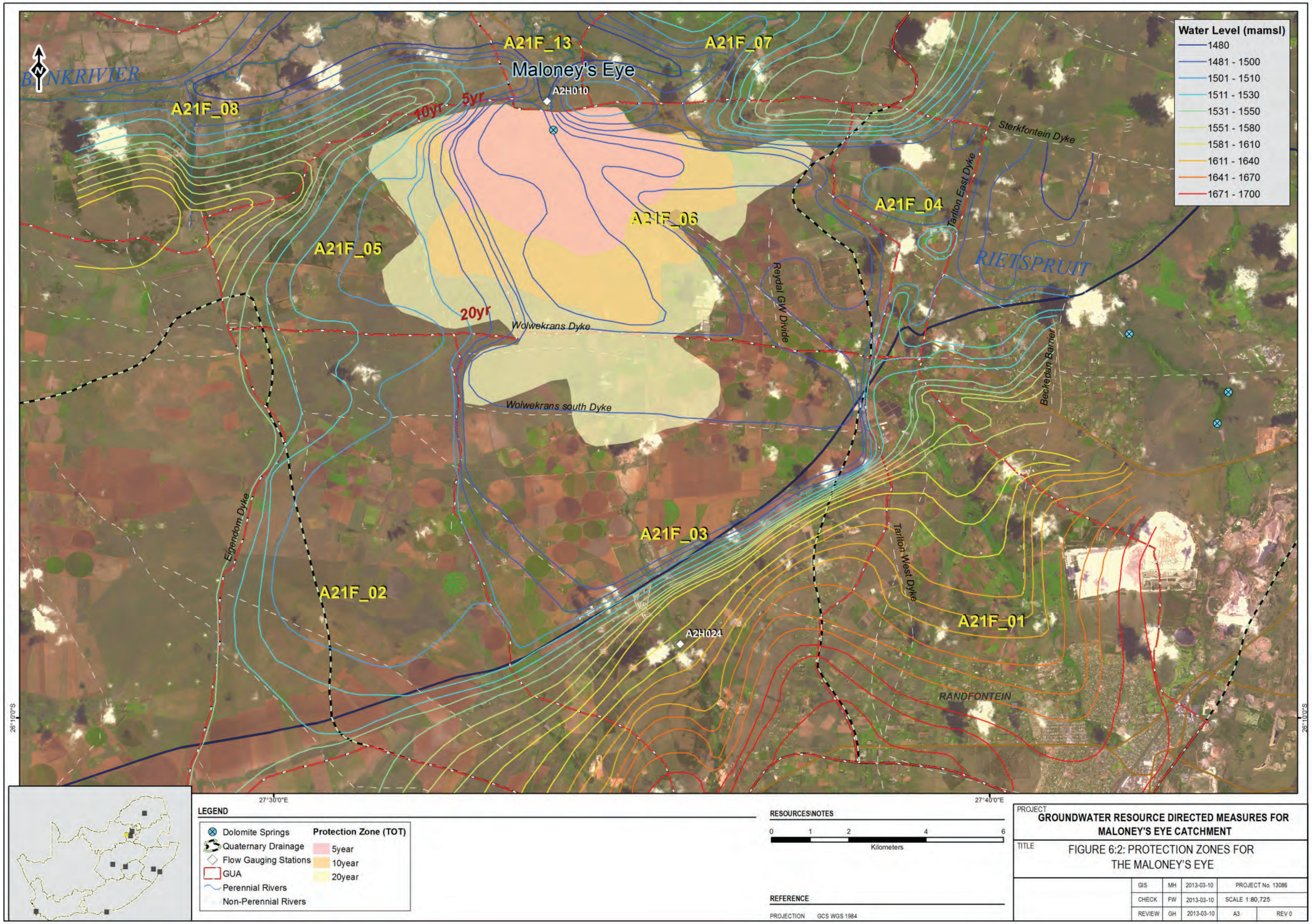


Figure 6-2 Protection zones for the Maloney's Eye based on travel time of particles

7 CONCLUSIONS AND RECOMMENDATIONS

The Steenkoppies DC hosts one of the most valuable resources of groundwater in the country, key to an irrigated agricultural industry worth three quarters of a billion Rand and employing thousands of people. The flow of the Maloney's Eye spring also depends on the groundwater in the compartment. A steady increase in irrigation has taken place since the 1970s in the Steenkoppies DC, and sporadic attempts to resolve the water crisis in the compartment before it occurred have not been successful. It is considered that there is enough data to make certain fundamental recommendations.

It is evident that irrigation abstraction influenced the flow of the Maloney's Eye significantly since the mid-1980s. The flow simulated for pristine conditions (no abstraction) indicate a minimum flow of 450 l/s (14.2 Mm^3/a) from the Maloney's Eye for the period 1908-2011.

Crucial to the sustainable use of the groundwater resource in the Steenkoppies and Lower Magalies River is the establishment of a groundwater management plan. Numerous studies have documented and reported on measures to better manage the Maloney's Eye (e.g. Bredenkamp et al., 1987, Barnard, 1997 and Holland, et al., 2009). However, a groundwater management plan that provides the framework to implement a long groundwater management strategy is lacking. As a result, although, the Steenkoppies Aquifer Management Association (SAMA) is in the process of establishing a WUA and the farmers are keen to install flow meters, rainfall stations and to equip boreholes with loggers to improve management of their groundwater resource. However, the roles and responsibilities need to be established and at this stage it's unclear what DWA's role is but it's hoped that they will assist with the interpretation of the data and assist with management of the resource. There remains, however, the problem of inadequate technical capacity at DWA.

A regional groundwater model has been developed for the Steenkoppies DC and the Lower Magalies River. The model can be utilized to simulate the effect of different operational and management scenarios and their impact on the flow of the Maloney's Eye. The presented model can be used as a tool to determine the optimal abstraction rate while giving cognizance to the sustainability of the resource. With minimal further customization the model can be expanded to a mass transport model to simulate water quality impacts across the entire quaternary catchment

Groundwater protection zones have been developed and proposed for the Maloney's Eye. By placing some form of regulatory control on activities taking place on land which falls within the various zones, their impact on the quantity (and quality) of the Eye can be minimised. The concept can be applied to currently utilized groundwater resources as well as to aquifers (boreholes) that might be utilised at some time in the future.

Groundwater protection zones may be a key component of a management plan for a given groundwater supply, and protection zones would typically be control measures in this context. This would subject them (a) to operational monitoring for assessing whether or not the required restrictions on land use and control of human activities are in place, and (b) to verification for checking whether they are indeed effectively protecting groundwater at the point of abstraction. Groundwater quality monitoring in this context would serve to verify the effectiveness of the specific protection zone concept in terms of both its design and implementation. However, monitoring implementation and verification of water quality are equally important for supplies that are not incorporated in a management plan.

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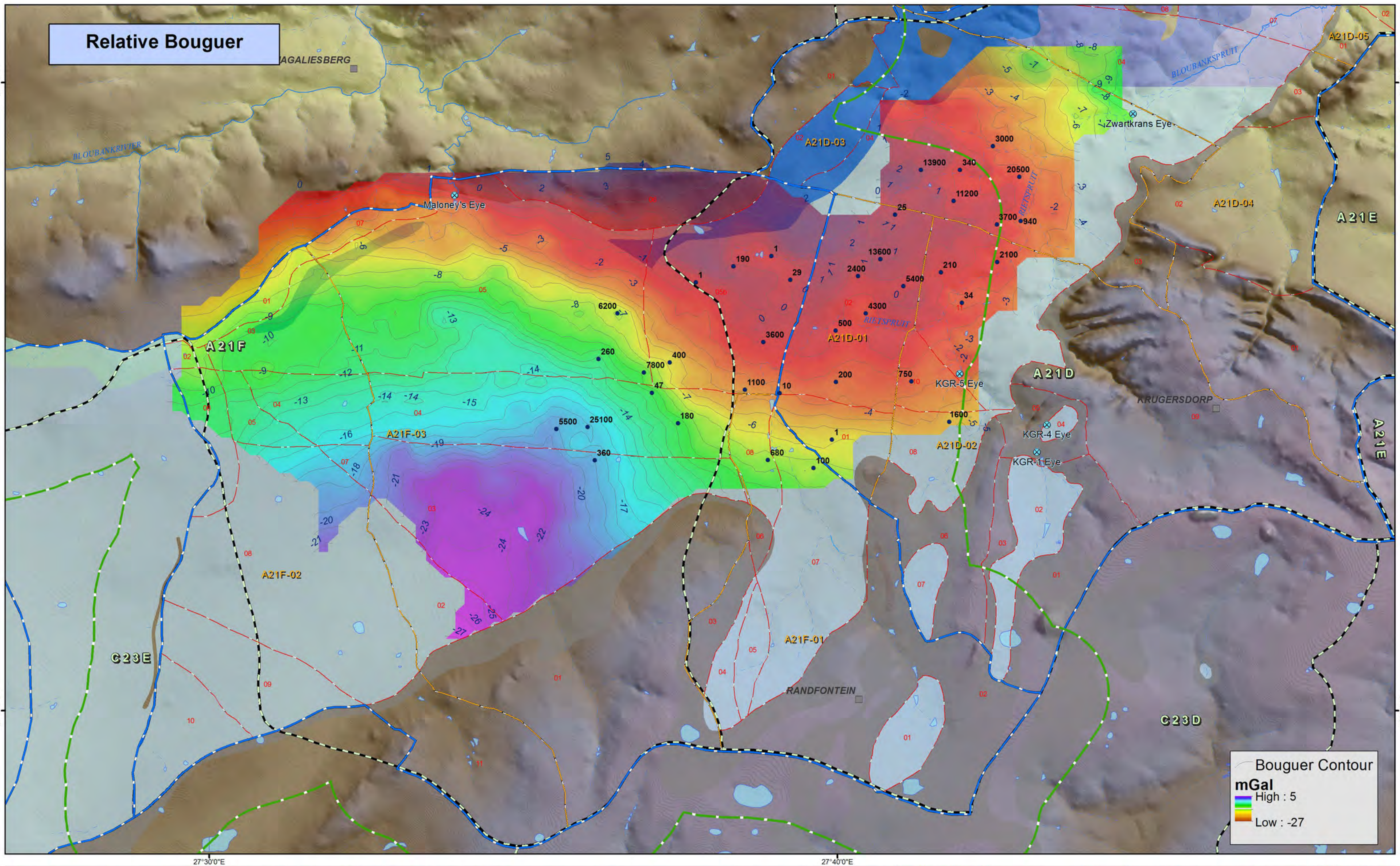
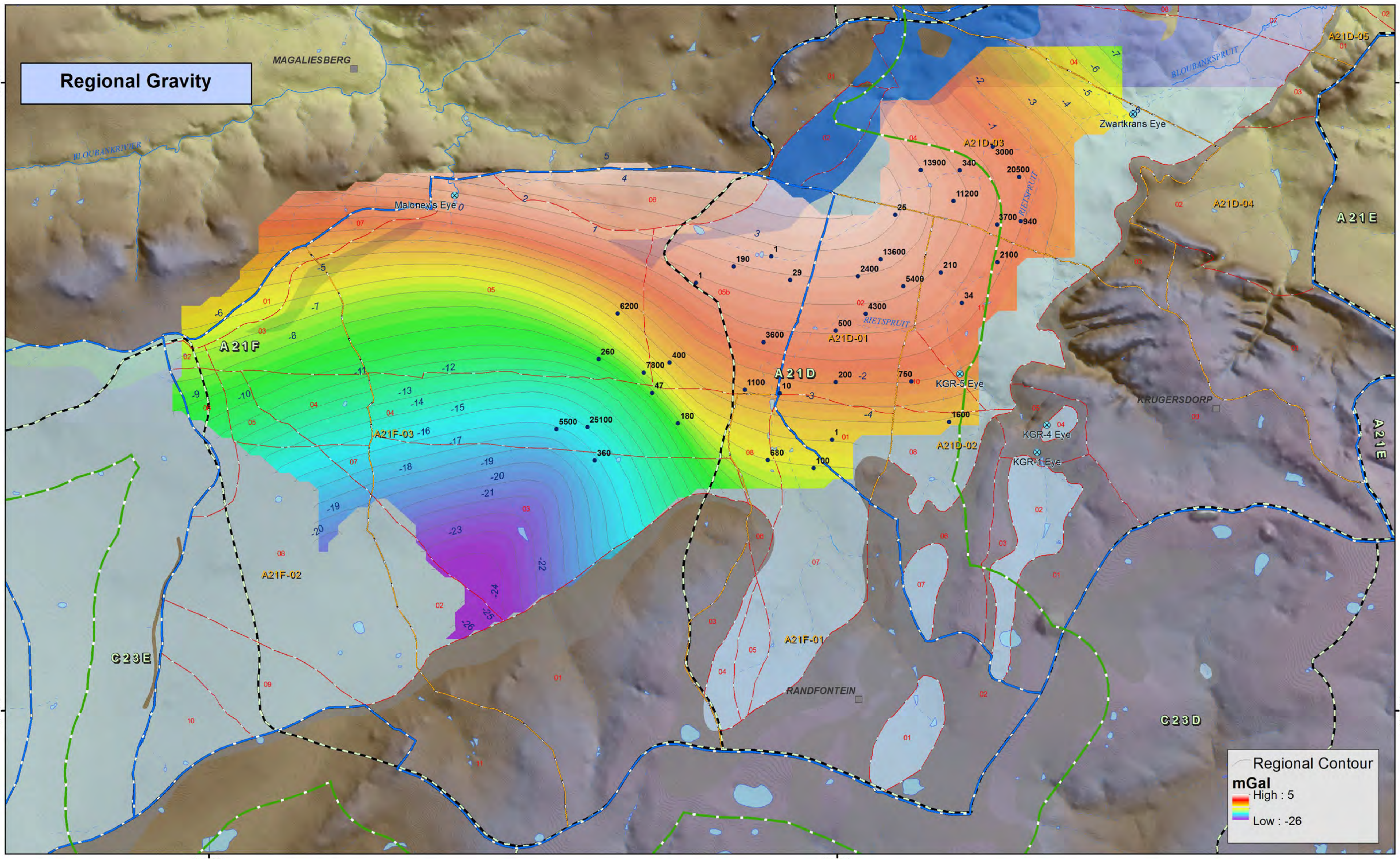
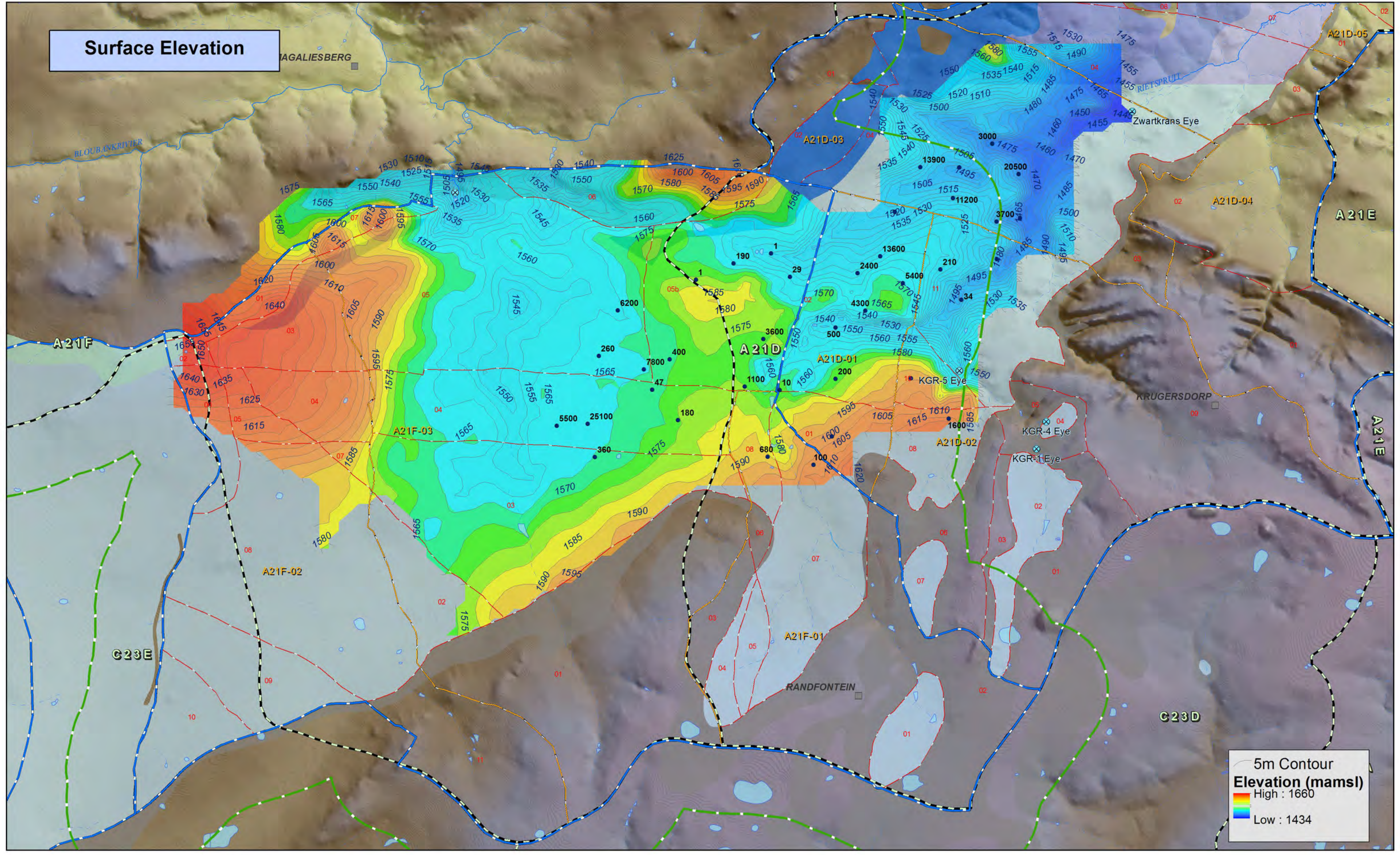
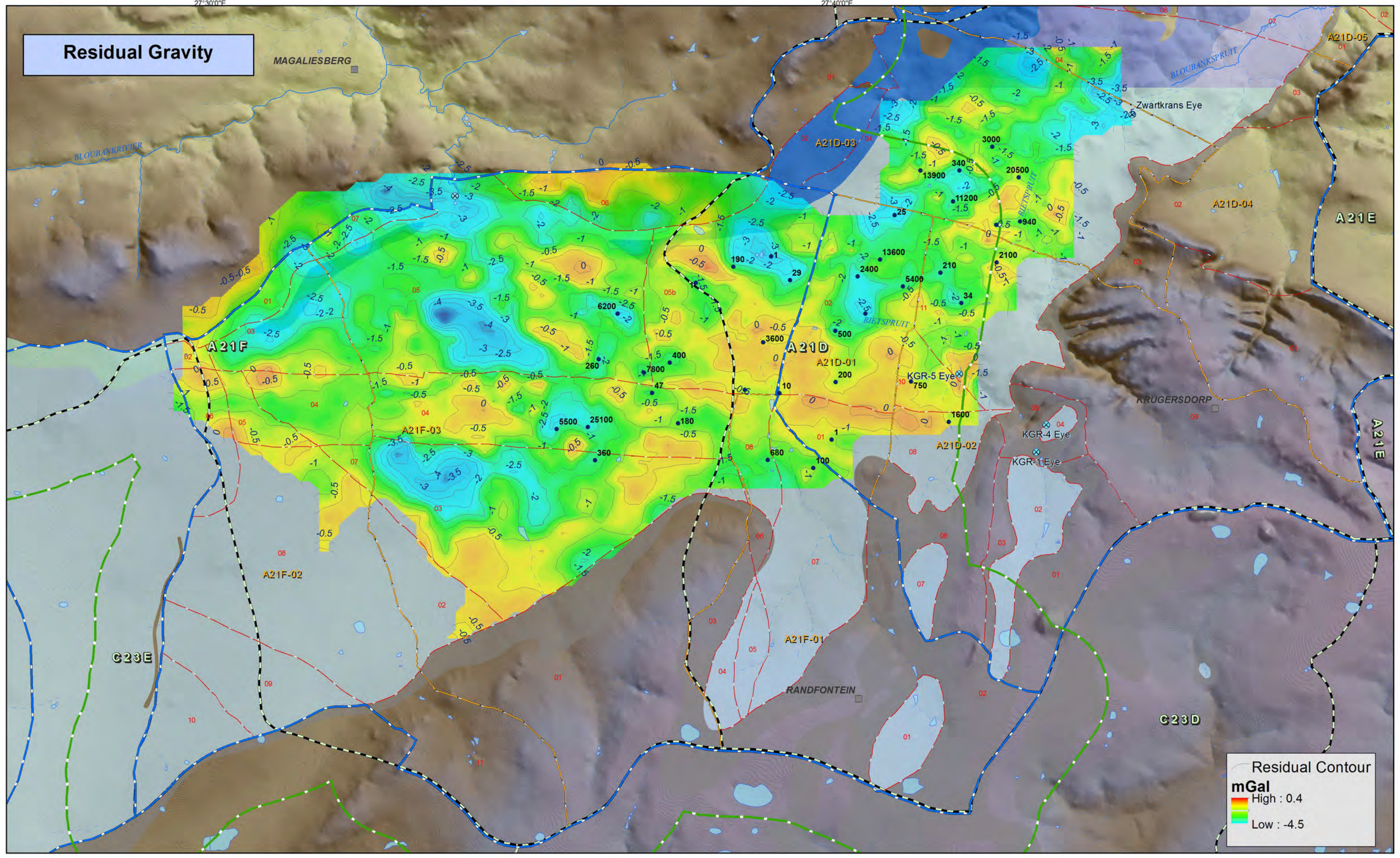
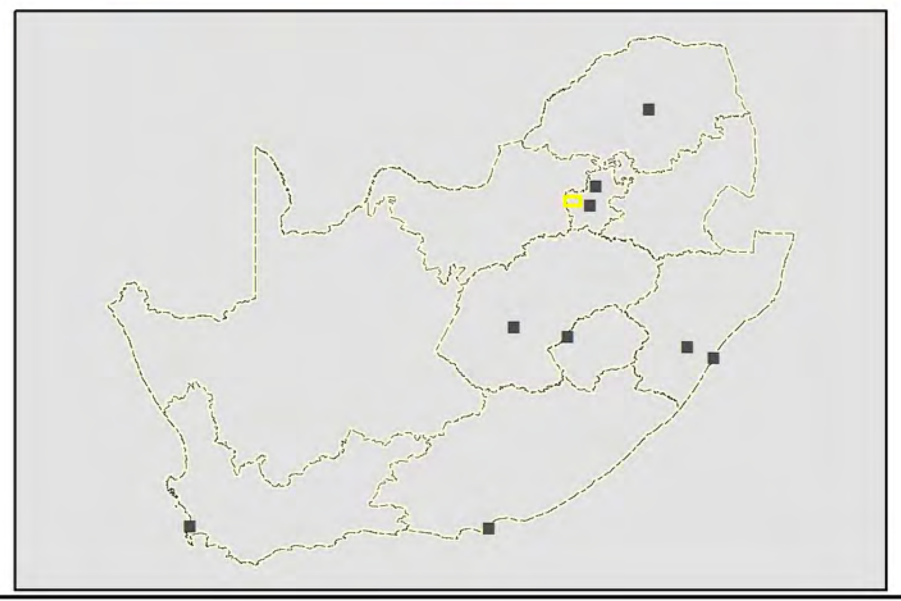
APPENDIX A – Gravity survey A1 map











LEGEND

- • Transmissivity m^2/d
- ⊗ Dolomite Springs
- ∼ Perennial Rivers
- Non-Perennial Rivers
- ☐ Area of Interest
- ☐ GMA GW Management Area
- ☐ GMU GW Management Unit
- ☐ GU GW Resource Unit
- Quaternary Drainage

Surface Geology

- ■ Rooihoogte Formation
- ■ Chert Breccia
- ■ Frisco
- ■ Eccles
- ■ Lyttleton
- ■ Monte Christo
- ■ Oaktree
- ■ Malmani Subgroup
- ■ Black Reef Formation

RESOURCES\NOTES

REFERENCE

PROJECTION GCS WGS 1984

PROJECT

GROUNDWATER RESOURCE DIRECTED MEASURES FOR MALONEY'S EYE CATCHMENT

TITLE

GRAVITY SURVEY RESULTS

GIS	MH	2012-11-29	PROJECT No. 13086	
CHECK	MH	2012-11-29	SCALE	
REVIEW	FW	2012-11-29	A1	REV 0

APPENDIX B – Numerical groundwater model report

Appendix B

Groundwater Resource Directed Measures for Maloney’s Eye Catchment – Numerical Modelling Report

H Janse van Rensburg H

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1 INTRODUCTION

1.1 Background

In view of the very high water use/demand for the agricultural irrigation in the Steenkoppies Dolomite Compartment, a sub-portion of the quaternary catchment A21F and currently with reduced flows discharging from the Maloney’s Eye, there is a need to carry out an intermediate/comprehensive level of the groundwater Reserve. Key components of the Reserve may be estimated by means of a numerical groundwater flow model.

1.2 Brief

Golder Associates Africa (Pty) Ltd was requested to submit a proposal as lead Professional Service Provider (PSP) to conduct a comprehensive groundwater Reserve determination of the Steenkoppies Dolomite Compartment (DC). The foundation of the reserve determination is based on a numerical groundwater model compiled for the study area. The development of the preliminary numerical model and results are described in this report.

1.3 Objectives of the Investigation

The objectives of the study are to:

- Develop a conceptual model for the Steenkoppies Dolomite Compartment, a sub-portion of the quaternary catchment A21F characterising (a) groundwater flow and the interrelationship between local aquifers, (b) areas of groundwater recharge and discharge, and (c) the depth to the water table. The conceptual model must successfully incorporate the influence of regional structural features on groundwater movement, including the role of fracture zones acting as preferential groundwater flow paths.
- Develop and calibrate a regional (quaternary catchment level) numerical groundwater model quantifying the elements of the conceptual model listed above based on existing information.
- Apply the numerical groundwater model to calculate the impact of current activities on groundwater flow, aquifer recharge and discharge, and the depth of the water table. The impacts of anticipated activities can be considered in subsequent phases of the study.
- Develop recommendations to address any shortcomings and data knowledge gaps that need to be addressed in order to improve on the future calibration of the groundwater model and to verify the long-term predictions made in terms of flow.
- Use the preliminary model to provide support in the quantification of the Reserve components.
- For the Water Research Commission/DWA to own, on completion of this project, a preliminary calibrated groundwater flow model which can be used to ascertain the groundwater impacts of future development scenarios or general groundwater management across the region.

1.4 Methodology

In order to achieve the objectives of the study the following methodology was adopted.

- A desk study and data collection and evaluation phase.
- The construction of a hydrogeological conceptual model for the area.
- Construction and calibration of a groundwater flow model, which accurately describes groundwater flow through the aquifer system(s).
- Using the model, determine the impact of current abstraction on the flow of the Maloney’s Eye and on the hydrogeology of the study area

2 GROUNDWATER FLOW MODEL DEVELOPMENT

2.1 Conceptual Model of the Aquifer System (Key Concept)

The first step in the modelling procedure is the construction of a conceptual model of the problem and the relevant aquifer domain. The conceptual model consists of a set of assumptions that reduce the real problem and the real domain to simplified versions that are acceptable in view of the objectives of the modelling and of the associated management problem.

The data gathered during the desk study and data evaluation phase of the study has been used to develop a hydrogeological conceptual model for the area, which forms the basis for the numerical modelling. The conceptual model is outlined below.

In a typical hydrogeological setting groundwater flow and aquifer development are closely linked to the geology and structural geology of an area. There is no reason to believe that the area under investigation will not conform to this assumption and therefore the surface geology as depicted in Figure 2-1 forms the basis on which the conceptual hydrogeological model is based spatially. The nature and distribution of the geological units, and possibly geological structures and dykes control the hydrogeology of the study area.

The aquifer(s) underlying the study area consist(s) mainly of hard rock aquifers associated with the Witwatersrand Supergroup (quartzite), the Ventersdorp Supergroup (Lava), Chuniespoort Group (dolomite) and the Pretoria Group (quartzite and shale) and Karoo Sequence (Ecca Group) sandstone and shale. Post-Karoo dolerite dykes and diabase dykes traverses the study area to divide the dolomite into “compartments”. It is generally accepted that very large transmissivities and storativities are associated with these dolomites (especially within the Monte Christo and Eccles Formations) where karstification is present. The dolomites are therefore capable to hold and transmit vast quantities of groundwater. Groundwater recharge are normally also orders of magnitudes higher than on other hardrock aquifers as a result of the large permeability that the dolomites exhibit. The 1:250 000 scale geology map available for the area however does not differentiate between the different dolomitic members across the study area.

Drilling and aquifer testing results obtained elsewhere have indicated that the quartzite and lava formations are very low yielding and very low in permeability (calculated transmissivity values vary between 10-2m2/d and 10-1m2/d) as found on the MMC Krugersdorp and the Doornkop TSF Sites to the south of the study area. Karstified dolomites in contrast have orders of magnitude higher permeability and transmissivity values in the order 1-20x103m2/d are not uncommon. Drilling in the area also indicated to a weathered profile down to 35-60m and fractured to 140m below surface.

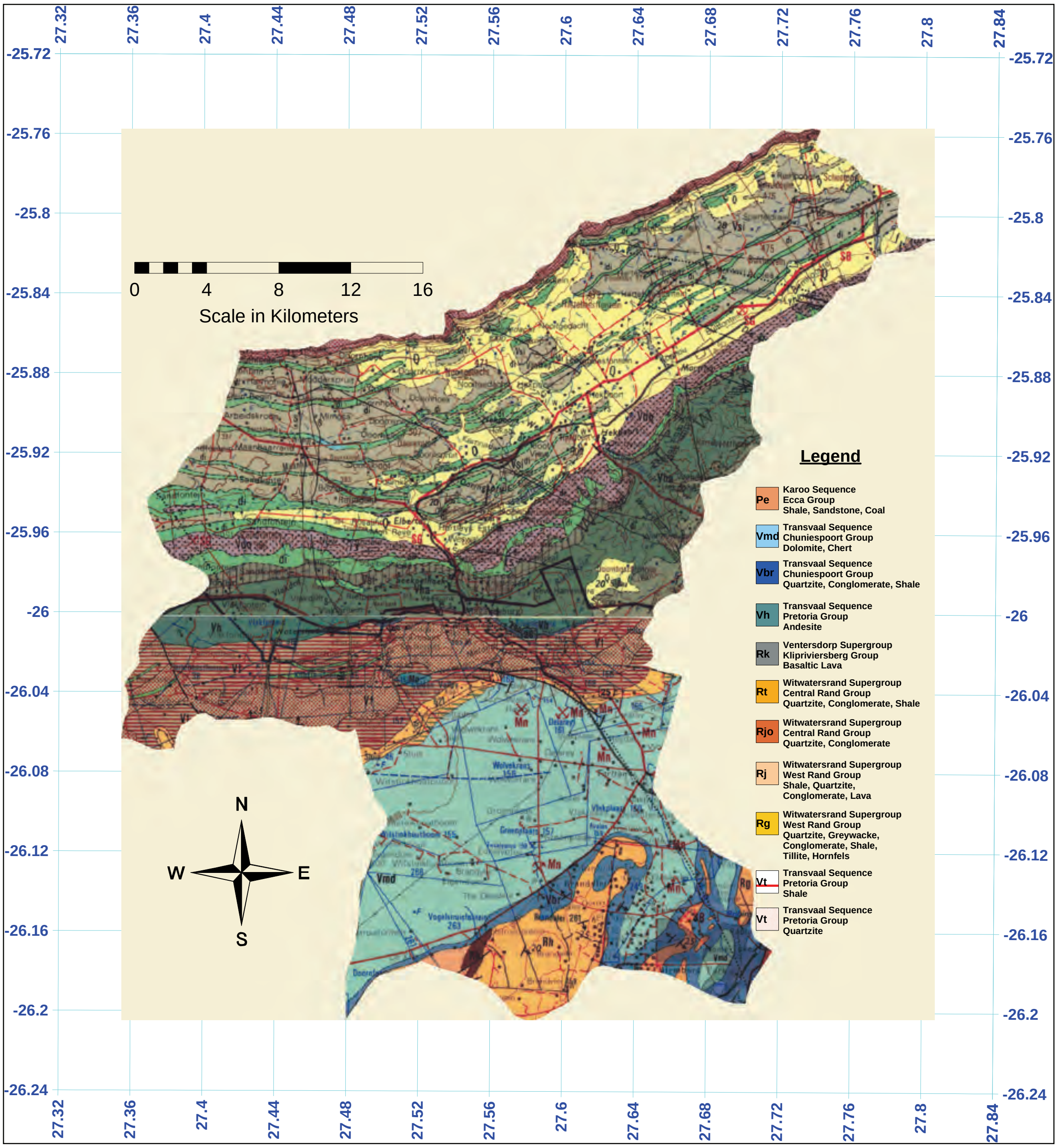


Figure 2-1 Geology map of the study area

Recharge to the aquifer is from precipitation during the rainy season. Monitoring data have indicated that there is a good relationship between the Cumulative Rainfall Departures from the mean rainfall (CRD) and the water level fluctuations in the dolomitic aquifer which indicates to dynamic recharge occurring (Figure 2-2). A good correlation between the flow of the Maloney's Eye and the CRD was also obtained indicating that rainfall is the main "driving force" behind the groundwater system's dynamics (Figure 2-3).

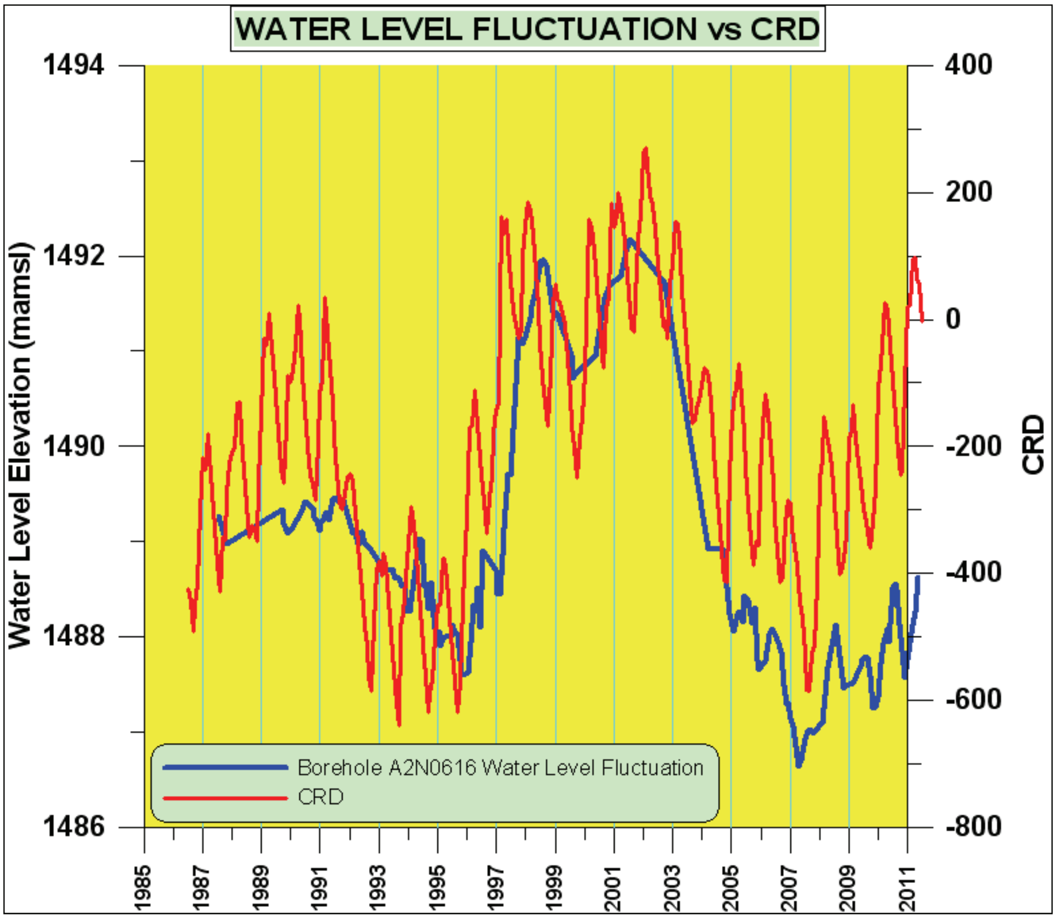


Figure 2-2 Water Level Fluctuation vs. CRD

2.2 Groundwater System Geometry

As a result of local recharge and discharge, groundwater divides developed approximately beneath the major surface water divides. Evidence of this is provided by the correlation between groundwater level elevation and topography and the groundwater flow directions (depicted in Figure 2-4). It is logical therefore to include large areas of the surface water sub-catchments of the Magalies River catchment (A21F) and the Steenkoppies Dolomitic Compartment which is located in the upper reaches of this catchment into the modelling domain.

The vertical extent of the groundwater system is determined from the drilling results. The boreholes indicate a maximum weathering depth of about 35-60m and fracturing depth up to 140m below surface. A uniform thickness of 140m for the aquifer(s) is assumed. The model will be calibrated using the water level elevations, which are a function of the product of the saturated aquifer thickness, the hydraulic conductivity (transmissivity) and effective aquifer recharge. Should the average aquifer thickness therefore be under/overestimated is will be compensated for by adjustment of the hydraulic conductivity values during model calibration.

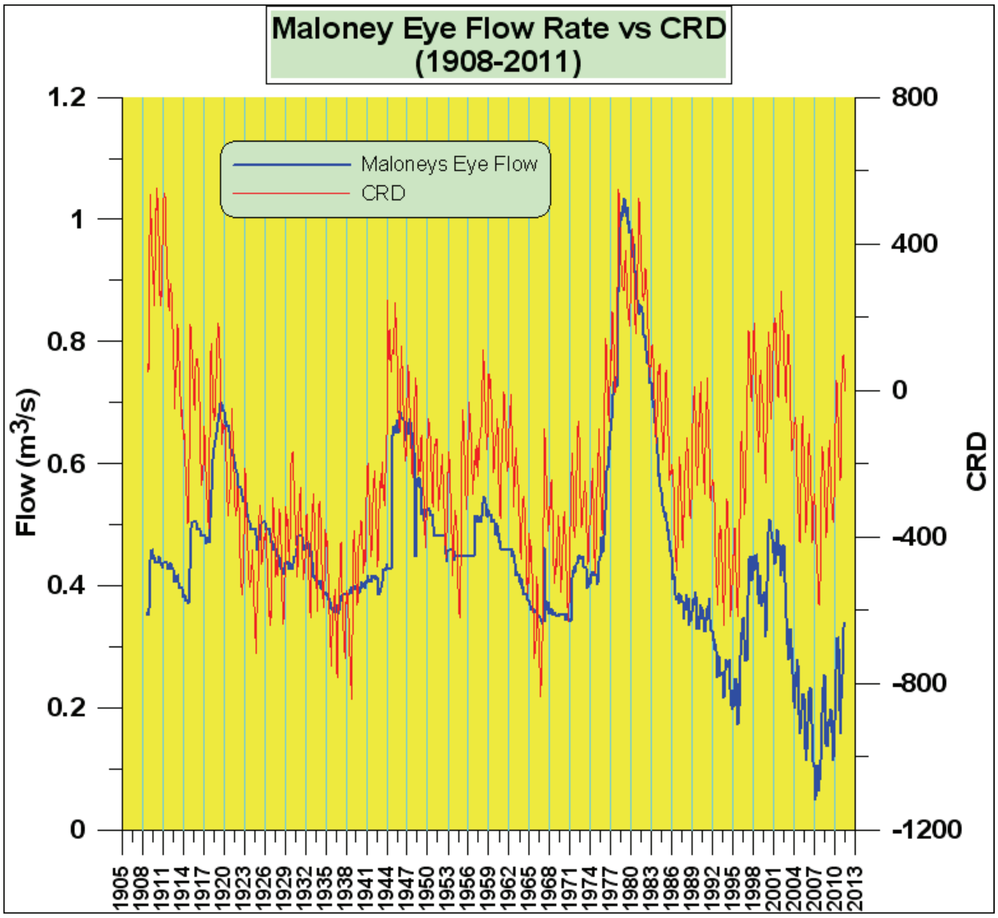


Figure 2-3 Maloney's Eye Flow vs. CRD

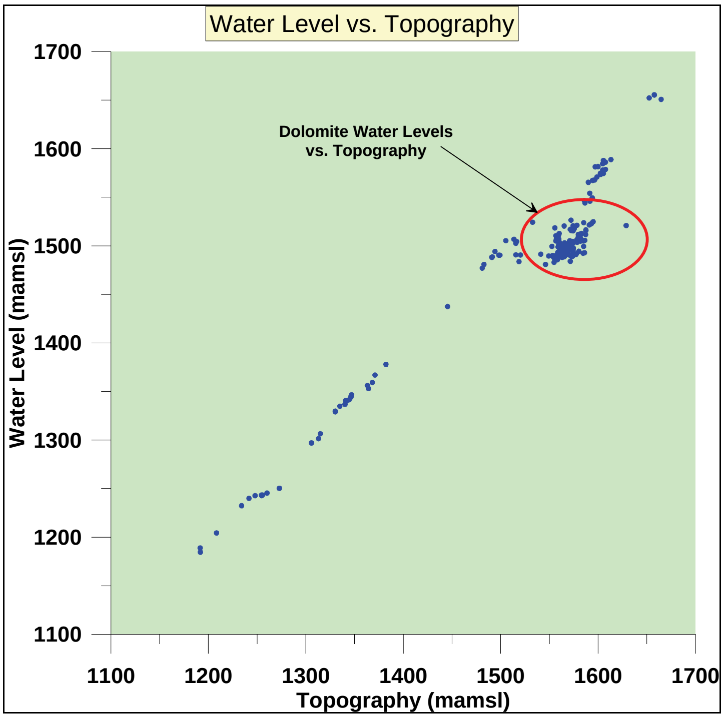


Figure 2-4 Water Levels vs. Topography

2.3 Area of Modelling and System Boundaries

In the absence of evidence of physical subsurface no-flow boundaries, the modelling area was selected based on topographical control i.e. along surface catchment and sub-catchment boundaries. According to standard modelling practice, this is a reasonable approach to follow since a good correlation exists between the groundwater level elevation and the surface topography. Boundaries of the numerical model were therefore chosen to reflect the geometry of the surface water catchment system. The boundaries of the larger Magalies River catchment to the northwest, north, northeast east and east around the perimeter of the model coincide to groundwater divides present beneath the surface water divides. The Steenkoppies Compartment in the south of the study area is bounded by a surface water/groundwater divide to the south, by the Tarlton Dyke to the east and the Eigendom Dyke to the west. The base of the model domain is set 140m below ground surface throughout the model area across the study area. Section 3.6 provides a detailed discussion of the boundary conditions and rationale for their selection.

2.4 Hydraulic Properties

No recent aquifer test data is available for the study area. From the limited available aquifer tests recently conducted to the south of the study area (in the Randfontein area) it is evident that hydraulic conductivity values (transmissivities) may vary by orders of magnitude both spatially and with depth. On average, the rock becomes solid below 140m from surface. The geological setting is complex as a result of the intrusion of diabase into the older rocks and faulting which may or may not be enhancing development of higher hydraulic conductivity zones. Aquifer parameter values for the dolomites could also be obtained from studies conducted in the 1980s. These tests confirmed very high transmissivity values across the dolomite aquifers associated with karstification of the dolomite.

2.5 Hydrostratigraphic Units

The major hydrostratigraphic units of probably different hydraulic properties that exist within the study area are:

- The Witwatersrand Supergroup (quartzite);
- The Ventersdorp Supergroup (Lava);
- Chuniespoort Group (dolomite);
- The Pretoria Group (quartzite and shale);
- Karoo Sequence (Ecca Group) sandstone and shale;
- Post-Karoo dolerite dykes and diabase dykes.

2.6 Recharge, Discharge and Flow Directions

The groundwater system within the study area is largely recharged via infiltration of precipitation. It is thought that most of the groundwater recharge occurring within the study area discharges internally to the surface drainage systems via springs and discharge to the base of river drainage systems.

3 APPROACH TO NUMERICAL MODELLING

3.1 Introduction

A numerical model was constructed to represent the conceptual groundwater system of the study area as presented above. The purpose of the model is to develop a tool that can be used to assess the potential groundwater conditions under a variety of development and/or management strategies.

3.2 Software Code Selection

The code selected for conducting the modelling of the study area is FEFLOW developed by the WASY Institute for Water Resources Planning and Systems Research, Ltd. Berlin, Germany. Feflow is an interactive groundwater modelling system for three and two-dimensional, areal and cross-sectional, fluid density-coupled, thermohaline or uncoupled, variably saturated, transient or steady state flow, mass and heat transport in subsurface water resources with or without one or multiple free surfaces.

Feflow can be used efficiently to describe the spatial and temporal distribution of groundwater contaminants, to model geothermal processes, to estimate the duration and travel times of pollutants in aquifers, to plan and design remediation strategies and interception techniques, and to assist in designing alternatives and effective monitoring schemes. Since its creation in 1979, Feflow has been continuously improved. The Feflow source code is written in ANSI C/C++ and contains more than 1,1 million programme lines. Feflow is used worldwide as a high-end groundwater-modelling tool at universities, research institutes, government offices and engineering companies

3.3 Model Area

The area depicted in Figure 3-1 forms the modelled area of approximately 1072km2. Model boundaries are selected along sub-catchment surface water divides and dykes.

3.4 Mode of Flow

In general, flow through a porous medium is three-dimensional (Bear and Verruijt, 1992). However, since the geometry of most aquifers is such that they are thin relative to their horizontal dimensions a simpler approach can be introduced. According to this approach, vertical flow components are neglected and we assume that the flow in the aquifer is essentially horizontal, or that it may be approximated as such. This is strictly true and not just an assumption in the case of flow in a horizontal, homogeneous, isotropic, confined aquifer of constant thickness and with fully penetrating wells. Nevertheless, the approximation is still a good one when the thickness of the aquifer varies, but in such a way that the variations are much smaller than the average thickness (Bear and Verruijt, 1992). In the case of this modelling study the aquifer is thin (a thickness of 140m is assumed) for the hard rock and dolomite aquifers relative to the modelled horizontal dimensions (51km x 41km) and a 2D-approach could therefore be adopted.

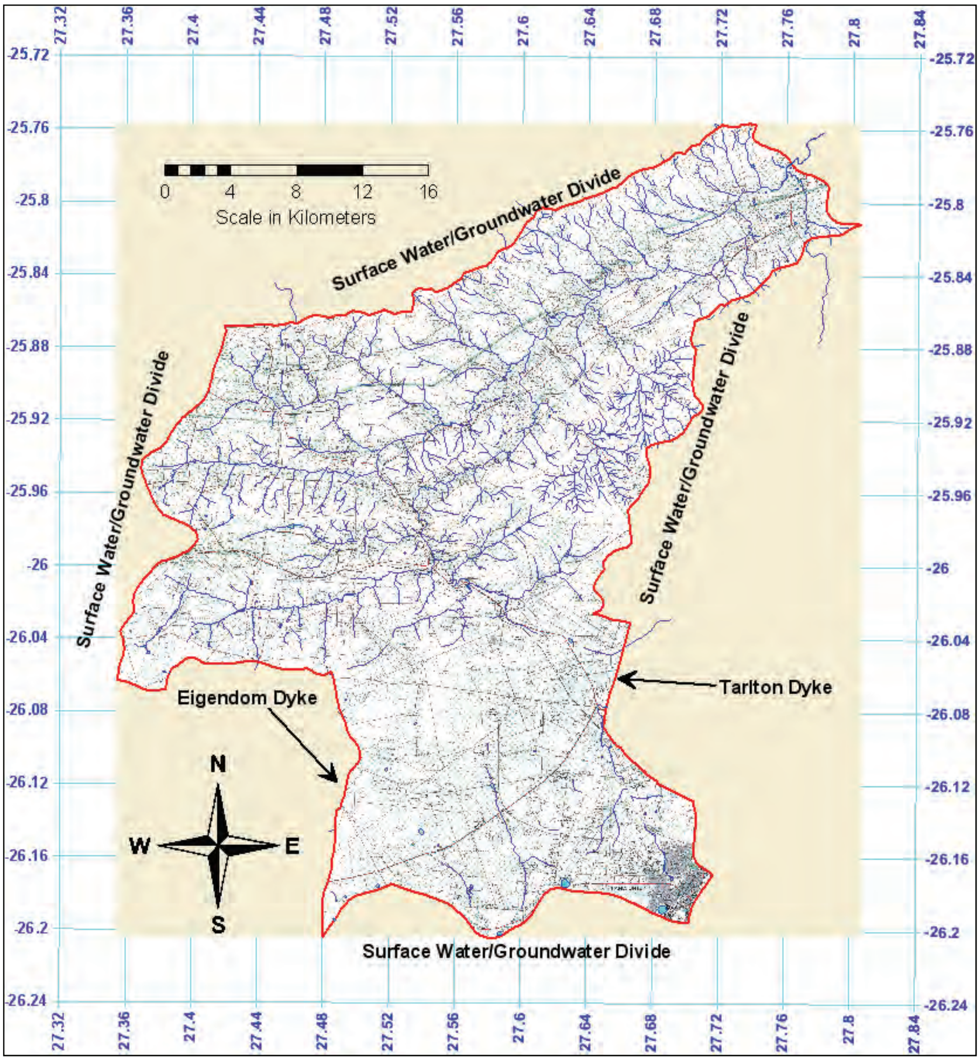


Figure 3-1 Boundary of Model Domain indicated by Red Line

3.5 Numerical Flow Model

A steady state groundwater flow model for the study area was constructed to simulate undisturbed groundwater flow conditions. These conditions serve as starting heads for the transient simulations of groundwater flow where the effect of water supply abstraction and temporal recharge will be taken into consideration.

A dynamic flow model using the modelling package FEFLOW (Diersch, 1979) was constructed for the study area. The simulation model (FEFLOW) used in this modelling study is based on three-dimensional groundwater flow and may be described by the following equation:

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})\pm W = S\frac{\partial h}{\partial t} \qquad (1)$$

where

h = hydraulic head [L]

K_x, K_y, K_z = Hydraulic Conductivity [L/T]

S = storage coefficient

t = time [T]

W = source (recharge) or sink (pumping) per unit area [L/T]

x,y,z = spatial co-ordinates [L]

3.6 Model Boundary Conditions

Boundary conditions express the way the considered domain interacts with its environment. In other words, they express the conditions of known water flux, or known variables, such as piezometric head. Different boundary conditions result in different solutions hence the importance of stating the correct boundary conditions. Boundary conditions in a groundwater flow model can be specified either as:

- Dirichlet Type (or constant head) boundary conditions or;
- Neuman Type (or specified flux) boundary conditions; and
- or a mixture of the above.

3.6.1 Model Perimeter Boundary Conditions

Groundwater flow directions largely follow topography, and the groundwater basin geometry can be approximated by the surface water drainage geometry. The boundaries of the numerical model are shown on Figure 3-1. The model area perimeter coincides to the surface water/groundwater divides. These boundaries are represented numerically by what is referred to as a “no-flow” boundary condition (Zero specified flux Neuman Type II boundary condition).

3.6.2 Internal Model Boundaries

The groundwater system within the study area is largely recharged via infiltration of precipitation. It is thought that most of the groundwater recharge occurring within the study area discharges internally to the surface drainage systems via springs and discharge to the base of river drainage systems (base flow). Constant head boundary conditions (seepage face) were therefore specified along the major surface drainages, which are known to receive base flow from groundwater as, indicated in Figure 3-2. A constant head boundary condition was also specified at the location of the Maloney’s Eye. The constant head boundary condition allows groundwater to discharge, in this case, from the model area at a rate dependent on the hydraulic conductivity and hydraulic gradient across the boundary. The constant head boundaries were constrained so that water can only be removed from the system – a reversal of the hydraulic gradient back towards the aquifer from the surface system would therefore not allow water to enter the aquifer from the surface water system. This therefore represents a true “drain type” (seepage face) boundary condition.

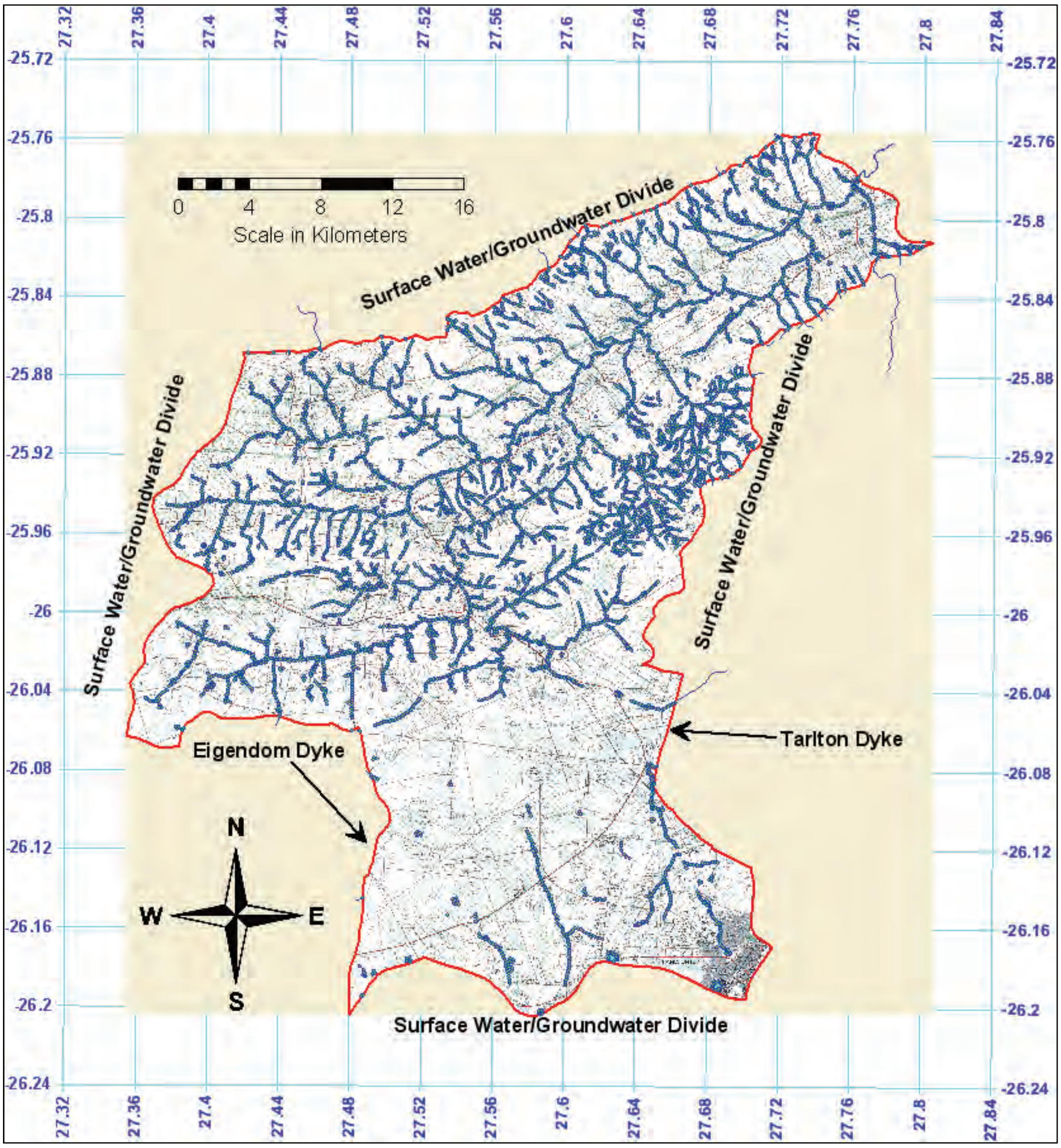

Internal Model Boundaries

Figure 3-2 Internal Modelling Boundaries (Blue Circles) (Type I Dirichlet) Representing Drain Nodes along Rivers and Streams.

3.6.3 Model Base Boundary Condition

The model domain was assumed to extend vertically to a depth of 140m in the hard rock aquifers and in the dolomite aquifers. It is assumed that the base of the model is impermeable.

3.6.4 Model Surface Boundary Condition

Boundary conditions applied to the top surface area of the model include the following. A defined quantity of background recharge is assigned (15-30mm/a on the hard rock aquifers and 84mm/a on the dolomite aquifers for the steady state simulation (calibration). This constitutes about 2-4% and 12% of MAP for the hard rock aquifers and for the dolomite aquifers respectively and is in line with the corresponding hydraulic conductivity values for the different aquifers in the area.

3.7 Hydrogeological Units

The geologic formations of the study area were discussed in the main report. Figure 2-1 shows the surface expression of the assigned hydrostratigraphic units in the model.

3.8 Hydraulic Stresses

The conceptualized water balance components that are considered were simulated in the numerical model using the available components of the Feflow software package. This included the “Inflow-Outflow from surface” package to simulate natural groundwater recharge and the constant head boundary condition Type I to simulate outflow from the internal model boundaries. Irrigation abstractions from the aquifers were simulated using the “Well Boundary” a Type IV boundary condition.

3.9 Calibration Approach

Calibration is the process of finding a set of parameters, boundary conditions, and stresses that best reproduce the observed water levels and/or fluxes (Anderson and Woesner, 1992). A standard trial-and-error approach to calibrate the model was used. Theoretically, hydraulic conductivity, hydraulic stresses (such as recharge rates from precipitation and borehole abstraction during transient calibration), and the hydraulic boundary conditions can be modified until the best possible match is made to the observed water level conditions. The water level data shown in Figure 3-3 was used for steady state model calibration purposes. From the contour spacing it is evident that the transmissivity of the dolomite is large (very wide contour spacing – low hydraulic gradients) and that of the hard rock to the south and north of the dolomite is small (very steep hydraulic gradients).

After the set of parameters that resulted in the best match to the observed steady state water levels was determined, a transient state simulation was conducted whereby temporal recharge and the relevant temporal groundwater abstraction was specified in the model and the specific storage parameter was altered to match the temporal water level changes observed.

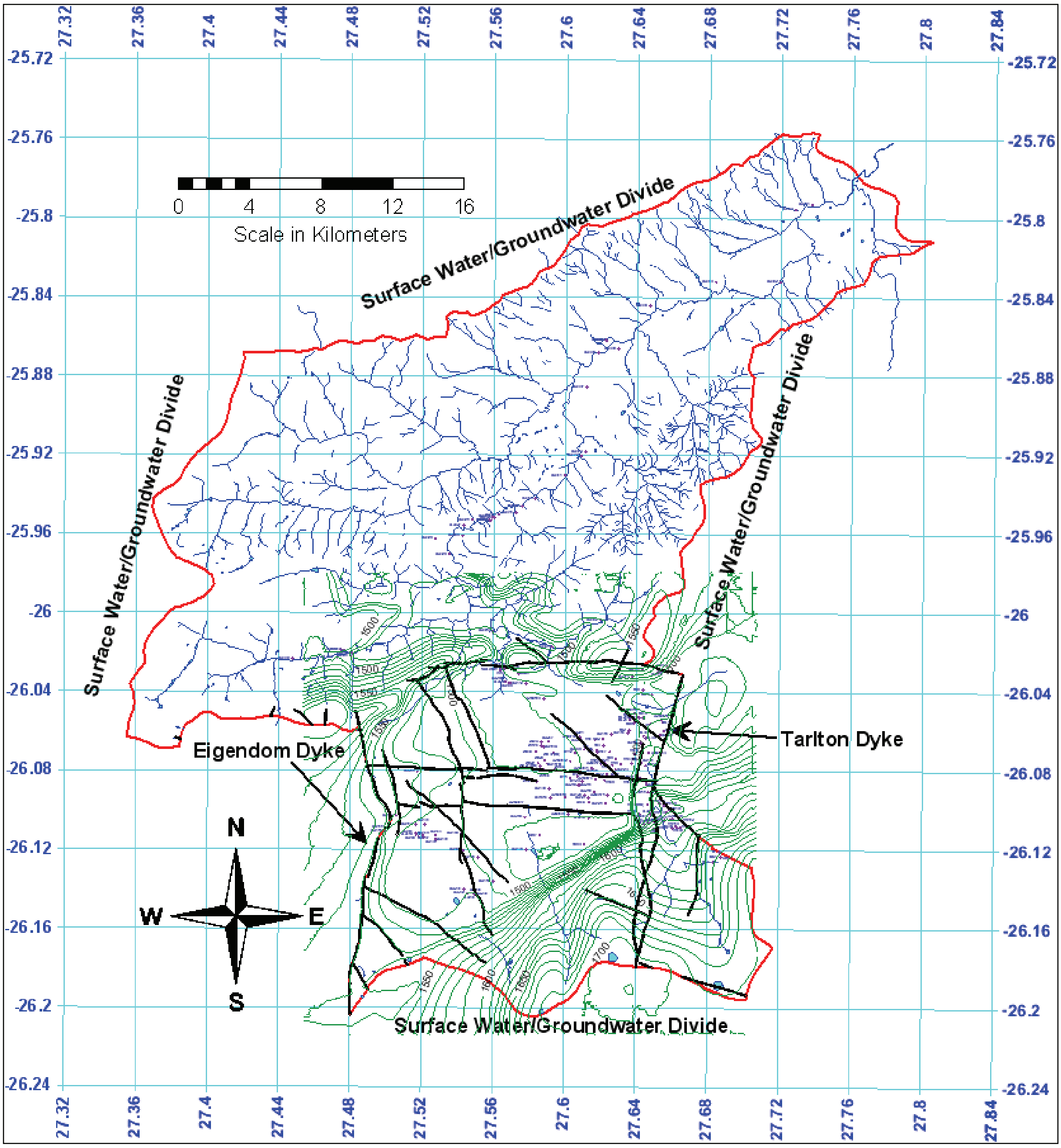


Figure 3-3 Observed Water Level Distribution (Green Contour Lines) used for Steady State Calibration

4 MODEL CONSTRUCTION AND CALIBRATION

4.1 Model Area and Finite Element Mesh

The numerical model includes all surface catchments associated with the Magalies River drainage and the Steenkoppies Dolomitic Compartment. It extends to cover a large region over a total area of 1072 square kilometres.

A finite element network (grid) was designed to provide a high resolution of the numerical solution, while at the same time, accommodating the large model area.

The finite element grid was compiled using the FEFLOW pre-processing software, which facilitated the construction of 6-noded triangular prism elements over the area of investigation as shown in Figure 4-1. The triangular grid consists of 192908 elements and 194554 nodes. The positions of the different geological units and dykes are incorporated in the modelling grid as well as the various surface catchments. The model consists of one layer with constant thicknesses of 140m. The elevation of the top slice was set equal to the topographic elevation. A 3D-view of the modelling area is provided in Figure 4-2.

4.2 Model Perimeter and Internal Boundaries

No-flow boundaries were used to represent the hydrologic boundaries for the entire model perimeter. Constant head boundaries were assigned along the major drainages and along major tributaries of these drainages to represent outflow boundaries. Constant head nodes were also specified on spring locations such as the Maloney's Eye. Thus, all groundwater within the study area was assumed to originate as spatially distributed recharge within the model domain. It is thought that most of the groundwater recharge occurring within the study area discharges internally to the surface drainage systems via springs and discharge to the base of river drainage systems (baseflow).

4.3 Upper Model Boundary

The topography was used to specify the upper modelling boundary in the model. FEFLOW's "inflow/outflow on top slice" condition was used to define recharge in Slice 1 (top of Layer 1) in the model.

4.4 Model Properties

4.4.1 Hydraulic Conductivity and Transmissivity

The major hydrogeological units in the study area are described in previous sections of the report. The hydraulic conductivities of these units were assigned to the model based on the estimated hydraulic properties obtained from pumping tests conducted to date and first model calibration and sensitivity runs.

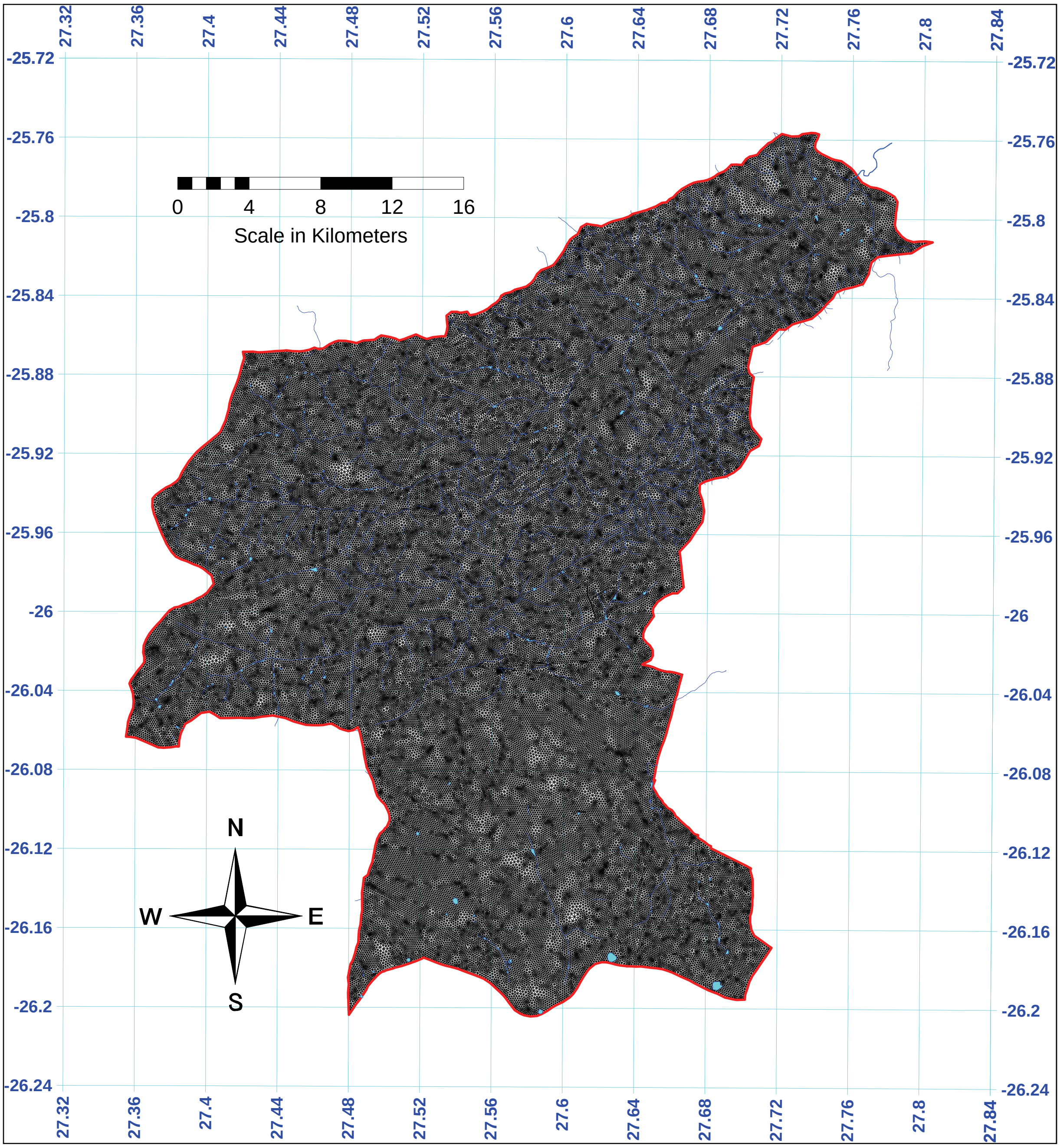


Figure 4-1 Finite Element Mesh

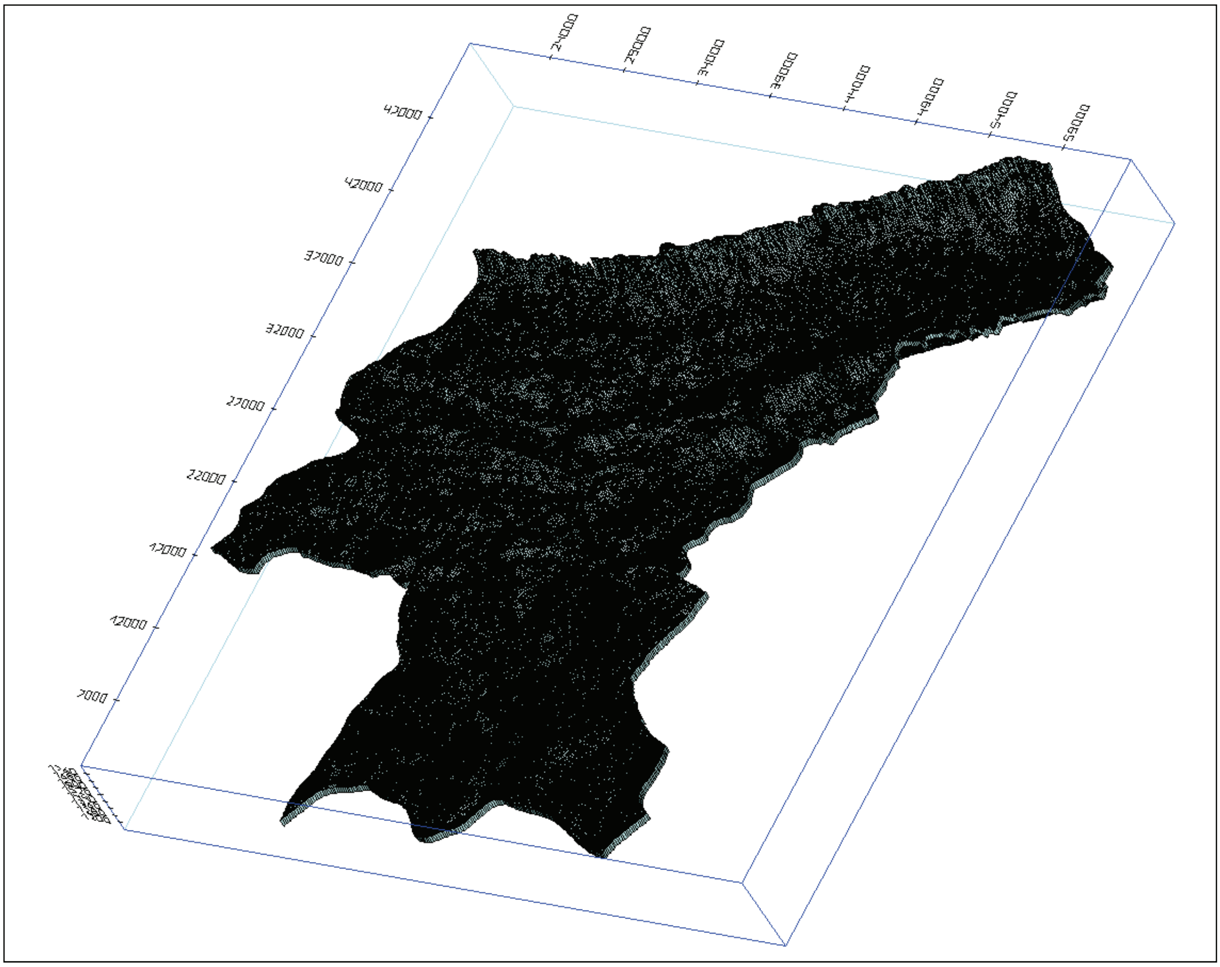


Figure 4-2 Three Dimensional View of the Finite Element Network

4.4.2 Storativity

For the steady-state model, storativity is not required. For transient state simulations a specific storage value of 5x10-5/m - 1x10-4/m was used for the hard rock aquifers – this would provide an equivalent aquifer storage coefficient of 0.007-0.014 or 0.7-1.4 percent, which is representative for these hard rock aquifer conditions. A specific storage value of 2 to 3x10-4/m was used for the dolomite aquifers which relates to storage coefficients of between 2.8 and 4.2% representative of these dolomitic aquifer conditions.

4.4.3 Recharge

The annual recharge is estimated to be in the order of 2-4% of MAP across the hard rock aquifers. Across the dolomitic areas the recharge is significantly higher (in the order of 84mm/a or 12% of MAP) and in line with the much larger permeabilities for these aquifers. The rainfall/recharge relationship will be discussed in more detail under the transient calibration. The spatial zoning used for the assignment of recharge is depicted in Figure 4-3.

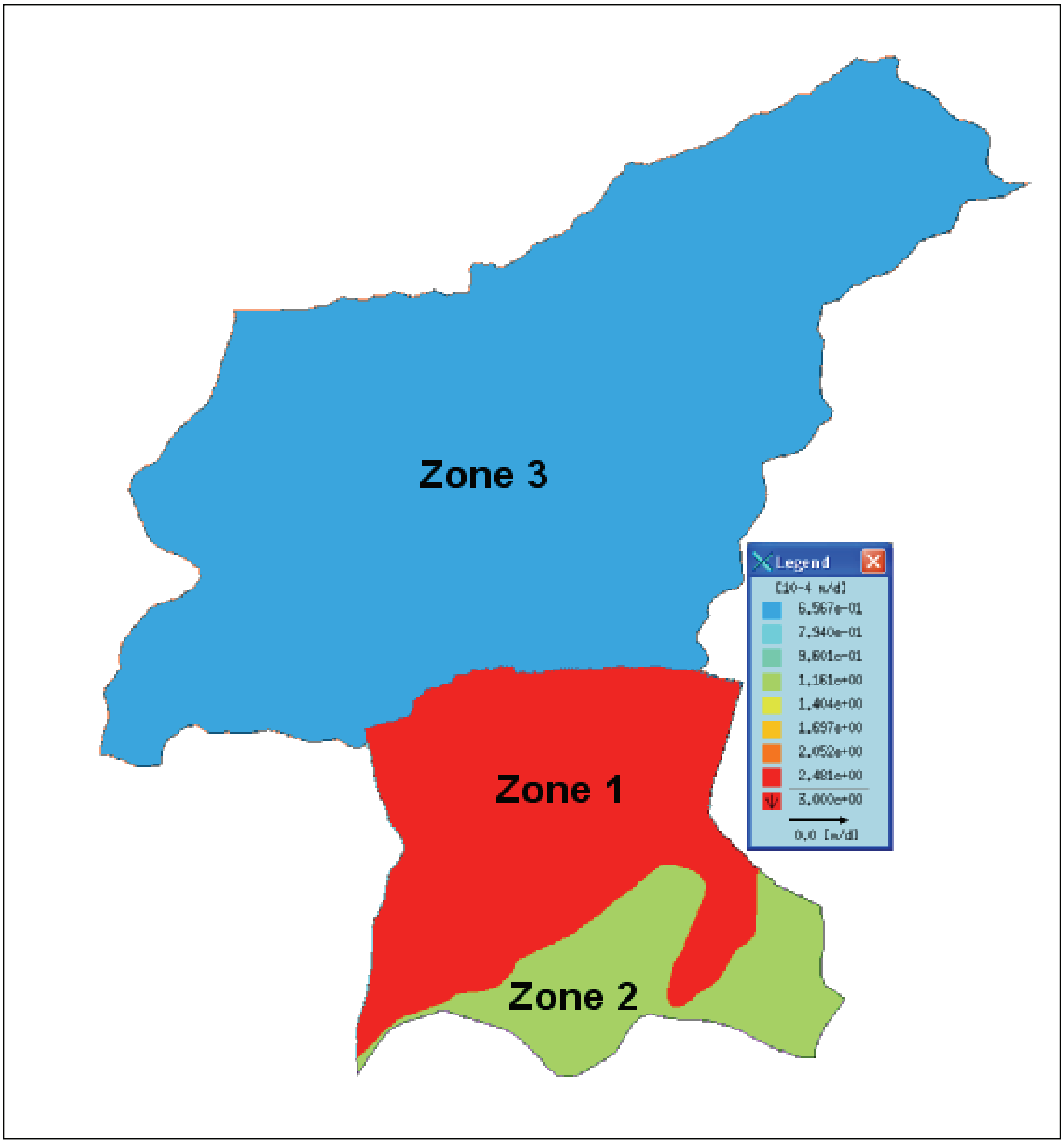


Figure 4-3 Spatial zoning used to assign recharge across the study area.

4.4.4 Evaporation

Evapotranspiration was not specified in the model. It is assumed that the (effective) recharge specified in the model has already overcome the effect of evapotranspiration losses from the system.

4.4.5 Initial Head Conditions

The initial head conditions specified in the model were interpolated from the measured groundwater levels using the Kriging technique and extrapolated to the nodes in the model.

4.5 Steady State Calibration

4.5.1 Steady State Flow Equation

For steady state conditions the groundwater flow equation (1) reduces to the following equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) \pm W = 0 \qquad (2)$$

According to the conceptual model for the system the calculated head distribution (hx, hy, hz) is dependent upon the recharge from rainfall, hydraulic conductivity and boundary conditions. For a given hydraulic conductivity value (or transmissivity value) and set of boundary conditions specified, the head distribution across the aquifer can be obtained for a specific recharge value. This simulated head distribution can then be compared to the measured head distribution and the effective recharge values can be altered until an acceptable correspondence between measured and simulated heads is obtained.

4.5.2 Steady State Calibration Approach

Steady state calibration was accomplished by varying the hydraulic conductivity values and keeping the recharge rate constant, until a reasonable match between the measured groundwater elevations and the simulated groundwater elevations was obtained. A constant recharge was used for the hard rock and dolomite zones because localized recharge variations (based on slope or soil type) cannot be determined with the limited data available at this time. For the purpose of this modelling study, a constant recharge rate across the zones is considered reasonable and likely to result in similar regional predictions compared to spatially distributed recharge. The model was calibrated using groundwater levels that could be obtained from the desk study phase of this investigation excluding water levels which could be identified as outlier values. Figure 4-4 shows the locations of target boreholes used for calibration purposes.

4.5.3 Simulation of Water Levels for State Conditions

Figure 4-5 and Figure 4-6 respectively show the simulated steady state groundwater elevations and groundwater flow directions for the steady state calibration. There are insufficient boreholes with groundwater level data to create an observed water table map for the entire model area. Therefore, the model output has been evaluated in a qualitative manner by observing the shape of the water table contours near known hydraulic boundaries, divides and drainages. The calibrated model water table is similar to what would be expected at the location of internal watersheds divides and major drainages. As shown on Figure 4-5, the water table closely conforms to local topographic features.

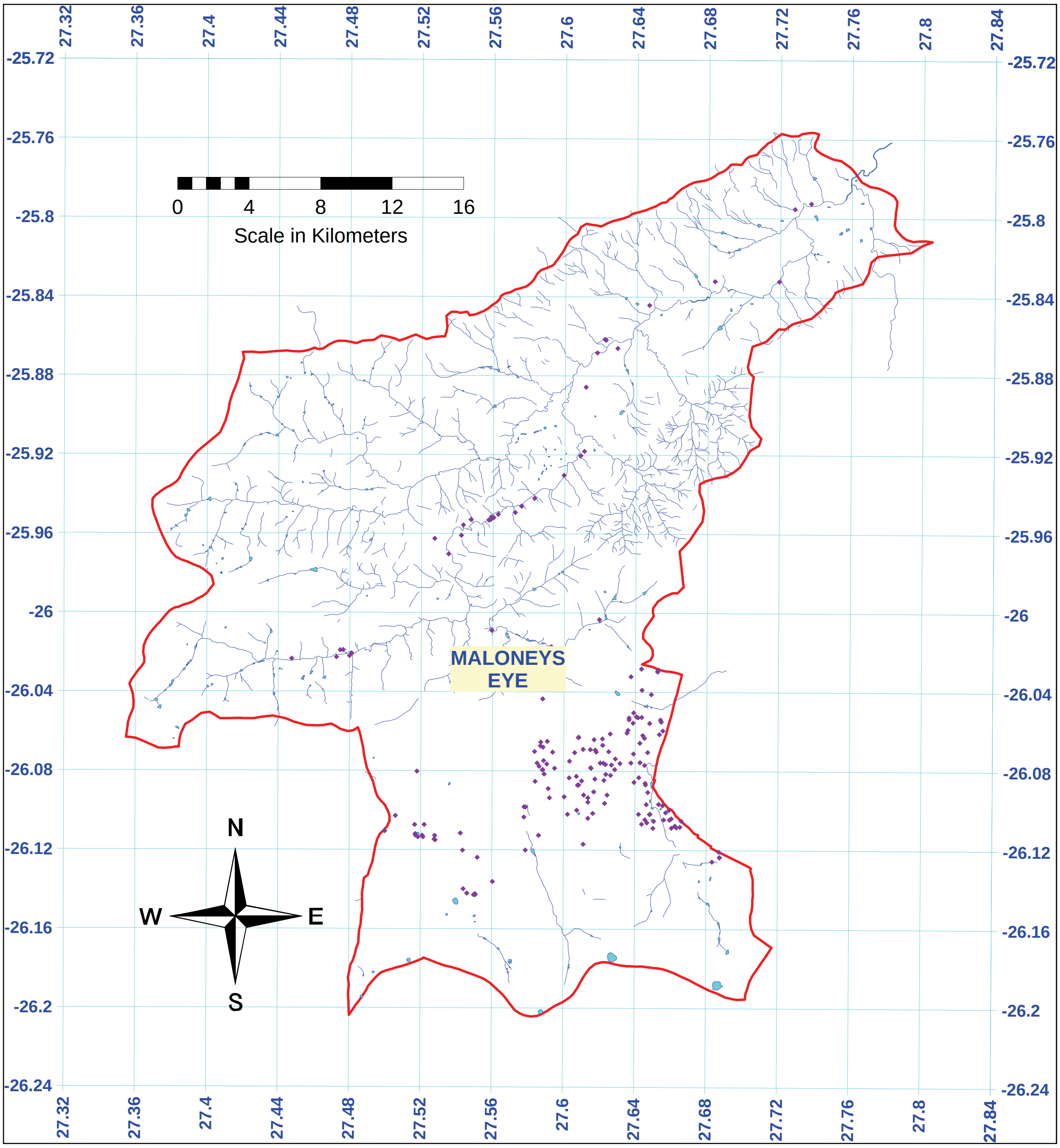


Figure 4-4 Positions of Boreholes (indicated by the purple diamonds) used for Steady State Calibrations Purposes

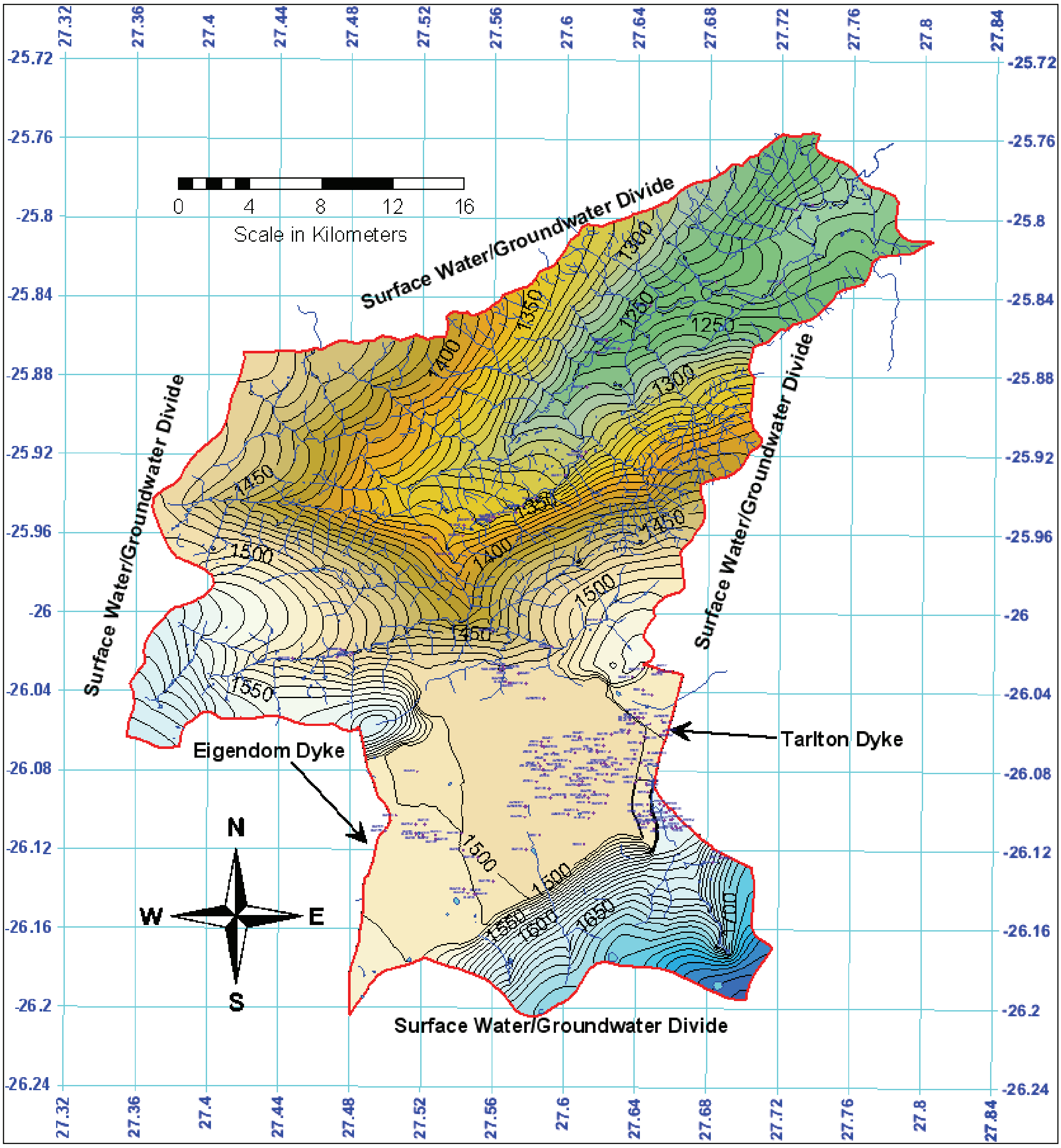


Figure 4-5 Simulated Steady State Water Levels

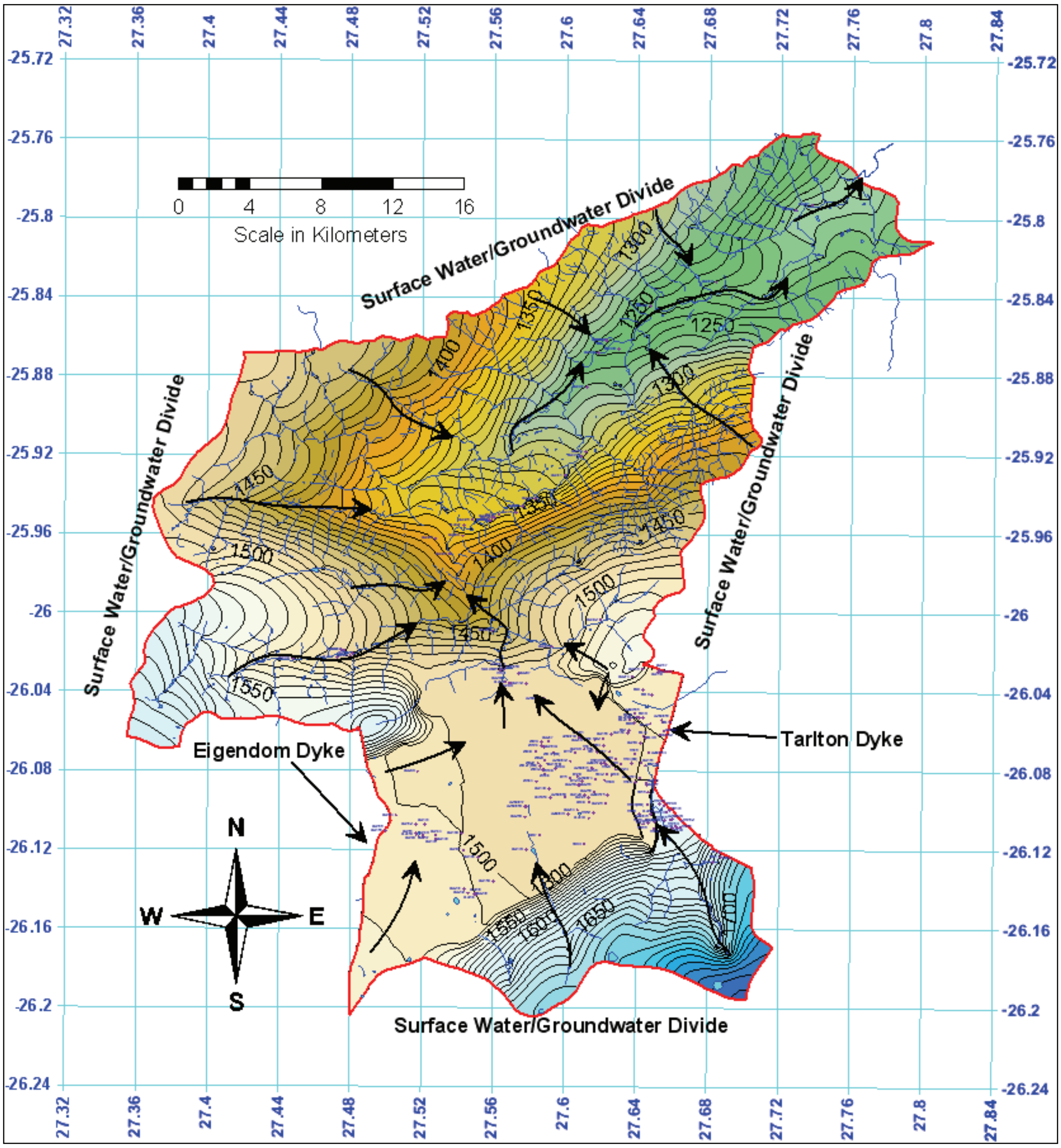


Figure 4-6 Groundwater Flow Directions indicated by Black Arrows

A small ME is not necessarily an indication of a good calibration, because negative and positive residuals, even if large, can cancel each other out, resulting in a small ME. The MAE addresses this as the mean of the absolute value of the differences in measured and simulated water levels:

MAE = $1/n \, \Sigma \, |(WLm- WLs)i|$.

The RMS error is the average of the squared differences in measured and simulated water levels.

RMS = $[1/n \, \Sigma(WLm- WLs)i^2]0.5$.

In keeping with standard practice, the RMS error was evaluated as a ratio to the total water level change across the model domain. If the ratio is small, the errors are only a small part of the overall model response (Anderson and Woessner 1992). The ME, MAE, and RMS error were calculated using all of the calibration targets for the available data set. The Mean Error for the data set is 0.51 metres. The Mean Absolute Error for the data set is 5.8 metres. The Root Mean Squared error is 8.16 metres and 1.73 percent of the range of water level change across the model domain (see Table 4-1).

The observed groundwater levels were plotted against the simulated water levels in a scatter plot for the data set (Figure 4-7) and in a line-graph (Figure 4-8). Deviations from the straight line indicating a perfect match between the observed and simulated values should be randomly distributed indicating that there is no bias toward over or under predicting the groundwater levels (Anderson and Woessner 1992). A correlation coefficient of 99% was obtained between the simulated and observed groundwater elevations for the data set. The plot of the modelling errors for the simulated data set (Figure 4-9) indicates that the model is generally not under or over-predicting the groundwater elevations.

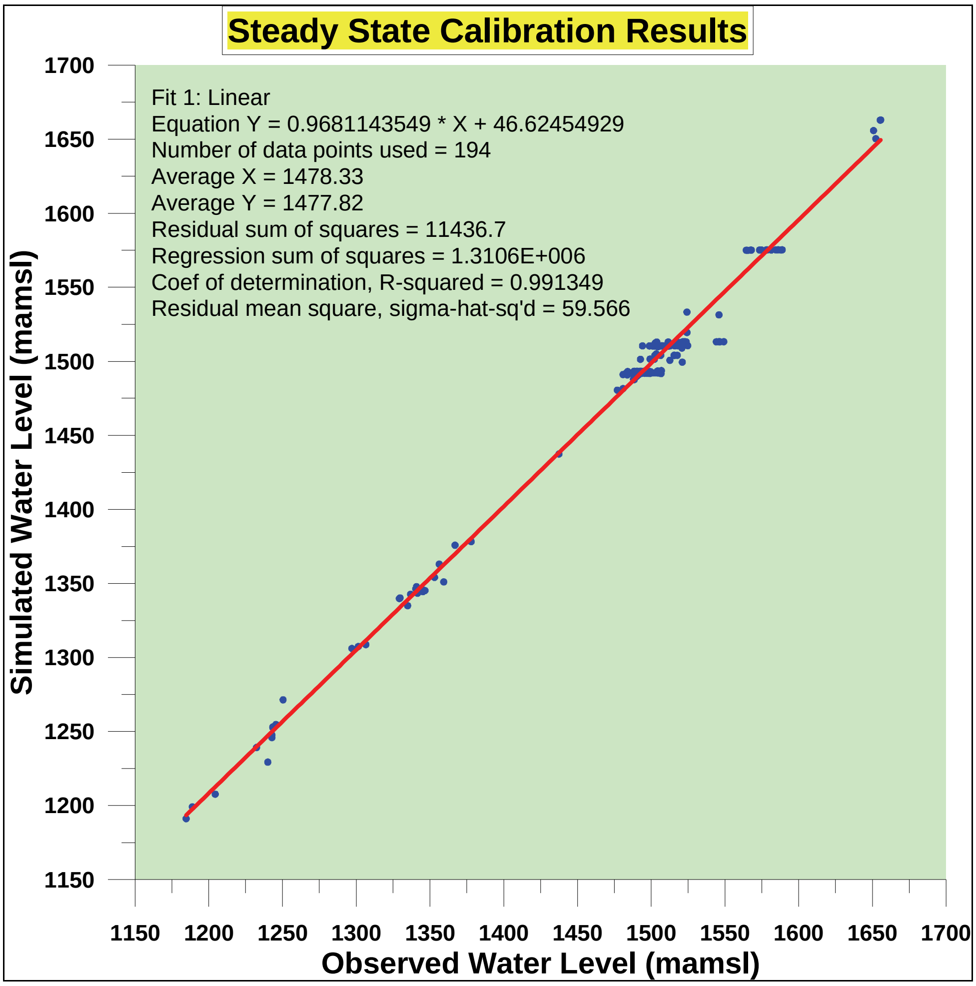


Figure 4-7 Scatter Plot of Simulated Versus Observed Groundwater Levels

Table 4-1 Steady State Calibration Measures for Steady State Model

Borehole	**Observed SWL (mamsl)**	**Simulated Water Level (mamsl)**	**ME (m)**	**MAE (m)**	**RMS (m)**
			(WLm- WLs)i	**|(WLm- WLs)i|**	**(WLm- WLs)i2**
706	1489.06	1489.75	-0.69	0.69	0.48
A2N0553	1515.50	1504.05	11.46	11.46	131.27
A2N0555	1500.74	1510.37	-9.63	9.63	92.73
A2N0556	1510.37	1510.39	-0.03	0.03	0.00
A2N0558	1490.33	1490.07	0.26	0.26	0.07
A2N0559	1490.29	1489.94	0.35	0.35	0.12
A2N0560	1489.46	1491.47	-2.02	2.02	4.07
A2N0568	1489.93	1493.21	-3.28	3.28	10.78
A2N0569	1488.07	1492.91	-4.83	4.83	23.35
A2N0570	1493.87	1493.17	0.70	0.70	0.49
A2N0571	1491.57	1492.06	-0.49	0.49	0.24
A2N0572	1491.85	1492.11	-0.26	0.26	0.07
A2N0573	1494.62	1492.18	2.45	2.45	5.98
A2N0574	1493.13	1493.03	0.09	0.09	0.01
A2N0575	1489.26	1493.14	-3.88	3.88	15.03
A2N0576	1544.15	1513.18	30.97	30.97	958.94
A2N0577	1517.71	1504.06	13.64	13.64	186.13
A2N0579	1574.75	1575.22	-0.47	0.47	0.22
A2N0617	1489.83	1493.20	-3.37	3.37	11.37
A2N0749	1491.77	1491.93	-0.16	0.16	0.03
BE-1	1655.35	1662.90	-7.56	7.56	57.14
CES-1	1655.62	1663.05	-7.43	7.43	55.28
DY12	1491.83	1492.08	-0.25	0.25	0.06
DY18	1491.30	1492.91	-1.61	1.61	2.61
DY20	1488.81	1492.96	-4.15	4.15	17.21
DY5	1490.61	1492.85	-2.24	2.24	5.01
G36354	1493.42	1492.87	0.54	0.54	0.29
GA107	1483.77	1490.83	-7.05	7.05	49.73
GA109	1490.49	1490.85	-0.36	0.36	0.13
GA112	1480.88	1491.09	-10.20	10.20	104.12
GA116	1545.98	1531.39	14.59	14.59	212.84
GA117	1512.80	1510.43	2.38	2.38	5.65
GA118	1512.18	1510.43	1.75	1.75	3.08
GA119	1510.86	1510.43	0.44	0.44	0.19
GA123	1498.22	1492.19	6.03	6.03	36.41
GA126	1490.84	1493.12	-2.28	2.28	5.21
GA127	1491.06	1493.02	-1.97	1.97	3.88
GA129	1492.20	1492.99	-0.78	0.78	0.61
GA132	1501.92	1510.37	-8.46	8.46	71.54
GA134	1511.08	1510.38	0.70	0.70	0.49
GA136	1491.48	1492.06	-0.58	0.58	0.34
GA138	1489.70	1492.07	-2.36	2.36	5.59

Borehole	**Observed SWL (mamsl)**	**Simulated Water Level (mamsl)**	**ME (m)**	**MAE (m)**	**RMS (m)**
			(WLm- WLs)i	**|(WLm- WLs)i|**	**(WLm- WLs)i2**
GA139	1489.45	1492.79	-3.33	3.33	11.10
GA140	1489.10	1493.23	-4.13	4.13	17.07
GA141	1505.54	1510.31	-4.78	4.78	22.80
GA144	1505.56	1510.34	-4.78	4.78	22.87
GA145	1504.84	1510.35	-5.52	5.52	30.43
GA146	1507.89	1510.35	-2.47	2.47	6.09
GA147	1511.82	1510.38	1.44	1.44	2.09
GA148	1511.67	1510.37	1.29	1.29	1.68
GA149	1508.08	1510.40	-2.32	2.32	5.39
GA150	1509.84	1510.39	-0.55	0.55	0.31
GA151	1509.70	1510.39	-0.69	0.69	0.47
GA152	1504.95	1510.33	-5.38	5.38	28.95
GA154	1524.79	1510.60	14.20	14.20	201.56
GA155	1516.40	1510.55	5.85	5.85	34.21
GA156	1515.79	1510.55	5.23	5.23	27.37
GA159	1499.21	1501.52	-2.30	2.30	5.31
GA160	1502.49	1504.04	-1.56	1.56	2.42
GA161	1515.70	1504.03	11.67	11.67	136.21
GA163	1491.84	1492.22	-0.38	0.38	0.15
GA164	1499.44	1492.19	7.26	7.26	52.64
GA165	1494.38	1492.12	2.26	2.26	5.09
GA167A	1485.63	1492.02	-6.39	6.39	40.87
GA167B	1488.11	1492.24	-4.13	4.13	17.04
GA178	1490.43	1493.36	-2.93	2.93	8.60
GA190	1504.41	1509.80	-5.39	5.39	29.01
GA195	1492.70	1501.38	-8.68	8.68	75.37
GA197	1502.14	1501.41	0.73	0.73	0.53
GA214	1499.45	1493.04	6.41	6.41	41.08
GA219	1498.90	1491.92	6.99	6.99	48.80
GA221	1493.42	1491.93	1.49	1.49	2.22
GA231	1505.00	1510.45	-5.45	5.45	29.72
GA232	1507.55	1510.46	-2.92	2.92	8.50
GA234	1506.92	1510.43	-3.51	3.51	12.31
GA235	1503.42	1504.98	-1.56	1.56	2.42
GA236	1512.68	1500.71	11.97	11.97	143.32
GA238	1520.82	1508.97	11.85	11.85	140.46
GA239	1546.65	1513.19	33.46	33.46	1119.58
GA247	1488.51	1491.98	-3.46	3.46	12.00
GA256	1498.73	1493.05	5.68	5.68	32.26
GA260	1491.61	1492.94	-1.33	1.33	1.78
GA261	1491.69	1492.93	-1.25	1.25	1.56
GA269	1488.49	1493.27	-4.79	4.79	22.90

Borehole	Observed SWL (mamsl)	Simulated Water Level (mamsl)	ME (m)	MAE (m)	RMS (m)
			(WLm- WLs)i	|(WLm- WLs)i|	(WLm- WLs)i2
GA274	1524.27	1533.24	-8.97	8.97	80.44
GA275	1520.65	1512.93	7.72	7.72	59.64
GA277	1517.89	1512.92	4.97	4.97	24.75
GA283	1490.73	1490.76	-0.03	0.03	0.00
GA287	1491.35	1490.85	0.50	0.50	0.25
GA299	1356.25	1362.99	-6.74	6.74	45.42
GA300	1188.81	1199.08	-10.27	10.27	105.49
GA301	1184.60	1191.09	-6.50	6.50	42.23
GA302	1204.30	1207.63	-3.33	3.33	11.07
GA303	1232.35	1239.17	-6.82	6.82	46.53
GA304	1243.42	1253.11	-9.69	9.69	93.80
GA305	1243.42	1252.60	-9.18	9.18	84.33
GA306	1245.47	1254.69	-9.22	9.22	85.00
GA307	1250.32	1271.36	-21.05	21.05	443.00
GA308	1242.77	1245.85	-3.08	3.08	9.49
GA309	1242.77	1247.58	-4.81	4.81	23.14
GA310	1239.97	1229.28	10.69	10.69	114.28
GA311	1306.48	1308.66	-2.18	2.18	4.77
GA312	1297.04	1306.06	-9.02	9.02	81.36
GA313	1301.42	1307.43	-6.01	6.01	36.14
GA314	1334.81	1334.97	-0.16	0.16	0.02
GA315	1344.23	1346.38	-2.15	2.15	4.62
GA316	1329.69	1340.22	-10.53	10.53	110.78
GA317	1329.19	1339.77	-10.58	10.58	111.99
GA318	1346.58	1345.18	1.40	1.40	1.96
GA320	1336.82	1342.67	-5.85	5.85	34.18
GA321	1345.21	1344.46	0.74	0.74	0.55
GA322	1341.57	1343.34	-1.77	1.77	3.15
GA323	1340.82	1347.81	-6.99	6.99	48.87
GA324	1340.33	1346.32	-6.00	6.00	35.97
GA326	1359.29	1351.01	8.28	8.28	68.58
GA327	1353.03	1354.04	-1.02	1.02	1.03
GA328	1377.90	1378.21	-0.31	0.31	0.09
GA329	1366.93	1375.79	-8.86	8.86	78.43
GA330	1437.49	1437.42	0.07	0.07	0.01
GA331	1480.89	1481.61	-0.73	0.73	0.53
GA332	1524.28	1519.44	4.84	4.84	23.42
GA335	1476.99	1480.53	-3.54	3.54	12.52
GA336	1488.52	1487.69	0.84	0.84	0.70
GA337	1488.21	1491.70	-3.48	3.48	12.14
GA340	1502.70	1512.34	-9.64	9.64	92.94
GA341	1506.73	1491.73	15.00	15.00	225.07

Borehole	**Observed SWL (mamsl)**	**Simulated Water Level (mamsl)**	**ME (m)**	**MAE (m)**	**RMS (m)**
			(WLm- WLs)i	**|(WLm- WLs)i|**	**(WLm- WLs)i2**
GA342	1504.36	1493.52	10.85	10.85	117.65
GS33	1491.87	1493.04	-1.17	1.17	1.37
GS7	1494.87	1493.31	1.56	1.56	2.44
MALONEY	1488.00	1488.00	0.00	0.00	0.00
PE	1650.80	1655.85	-5.04	5.04	25.41
RD 8	1494.08	1510.40	-16.33	16.33	266.51
RD9	1502.76	1492.21	10.55	10.55	111.20
RL13	1518.52	1510.39	8.13	8.13	66.08
RL19	1498.76	1510.38	-11.62	11.62	135.09
RL2	1492.38	1492.19	0.19	0.19	0.03
RL21	1504.75	1510.38	-5.63	5.63	31.65
RL22	1502.99	1510.37	-7.39	7.39	54.54
RL25	1496.85	1492.20	4.65	4.65	21.59
RL26	1496.87	1492.20	4.67	4.67	21.79
RL32	1505.09	1510.38	-5.29	5.29	28.01
RL34	1506.91	1493.73	13.19	13.19	173.94
RL38	1506.45	1504.04	2.41	2.41	5.81
RL8	1506.54	1510.40	-3.86	3.86	14.90
VD-1	1652.31	1650.37	1.95	1.95	3.79
VS 18(HB)	1523.78	1513.12	10.66	10.66	113.69
VS 4(HB)	1494.64	1492.21	2.43	2.43	5.89
VS 41(HB)	1581.41	1575.18	6.23	6.23	38.82
VS1	1495.65	1492.03	3.62	3.62	13.07
VS138	1565.43	1575.02	-9.59	9.59	91.99
VS139	1564.47	1575.06	-10.59	10.59	112.11
VS140	1567.41	1575.14	-7.73	7.73	59.75
VS141	1567.93	1575.14	-7.22	7.22	52.10
VS146	1573.49	1575.22	-1.72	1.72	2.96
VS147	1587.87	1575.29	12.59	12.59	158.44
VS148	1584.47	1575.29	9.18	9.18	84.22
VS149	1586.07	1575.31	10.76	10.76	115.77
VS150	1578.06	1575.29	2.76	2.76	7.63
VS151	1588.80	1575.33	13.48	13.48	181.59
VS152	1578.72	1575.30	3.42	3.42	11.72
VS16	1495.41	1492.21	3.20	3.20	10.25
VS2	1504.54	1492.08	12.46	12.46	155.27
VS20	1496.27	1492.06	4.21	4.21	17.74
VS21	1497.06	1492.17	4.89	4.89	23.95
VS23	1497.94	1492.17	5.77	5.77	33.27
VS3	1496.56	1492.10	4.47	4.47	19.94
VS31	1497.76	1492.05	5.71	5.71	32.63
VS32	1498.12	1492.06	6.06	6.06	36.75

Borehole	**Observed SWL (mamsl)**	**Simulated Water Level (mamsl)**	**ME (m)**	**MAE (m)**	**RMS (m)**
			(WLm- WLs)i	**|(WLm- WLs)i|**	**(WLm- WLs)i2**
VS38	1484.03	1493.09	-9.06	9.06	82.10
VS4	1496.84	1492.05	4.80	4.80	23.01
VS5	1497.37	1492.07	5.30	5.30	28.08
VS50	1521.09	1499.44	21.65	21.65	468.89
VS56	1503.78	1513.03	-9.25	9.25	85.55
VS58	1511.53	1513.13	-1.60	1.60	2.55
VS63	1521.47	1513.21	8.27	8.27	68.34
VS66	1522.75	1513.22	9.53	9.53	90.75
VS7	1498.01	1492.07	5.94	5.94	35.26
VS70	1549.23	1513.25	35.98	35.98	1294.91
VS75	1545.96	1513.28	32.67	32.67	1067.51
VS8	1496.36	1492.17	4.19	4.19	17.56
VS80	1492.80	1493.33	-0.53	0.53	0.28
VS9	1497.66	1492.19	5.47	5.47	29.90
WS 27(HB)	1488.35	1492.25	-3.89	3.89	15.17
WS 37(HB)	1485.72	1492.09	-6.36	6.36	40.47
WS13	1499.46	1491.96	7.49	7.49	56.17
WS14	1483.00	1491.99	-8.99	8.99	80.88
WS22	1488.39	1492.19	-3.79	3.79	14.40
WS29	1487.66	1492.18	-4.51	4.51	20.37
WS30	1488.85	1492.03	-3.18	3.18	10.10
WS32	1489.82	1492.36	-2.54	2.54	6.45
WS33	1498.31	1492.35	5.96	5.96	35.57
WS34	1499.55	1492.50	7.05	7.05	49.68
WS43	1501.21	1492.23	8.98	8.98	80.71
WS44	1491.49	1492.69	-1.20	1.20	1.44
706	1489.06	1489.75	-0.69	0.69	0.48
A2N0553	1515.50	1504.05	11.46	11.46	131.27
A2N0555	1500.74	1510.37	-9.63	9.63	92.73
A2N0556	1510.37	1510.39	-0.03	0.03	0.00
A2N0558	1490.33	1490.07	0.26	0.26	0.07
A2N0559	1490.29	1489.94	0.35	0.35	0.12
			Σ = 100	Σ = 1125	Σ = 12909
			1/n = 0.51	1/n = 5.8	1/n = 66.54
					SQRT = 8.16
					RMS% of water level range = 1.73

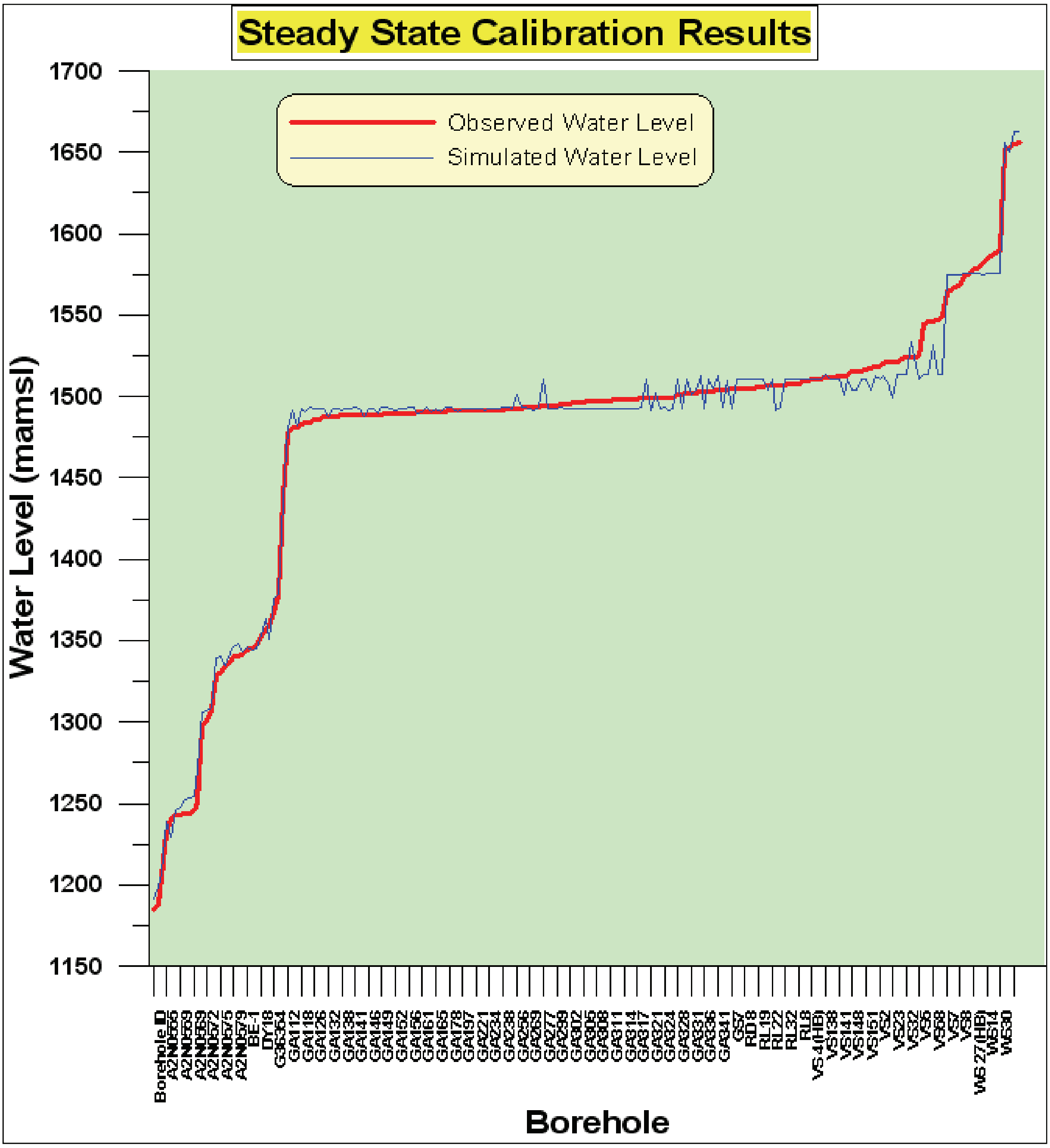


Figure 4-8 Line Plot of Simulated Versus Observed Groundwater Levels

4.5.4 Calibrated Hydraulic Conductivity and Transmissivity

The hydraulic conductivity and transmissivity for the different geological layers and zones for the calibrated model are summarized in Table 4-2 and the zones depicted in Figure 4-10 and Figure 4-11. Figure 4-11 depicts the differentiation of the transmissivity values assigned according to the gravimetric survey conducted delineating the gravimetric low values associated with enhanced karstification (see differentiation Zone E and Zone F).

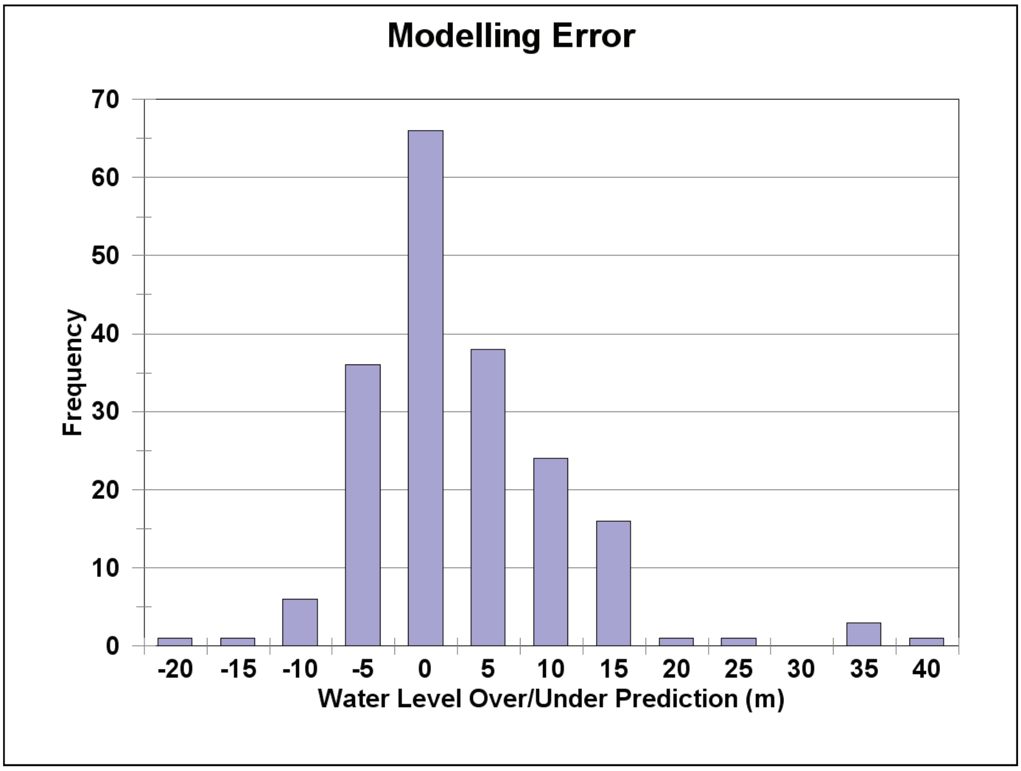


Figure 4-9 Frequency Distribution of Modelling Errors

Table 4-2 Calibrated Hydraulic Conductivity and Transmissivity

Layer	Zone	Thickness	K-value	K-value	T-value
		m	m/s	m/d	m^2/d
1	A	140	0.002757×10^{-4}	0.0238	3.33
1	B	140	0.004136×10^{-4}	0.0357	4.9
1	C	140	0.015×10^{-4}	0.1296	18.2
1	D	140	5×10^{-4}	43.2	6048
1	E	140	10×10^{-4}	86.4	12096
1	F	140	19×10^{-4}	164	22960

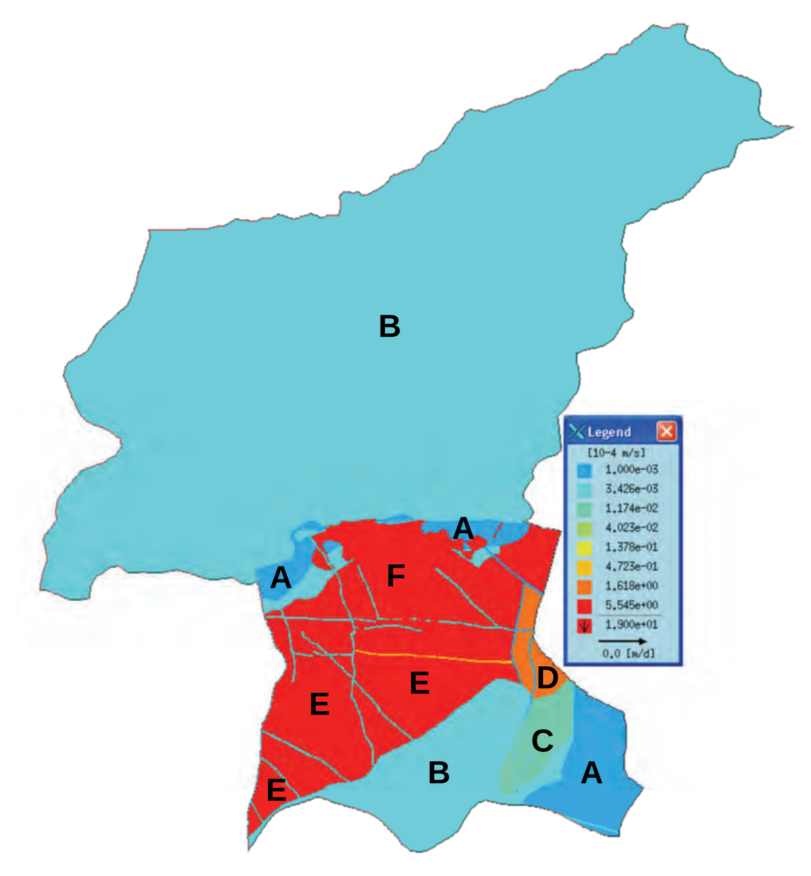


Figure 4-10 Hydraulic Conductivity & Transmissivity Distribution Model Layer 1

4.6 Transient State Calibration

4.6.1 Introduction

In order to verify that the steady state calibrated model behaves properly and is able to simulate the responses of the aquifers temporally and spatially, a transient calibration of the model is required. Transient calibration involves the specification of temporal groundwater recharge which (obviously) is a function of rainfall, the specification of temporal abstraction from the aquifers and the specification of aquifer storage parameters. The objective is then to simulate as outputs the temporally observed water level and spring flow fluctuations.

4.6.2 Initial Water Level Conditions

For transient state calibration purposes the simulated steady state head distribution as depicted in Figure 4-5 was used as initial conditions in the model.

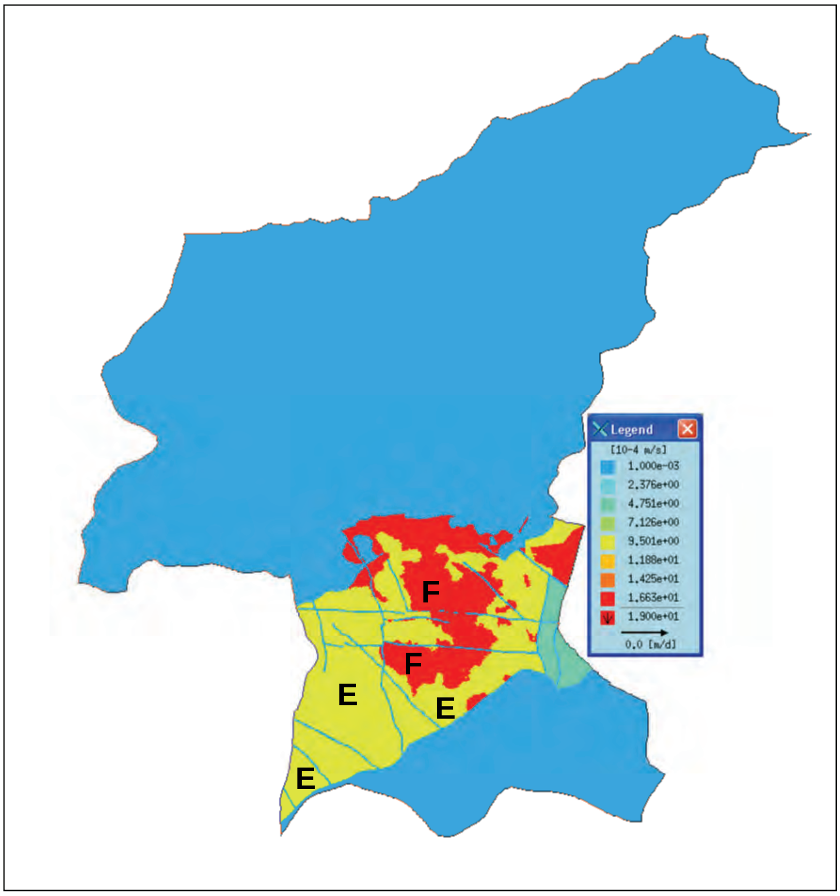


Figure 4-11 Hydraulic Conductivity & Transmissivity Distribution Model Layer 1

4.6.3 Temporal Rainfall

The rainfall sequence as depicted in Figure 4-12 was used as input to determine the temporal recharge input required in the model in order to simulate the Maloney's Eye spring flow as depicted in Figure 4-13.

The average monthly rainfall for the area over the period (1908-2011) was 56 mm/month and average annual rainfall amounts to 676 mm/annum. The median monthly rainfall over the period was 39 mm/month. The monthly maximum rainfall was 388 mm/month recorded in January 1909. Three other occurrences of more than 300 mm/month were recorded in February 1944; January 1978 and March 1997.

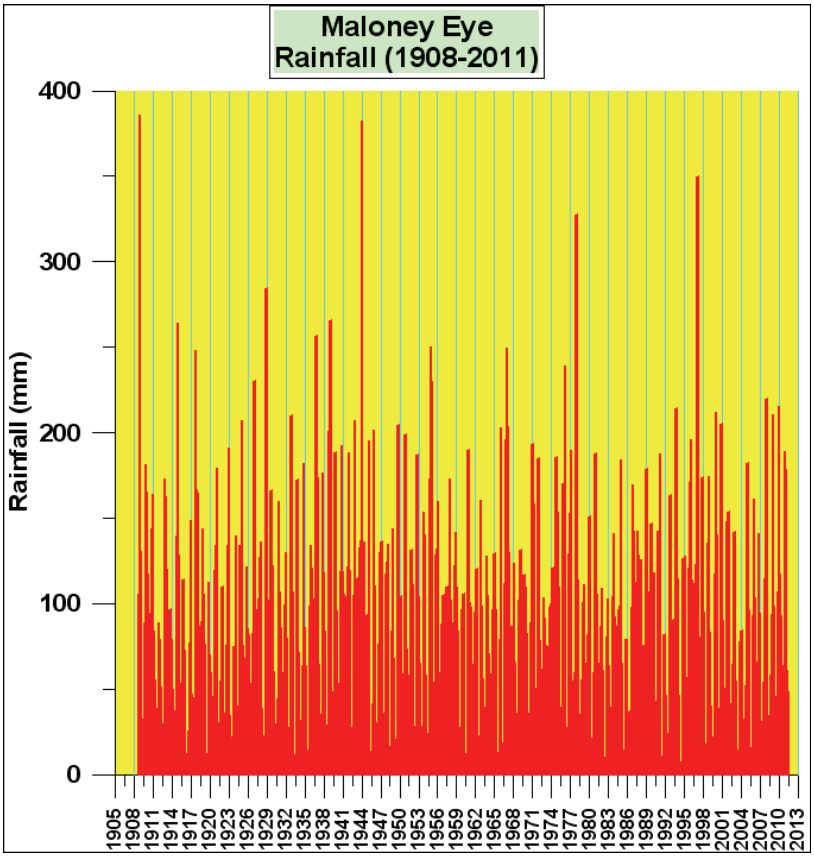


Figure 4-12 Rainfall record (1908-2011)

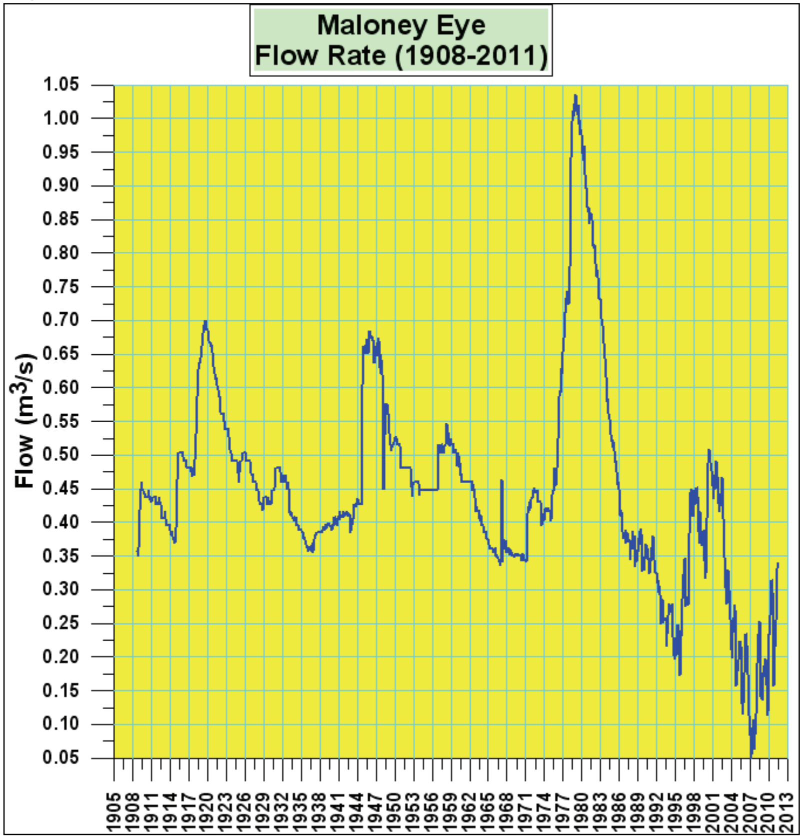


Figure 4-13 Maloney's Eye Spring Flow Record (1908-2011)

4.6.4 Temporal Spring Flow Measured at Maloney's Eye

The temporal spring flow measured at the Maloney's Eye is depicted in Figure 4-13 for the period 1908-2011. Frequency histograms constructed for the spring flow for different time periods are depicted in Figure 4-14 (1908-2011); Figure 4-15 (1908-1974) and Figure 4-16 (1975-2011).

From the temporal spring flow measurements and frequency histograms the following can be concluded:

- Maximum spring flow measured – 1050 l/s;
- Minimum spring flow measured – 50 l/s;
- Prior to 1977 the maximum spring flow measured was 700 l/s – it is accepted now that the measuring weir(s) prior to 1977 might not have been able to capture all flow from the Maloney's Eye;
- Prior to 1974 the least flow recorded was 350 l/s; since 1974 the lowest flow being recorded was 50 l/s; the effect of abstraction since 1985 on the spring flow is therefore evident.

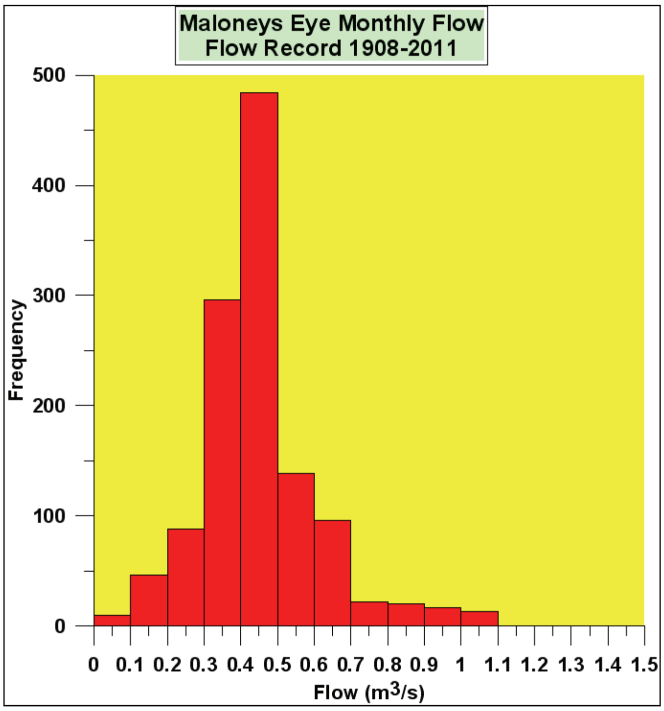


Figure 4-14 Frequency Histogram – Maloney's Eye Monthly Flow (1908-2011)

4.6.5 Temporal Irrigation Abstraction

Temporal irrigation abstraction was specified at borehole positions as indicated in Figure 4-17 (red dots). Abstraction rates were assigned according to seven different abstraction functions over time as depicted in Figure 4-18. The identification numbers of the different functions are also indicated on Figure 4-17 and present the abstraction rate for the particular borehole. The derivation of the abstraction numbers is discussed in the main report.

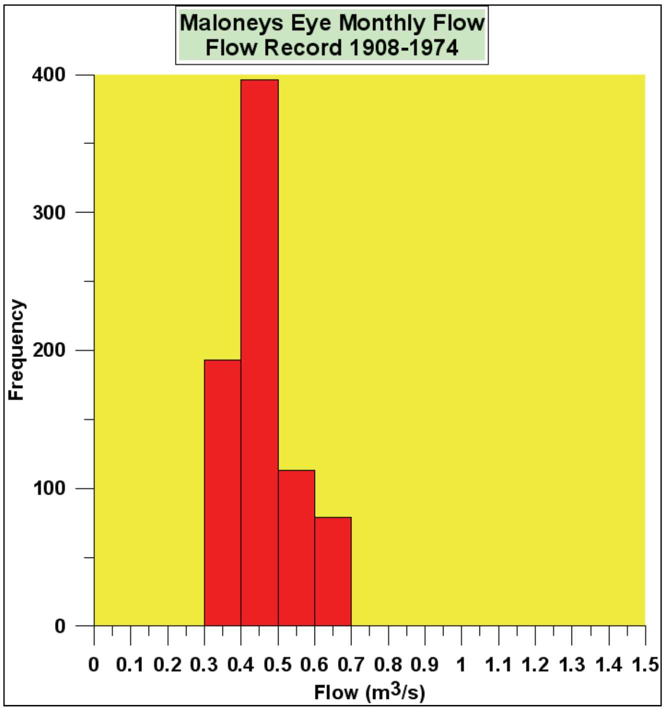


Figure 4-15 Frequency Histogram – Maloney's Eye Monthly Flow (1908-1974)

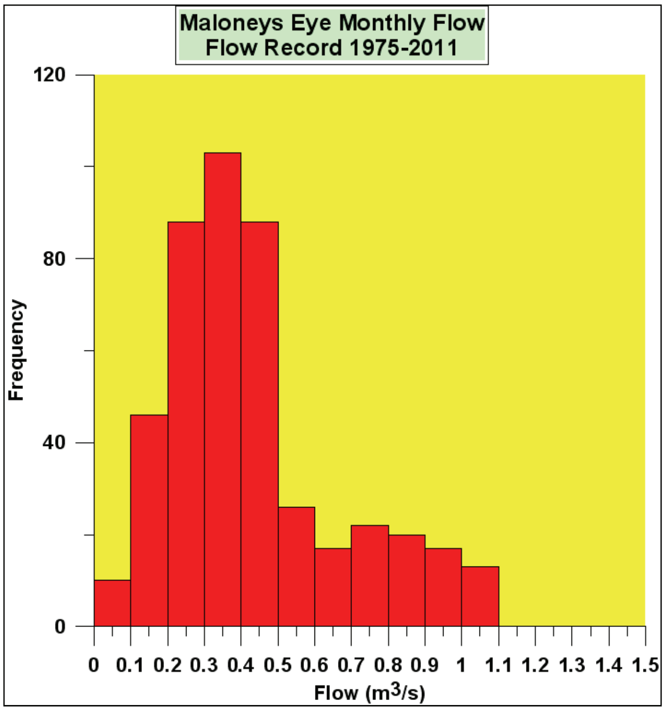


Figure 4-16 Frequency Histogram – Maloney's Eye Monthly Flow (1975-2011)

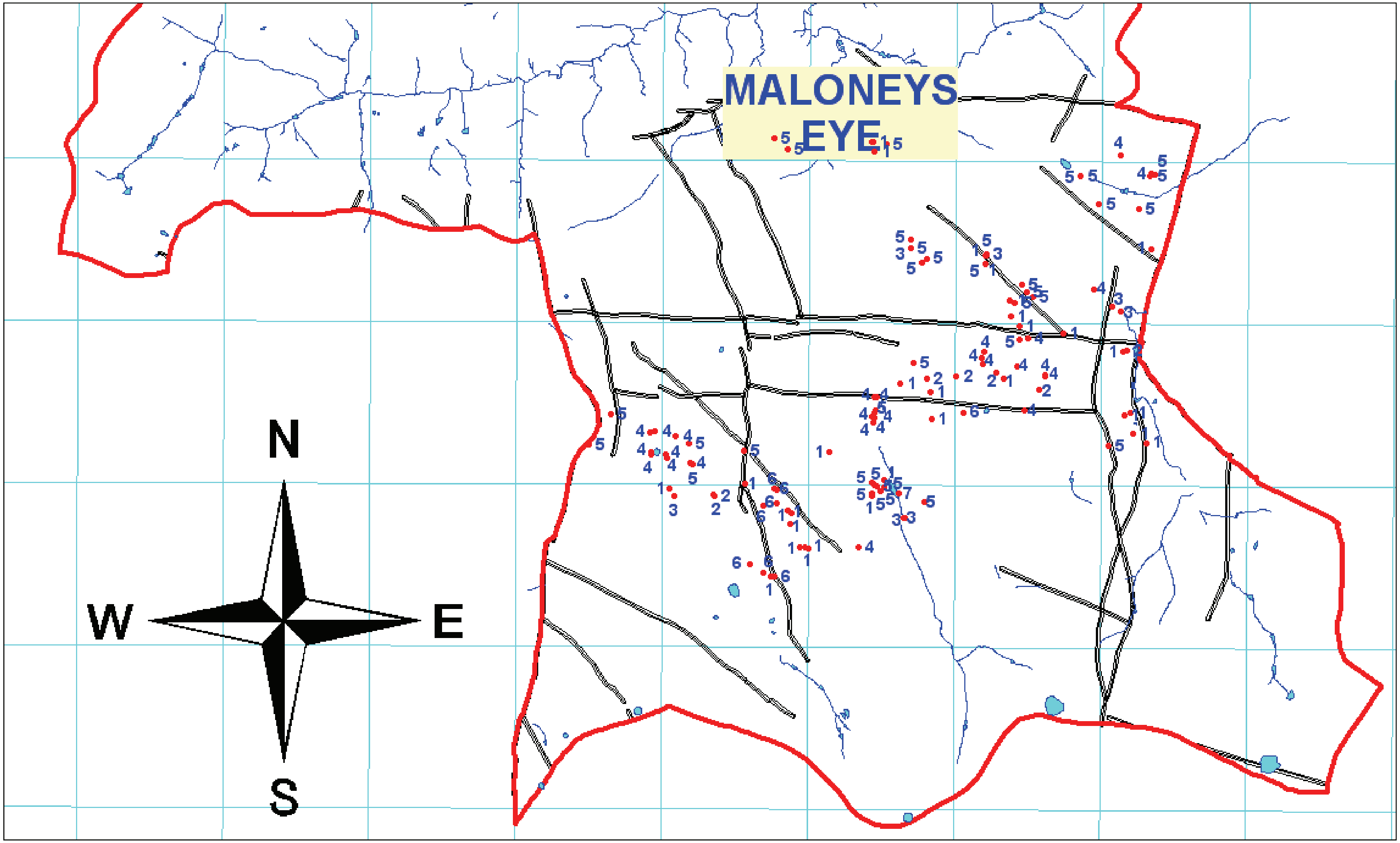


Figure 4-17 Irrigation borehole positions (red dots) and abstraction identification numbers

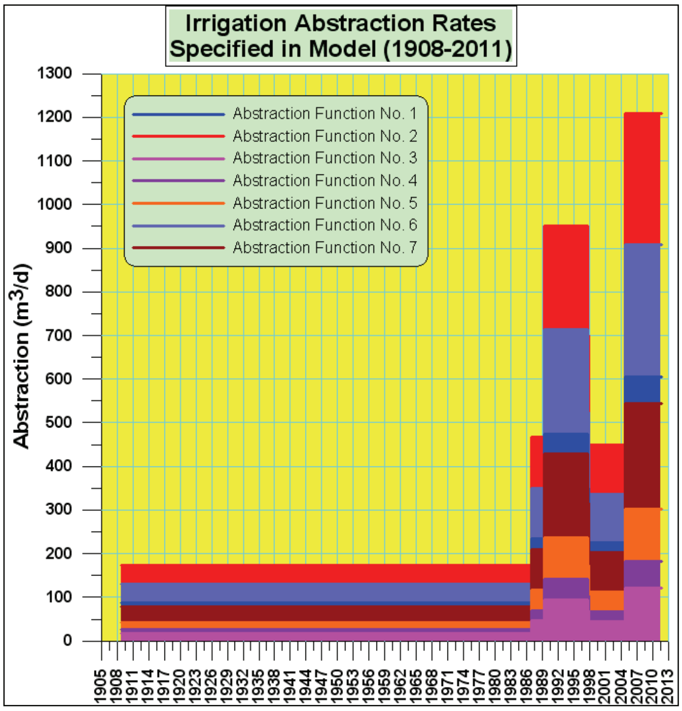


Figure 4-18 Abstraction functions specified for irrigation

4.6.6 Storativity

For transient state simulations a storage parameter needs to be assigned to the model. For transient state simulations a specific storage value of $5x10^{-5}$/m - $1x10^{-4}$/m was used for the hard rock aquifers – this would provide an equivalent aquifer storage coefficient of 0.007-0.014 or 0.7-1.4 percent, which is representative for these hard rock aquifer conditions. A specific storage value of 2 to $3x10^{-4}$/m was used for the dolomite aquifers which relates to storage coefficients of between 2.8 and 4.2% representative of these dolomitic aquifer conditions. The storage distribution map is presented in Figure 4-19.

4.6.7 Transient State Calibration Methodology and Results

It was shown in Figure 2-2 and Figure 2-3 that there exist a good correlation between the cumulative departure from the mean rainfall (CRD) and the water level fluctuations and the Maloney's Eye flow record. This is indicative that the rainfall events recharges through to groundwater in dynamic fashion. The CRD is a graph that is constructed by accumulating the monthly differences between a specific monthly rainfall and the average monthly rainfall of the rainfall sequence (series). Increasing CRD trends are therefore indicative of consecutive above average rainfall events (causing groundwater recharge and therefore rising water levels and spring flows) whilst decreasing CRD trends are indicative of consecutive below average rainfall events with no or very little groundwater recharge and therefore declining water levels and spring flows. The constructed CRD using the Maloney rainfall record is depicted in Figure 4-20.

The relationship between groundwater recharge and rainfall will now be further investigated in this transient state modelling calibration phase.

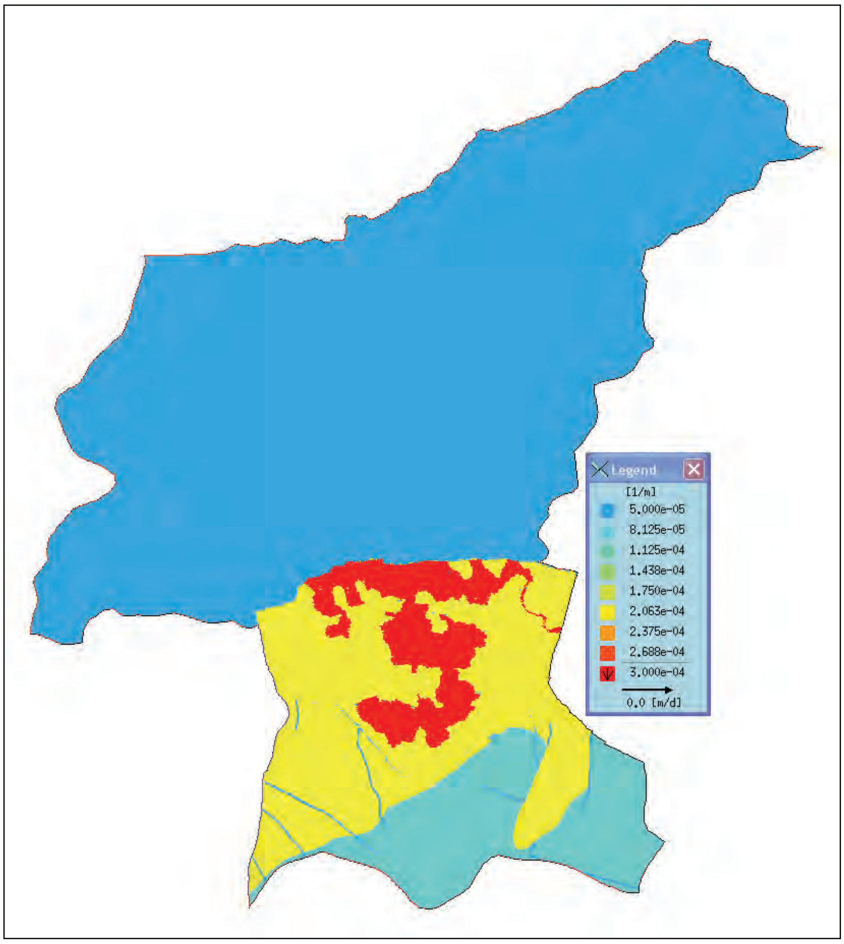


Figure 4-19 Map showing distribution of storage across modelling domain

From the discussion above it follows logically that some (unknown) relationship between groundwater recharge and rainfall must exist. Clearly this is not some straightforward relationship since the relationship might be influenced by numerous factors such as rainfall and rainfall intensity; soil moisture conditions; variations in unsaturated soil hydraulic parameters spatially and with depth; surface catchment runoff characteristics to name but a few. Since the direct cause/effect relationship between the CRD vs. Water Levels and Maloney's Eye flow rate was observed a simpler (less complicated) approach was followed by assuming some direct empirical relationship between rainfall and recharge events. Since the frequency of spring flow and rainfall measurements were provided on a monthly basis the water balance of the model was calculated on a monthly time-step over the period 1908-2011.

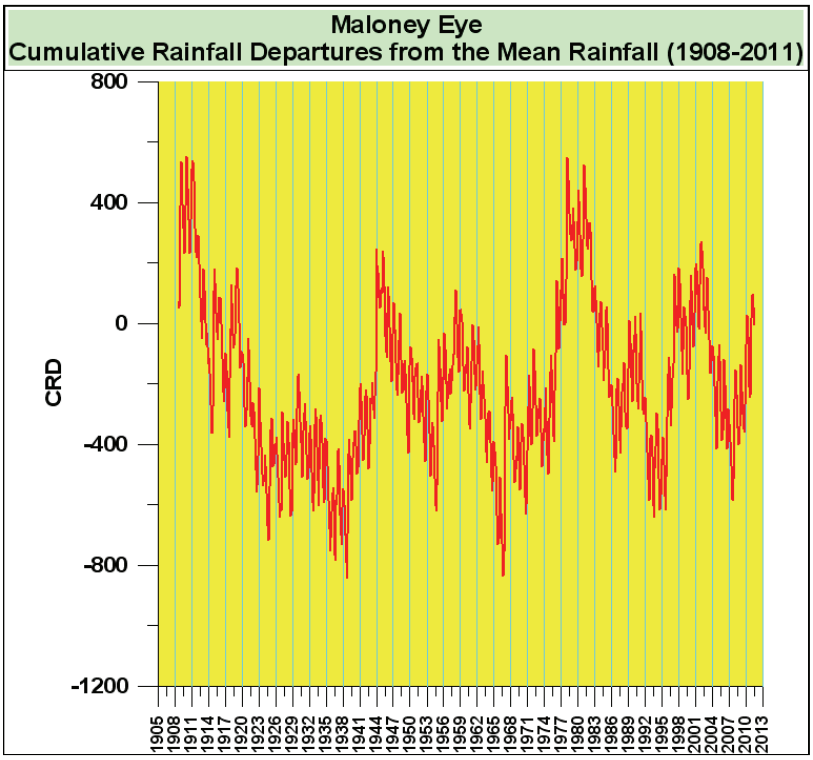


Figure 4-20 Cumulative Rainfall Departures from the Mean Rainfall (1908-2011)

The process of finding a rainfall/recharge relationship was one of “trial-and-error”. It should be stated upfront that as is the case with the solution of the groundwater flow equation, the final recharge-rainfall relationship obtained is “non-unique” meaning that there are possibly many more relationships which may produce similar (or better) calibration results. The process was started using a simple linear relationship between rainfall and groundwater recharge. The resulting simulated vs. observed flow rates at Maloney’s Eye is presented in Figure 4-21. It is clear from the simulated results that although a general (poor) correspondence can be observed between the simulated and observed flow rates that the relationship falls short to describe the absolute “highs” and “lows” within the observed flow record. There is also “spikiness” within the simulated flow which indicated that the direct monthly record needed some “smoothing” to be applied to the rainfall record. “Smoothing” of the record would be acceptable since recharge of a particular rainfall event does not necessarily recharge the aquifer instantaneously and some “carry-over” of recharge between months may occur.

Based upon previous work conducted on dolomitic terrain it was concluded that an exponential relationship between recharge and rainfall produced acceptable results. Such a relationship would entail that moderate recharge rates would occur at moderate rainfall events. However once rainfall gets higher the rate of recharge would increase disproportionately with rainfall. This would make sense since the soil moisture deficits would already have been overcome with large monthly rainfalls effecting saturated conditions in the soil zone close to surface causing development of maximum hydraulic conductivity values maximizing vertical infiltration rates into the aquifers.

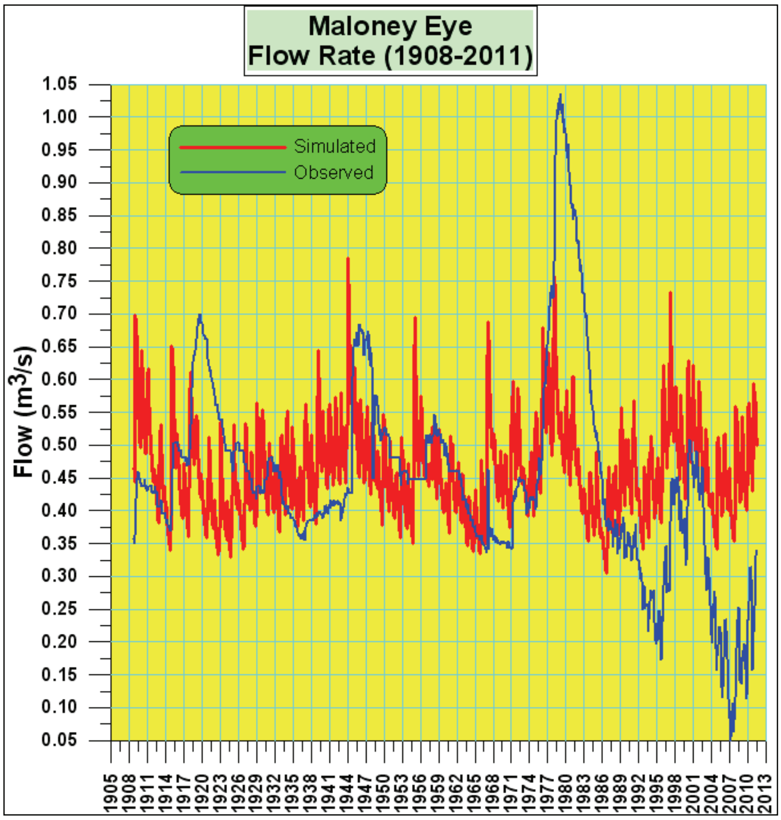


Figure 4-21 Simulated vs. observed flow rates at Maloney's Eye using a linear relationship between rainfall and recharge

In the case of the Steenkoppies Compartment an additional (external) source of recharge was identified – since the hardrock area to the south of the Steenkoppies Dolomite Compartment has a well-developed steeper surface gradient it is thought that this would provide additional run-off to cause "flash flood" conditions onto the Steenkoppies Compartment. The Steenkoppies Compartment is riddled with sinkholes which would then provide the pathway for run-off water to recharge into the underground.

Taking the above concepts into consideration, numerous simulation runs were performed over the historical period (2008-2011) and a recharge to rainfall relationship developed to represent the flow at the Maloney's Eye on a trial-and error approach. The finally accepted calibration for the spring flow of Maloney's Eye is presented in Figure 4-22.

Final calibration parameters include the following:

- A nine month moving average was applied on the recharge series.
- Recharge (mm/month) was derived as a fraction of rainfall. This relationship is depicted in Figure 4-23 for the Steenkoppies Compartment.
- The recharge fraction was obtained from the following formula:

Recharge Fraction = 1.0*[0.025e(0.011*Rainfall)]

The obtained recharge to rainfall relationship is depicted in Figure 4-24 for the Steenkoppies Compartment.

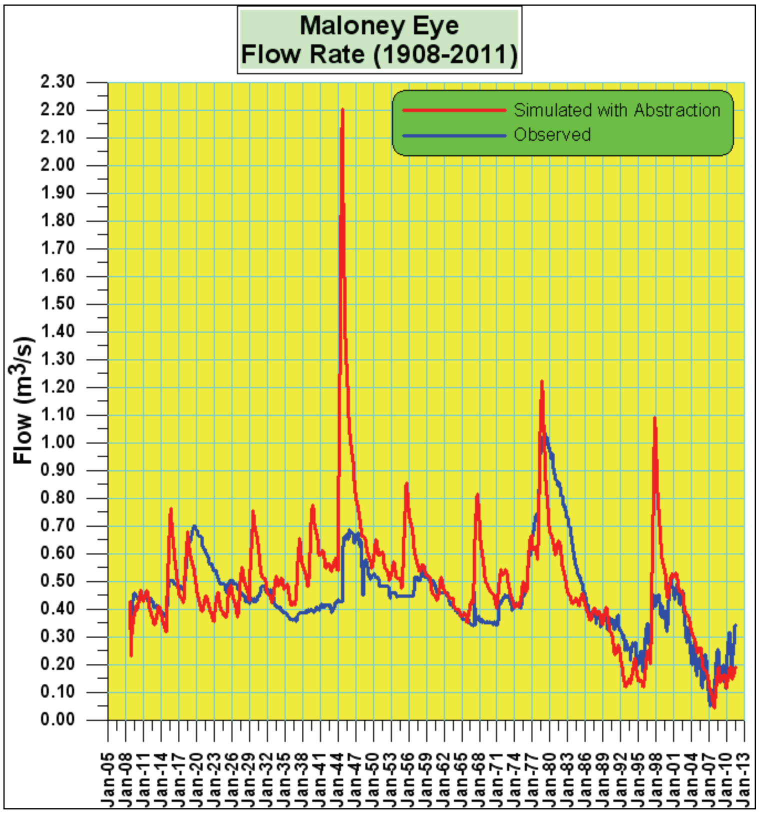


Figure 4-22 Simulated vs. observed flow rates at Maloney's Eye using an exponential relationship between rainfall and recharge

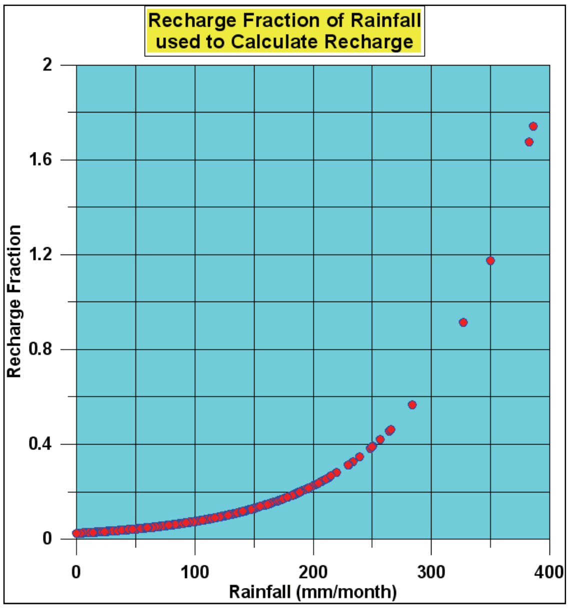


Figure 4-23 Recharge fraction of rainfall used to calculate the recharge from rainfall in the Steenkoppies Compartment

It is evident from the graphs presented in Figure 4-23 and Figure 4-24 that recharge can exceed rainfall for extreme rainfall events larger than 350 mm/month due to the conceptual surface run-off from the hard rock aquifers to the south of the Steenkoppies Compartment.

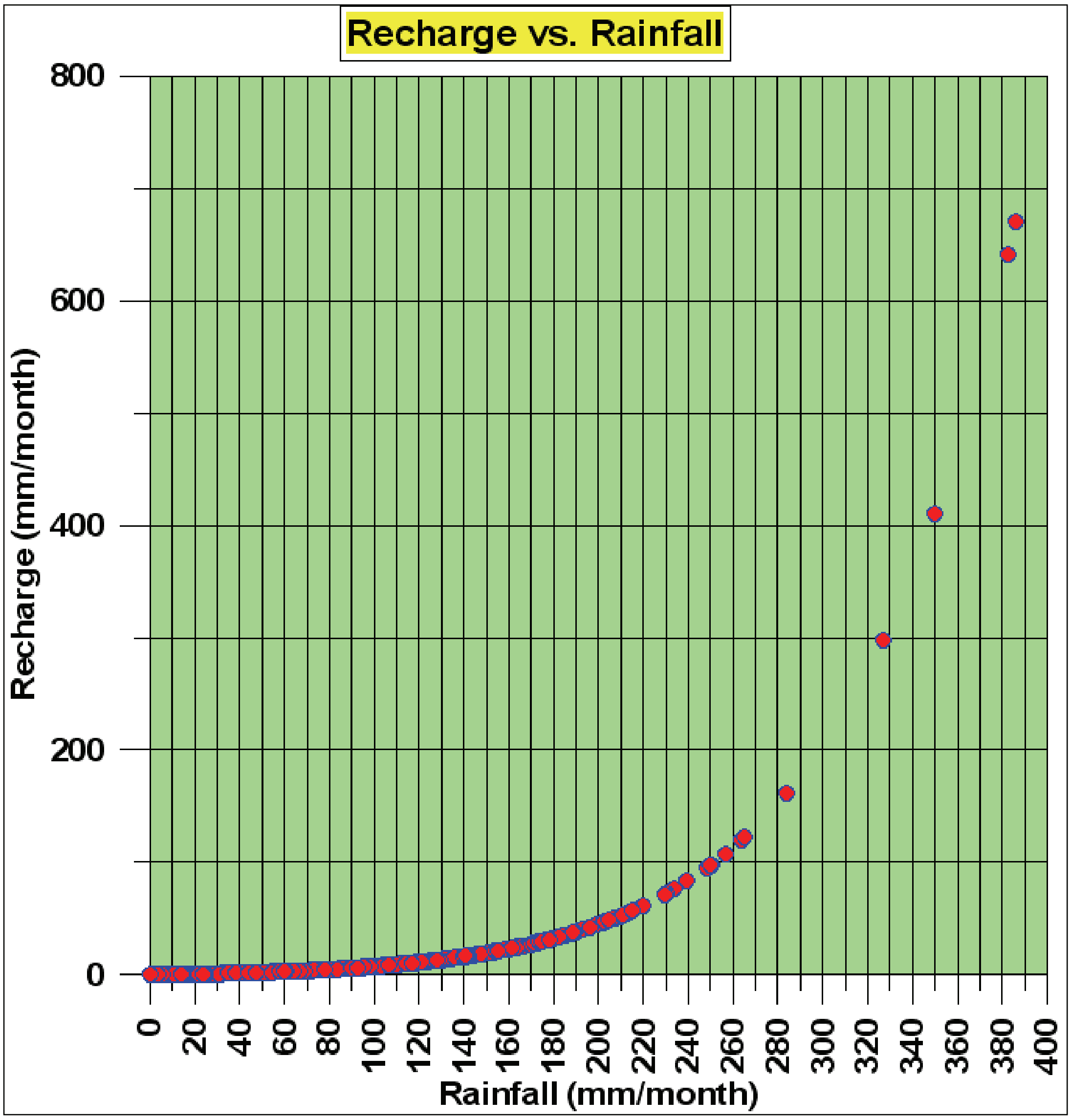


Figure 4-24 Recharge vs. Rainfall relationship obtained for the Steenkoppies Compartment

The recharge to rainfall relationships used for all three zones modelled are depicted in Figure 4-25 and Figure 4-26. The graphs present the same data sets respectively on a linear and logarithmic Y-axis. See Figure 4-3 for recharge zones.

The temporal recharge specified for the three aquifer zones are depicted in Figure 4-27.

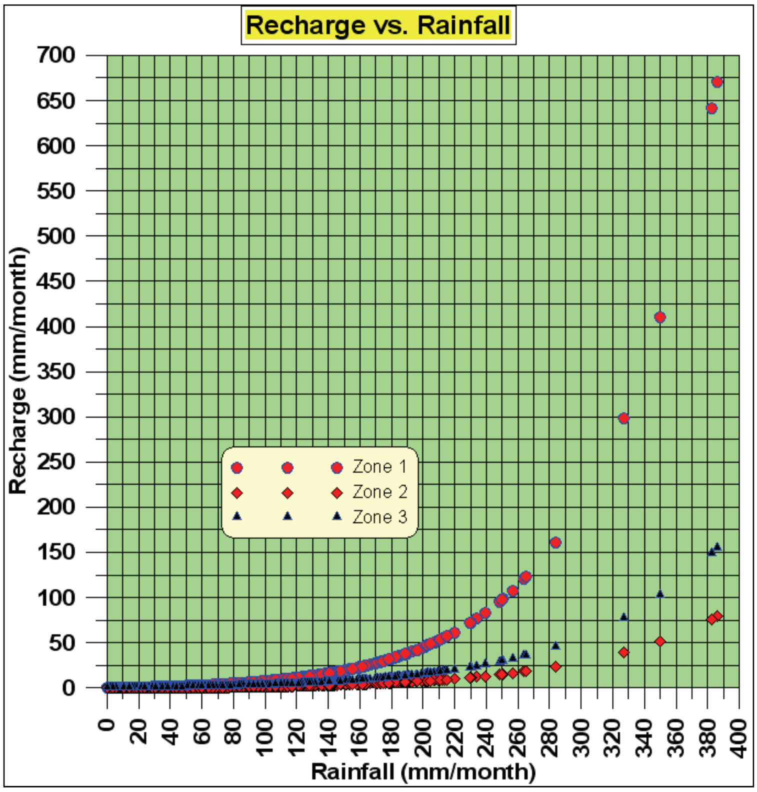


Figure 4-25 Recharge vs. Rainfall relationship obtained for all three zones modeled (linear Y-axis)

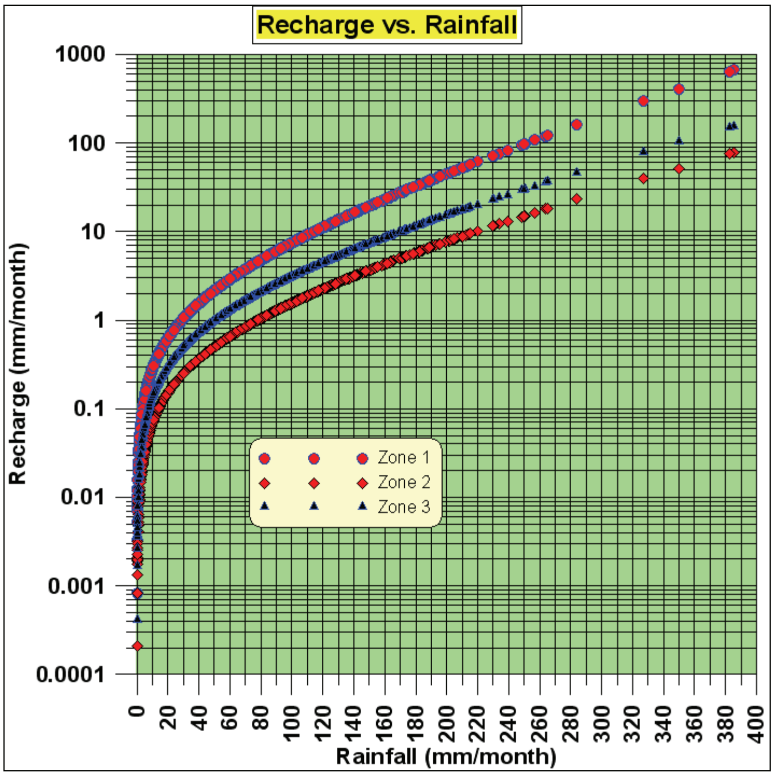


Figure 4-26 Recharge vs. Rainfall relationship obtained for all three zones modeled (logarithmic Y-axis)

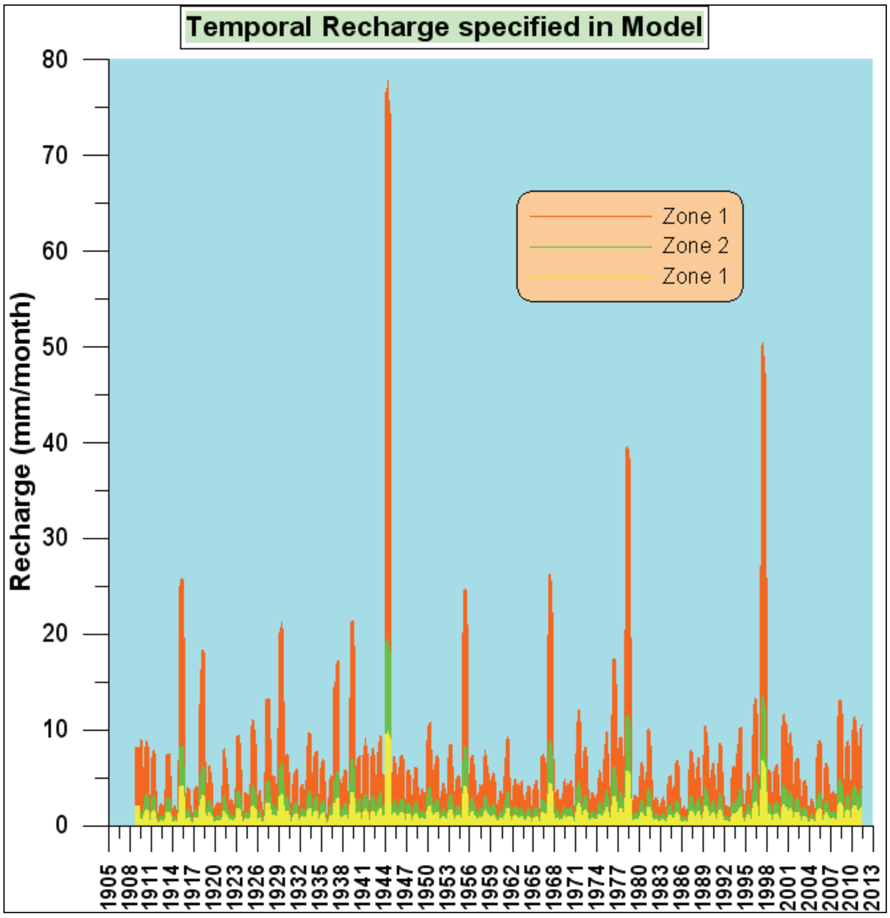


Figure 4-27 Temporal recharge specified across the three aquifer zones

From Figure 4-22 it is evident that the combination of temporal recharge, abstraction and boundary conditions assigned produced a reasonable resemblance between the observed and simulated flow of the Maloney's Eye. This is especially valid since the late 1940s. The model still simulates however quite large peak flows during the high flow (high rainfall) events. This could be attributable to various factors; either the observed flow records did not capture all the flow during a high rainfall event or the modelled input of recharge still needs to be distributed further temporally.

4.6.8 Effect of Irrigation Abstraction on Maloney's Eye Flow

The effect of abstraction on spring flow can be illustrated by performing a non-pumping scenario. Figure 4-28 shows the comparative results between the spring flow rates using irrigation abstraction vs. no irrigation abstraction. It is evident from this figure that the greatest deviation between the scenarios occurred since the mid-1980s. This would suggest that irrigation rates increased over this period (mid 1980s till present). The increase in irrigation abstraction is depicted in Figure 4-18.

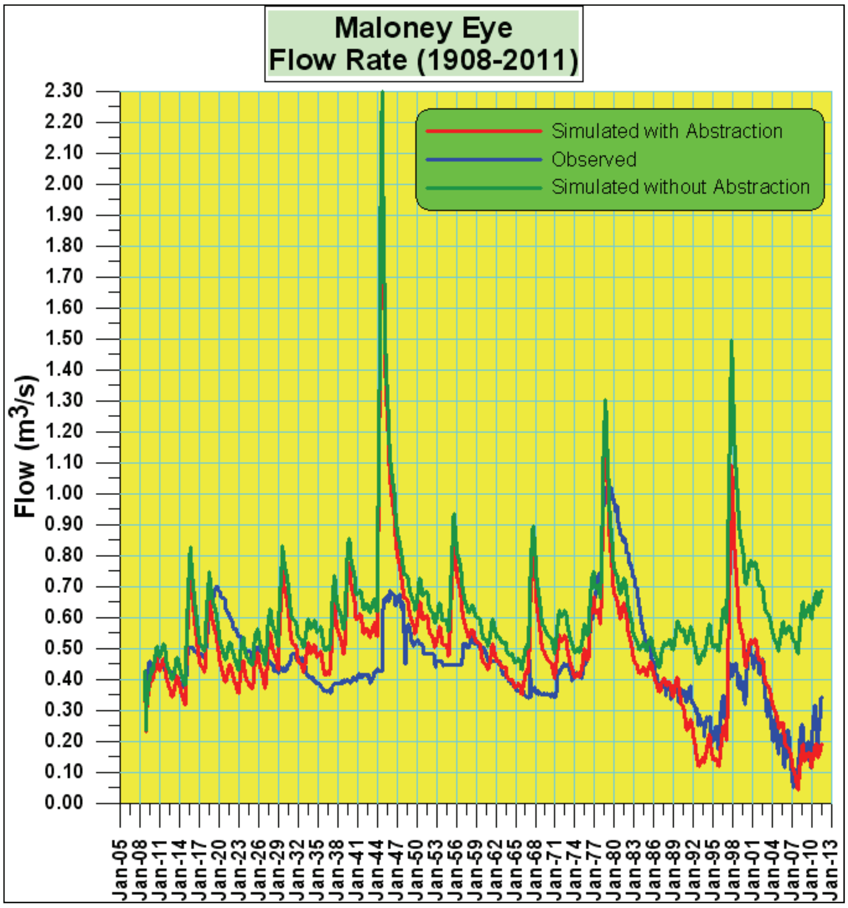


Figure 4-28 Spring flow simulated with and without irrigation abstraction

4.6.9 Simulated vs. Observed Water Levels (1908-2011)

A further measure of calibration is to compare the temporal observed water level fluctuations measured in observation boreholes to the simulated. Figure 4-29 to Figure 4-36 show the comparisons for a number of boreholes. It is evident that in most cases the “signature” of the temporal water level fluctuations is sufficiently well represented by the simulation. The “off-set” in some cases is a function of the steady state starting water levels. In all cases this “off-set” is minimal (within 2 metres) and within the normal range of seasonal tolerance of water level fluctuations.

4.6.10 Temporal recharge specified on Groundwater Management Units, simulated base flow and Statistics for the GMUs

A breakdown of the temporal recharge simulated across the six groundwater management units (GMUs) feeding to the Maloney’s Eye are provided in this section of the report. Figure 4-37 provides the locations of the six GMUs contributing to the flow of the Maloney’s Eye. Figure 4-38 shows the recharge rates for each of the GMUs over the period 1908-2011. A breakdown of the statistics of the recharge and base flow rates and frequency histograms for each of the GMUs are depicted Figure 4-40 to Figure 4-81. This data is utilised in the main document in the determination of the Reserve.

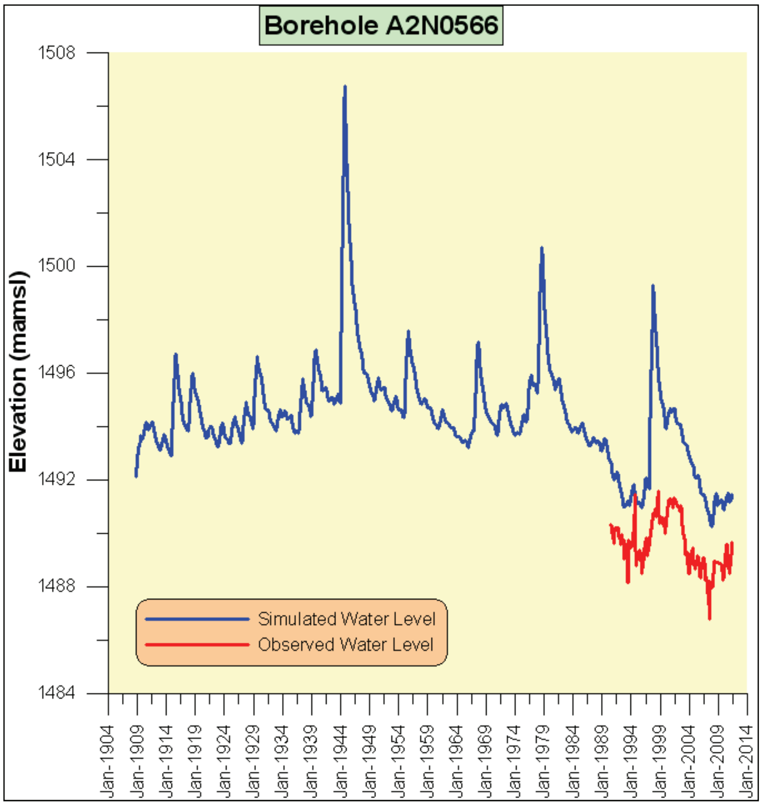


Figure 4-29 Simulated vs. Observed Water Levels – Borehole A2N0566

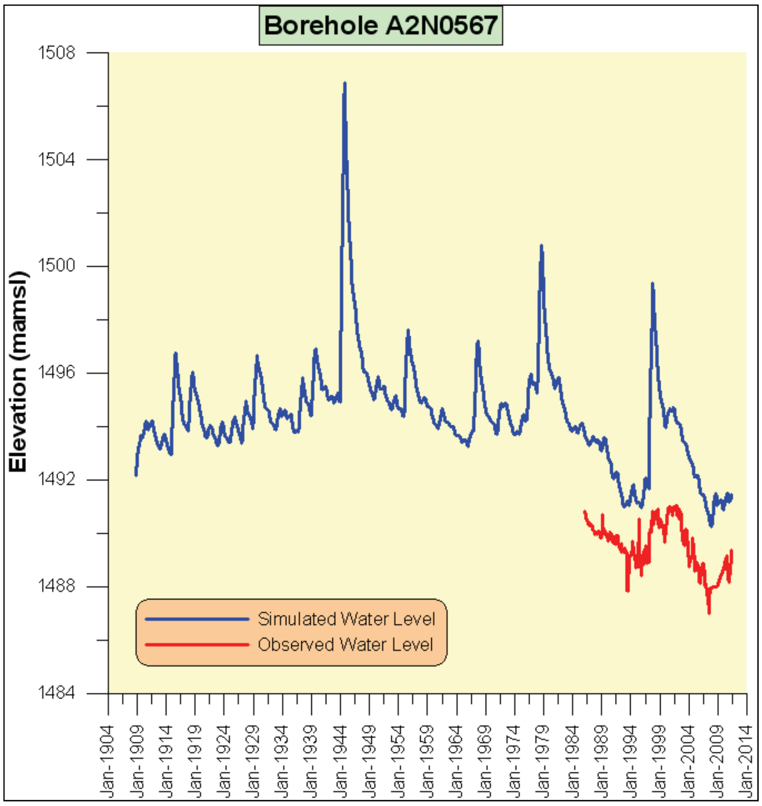


Figure 4-30 Simulated vs. Observed Water Levels – Borehole A2N0567

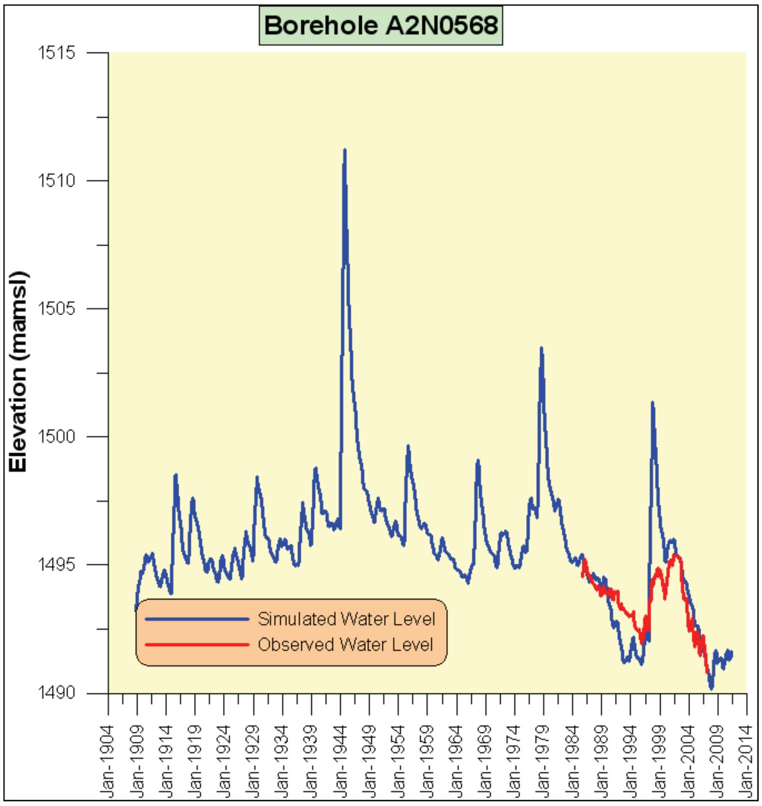


Figure 4-31 Simulated vs. Observed Water Levels – Borehole A2N0568

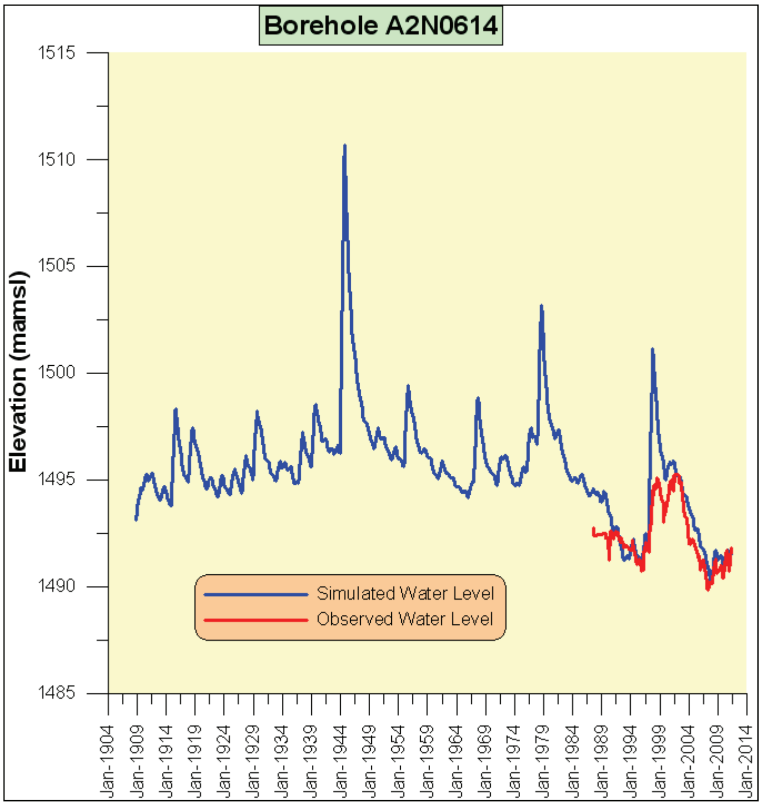


Figure 4-32 Simulated vs. Observed Water Levels – Borehole A2N0614

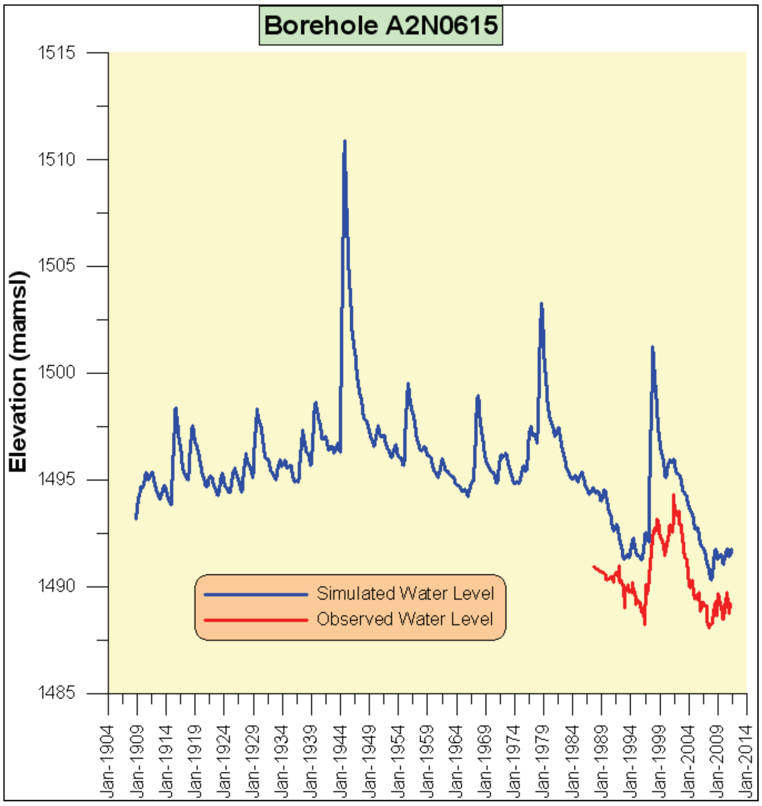


Figure 4-33 Simulated vs. Observed Water Levels – Borehole A2N0615

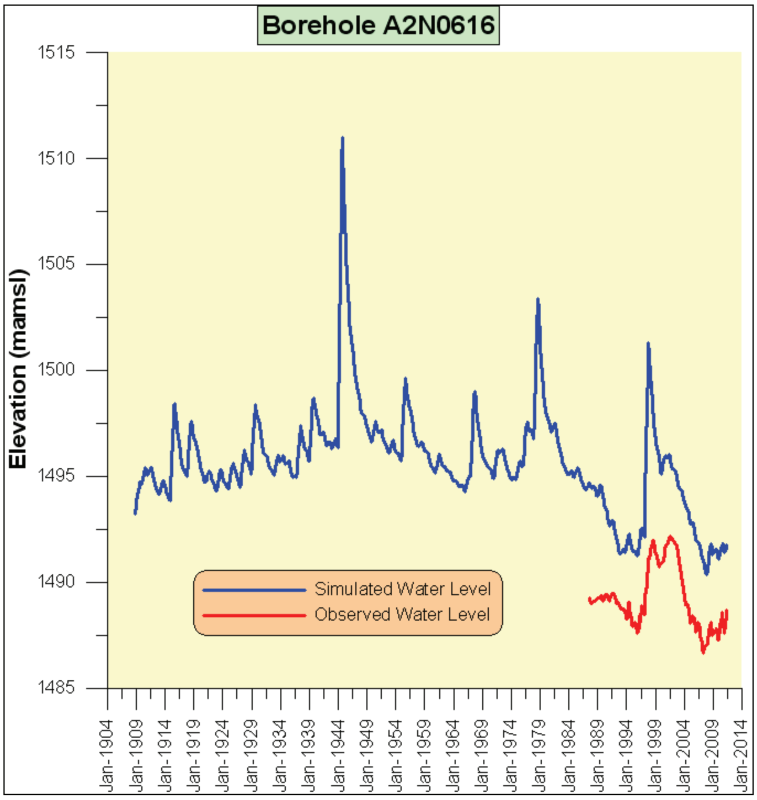


Figure 4-34 Simulated vs. Observed Water Levels – Borehole A2N0616

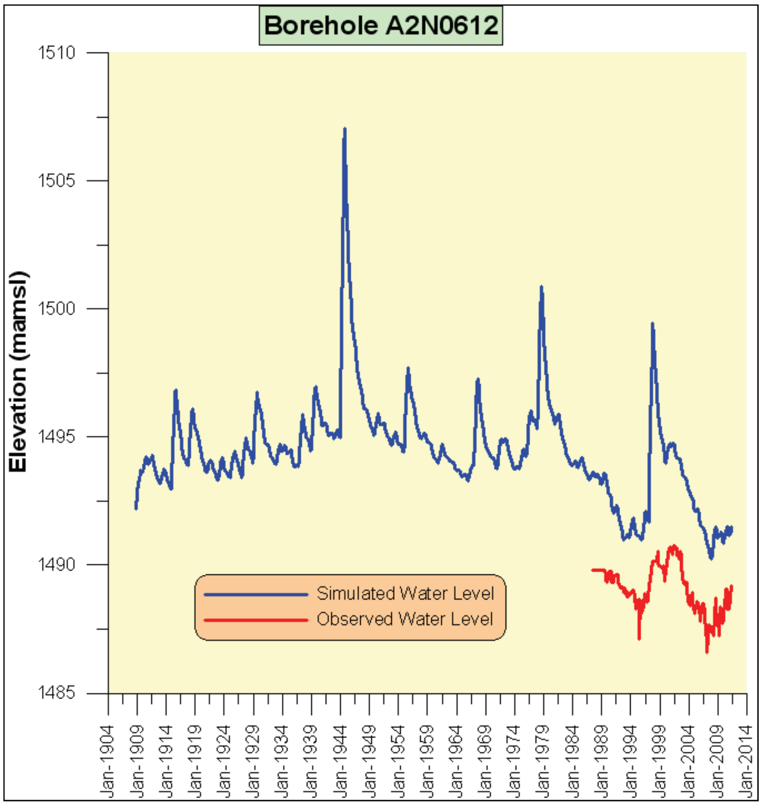


Figure 4-35 Simulated vs. Observed Water Levels – Borehole A2N0612

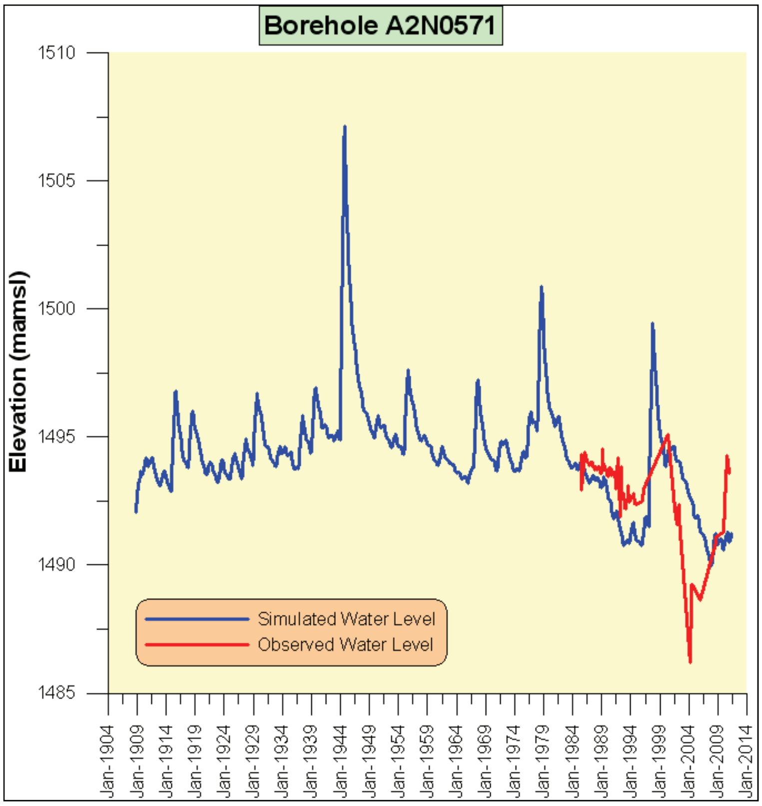


Figure 4-36 Simulated vs. Observed Water Levels – Borehole A2N0571

Table 4-3 General statistics associated with the recharge on the GMUs feeding the Maloney's Eye

Unit	A2F_05	A2F_06	A2F_04	A2F_02	A2F_03	A2F_01
	m^3/d	m^3/d	m^3/d	m^3/d	m^3/d	m^3/d
Mean	6718	13564	3109	15435	16564	8730
Median	4703	9497	2177	10959	11900	6393
Mode	7860	15873	3639	16887	16905	7791

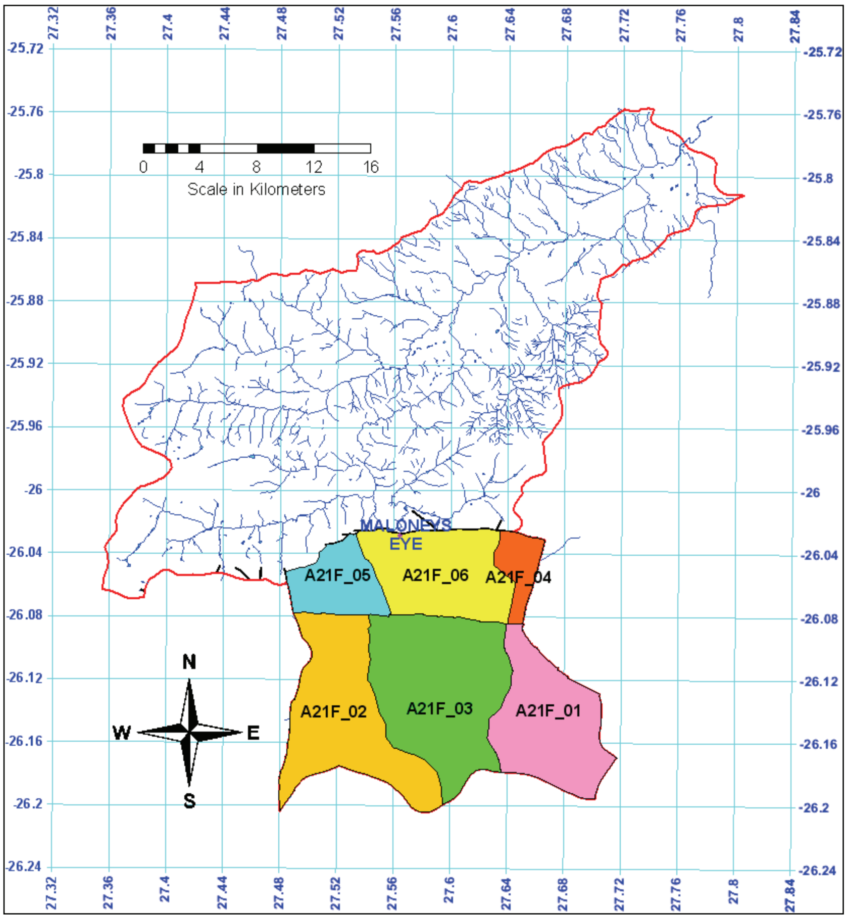


Figure 4-37 Positions of Groundwater Management Units effecting Water Balance of the Maloney's Eye

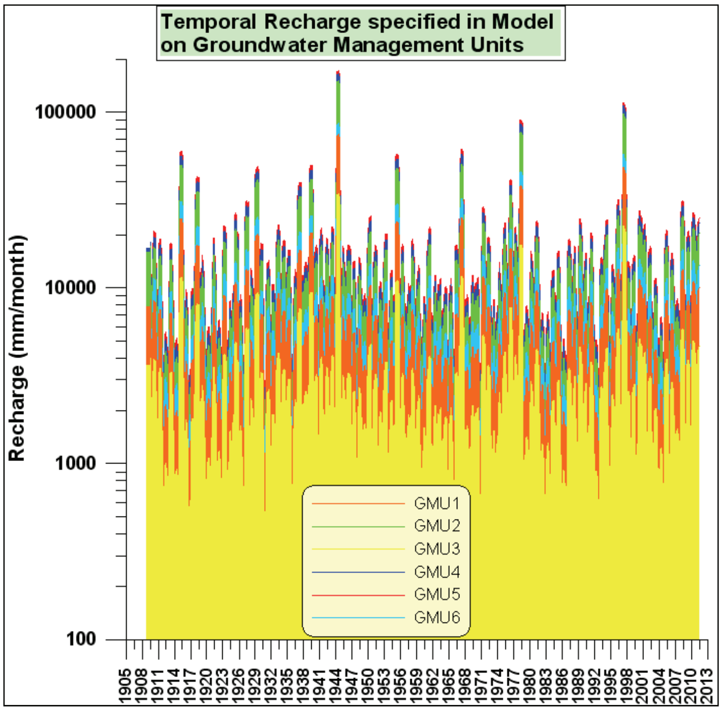


Figure 4-38 Temporal recharge specified in model on groundwater management units

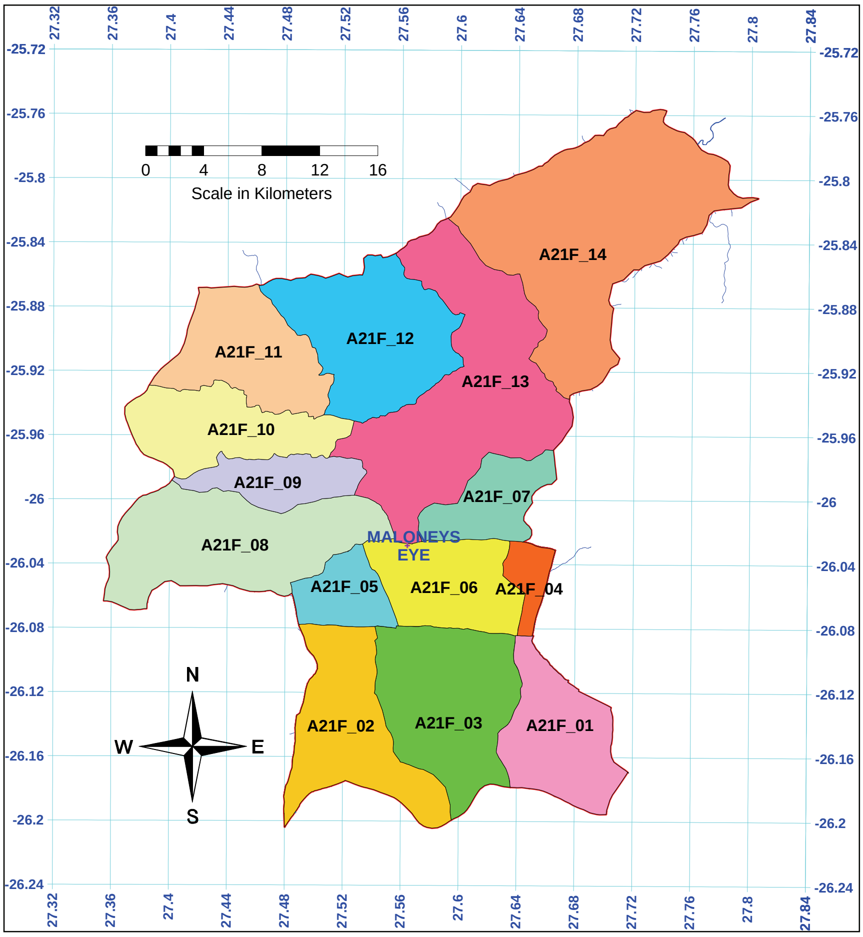


Figure 4-39 Groundwater Management Units (GMU or GUA)

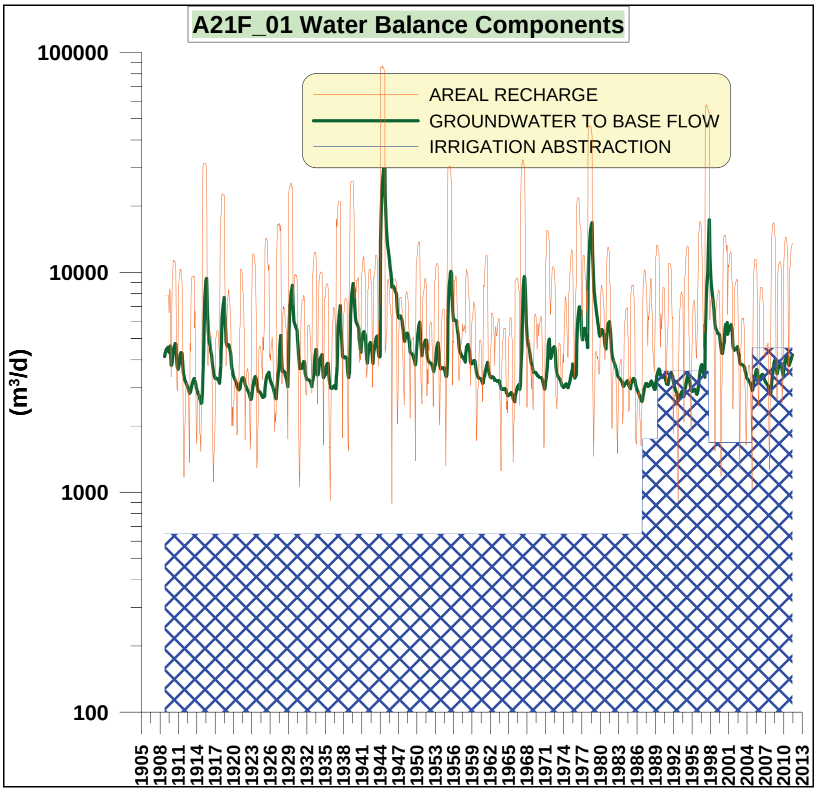


Figure 4-40 A21F_01 Water Balance Components

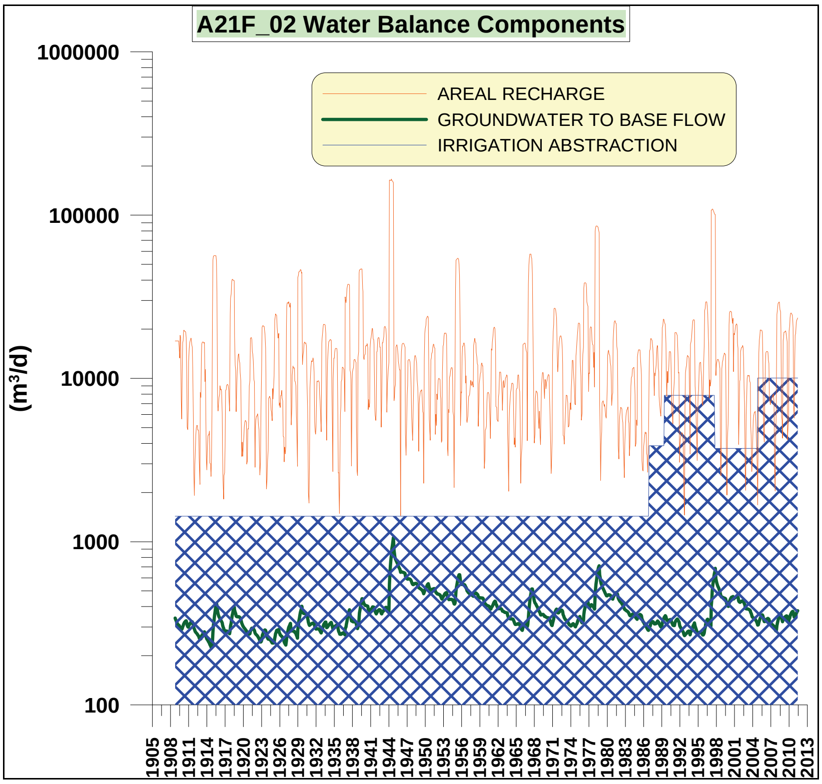


Figure 4-41 A21F_02 Water Balance Components. Baseflow is represented by Maloney's Eye Flow

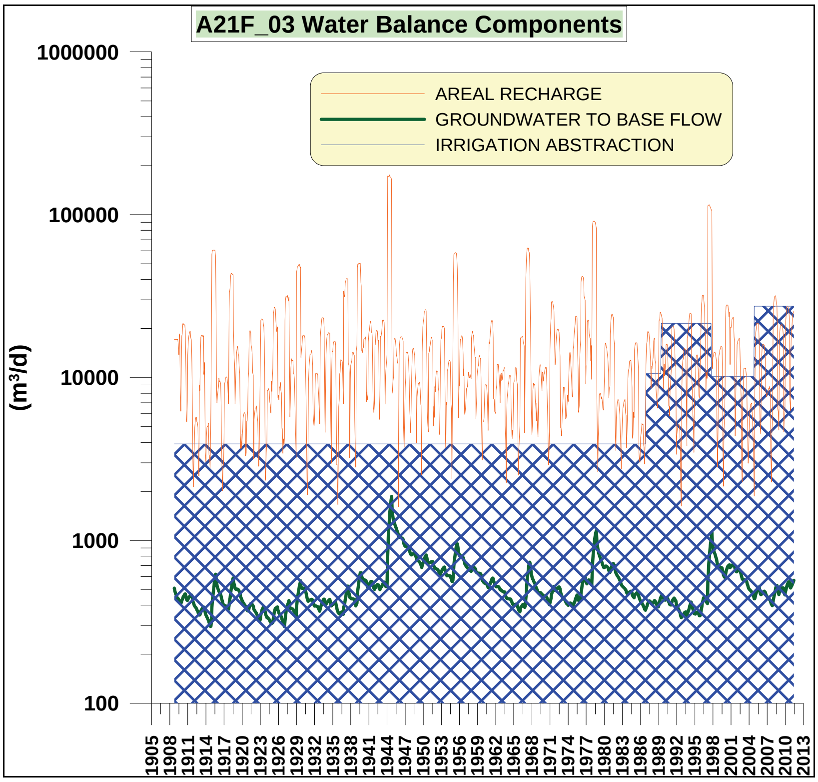


Figure 4-42 A21F_03 Water Balance Components

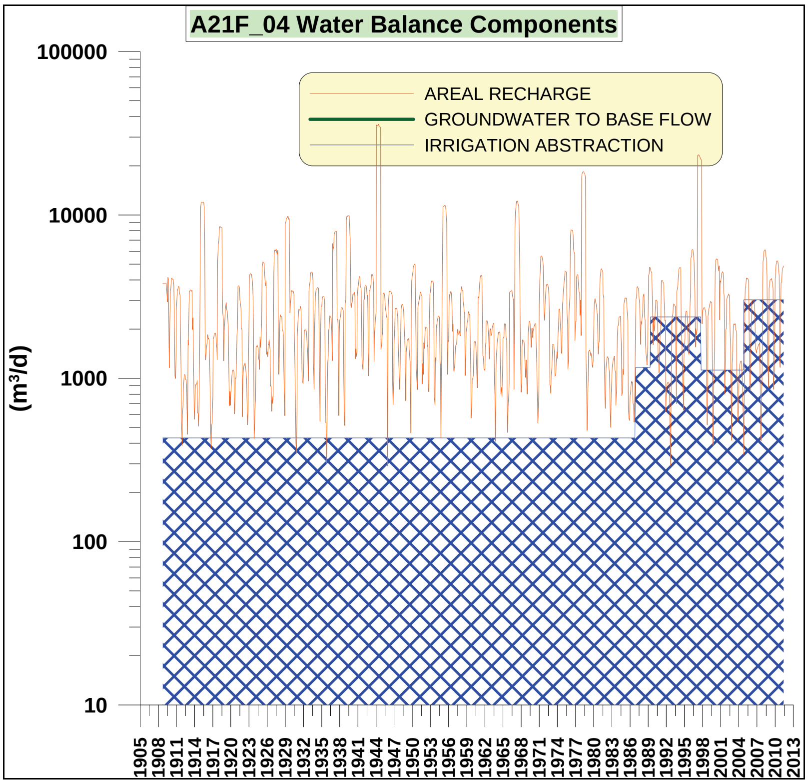


Figure 4-43 A21F_04 Water Balance Components

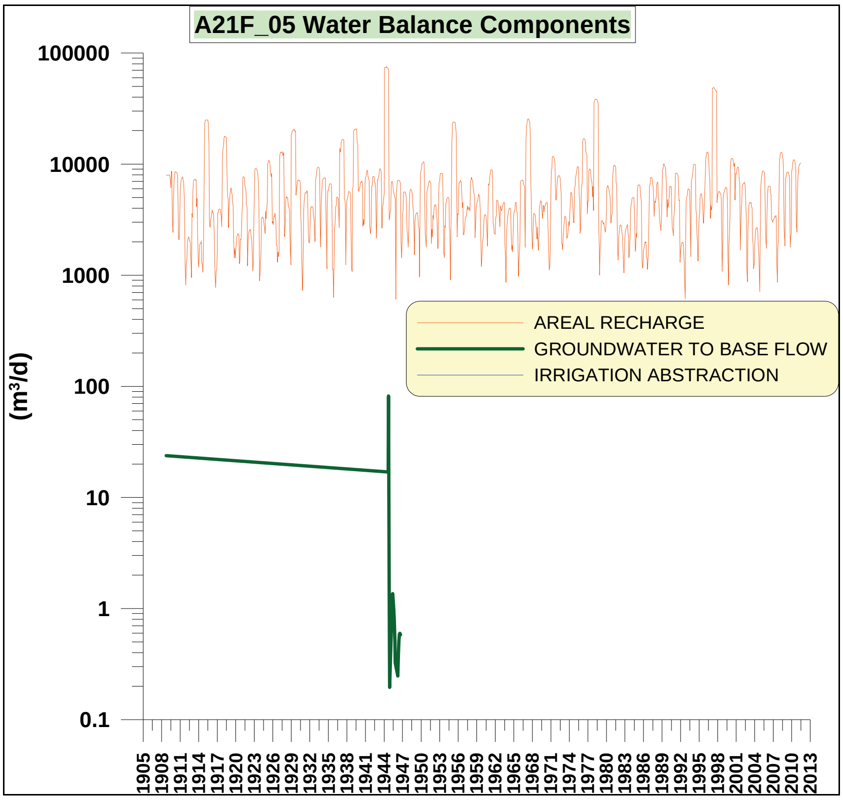


Figure 4-44 A21F_05 Water Balance Components

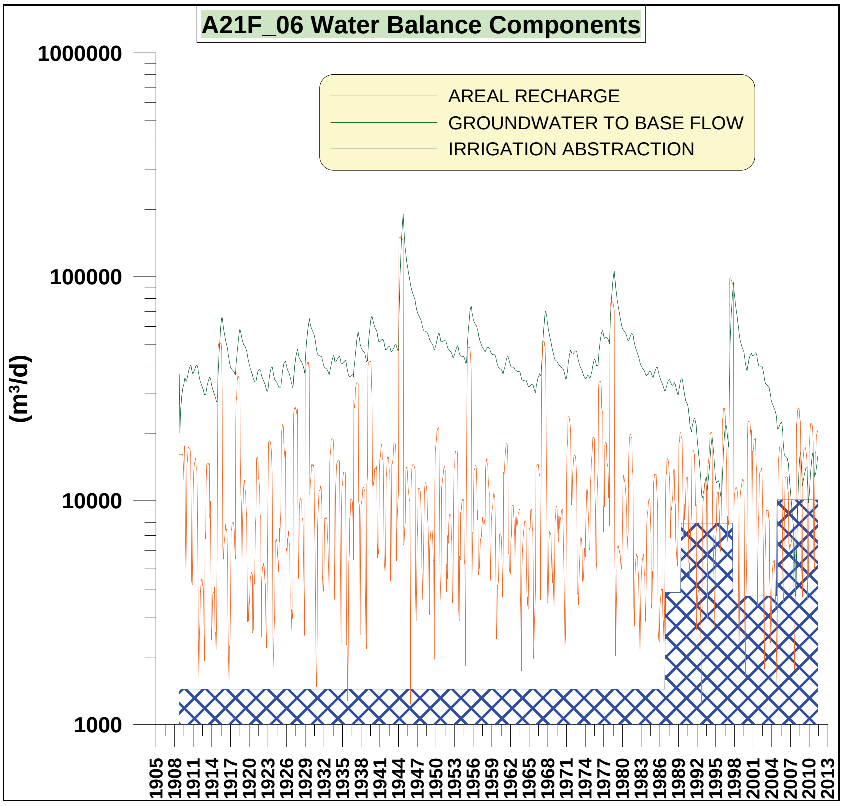


Figure 4-45 A21F_06 Water Balance Components

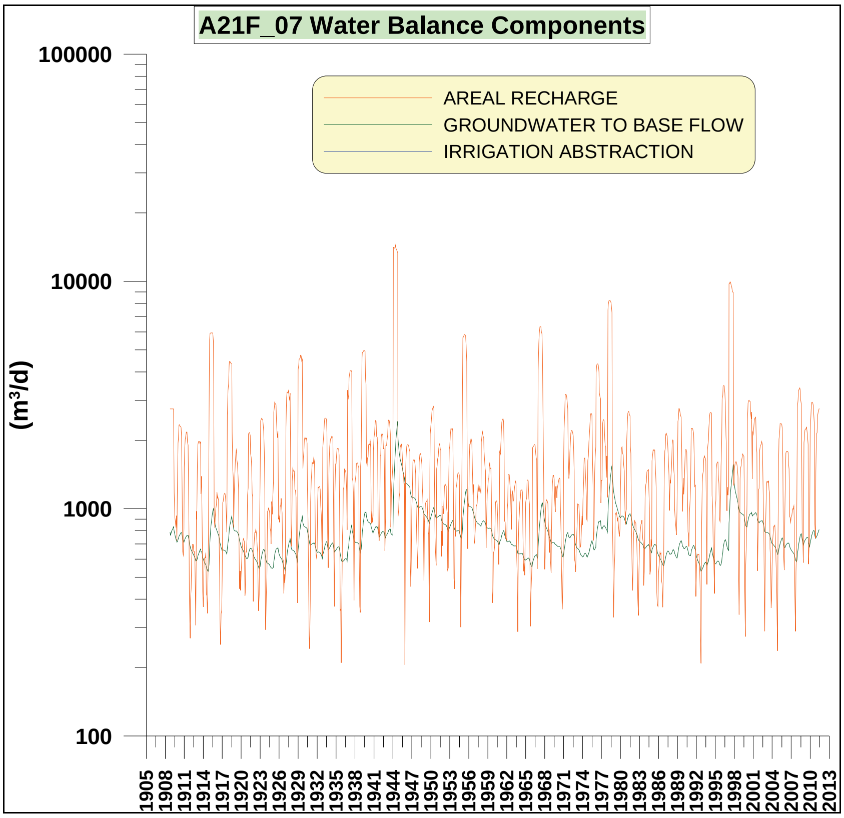


Figure 4-46 A21F_07 Water Balance Components

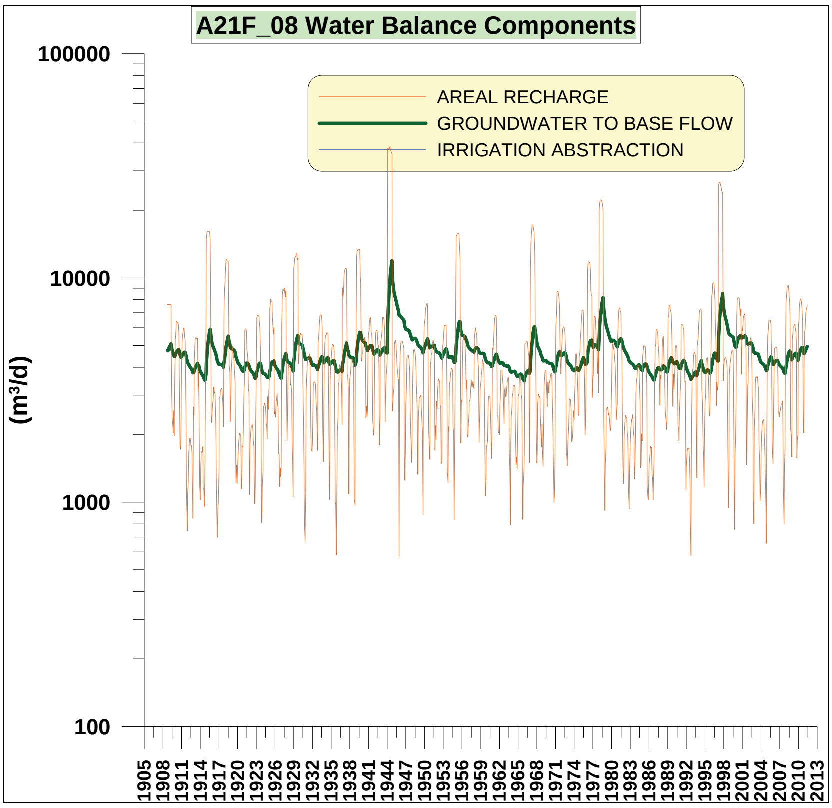


Figure 4-47 A21F_08 Water Balance Components

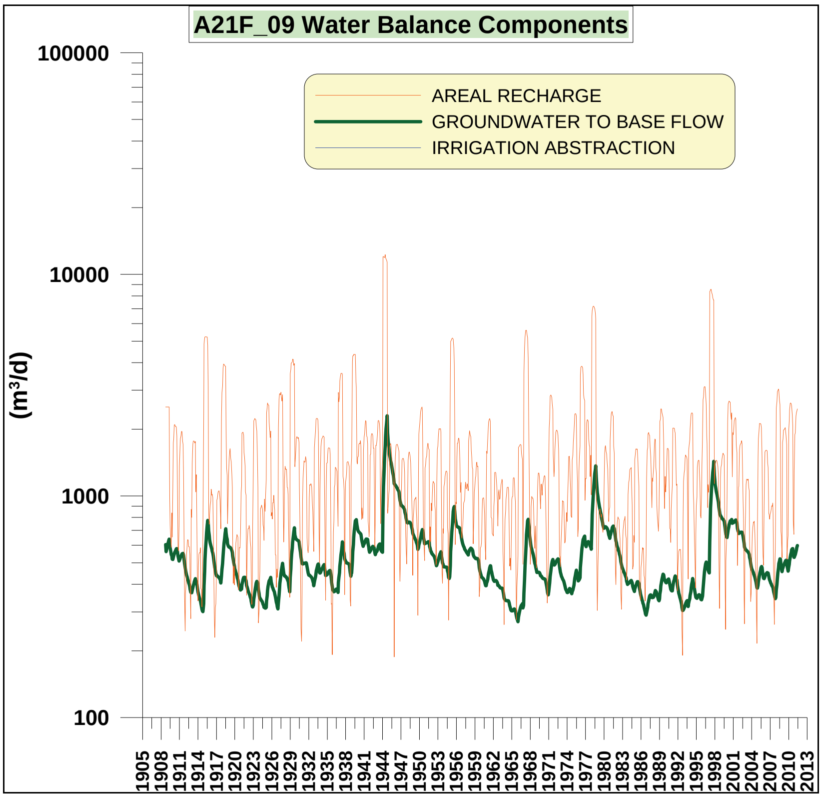


Figure 4-48 A21F_09 Water Balance Components

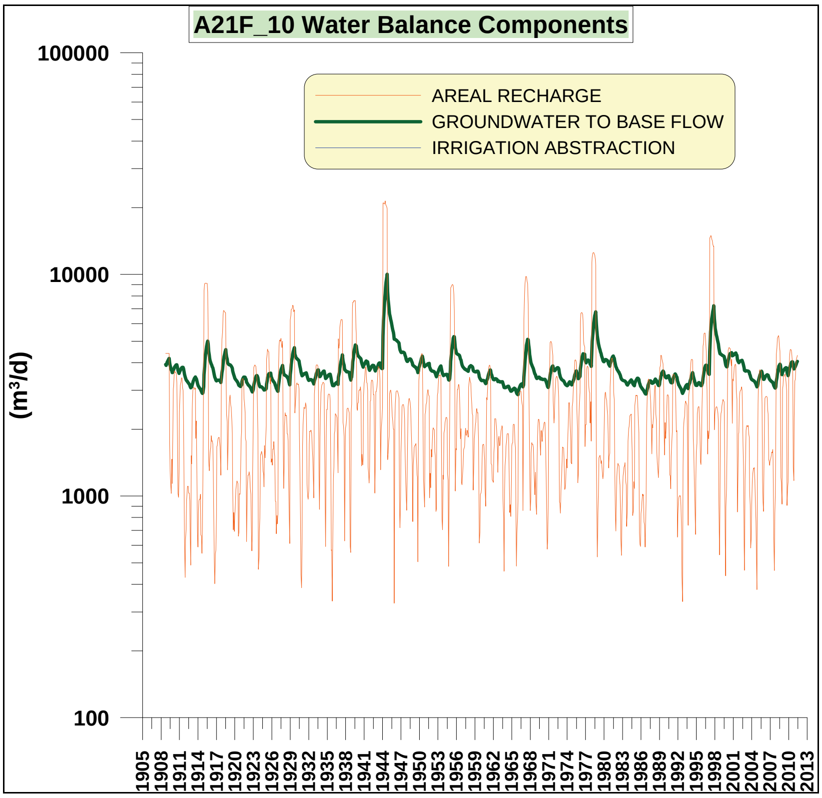


Figure 4-49 A21F_10 Water Balance Components

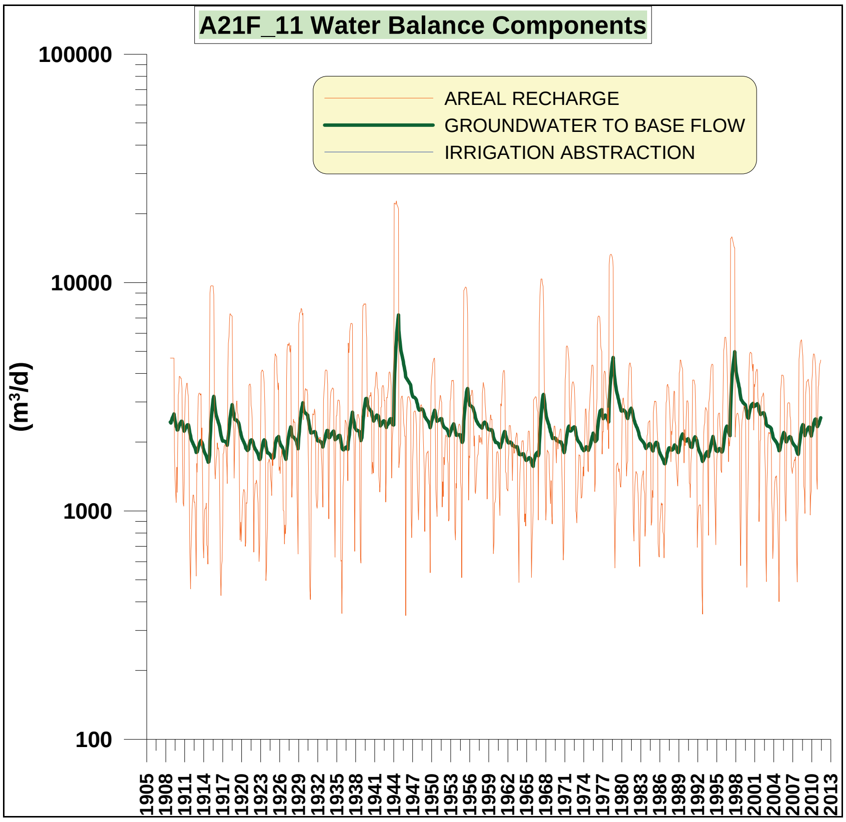


Figure 4-50 A21F_11 Water Balance Components

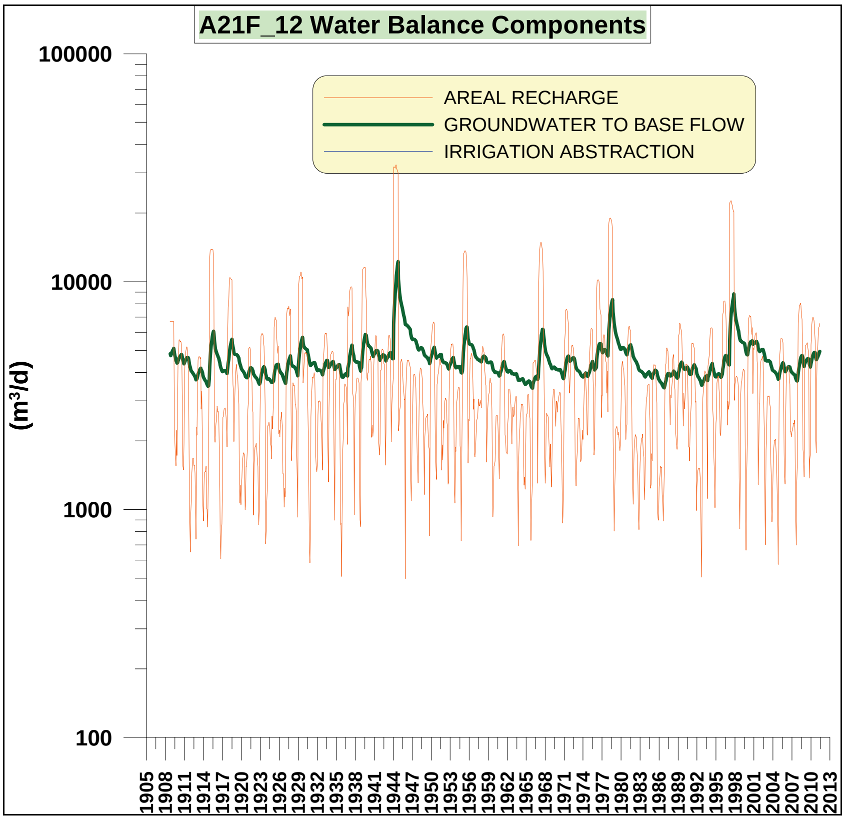


Figure 4-51 A21F_12 Water Balance Components

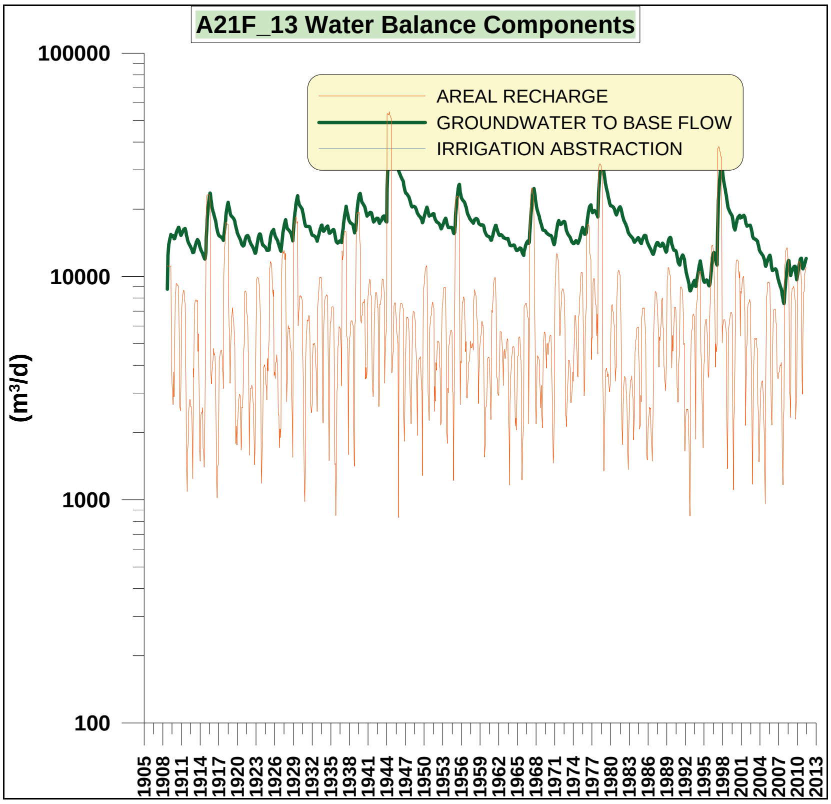


Figure 4-52 A21F_13 Water Balance Components

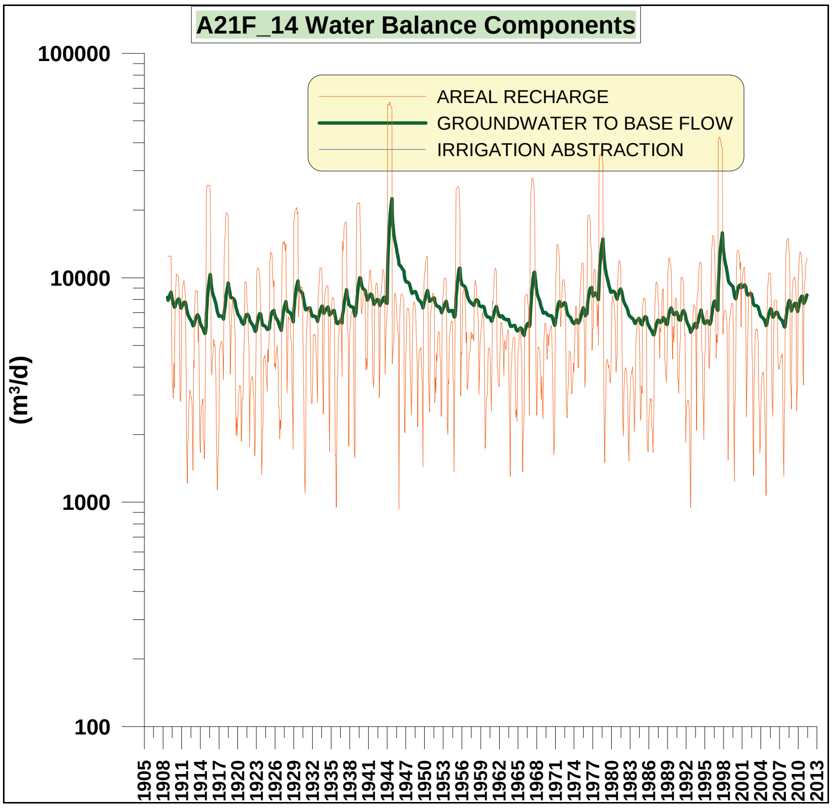
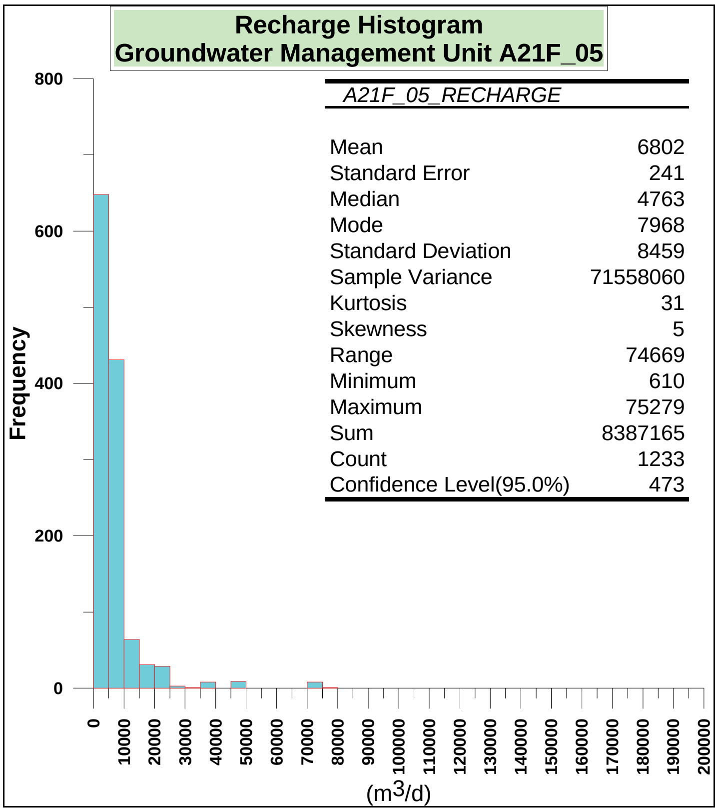
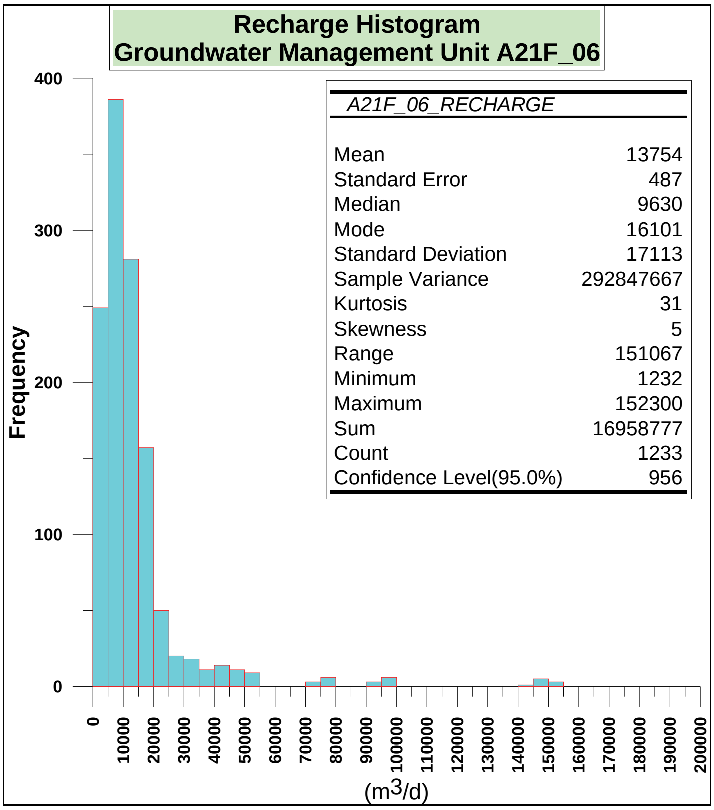


Figure 4-53 A21F_14 Water Balance Components



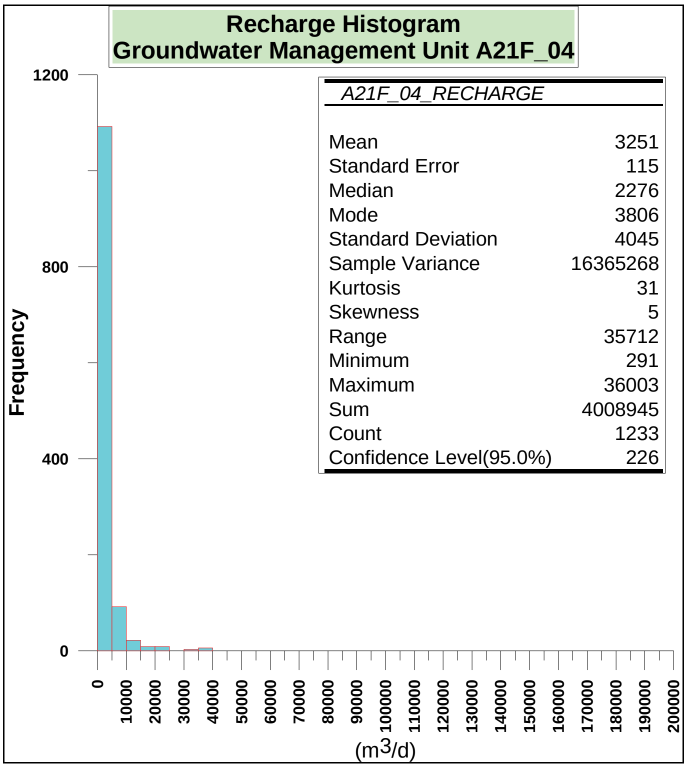
A21F_05_RECHARGE	
Mean	6802
Standard Error	241
Median	4763
Mode	7968
Standard Deviation	8459
Sample Variance	71558060
Kurtosis	31
Skewness	5
Range	74669
Minimum	610
Maximum	75279
Sum	8387165
Count	1233
Confidence Level(95.0%)	473

Figure 4-54 Recharge Histogram and Statistics GMU A2F_05



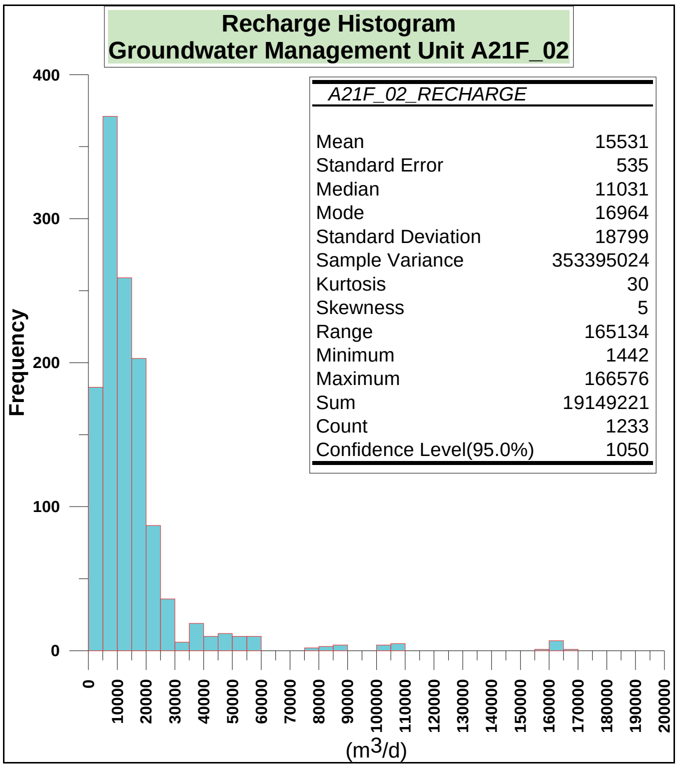
A21F_06_RECHARGE	
Mean	13754
Standard Error	487
Median	9630
Mode	16101
Standard Deviation	17113
Sample Variance	292847667
Kurtosis	31
Skewness	5
Range	151067
Minimum	1232
Maximum	152300
Sum	16958777
Count	1233
Confidence Level(95.0%)	956

Figure 4-55 Recharge Histogram and Statistics GMU A2F_06



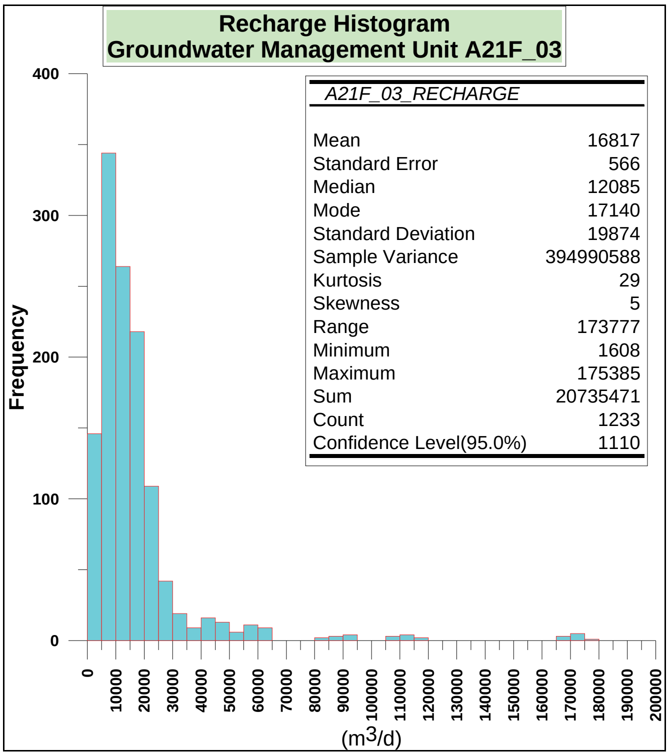
A21F_04_RECHARGE	
Mean	3251
Standard Error	115
Median	2276
Mode	3806
Standard Deviation	4045
Sample Variance	16365268
Kurtosis	31
Skewness	5
Range	35712
Minimum	291
Maximum	36003
Sum	4008945
Count	1233
Confidence Level(95.0%)	226

Figure 4-56 Recharge Histogram and Statistics GMU A2F_04



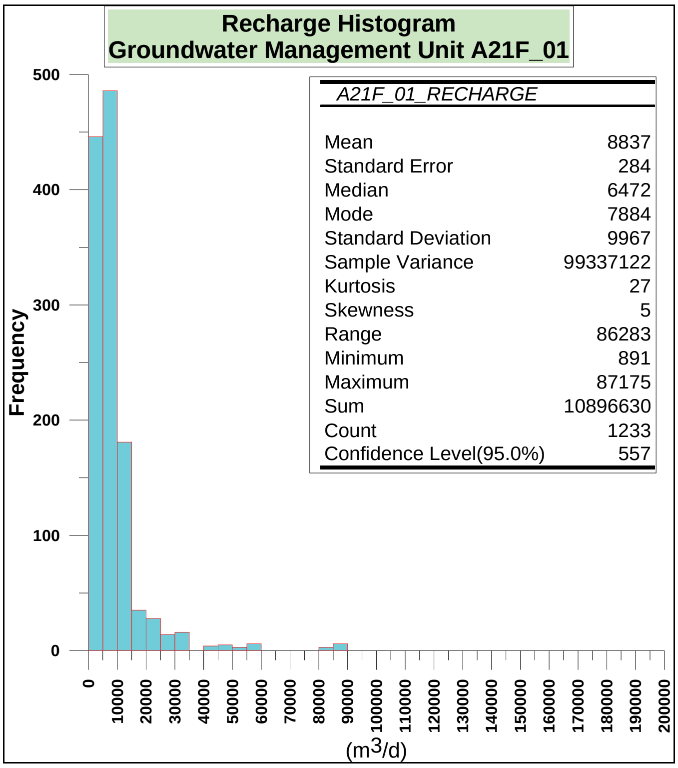
A21F_02_RECHARGE	
Mean	15531
Standard Error	535
Median	11031
Mode	16964
Standard Deviation	18799
Sample Variance	353395024
Kurtosis	30
Skewness	5
Range	165134
Minimum	1442
Maximum	166576
Sum	19149221
Count	1233
Confidence Level(95.0%)	1050

Figure 4-57 Recharge Histogram and Statistics GMU A2F_02



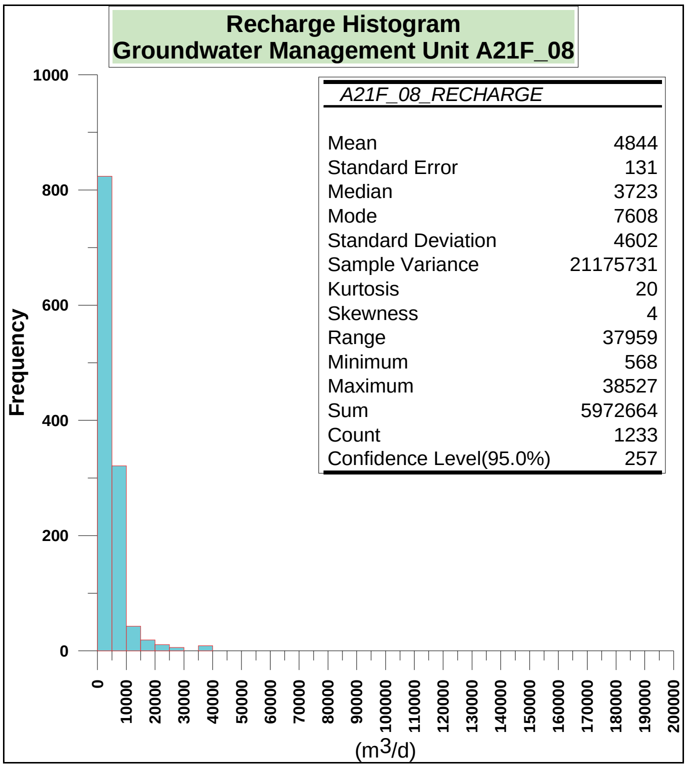
A21F_03_RECHARGE	
Mean	16817
Standard Error	566
Median	12085
Mode	17140
Standard Deviation	19874
Sample Variance	394990588
Kurtosis	29
Skewness	5
Range	173777
Minimum	1608
Maximum	175385
Sum	20735471
Count	1233
Confidence Level(95.0%)	1110

Figure 4-58 Recharge Histogram and Statistics GMU A2F_03



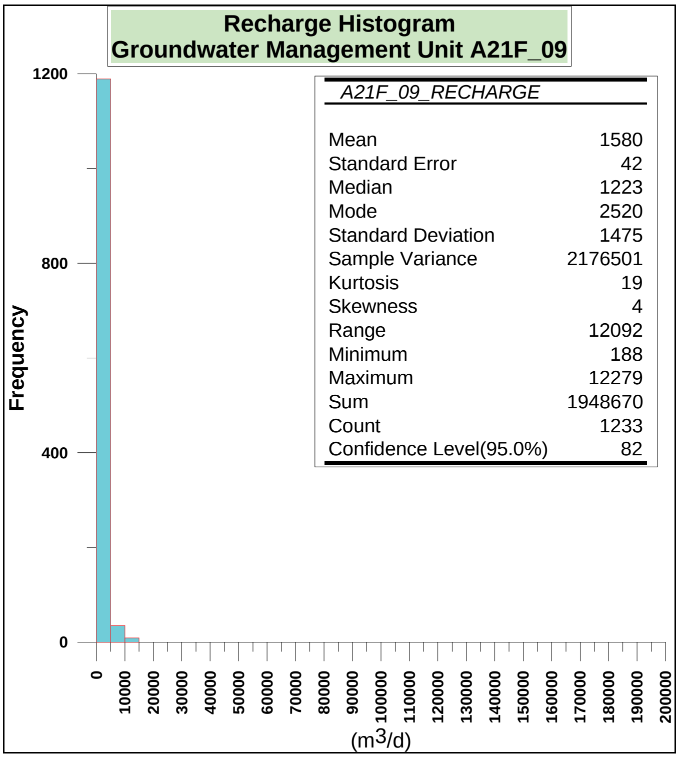
A21F_01_RECHARGE	
Mean	8837
Standard Error	284
Median	6472
Mode	7884
Standard Deviation	9967
Sample Variance	99337122
Kurtosis	27
Skewness	5
Range	86283
Minimum	891
Maximum	87175
Sum	10896630
Count	1233
Confidence Level(95.0%)	557

Figure 4-59 Recharge Histogram and Statistics GMU A2F_01



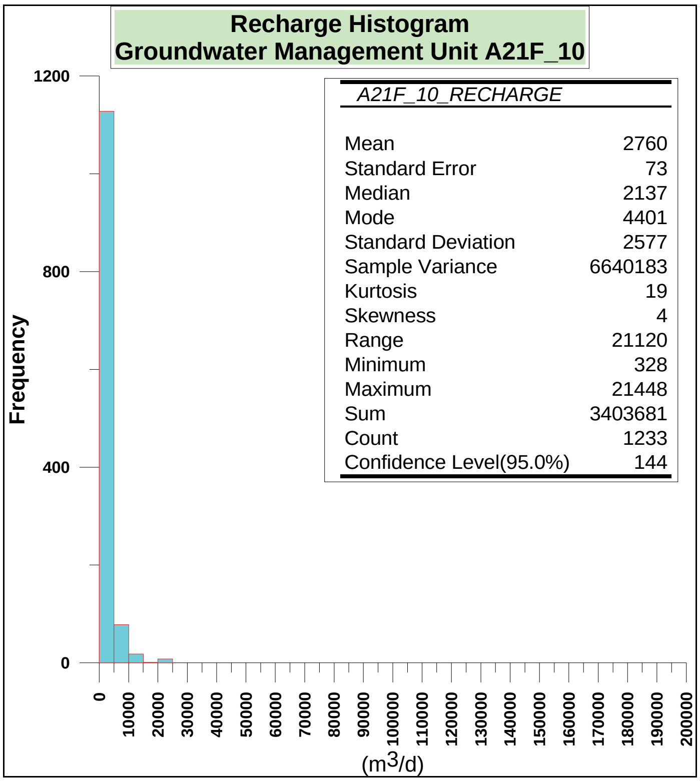
A21F_08_RECHARGE	
Mean	4844
Standard Error	131
Median	3723
Mode	7608
Standard Deviation	4602
Sample Variance	21175731
Kurtosis	20
Skewness	4
Range	37959
Minimum	568
Maximum	38527
Sum	5972664
Count	1233
Confidence Level(95.0%)	257

Figure 4-60Recharge Histogram and Statistics GMU A2F_08



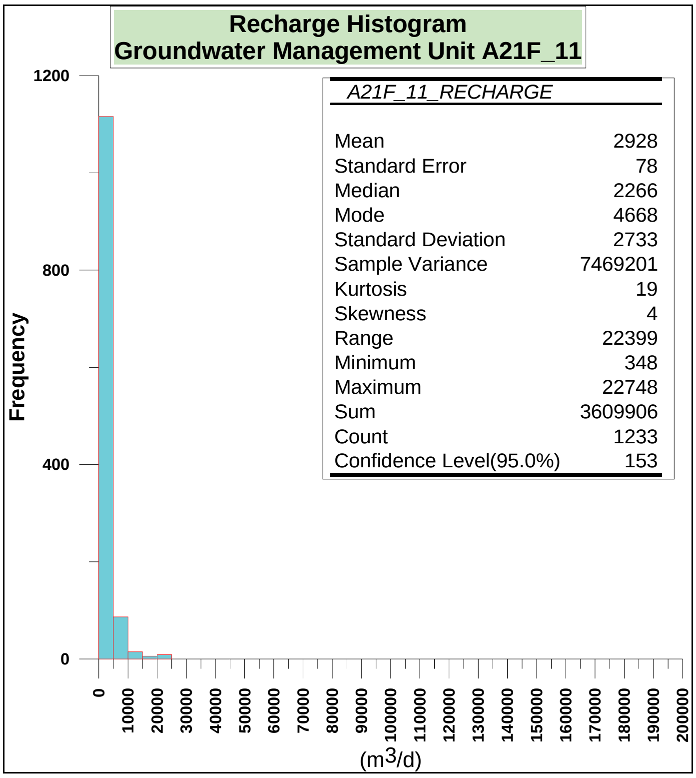
A21F_09_RECHARGE	
Mean	1580
Standard Error	42
Median	1223
Mode	2520
Standard Deviation	1475
Sample Variance	2176501
Kurtosis	19
Skewness	4
Range	12092
Minimum	188
Maximum	12279
Sum	1948670
Count	1233
Confidence Level(95.0%)	82

Figure 4-61 Recharge Histogram and Statistics GMU A2F_09



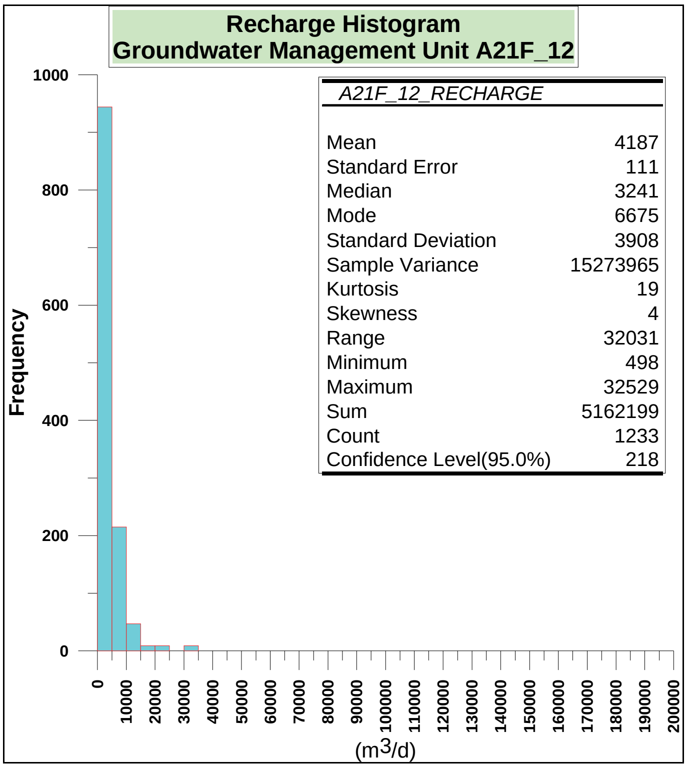
A21F_10_RECHARGE	
Mean	2760
Standard Error	73
Median	2137
Mode	4401
Standard Deviation	2577
Sample Variance	6640183
Kurtosis	19
Skewness	4
Range	21120
Minimum	328
Maximum	21448
Sum	3403681
Count	1233
Confidence Level(95.0%)	144

Figure 4-62 Recharge Histogram and Statistics GMU A2F_10



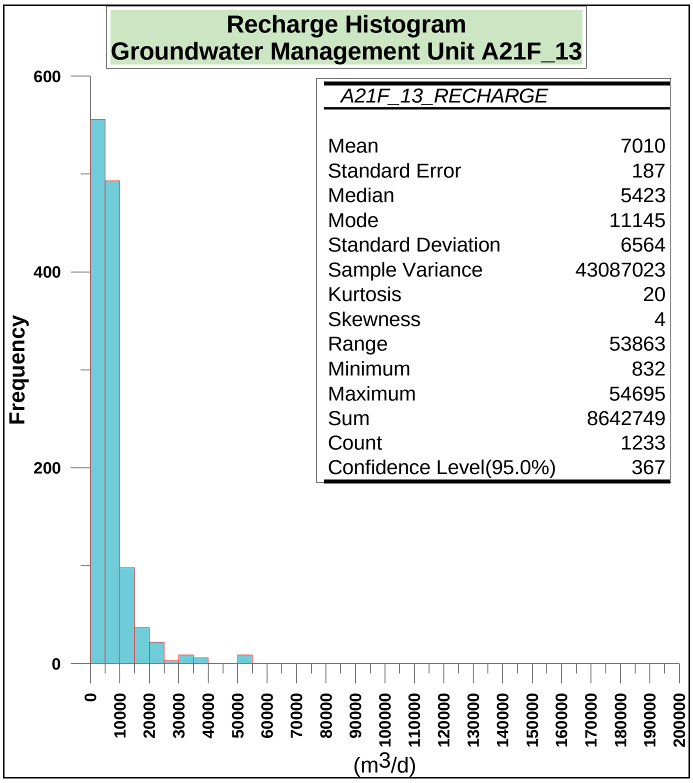
A21F_11_RECHARGE	
Mean	2928
Standard Error	78
Median	2266
Mode	4668
Standard Deviation	2733
Sample Variance	7469201
Kurtosis	19
Skewness	4
Range	22399
Minimum	348
Maximum	22748
Sum	3609906
Count	1233
Confidence Level(95.0%)	153

Figure 4-63 Recharge Histogram and Statistics GMU A2F_11



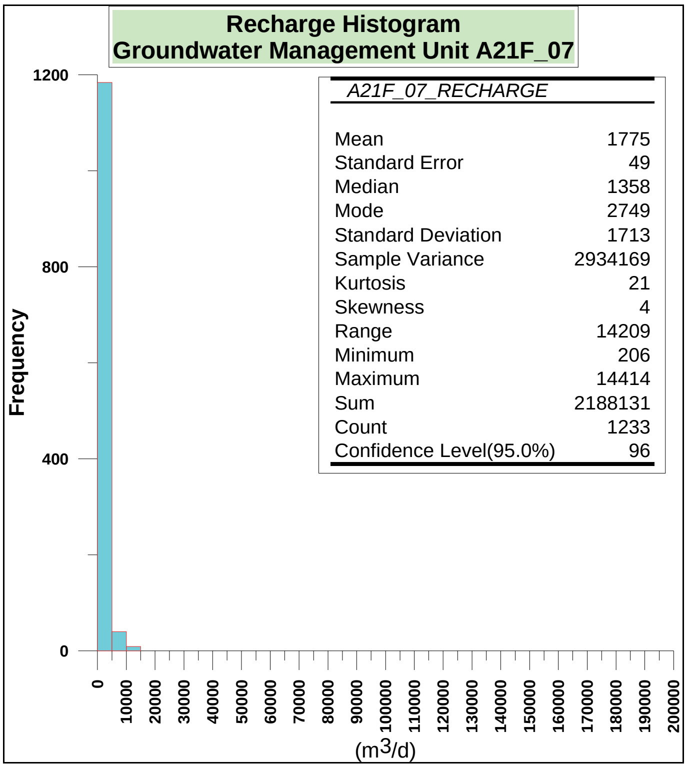
A21F_12_RECHARGE	
Mean	4187
Standard Error	111
Median	3241
Mode	6675
Standard Deviation	3908
Sample Variance	15273965
Kurtosis	19
Skewness	4
Range	32031
Minimum	498
Maximum	32529
Sum	5162199
Count	1233
Confidence Level(95.0%)	218

Figure 4-64 Recharge Histogram and Statistics GMU A2F_12



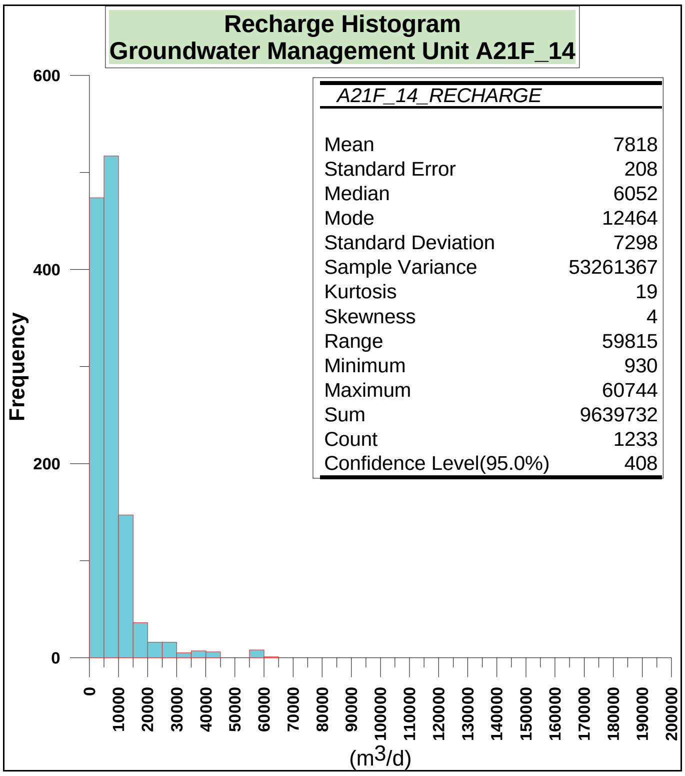
A21F_13_RECHARGE	
Mean	7010
Standard Error	187
Median	5423
Mode	11145
Standard Deviation	6564
Sample Variance	43087023
Kurtosis	20
Skewness	4
Range	53863
Minimum	832
Maximum	54695
Sum	8642749
Count	1233
Confidence Level(95.0%)	367

Figure 4-65 Recharge Histogram and Statistics GMU A2F_13



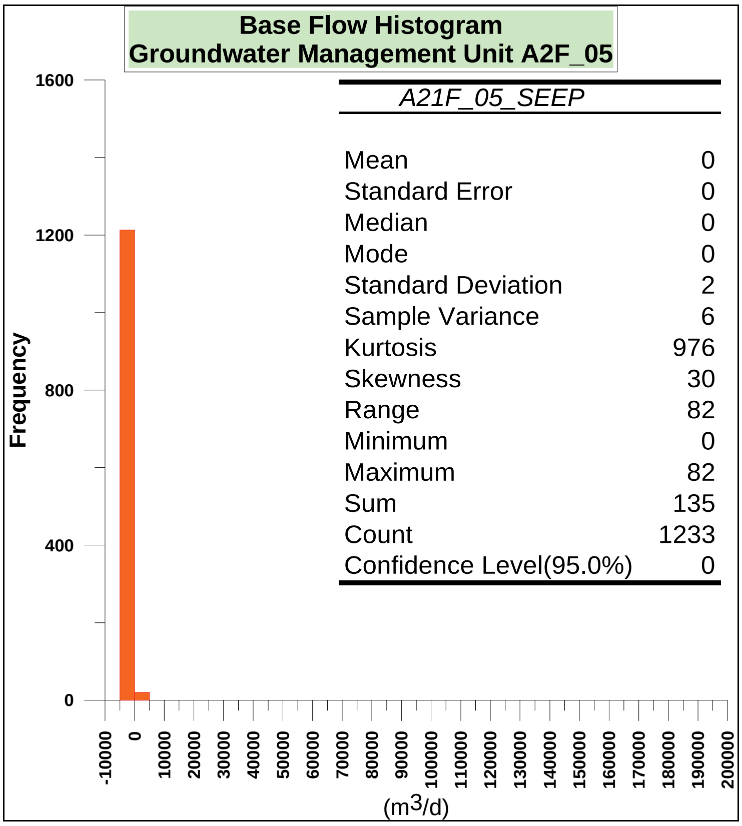
A21F_07_RECHARGE	
Mean	1775
Standard Error	49
Median	1358
Mode	2749
Standard Deviation	1713
Sample Variance	2934169
Kurtosis	21
Skewness	4
Range	14209
Minimum	206
Maximum	14414
Sum	2188131
Count	1233
Confidence Level(95.0%)	96

Figure 4-66 Recharge Histogram and Statistics GMU A2F_07



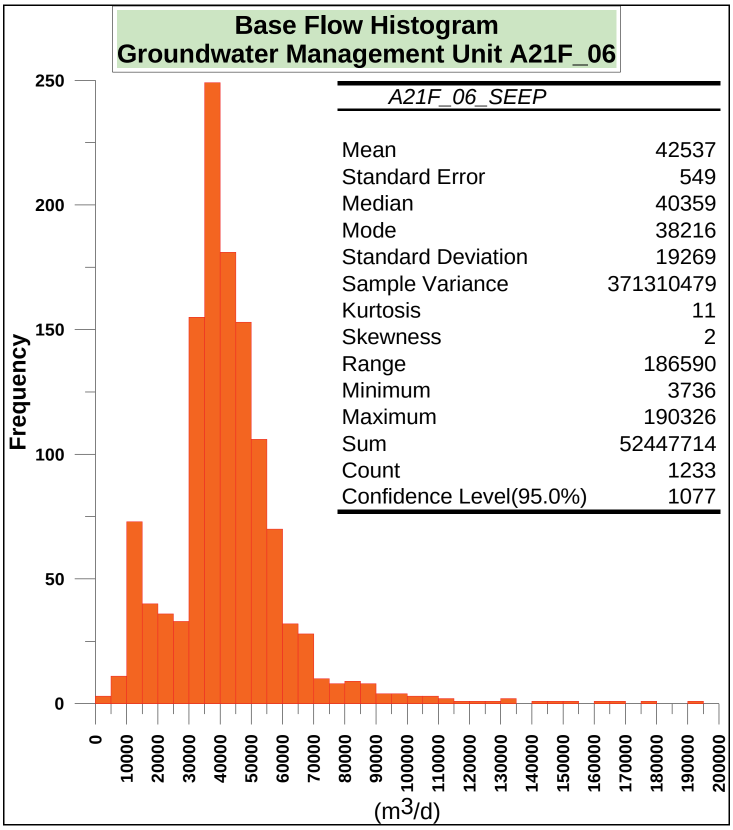
A21F_14_RECHARGE	
Mean	7818
Standard Error	208
Median	6052
Mode	12464
Standard Deviation	7298
Sample Variance	53261367
Kurtosis	19
Skewness	4
Range	59815
Minimum	930
Maximum	60744
Sum	9639732
Count	1233
Confidence Level(95.0%)	408

Figure 4-67 Recharge Histogram and Statistics GMU A2F_14



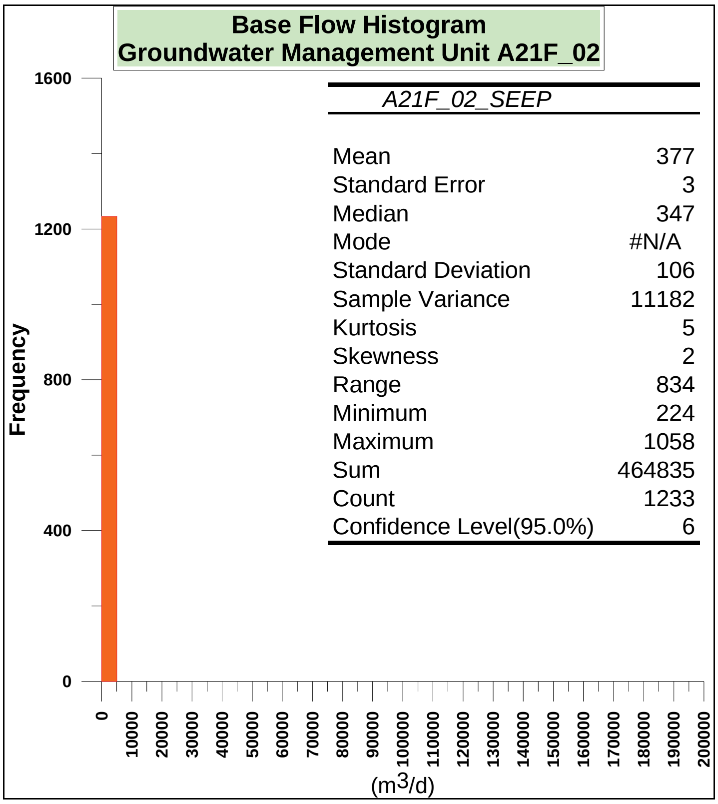
A21F_05_SEEP	
Mean	0
Standard Error	0
Median	0
Mode	0
Standard Deviation	2
Sample Variance	6
Kurtosis	976
Skewness	30
Range	82
Minimum	0
Maximum	82
Sum	135
Count	1233
Confidence Level(95.0%)	0

Figure 4-68 Base FLow Histogram and Statistics GMU A2F_05



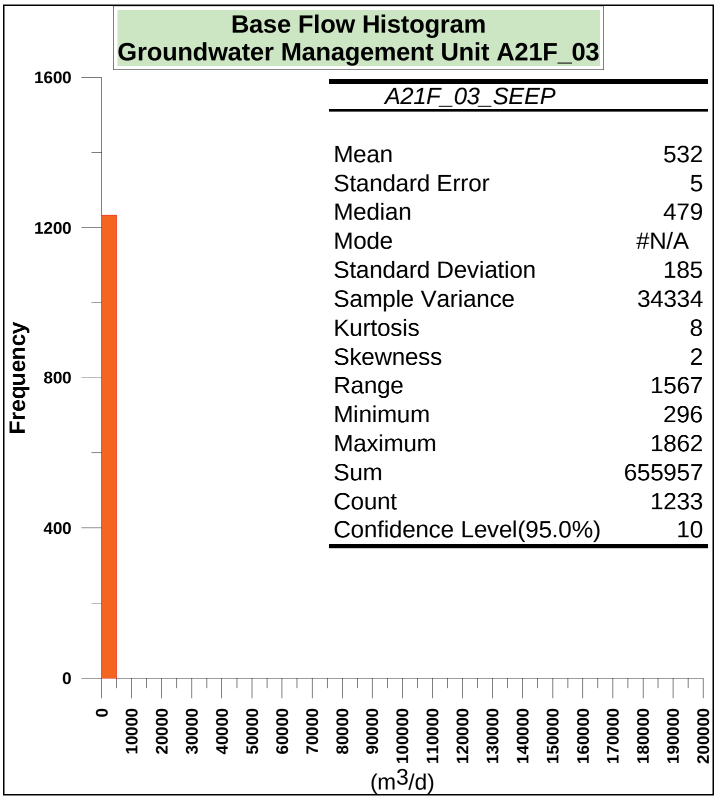
A21F_06_SEEP	
Mean	42537
Standard Error	549
Median	40359
Mode	38216
Standard Deviation	19269
Sample Variance	371310479
Kurtosis	11
Skewness	2
Range	186590
Minimum	3736
Maximum	190326
Sum	52447714
Count	1233
Confidence Level(95.0%)	1077

Figure 4-69 Base FLow Histogram and Statistics GMU A2F_06



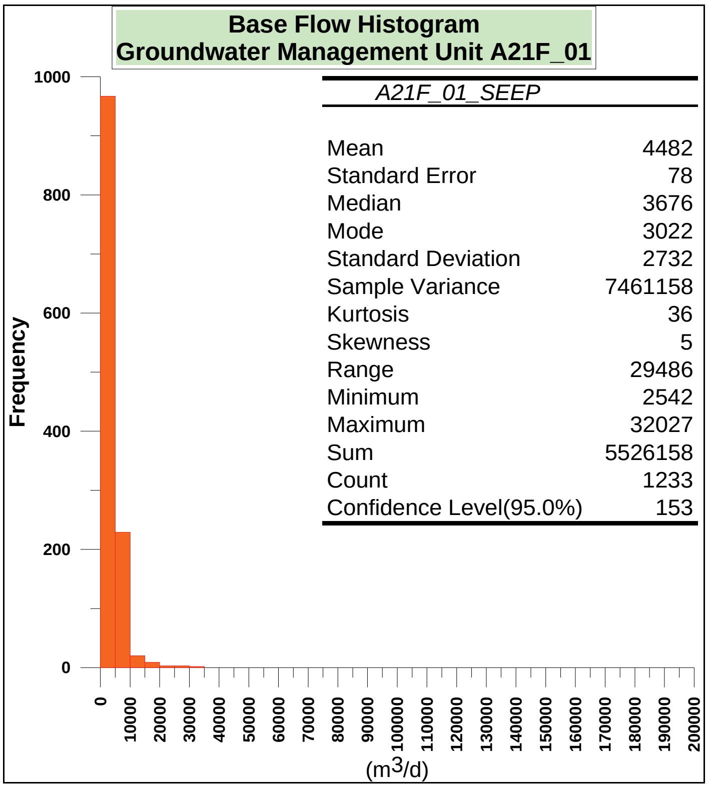
A21F_02_SEEP	
Mean	377
Standard Error	3
Median	347
Mode	#N/A
Standard Deviation	106
Sample Variance	11182
Kurtosis	5
Skewness	2
Range	834
Minimum	224
Maximum	1058
Sum	464835
Count	1233
Confidence Level(95.0%)	6

Figure 4-70 Base FLow Histogram and Statistics GMU A2F_02



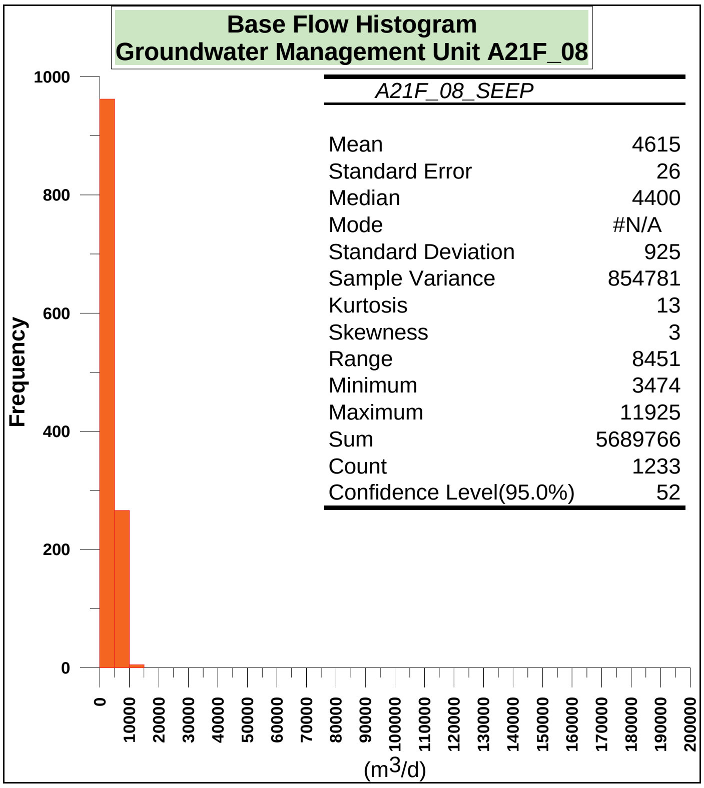
A21F_03_SEEP	
Mean	532
Standard Error	5
Median	479
Mode	#N/A
Standard Deviation	185
Sample Variance	34334
Kurtosis	8
Skewness	2
Range	1567
Minimum	296
Maximum	1862
Sum	655957
Count	1233
Confidence Level(95.0%)	10

Figure 4-71 Base FLow Histogram and Statistics GMU A2F_03



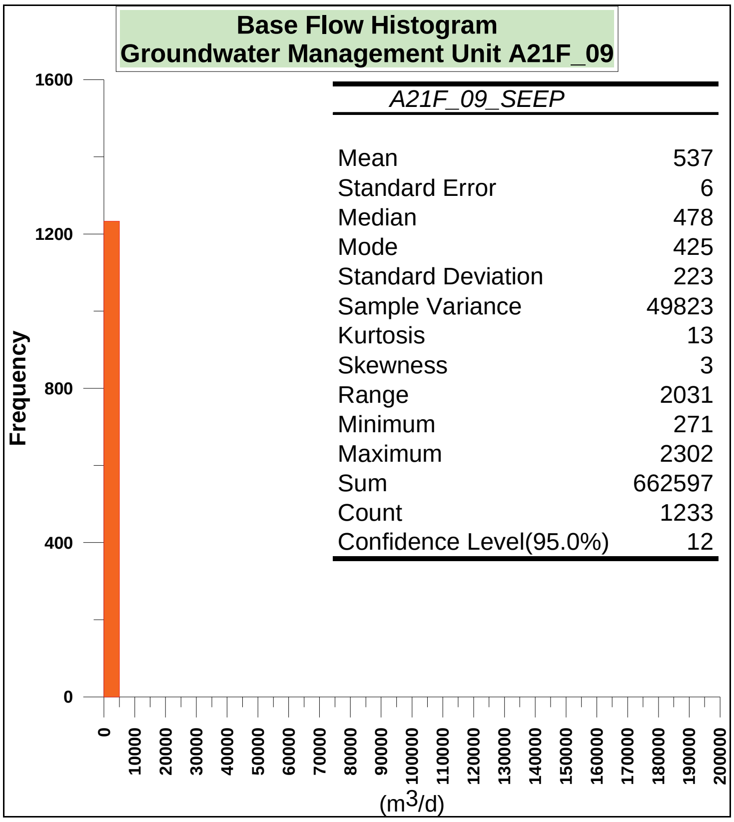
A21F_01_SEEP	
Mean	4482
Standard Error	78
Median	3676
Mode	3022
Standard Deviation	2732
Sample Variance	7461158
Kurtosis	36
Skewness	5
Range	29486
Minimum	2542
Maximum	32027
Sum	5526158
Count	1233
Confidence Level(95.0%)	153

Figure 4-72Base FLow Histogram and Statistics GMU A2F_01



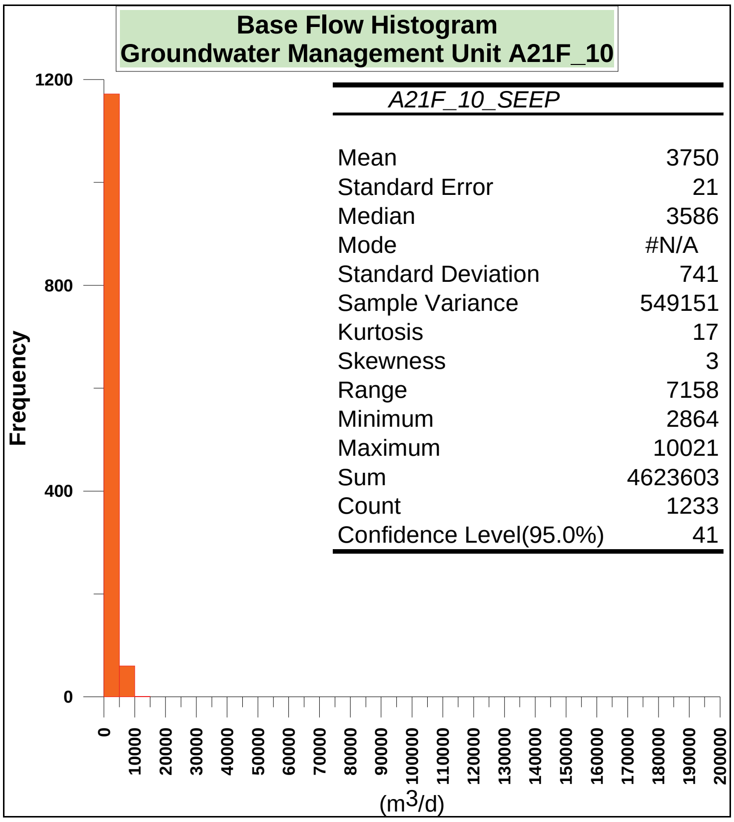
A21F_08_SEEP	
Mean	4615
Standard Error	26
Median	4400
Mode	#N/A
Standard Deviation	925
Sample Variance	854781
Kurtosis	13
Skewness	3
Range	8451
Minimum	3474
Maximum	11925
Sum	5689766
Count	1233
Confidence Level(95.0%)	52

Figure 4-73 Base FLow Histogram and Statistics GMU A2F_08



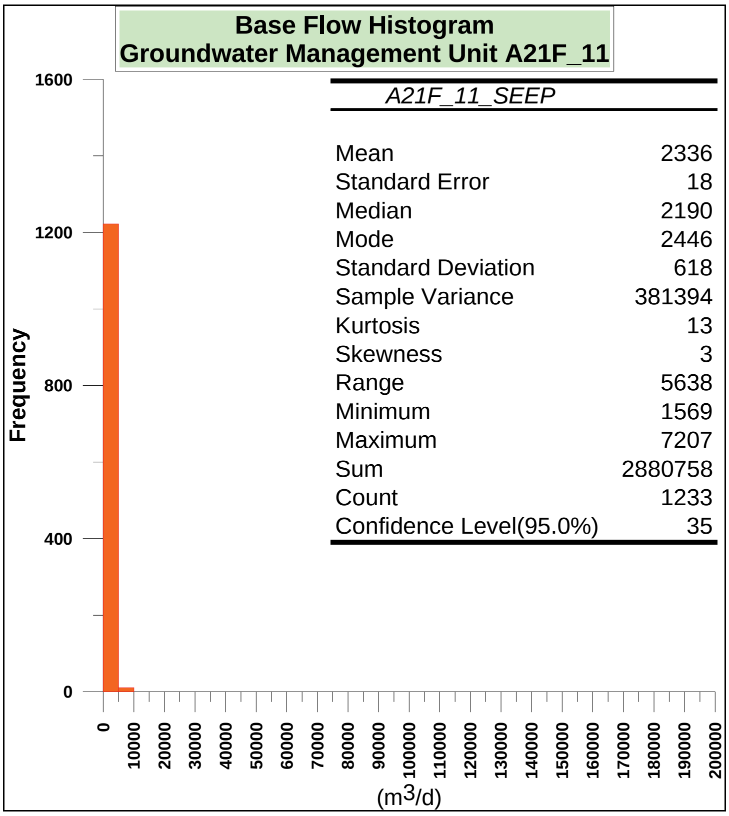
A21F_09_SEEP	
Mean	537
Standard Error	6
Median	478
Mode	425
Standard Deviation	223
Sample Variance	49823
Kurtosis	13
Skewness	3
Range	2031
Minimum	271
Maximum	2302
Sum	662597
Count	1233
Confidence Level(95.0%)	12

Figure 4-74 Base FLow Histogram and Statistics GMU A2F_09



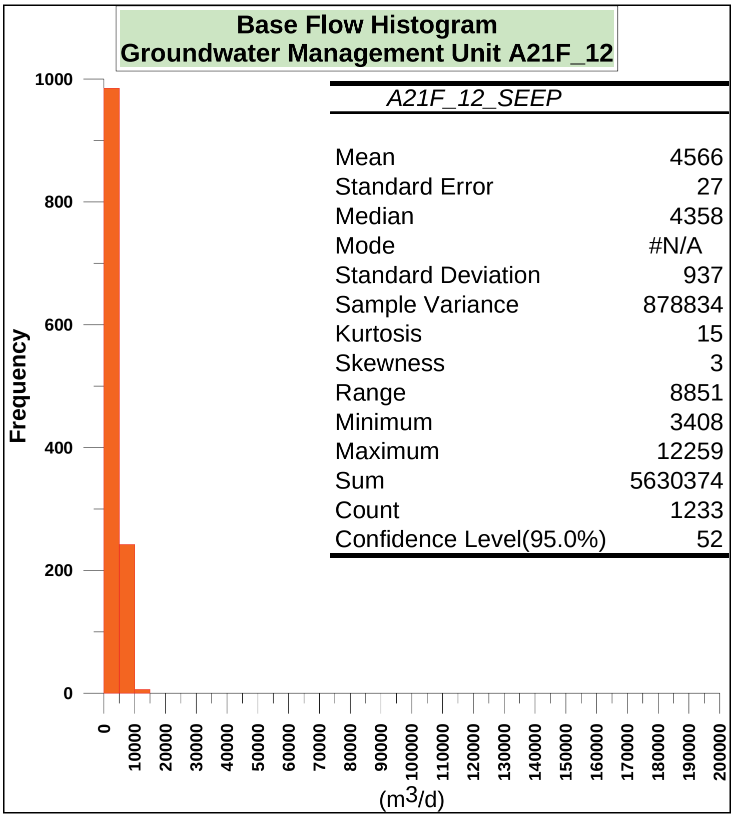
A21F_10_SEEP	
Mean	3750
Standard Error	21
Median	3586
Mode	#N/A
Standard Deviation	741
Sample Variance	549151
Kurtosis	17
Skewness	3
Range	7158
Minimum	2864
Maximum	10021
Sum	4623603
Count	1233
Confidence Level(95.0%)	41

Figure 4-75 Base FLow Histogram and Statistics GMU A2F_10



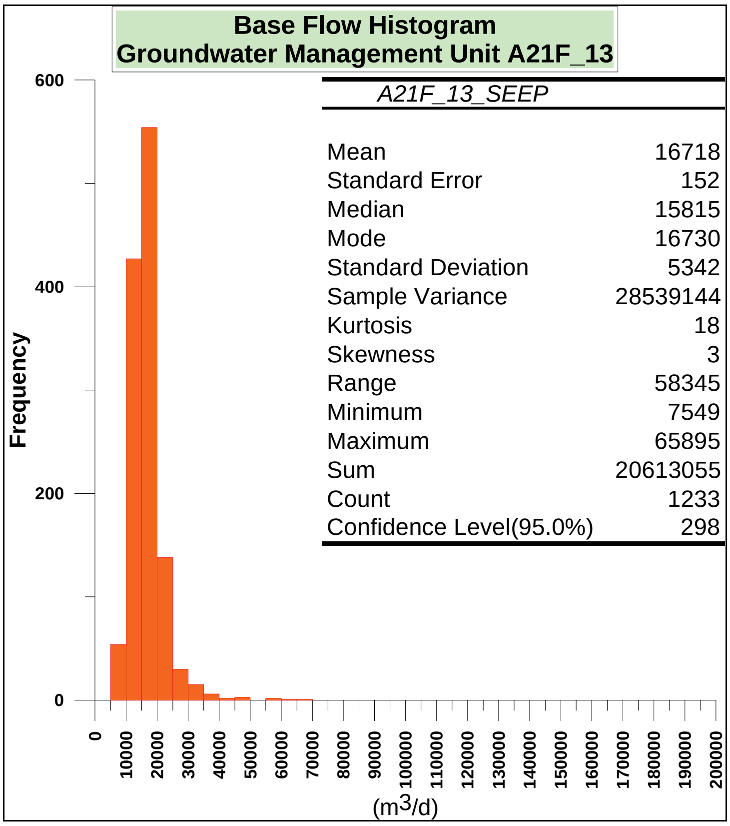
A21F_11_SEEP	
Mean	2336
Standard Error	18
Median	2190
Mode	2446
Standard Deviation	618
Sample Variance	381394
Kurtosis	13
Skewness	3
Range	5638
Minimum	1569
Maximum	7207
Sum	2880758
Count	1233
Confidence Level(95.0%)	35

Figure 4-76 Base FLow Histogram and Statistics GMU A2F_11



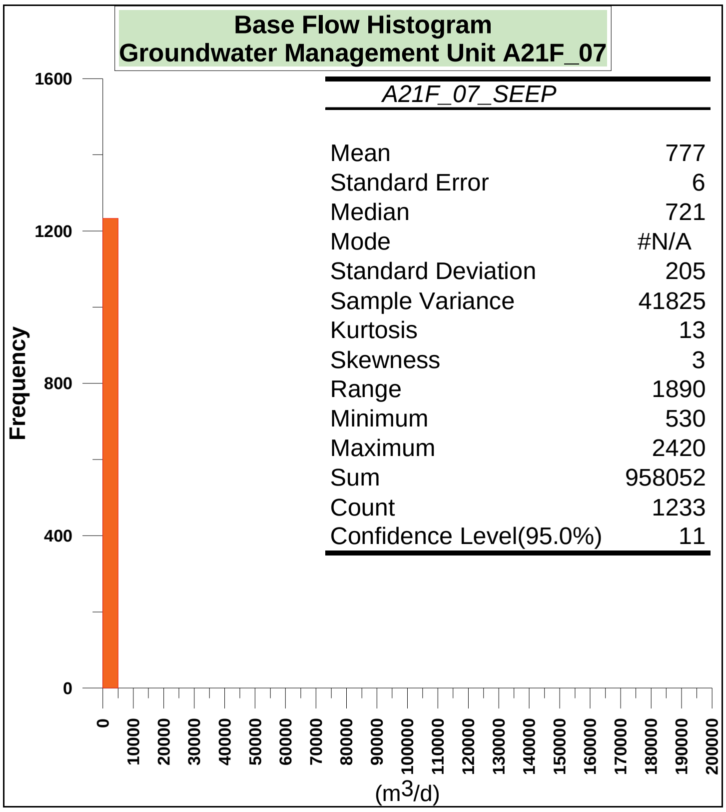
A21F_12_SEEP	
Mean	4566
Standard Error	27
Median	4358
Mode	#N/A
Standard Deviation	937
Sample Variance	878834
Kurtosis	15
Skewness	3
Range	8851
Minimum	3408
Maximum	12259
Sum	5630374
Count	1233
Confidence Level(95.0%)	52

Figure 4-77 Base FLow Histogram and Statistics GMU A2F_12



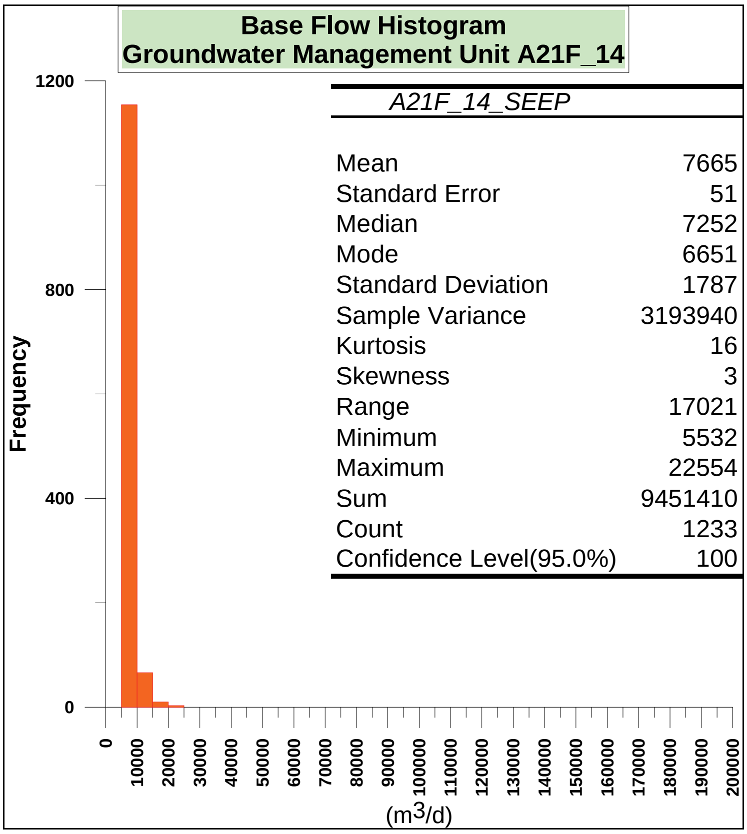
A21F_13_SEEP	
Mean	16718
Standard Error	152
Median	15815
Mode	16730
Standard Deviation	5342
Sample Variance	28539144
Kurtosis	18
Skewness	3
Range	58345
Minimum	7549
Maximum	65895
Sum	20613055
Count	1233
Confidence Level(95.0%)	298

Figure 4-78 Base FLow Histogram and Statistics GMU A2F_13



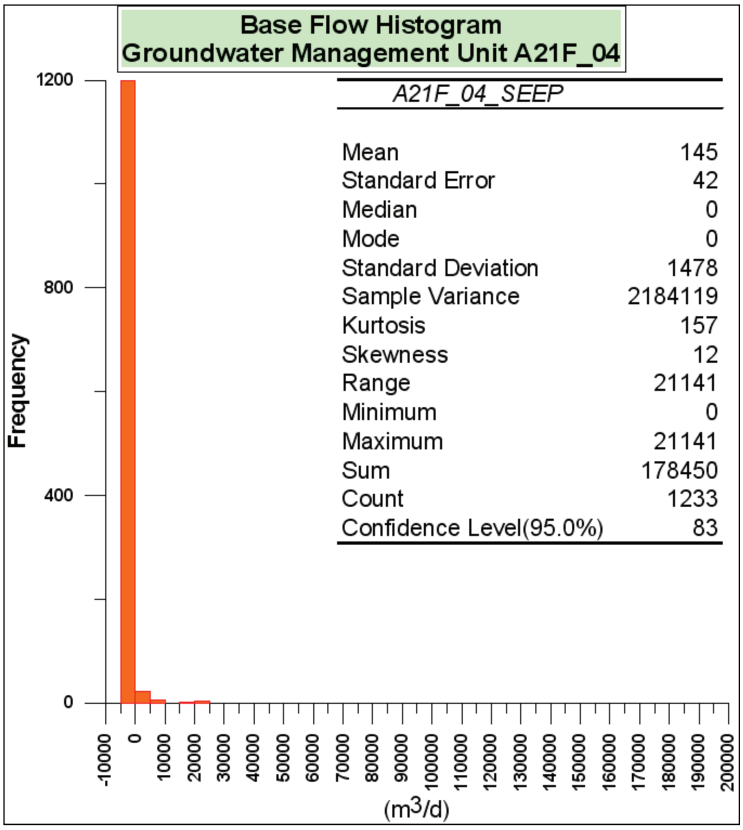
A21F_07_SEEP	
Mean	777
Standard Error	6
Median	721
Mode	#N/A
Standard Deviation	205
Sample Variance	41825
Kurtosis	13
Skewness	3
Range	1890
Minimum	530
Maximum	2420
Sum	958052
Count	1233
Confidence Level(95.0%)	11

Figure 4-79 Base FLow Histogram and Statistics GMU A2F_07



A21F_14_SEEP	
Mean	7665
Standard Error	51
Median	7252
Mode	6651
Standard Deviation	1787
Sample Variance	3193940
Kurtosis	16
Skewness	3
Range	17021
Minimum	5532
Maximum	22554
Sum	9451410
Count	1233
Confidence Level(95.0%)	100

Figure 4-80 Base FLow Histogram and Statistics GMU A2F_14



A21F_04_SEEP	
Mean	145
Standard Error	42
Median	0
Mode	0
Standard Deviation	1478
Sample Variance	2184119
Kurtosis	157
Skewness	12
Range	21141
Minimum	0
Maximum	21141
Sum	178450
Count	1233
Confidence Level(95.0%)	83

Figure 4-81 Base FLow Histogram and Statistics GMU A2F_4

5 CONCLUSIONS

The following is concluded from the groundwater flow calibrations:

- The hydraulic conductivity zoning used corresponds with the nature and distribution of the geological units and control the hydrogeology of the study area, supported by extensive gravimetric surveys across the Steenkoppies Compartment. The zoning mimics the primary geological features across the regional study area. The large-scale, effective hydraulic conductivity values identified in the model calibration compare well with the hydraulic conductivity (transmissivity) data from the aquifer tests conducted historically and what are widely accepted values for this type of formations/aquifers.
- The background recharge values used in the model is consistent with estimates for dolomite- and hard rock-type aquifers. The temporal recharge to rainfall relationship obtained is able to reproduce the observed spring flows over an extensive time period and can be considered reasonable within the observed data limitations. An exponential recharge/rainfall relationship was derived for the modelled area in particular across the Steenkoppies dolomite compartment utilizing the flow record of the Maloney's Eye and the corresponding rainfall record. The flow record of the Maloney's Eye consists of natural recharge less large-scale irrigation abstraction. Temporal abstraction data is generally very sparse and reported data uncertain.
- Overall, the model structure and parameters used in the calibrated model appear appropriate and reasonable for the planned use. The model-calculated hydraulic heads are consistent with the target heads and the overall shape of the water table is consistent with that expected and discussed in the conceptual model. The model shows groundwater recharge occurring and discharging within the surface drainages and Maloney's Eye consistent with the conceptual model. A good correlation between the simulated and observed spring flow values was obtained.
- It is evident that irrigation abstraction influenced the flow of the Maloney's Eye significantly since the mid-1980s. The flow simulated for pristine conditions (no abstraction) indicate a minimum flow of 450 l/s from the Maloney's Eye for the period 1908-2011.
- The model was constructed to reflect the different groundwater management units (GMUs) across the quaternary catchment A21F. Based upon the long-term simulation (1908-2011) statistics for recharge and base-flow were compiled for each GMU. Part of the statistics includes a 95% confidence level for the mean annual recharge and base flow.
- The preliminary regional groundwater model can be updated and refined to achieve a higher level of confidence by addressing uncertainties in the temporal irrigation abstraction.
- The calibrated groundwater flow model was utilised to provide 5, 10 and 20-year protection zones for the Maloney's Eye. This is presented in the main report.
- The model can be utilized to simulate the effect of different operational and management scenarios and their impact on the flow of the Maloney's Eye. With minimal further customization the model can be expanded to a mass transport model to simulate water quality impacts across the entire quaternary catchment.

6 REFERENCES

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