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IMPROVING GROUNDWATER KNOWLEDGE IN SELECTED TRANSBOUNDARY AQUIFERS

Groundwater Recharge in the Karoo Sedimentary and Khakhea/Bray Dolomitic Aquifers

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ORASECOM SECRETARIAT

IMPROVING GROUNDWATER KNOWLEDGE IN SELECTED TRANSBOUNDARY AQUIFERS

GROUNDWATER RECHARGE IN THE KAROO SEDIMENTARY AND KHAKHEA BRAY DOLOMITIC AQUIFERS REPORT

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IMPROVING GROUNDWATER KNOWLEDGE IN SELECTED TRANSBOUNDARY AQUIFERS

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DOCUMENT INDEX

Index Number	ORASECOM Report Number	Report Title
1		**Inception report**
2		Draft final report Groundwater Recharge in the Karoo Sedimentary and Khakhea/Bray Dolomitic Aquifers

Index Number	ORASECOM Report Number	Report Title
3		Joint Survey Process Report
4		Joint Survey Technical Report
5		Groundwater Monitoring Background Report
6		Groundwater Monitoring Framework Report
7		Stakeholder’s Workshop Report
8		User manual of the established groundwater information system.

EXECUTIVE SUMMARY

This Report documents groundwater recharge in the Karroo Sedimentary and the Khakhea/Bray Dolomite Aquifers including: A Literature review of all groundwater recharge estimation studies in the study areas, additional information using rainfall time series data in updating the groundwater recharge of the main recharge areas. The Karoo sedimentary aquifer forms the headwaters of the Orange-Senqu River system. The Karoo sedimentary study area is defined by Tertiary catchments D11, D112, D15-D18, and D21-D23. The Khakhea/Bray aquifer is defined by the area of dolomitic outcrop of the Campbell-Rand dolomites, including where it is overlain by the Kalahari sands, and bounded by the area where the dolomites dip under banded ironstones.

For the implementation of groundwater management and the quantification of groundwater resources, the volumes of recharge to aquifers and its temporal distribution is required, since it defines the volume of the resource. Although in terms of groundwater resources, annual variations in recharge are somewhat buffered by aquifer storage, baseflow from a groundwater origin is less buffered and low recharge years can result in very low surface water flows, which have an impact on the ecology as well as the yield of dams and surface water resources. Baseflows, i.e. the dry weather and non-rainy season streamflows originating from the groundwater store, take on hydrological significance in that they constitute the so-called "low flows" which sustain aquatic habitats and the dry season flows into reservoirs, as well as providing a source of water to people and animals who have not yet been supplied with reticulated water.

In the Khakhea/Bray aquifer, recharge and water level was simulated and calibrated against observed water levels from 1983-1993, using the Cumulative Rainfall Departure Method. Recharge is seen to be episodic and highly variable, with only 2 recharge events during the period, 1983-1993.

The mean annual recharge is 1.68 mm/a, or 0.44% of rainfall. The monthly recharge values were aggregated to derive an annual rainfall-recharge relationship, which was found to be as follows:

Recharge = (Rainfall -344) * 0.0372.

Recharge only occurs when rainfall exceeds 100 mm/month. This rainfall has a return period of 22 months.

Calculated recharge for the entire aquifer is 14.79 Mm^3/a. In the Resource Unit directly shared between South Africa and Botswana it is 6.21 Mm^3/a. 1220 km^2 (59%) of the 2061 km^2 lie within South Africa and the remainder (41%) is in Botswana. In 2016 a restriction was implemented reducing the total abstraction to 8.2 Mm^3/a on the South African side. Demand from this resource unit is currently 10.2 Mm^3/a, of which 8.2 Mm^3/a, is for irrigation on the South African side.

This volume must be added 0.6 Mm^3/a, of irrigation on the Botswana side, along the Molopo River. The current combined groundwater use of 8.8 Mm^3/a exceeds the calculated recharge of 6.21 Mm^3/a in the shared compartment, hence why the significant water level decline that occurred in the study area, of up to 60 m.

It is likely that the recharge to the other resource units drains to the shared unit, since no natural outlets or springs exist. The current total abstraction total abstraction of 10.2 Mm^3/a, is less than recharge, but it remains to be seen whether water levels will recover.

The importance of quantifying and protecting recharge in the Karoo sedimentary aquifer spanning Lesotho and South Africa is that recharge drives the baseflow which forms a large component of flow in the Orange-Senqu River system. Since the requirements from a recharge study are twofold i.e. calculating recharge to determine its relevance to surface water baseflow protection, and calculating the groundwater resource, two types of information are required. These are the total recharge which drives both groundwater baseflow and interflow from springs; and aquifer recharge which reaches the regional aquifer and is available to boreholes. There must also be a water balance so that all of recharge is accounted for. Due to the large extent of the study area and the variable rainfall, point estimate of recharge would not be useful.

To derive a water balance for recharge and its eventual discharge, the WRSM2000 rainfall-runoff model was utilised, using the hydrological network agreed upon for the ORASECOM IWRM Phase 2 (2011). The original hydrological data from the Phase 2 of the ORASECOM's IWRM Plan Development Study did not include the Sami surface-subsurface groundwater module. This was included, and the model was recalibrated against observed flows with groundwater. This was also to ensure that the accepted surface water hydrological characteristics did not change significantly from those derived under the ORASECOM's IWRM Plan Development Study Phase 2, undertaken in 2011 (2011 study). This involved recalibrating 5 existing networks of the 2011 study (figure 4-3 and 4-4), the Katse dam subsystem, the Senqu river system to the Oranjedraai river flow gauging weir, the D21A, D21B, D22 & D23 river flow gauging station networks to the Welbedacht dam.

The study shows that existing GRAII (Groundwater Resource Assessment Phase II) recharge data is a large over estimate in the Karoo Sedimentary aquifer, especially in the Highlands. The observed surface water or river baseflows do not support such large recharge volumes. This can be attributed to the GRAII results being based on the Chloride (Cl) recharge estimation method, which assumes that all Cl from precipitation ends up in groundwater. This assumption is not valid in the area such as the karoo sedimentary aquifer where surface water runoff is high. The Cl method therefore overestimates the Cl load to groundwater, hence increasingly overestimates groundwater recharge with increasing volumes of surface water runoff.

The results show that catchments underlain by basalt generate proportionally more surface water runoff than those underlain by sedimentary rocks. The basalt aquifers also generate a higher proportion of baseflow. In the basalt catchments, over 90% of baseflow originates as interflow, and doesn't pass through the regional aquifer. This implies that over 90% of recharge is not accessible as a groundwater resource, resulting in the low borehole yields and limited groundwater resources in the basaltic Highlands. In the drier sedimentary lowlands, the bulk of recharge percolates to the regional aquifer.

For basalts, recharge can be defined by the following recharge-rainfall formula:

Recharge mm/a = (Rainfall – 396) *0.098.

For the Karoo sedimentary aquifer, the relationship between the two can be defined by the following formula:

Recharge mm/a = (Rainfall – 532) *0.12.

In terms of quantifying aquifer recharge to the regional aquifer and the groundwater available to boreholes, recharge to the Karoo sedimentary aquifer is proportionally higher than the basalt aquifer, since much of the recharge to the basalts is lost as interflow.

Aquifer recharge for the Karoo sedimentary aquifer can be defined by the following formula:

Recharge (mm/a) = 17.72 * LN Rainfall -105

Aquifer recharge for the basalt aquifer can be defined by the following formula:

Recharge (mm/a) = 17.87 * LN Rainfall -110

The total recharge (aquifer recharge and recharge generating interflow) in the Senqu River Basin is 945.03 Mm^3/a. The baseflow component is 760.76 Mm^3/a, of a total of 4165 Mm^3/a of discharge from the basin. This therefore means groundwater contributes 18% of discharge. Aquifer recharge is 221.1 Mm^3/a. Of this volume, 36.83 M^3/a (17%), generates baseflow from groundwater. Total Rainfall is 19279 Mm^3/a; hence aquifer recharge is only 1.1% of rainfall.

Total recharge in the Upper Caledon River basin is 337.10 Mm^3. Annual baseflow in the basin is 196.13 Mm^3 of 1241.62 Mm^3/a of runoff, therefore groundwater contributes 16% of discharge from the basin. Aquifer recharge is 176.11 Mm^3/a. Of this volume, 35.13 M^3/a (20%) generates groundwater baseflow. Total Rainfall is 11037.79 Mm^3/a; hence aquifer recharge is only 1.6% of rainfall.

TABLE OF CONTENTS

<u>LIST OF FIGURES</u>

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation or Acronym	Definition
CRD	Cumulative Rainfall departure
GRES	Groundwater Recharge Estimation Study
GWHC	Groundwater Hydrology Committee
GRAII	Phase II of the Groundwater Resources Assessment Study of South Africa
IWRM	Integrated Water Resources Management
JBS	Joint Basin Survey
ORASECOM	Orange-Senqu River Commission
SADC	Southern African Development Community
STAS	Stampriet Transboundary Aquifer System
SWI	Shared Watercourse Institutions
WR2012	Water Resources South Africa 2012
WRSM2000	Water Resources Simulation Model 2000 (Pitman Model)

LIST OF DEFINITIONS

Abstraction	The removal of water from a resource, e.g. the pumping of groundwater from an aquifer.
Aquifer	A geological formation, which has structures or textures that hold water or permit appreciable water movement through them.
Aquifer Recharge	Rate of replenishment to the regional aquifer
Aquifer hydraulic properties	The properties of permeability and specific yield, or transmissivity and storativity that determine the rate at which an aquifer transmits water, and the volume of water it releases from storage
Baseflow	The contribution of subsurface water to surface water channels to maintain dry season flows
Groundwater baseflow	The contribution to baseflow from the regional aquifer
Interflow	The contribution of subsurface water to surface water courses as baseflow before entering the regional aquifer
Ephemeral river	Rivers that do not flow continuously and have limited if any baseflow
Fault	A zone of rock displacement resulting from tension or compression forces
Formation	A sequence of rock layers of similar lithology deposited continuously
Harvest Potential	The maximum volume of ground water that may be abstracted per area without depleting the aquifers. It is based on estimated mean annual recharge and a rainfall reliability factor, which gives an indication of the possible drought length.
Permeability	The rate at which a permeable material transmits a fluid, expressed as a length per unit time
Recharge	Rate of ingress or replenishment of water into an aquifer expressed as a volume or depth per unit of time
Static (Rest) water level	Water levels are not influenced by pumping and constitute the water table influenced only by atmospheric pressure.
Storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the average

hydraulic conductivity (K) and thickness (b) of the saturated portion of an aquifer (T = Kb).

1 INTRODUCTION

1.1 BACKGROUND

ORASECOM is one of the first Shared Watercourse Institutions (SWIs) established in 2000, under the SADC Protocol on Shared Watercourses. ORASECOM provides technical advice to its State Parties on matters relating to the development, utilisation and conservation of the water resources in the Orange-Senqu River System. ORASECOM comprises of the Council of Commissioners, the Secretariat, the Groundwater Hydrology Committee (GWHC) and four Task Teams responsible for technical, communications, finance and legal issues. There is also a working group responsible for water resources quality management in the Basin, which meets on an ad-hoc basis. The 2000 ORASECOM Agreement is also being revised to include a Committee of Ministers Responsible for Water in the Basin, known as the Forum of the Parties.

The importance of groundwater has generally been understated in the past. Since its inception ORASECOM has made efforts to resolve this, but it is only in recent years that the significance of groundwater at the regional and basin wide level is being given due consideration. This is important for the following reasons: (i) groundwater provides the single important water supply source, water security and supports livelihoods of majority of rural communities and those resident in the semi-arid and arid regions of the basin; (ii) groundwater and surface water are closely linked. This is especially true in the wetter source areas where the strengths of springs and the base flows of perennial streams are closely related to the condition of the water table; (iii) there are four transboundary aquifers in the basin, which are the focus of this study. Shared management is clearly essential; and (iv) the conjunctive use of groundwater and surface water storage can contribute to improved water security.

The rationale for this study consists of upgrading knowledge for 3 components:

1. **Recharge**: The current understanding of transboundary aquifers is poor as is the management of such resources. Main recharge areas, recharge magnitudes and flow patterns are poorly known. Recharge estimates made by previous studies need to be reviewed.
2. **Monitoring of Important Features and Characteristics of Transboundary Aquifers:** There are currently no joint monitoring programmes of the four transboundary aquifers of the Orange-Senqu River Basin, except the STAS.
3. **Groundwater Focused Information System:** ORASECOM has developed an internet-based water information system, commonly known as "WIS". The WIS (http://wis.orasecom.org/) currently provides the following functions:- (i) repository and cataloguing to ensure integrity of data and information acquired and produced by ORASECOM and the projects associated with it; (ii) web-based search and discovery of data to enable discovery of ORASECOM data and information; (iii) data exchange and sharing with appropriate users, including download of ORASECOM data and information for different user groups, while respecting third party data ownership rights; (iv) web based provision of data products to the general public, and (v) profiles of the data custodians in the riparian States and links to their websites to facilitate data and information discovery and sharing. Unfortunately, most of the information and data found on the WIS are on surface water.

This report addresses the first component.

1.2 STUDY AREA

There are four transboundary aquifers in the basin (Figure 1-1 and Table 1-1). Of the 4 systems, the STAS is covered by another programme. Information on the Coastal Sedimentary Aquifer is confidential as it is a restricted diamond mining land. Consequently, this report will focus on the Karoo Sedimentary Aquifer and the Khakhea /Bray Dolomitic aquifer.

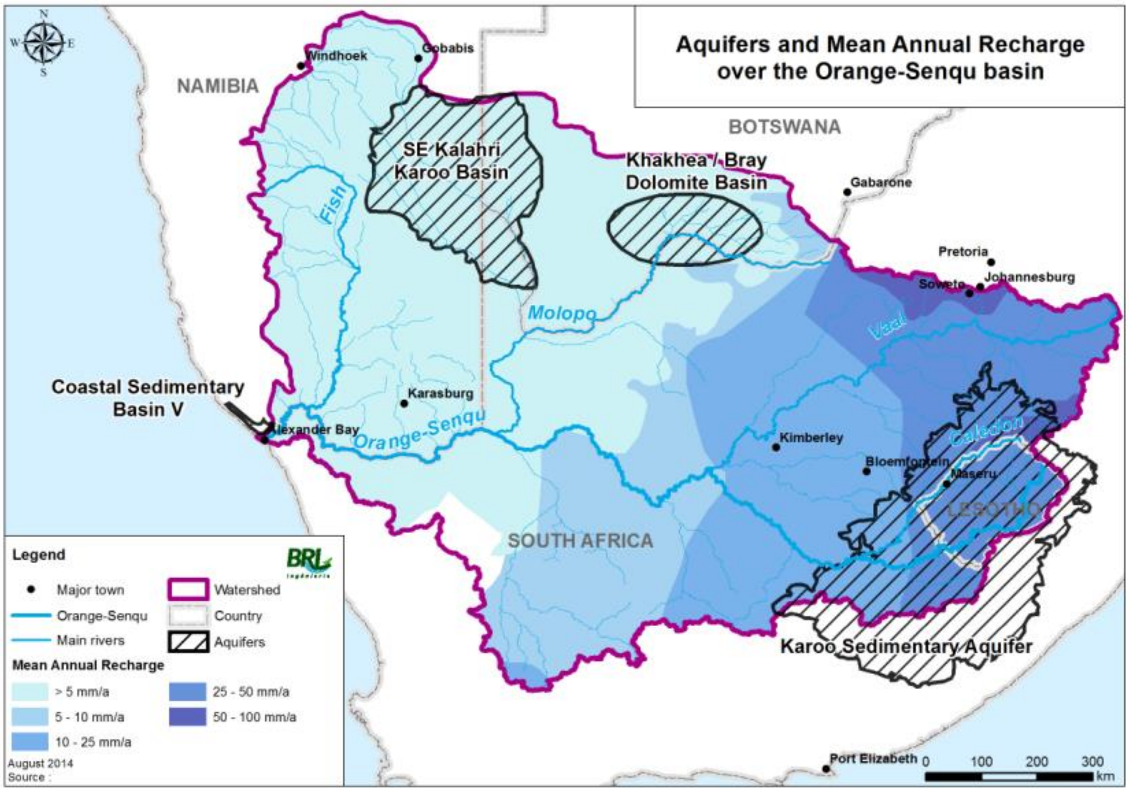


Figure 1-1 Four Transboundary Aquifers and the Mean Annual Recharge over the Orange-Senqu River Basin

1.3 SCOPE OF WORK

The scope of work for this task was expressed as:

Documenting of Groundwater Recharge in the Karroo Sedimentary and the Khakhea/Bray Dolomite Aquifers:

- Undertake a Literature review of all groundwater recharge estimation studies undertaken in the Karroo Sedimentary and the Khakhea/Bray Dolomite Aquifers;
- use rainfall time series data in updating the groundwater recharge of the main recharge areas in the above-mentioned transboundary aquifers;
- update and document the latest groundwater recharge estimates at key recharge areas in the Karroo Sedimentary and the Khakhea/Bray Dolomite Aquifers;
- Validate the groundwater recharge estimates with the key stakeholders through a workshop; and
- Develop a final report on updated recharge estimates in the two aquifers based on inputs from the stakeholders' workshop.

1.4 Study Areas

The proposed study area is the Karoo sedimentary aquifer forming the headwaters of the Orange Senqu system. The Karoo sedimentary study area is defined by Tertiary catchments D11, D112, D15-D18, and D21-D23.

The Khakhea-Bray is defined by the area of dolomitic outcrop of the Campbell-Rand dolomites, including where it is overlain by Kalahari sands, and bounded by where the dolomites dip under banded ironstones.

1.5 Recharge Estimation

For the implementation of groundwater management and the quantification of groundwater resources, the volumes of recharge to aquifers and its temporal distribution is required, since it defines the volume of the resource. The quantification of recharge is increasingly given attention in the management of groundwater, particularly in semi-arid regions where the average rainfall is generally low and the evapotranspiration rates are high. To ensure the long-term sustainability of this resource, it is essential that the groundwater recharge be estimated. Recharge is the ultimate upper boundary defining potential groundwater abstraction if an aquifer is not to be mined out.

Although in terms of groundwater resources, annual variations in recharge are somewhat buffered by aquifer storage, baseflow from a groundwater origin is less buffered and low recharge years can result in very low flows, which have an impact on the ecology as well as the yield of dams and surface water resources.

Baseflows, i.e. the dry weather and non-rainy season streamflows originating from the groundwater store, take on hydrological significance in that they constitute the so-called “low flows” which sustain aquatic habitats and the dry season flows into reservoirs, as well as providing a source of water to people and animals who have not yet been supplied with reticulated water.

2 RECHARGE ESTIMATION METHODS

2.1 Recharge Estimation Methods

One of the challenges of recharge estimation is that there are numerous factors that influence recharge estimation methodologies. In addition, the high degree of spatial and temporal variability affects recharge estimation and results in high levels of uncertainty. As such, recharge is difficult to determine precisely. Even though there is a wealth of recharge estimation methods available for semi-arid areas, each has its own limitations.

Recharge can occur frequently or episodically and is controlled by the volumes, frequency and intensity and variation of rainfall over time in the recharge area, as well as by the thickness and type of overburden material. The daily and spatial variability of rainfall-recharge is somewhat evened out by the surface overburden and the equalisation of the resulting water levels is affected because of the transmissivity of the aquifer.

Although the quantification of recharge is difficult, it can be calculated using various methods. The most commonly used reliable and practical methods are listed in Table 2-1. The methods that were utilised for recharge estimation in the study areas are described further, in sections 2.2 to 2.5.

Table 2-1 Recharge estimation methods

Method	Comments/requirements
1. Chloride mass balance: - the most independent method based on the ratio of Chloride concentrations of rain to that of groundwater	Chloride concentrations in rainfall and groundwater are required. It is assumed that all chloride in rainfall is transferred to groundwater and no sources or sinks exist. For this reason, the method doesn't work where runoff is high or where saline geology exists
2. Bicarbonate method: - This method could be used If the CMB method fails because of too high Chloride in the groundwater	First must be calibrated according to reliable estimates based on other methods of which the chloride mass balance method is the most reliable
3. Equal volume interpretation of the water balance	Needs data on pumping or of spring flows or baseflow and many water levels
4. Cumulative rainfall departure and moving average of rainfall	Requires an estimate of S and the aquifer area; abstraction, also, a long series of monthly water level data
5. Hydrodynamic groundwater modelling, which determines the water balance and flow between grid elements.	Depends on the reliability of the simulation of groundwater levels. Needs skilled modelling expertise
6. Simulation of the re-appearance of bomb C14 in the rainfall in the spring discharge.	The recharge is separated in low and high rainfall recharge to incorporate fast and slow recharge that has different C14 inputs into the aquifer Recharge parameters as well as the turn-over time of the aquifer is determined. The latter represent the

	storage of the groundwater relative to the average recharge
7. Using a recharge-rainfall relationship by which the variability of recharge can be simulated from rainfall records. This method has been used in the present study to derive regional estimates of the recharge purely from the rainfall.	Assumes the rainfall-recharge relationship is similar to the area in which the relationship was derived
8. Integrated surface-subsurface models	They maintain a water balance with recharge driving baseflow. They require flow data and rainfall data for calibration

2.2 Chloride Mass Balance Method

This method assumes a Chloride Mass Balance formula so that Recharge is calculated by:

$R = (Cl_p / Cl_{gw}) * MAP$

Where R = recharge (mm/a)

MAP = Mean Annual Precipitation (mm/a)

Cl_p = chloride in rain (mg/l)

Cl_{gw} = chloride in groundwater (mg/l)

The Chloride Mass Balance method assumes a conservation of mass between the input of atmospheric chloride (rainfall) and the chloride flux in the subsurface, thereby assuming that chloride is a conservative tracer. This method of recharge estimation assumes that the various chloride concentrations have resulted from natural, hydrological and evaporative processes. As such, no chloride was added by dissolution of aquifer material, from salts contained within the aquifer matrix, or has entered the aquifer via pollution; and none has been exported by surface runoff.

The percentage of rainfall entering the groundwater, representing average annual recharge, can, therefore, be derived from the ratio of the chloride concentration in rainfall relative to that of groundwater.

Mean Annual Precipitation: Knowledge of the rainfall patterns and the amount of rainfall that has fallen in the study area is essential, given that this information is critical to the quantification of recharge.

Chloride in Groundwater: Reliable (accurate laboratory analysis) and spatially representative chloride concentration data in groundwater is essential to enable assessment of recharge.

Chloride in Rainwater: Reliable, time-related chloride data for all the rainfall stations in the area would have also proved valuable, however, such data does not exist. Within Southern Africa there is a lack of rainwater chloride concentration data. However, a rainfall chloride map was created during the GRAII study of South Africa (DWAF, 2006).

2.3 Cumulative Rainfall Departure Method

This method assumes that the response of the groundwater levels reacts in an equivalent manner to the cumulative departures of the rainfall in excess of or below the long-term monthly average rainfall. Groundwater level fluctuations are assumed to correspond to the moving average rainfall over a characteristic period, from which quantitative estimates of recharge could be derived for all types of aquifers, if water level measurements and rainfall data are available.

The cumulative rainfall departure method utilises the following equations:

$CRD_i = R_i - k\, R_{avg} + R_{i-1}$

Where:

CRD_i is cumulative rainfall departure (CRD) for month i [mm];

R_i is rainfall in month i[mm];

R_{avg} is average monthly rainfall for the entire rainfall record [mm];

k is a constant representing pumping or injection (equals 1 for no pumping) [dimensionless].

Most often, an acceptable correlation exists between the CRD and the groundwater level, This correlation is expressed as the proportionality constant a so that:

$H_i = a\, R_i + H_w$

Where H_w = average depth of the groundwater level below surface;

Or when expressed as a change in water level $\Delta\eta_\iota$:

$\Delta\eta_\iota$: = a (R_i-kR_{avg})

Constant a represents a lumped coefficient of recharge and storativity (Recharge/s). The objective is to find a fixed proportion of rainfall for every month above average rainfall that contributes to recharge. The correlation between the CRD and the groundwater levels is often improved by introducing the concept of lag effects to incorporate the time lag required to observe the effect of a recharge event on the water table. The lag effect often includes both a short memory [months]; and a long-term memory for the redistributed effect of recharge over long term, usually reflecting subtle climatic or hydrological cyclicity[months]. Thereby, instead of average rainfall, a long term moving average of rainfall is used.

The relationship between monthly CRD and water levels is sought using iteration/optimization techniques. By changing parameters such as the long and short-term memory iteratively, the best fit can be found.

2.4 Empirical Rainfall-Recharge relationship

Empirical rainfall-recharge relationships are used to obtain approximate values of possible recharge once the long term annual precipitation is known. Primarily, the relationship needs to be calibrated by other techniques to estimate the recharge. Any relationship obtained is valid for a long-term average and is site-specific. However, some relations developed for specific geological conditions could be applied in similar conditions.

Bredenkamp (1995) obtained a linear relationship between rainfall and recharge for dolomites in South Africa:

$Recharge = A\,x$ (Rainfall - B)

Where B represents the threshold rainfall that is required to initiate recharge, Rainfall is the annual precipitation, and A is lumped catchment parameter representing the fraction of rainfall above the threshold that generates recharge.

Other relationships also commonly take an exponential form such as:

Recharge = A $e^{\text{Rainfall X b}}$

2.5 Groundwater Models

To use the groundwater flow equation represented by a mathematical model to estimate the distribution of hydraulic heads, or the direction and rate of groundwater flow, a partial differential equation (PDE) must be solved. Both initial conditions (heads at time (t) =0) and boundary conditions (representing either the physical boundaries of the domain, or an approximation of the domain beyond that point) are needed in the process of solving the equation.

The topic of numerical groundwater models is complex. The model domain uses grids or meshes to solve the groundwater flow equation by breaking the problem area (domain) into many small elements (squares, rectangles, triangles, blocks, etc.) and solving the flow equation for each element (all material properties are assumed constant or possibly linearly variable within an element), then linking together all the elements using conservation of mass across the boundaries between the elements.

MODFLOW is a well-known example of a general finite difference groundwater flow model. It was developed by the US Geological Survey as a modular and extensible simulation tool for modelling groundwater flow.

Models require extensive data on permeability and boundary conditions if a unique solution is to be found for recharge. They also require a well distributed field of water level observations for calibration. If permeability is not well known, there is a risk of many possible recharge/permeability/boundary conditions that could provide a calibrated fit.

2.6 Integrated surface-subsurface models

As part of GRAII, a methodology and algorithms were developed whereby recharge, baseflow and the impacts on baseflow from groundwater abstraction and its proximity to river channels could be simulated. The methodology was incorporated into the WRSM2000 Model (Pitman Model) as part of WR2005 (Water Resources 2005) (It is commonly referred to as the Sami Model in South Africa).

The model simulates the following surface water and groundwater interactions:

BASEFLOW

- Interflow occurring from the unsaturated zone contributing to hydrograph recession following a large storm event, or discharge from perched water tables via temporary or perennial springs located above low permeability layers, which may cause prolonged baseflow following rain events, even when the regional water table is below the stream channel
- Groundwater baseflow discharged from the regional aquifer to surface water as baseflow to river channels, either to perennial effluent or intermittent streams.

RIVER LOSSES

- Transmission losses of surface water when river stage is above the groundwater table in phreatic aquifers with a water table in contact with the river.

BASEFLOW REDUCTION

- Groundwater baseflow reduction by reduction of groundwater flow to rivers and induced recharge caused by pumping of aquifer systems near rivers causing a flow reversal.
- Evapotranspiration from shallow groundwater table areas

This groundwater module replaces the original subsurface component of the Pitman Model and derives a time-series of recharge, from which a percolating storage and aquifer storage are replenished. Depletion of storages is by interflow (from percolating storage), groundwater baseflow, evapotranspiration, outflow to other catchments and abstraction. The model and verification studies are described in (Sami, 2014).

Monthly aquifer recharge is calculated from the Pitman S soil moisture variable by:

$$RE = HGGW\left(\frac{S-SL}{ST-SL}\right)^{GPOW}$$

Where

RE = variable of potential aquifer recharge (mm). If the percolating storage is full, the surplus is discharged as interflow

HGGW = parameter of maximum recharge in mm at maximum soil moisture (ST)

S = variable of soil moisture in mm

SL = Parameter of soil moisture threshold below which there is no recharge

GPOW = Parameter of the storage-recharge relationship

The output of the algorithm is a monthly time series of recharge to the percolating store.

Since recharge calculated from the Pitman S variable is not lagged relative to rainfall, recharge is directly related to monthly rainfall. However, the lag between rainfall and recharge to the regional aquifer may be significant in some aquifers. Significant lags may also exist between recharge reaching the aquifer and baseflow generation where long travel times exist, such as in dolomites, with long lag times resulting in eyes that flow all year. Therefore, it is necessary to lag recharge so that baseflow is not all generated in the month when a large rain event occurs. Attenuation for the travel time from the soil to the regional aquifer is accomplished through a storage (percolating storage) that conceptually represents the percolating zone between the soil and aquifer. Recharge is added to this zone, and then released to the aquifer at a slower rate, depending on the size of the store and the storage level.

Baseflow, and consequently recharge, is calibrated according to flow data at gauging weirs. Recharge can also be calibrated against independent recharge values that are available, however, the need to calibrate recharge and baseflow to fit surface water flows as well constrains the model user to realistic recharge values. This is the tyranny of a water balance when using integrated models; the subsurface water balance must balance with the surface water balance if a comprehensive calibration is to be achieved. Excessive recharge cannot be 'lost', and insufficient recharge cannot be calibrated against observed baseflows.

Estimated parameters are available for all of South Africa and Lesotho. Inputs required are rainfall, abstractions, dams; and gauging weir data against which to calibrate.

3 KHAKHEA-BRAY AQUIFER

3.1 Introduction

In the Khakhea/Bray area, two main aquifer types can be identified, namely porous sedimentary and karstic. The porous aquifer, that stores and transmits water via the interstitial pore space in the sedimentary formations is represented by alluvial and Kalahari Bed aquifers. The karstic fractured aquifer is of carbonate rocks where solution weathering along joints, fractures, and bedding has enhanced the water-bearing capabilities of the rock.

3.2 Climate

The study area is characterised by a low annual rainfall. Data series of sufficient length is available for the following rainfall stations from WR2012 (table 3-1 and figure 3-1). The average for all stations is 376 mm/a.

Table 3-1 Rainfall stations

Station	Name	Latitude	Longitude	Years of record	Status	MAP (mm/a
504 050	Pomfret	25 49	23 31	1948-1989	Closed	380
505 347	Vergelegen	25 46	24 11	1952-1989	Closed	425
505 493	Boshoek	25 43	24 17	1932-2006	Closed	447
504 306	Python	25 36	23 41	1973-1990	Closed	316
541 297	Bray	25 27	23 40	1946-2009	Open	362
	Khakhea	24 21	23 30	1981-2002	?	409
	Werda	25 16	23 16	1981 -2002	?	295

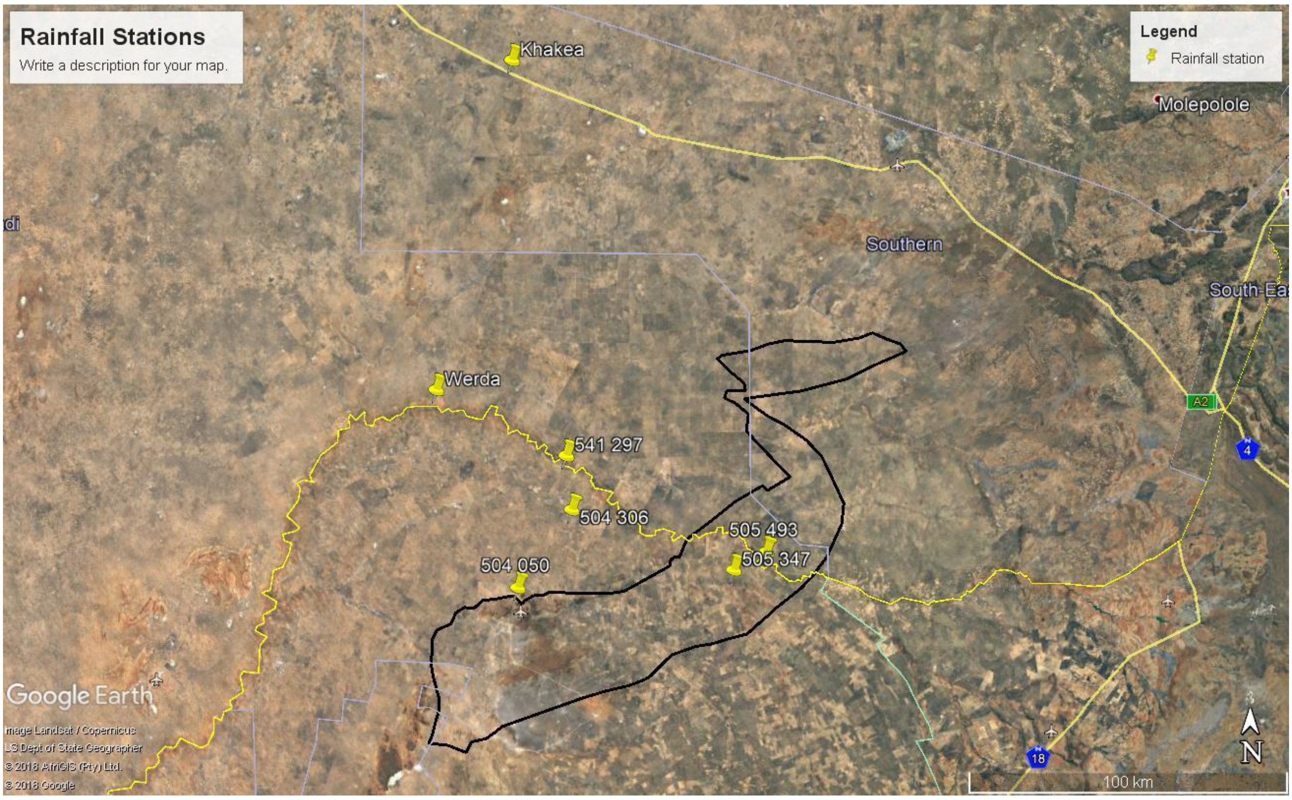


Figure 3-1 Location of rainfall stations

The rainfall distribution pattern for rainfall zone D4B in WR2012 was utilised to derive mean monthly and annual rainfall distributions for the study area (table 3-2 and figure 3-2 and figure 332). Rainfall is less than evaporation in all months except the wettest years on record. Rainfall varies from 174-715 mm/a.

Table 3-2 Mean monthly rainfall and evaporation

Rainfall			Evaporation		
Month	% of annual	Mean monthly mm	S-Pan mm	Pan factor	Mean monthly catchment Evapotranspiration mm
Oct	7.10	26.71	243	0.8	194
Nov	11.17	42.01	229	1	229
Dec	13.42	50.48	252	1	252
Jan	17.68	66.47	248	1	248
Feb	16.25	61.10	206	1	206
March	16.74	62.93	204	1	204
April	8.52	32.05	157	1	157
May	3.11	11.70	132	1	132
June	1.41	5.32	107	1	107
July	0.56	2.10	117	0.8	94
August	1.03	3.87	155	0.8	124
Sept.	2.23	8.38	201	0.8	161
TOTAL		376	2250		2107

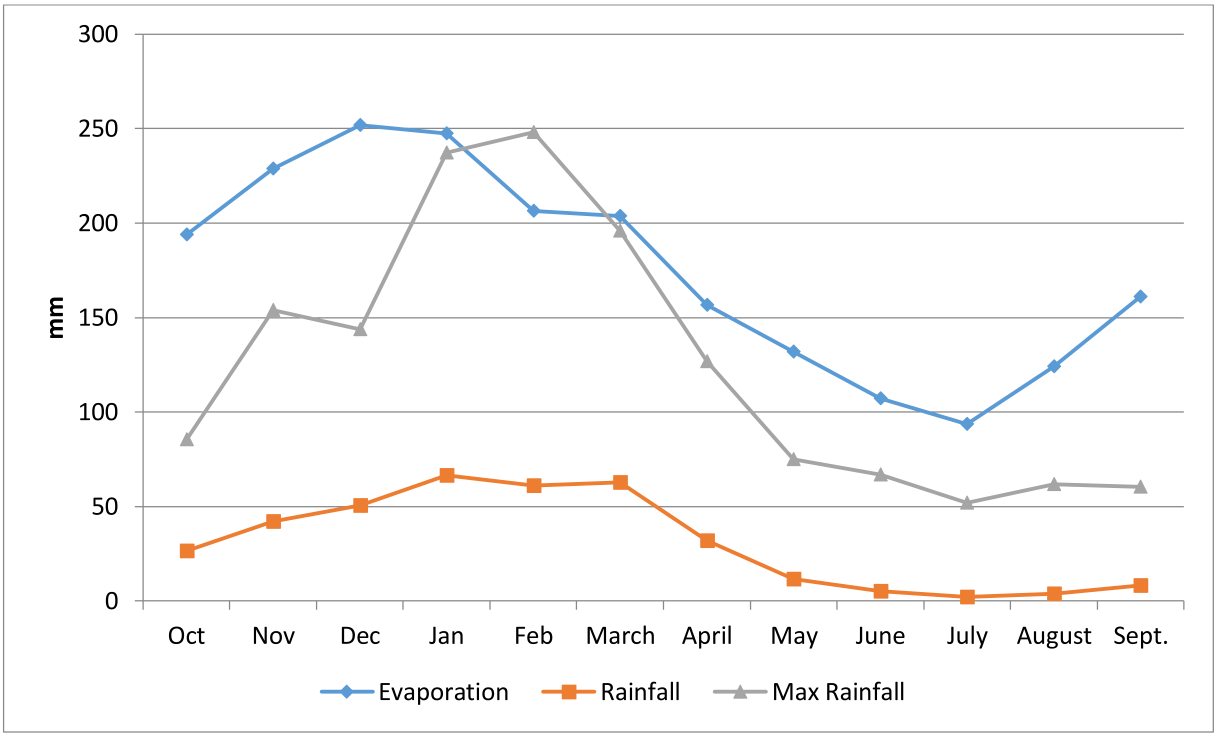


Figure 3-2 Mean monthly rainfall and evaporation

The mean annual rainfall was used to statistically derive drought rainfall based on the General Extreme Value Distribution (GEV) (figure 3-4). The 100-year drought rainfall is 155 mm/a. The 10- year drought rainfall is 231 mm/a.

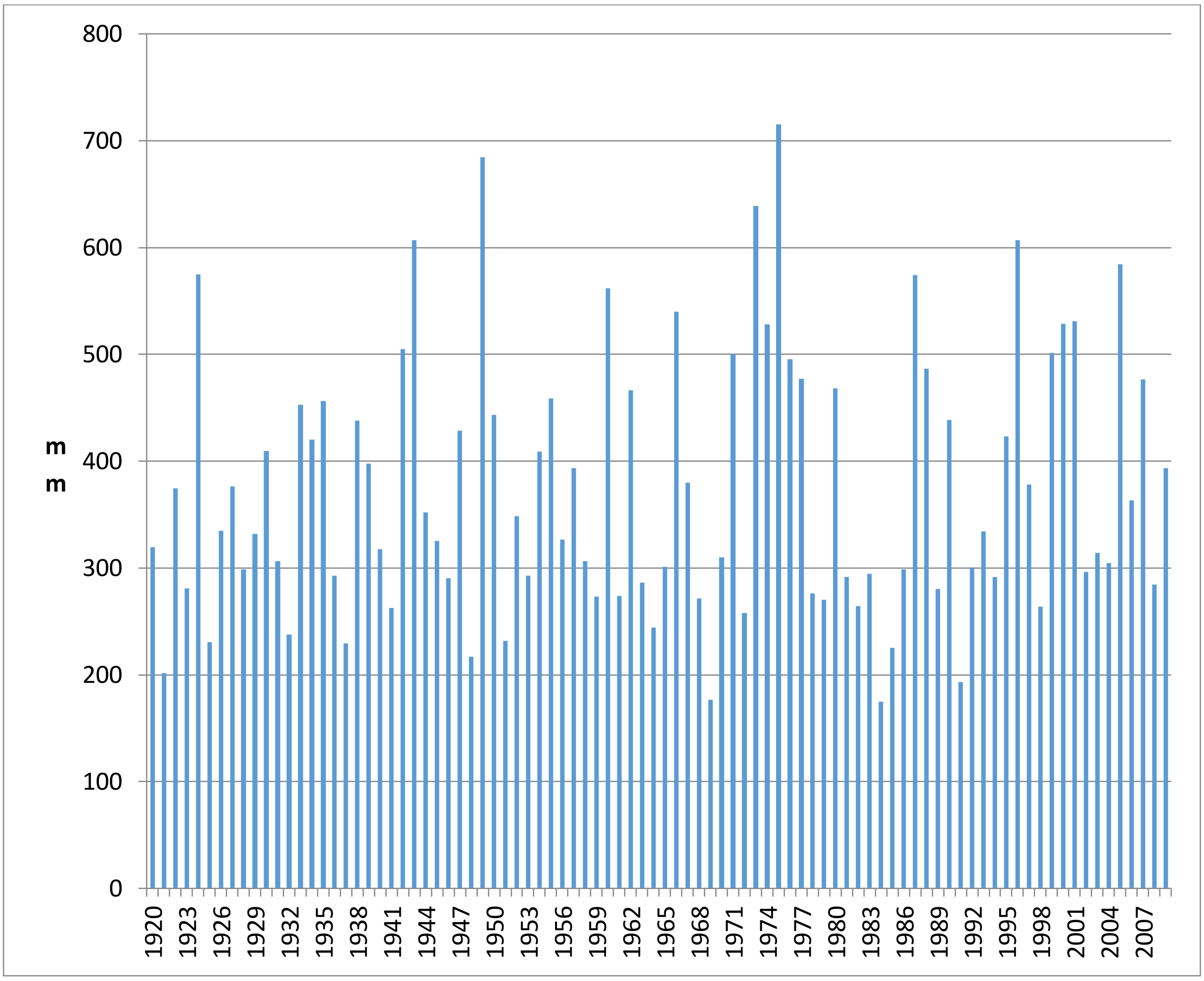


Figure 3-3 Mean annual rainfall

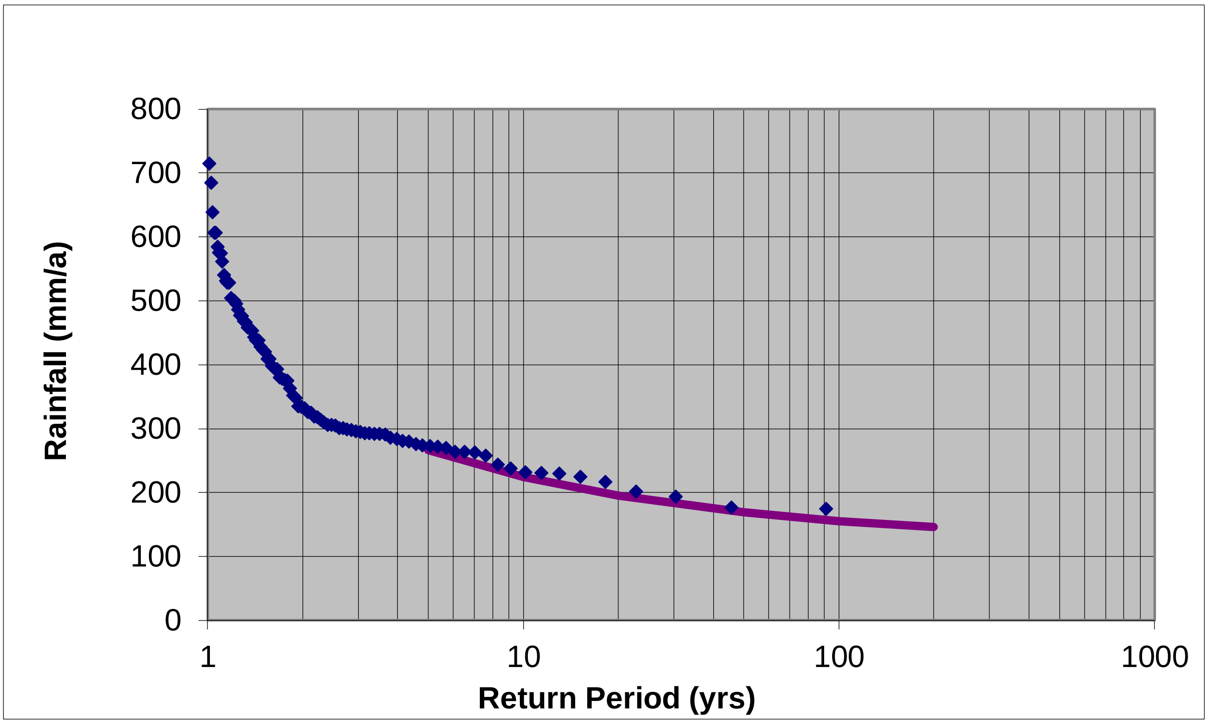


Figure 3-4 Mean annual rainfall and best fit GEV distribution

3.3 Drainage

The Molopo river is ephemeral and used to flow after heavy rainfall events, however the building of dams (Disaneng dam and recently the Modimola dam) upstream has impeded river flow. There is no groundwater baseflow to rivers in this area. Instead the Molopo river acts as a 'water loss' river, recharging groundwater during runoff events.

3.4 Geology

The Geology of the aquifer consists of 2 units of interest:

Kalahari Group: Quaternary and tertiary sediments, pan sediments (sand and clay), diatomaceous limestone and aeolian sand, with extensive coverage all over the area; and

Griqualand west/ Kanye basin: Predominantly carbonate rocks such as limestone, and dolomite with interbedded chert. They lie conformably on the Vryburg Formation, which is the base of the dolomite and consists of quartzite, flagstone and grit.

The stratigraphic succession of the area is given in Table 3-3. The geology is shown in Figure 3-5.

3.4.1 Lithology and stratigraphy

Archaean granites and gneiss form the basement of the area, outcropping to the south and east of the study area where the Kalahari cover is thin. They are characteristically associated with the Mesoarchaean Kraaipan - Amalia Group of rocks. Outcrops are restricted to a few highly weathered outcrops in stream beds that cut into the flattish terrane of sand and calcrete cover; water storage pits; trenches and, rarely, as flat whaleback pavement exposures. Outcrops are characterised by the abundance of variably fractured granitoids, among which gneissic tonalitic, trondhjemitic and granodioritic compositions are dominant.

The granites are overlain by quartzites of the Vryburg (South Africa)/Kanye (Botswana) Formation which reaches a thickness of only tens of meters. This is the basal unit of the Transvaal Supergroup in the Griqualand West Basin. TheVryburg Formation, is the equivalent of the Kanye Formation in Botswana. It consists of shales, siltstones, quartzites, subordinate carbonates and basaltic to amygdaloidal lavas and in Botswana has an age of about 2650 Ma.

Overlying the Vryburg Formation, the Schmidtsdrif Formation consists largely of a lower unit of platform carbonates, as well as fluvial quartz arenites. The Ghaap Plateau Formation consists of dolomites, limestones and cherts. These are known collectively as the CampbellRand Group in South Africa and the Taupone Group in Botswana. The Asbestos Hills Subgroup conformably overlying the Campbellrand Subgroup is divided into the basal Kuruman and overlying Griquatown Formations.

The dolomites of the Campbell Group reach thickness of 900-1650 m and are a significant water bearing formation. The dolomites are overlain in the west of the study area, by banded ironstone of the Asbestos Hills Subgroup. Intruded into these rocks are dolerite sills and dykes. This package of rocks dips at approximately 10° into a north-westerly direction. Large north-south trending faults are also present within the area.

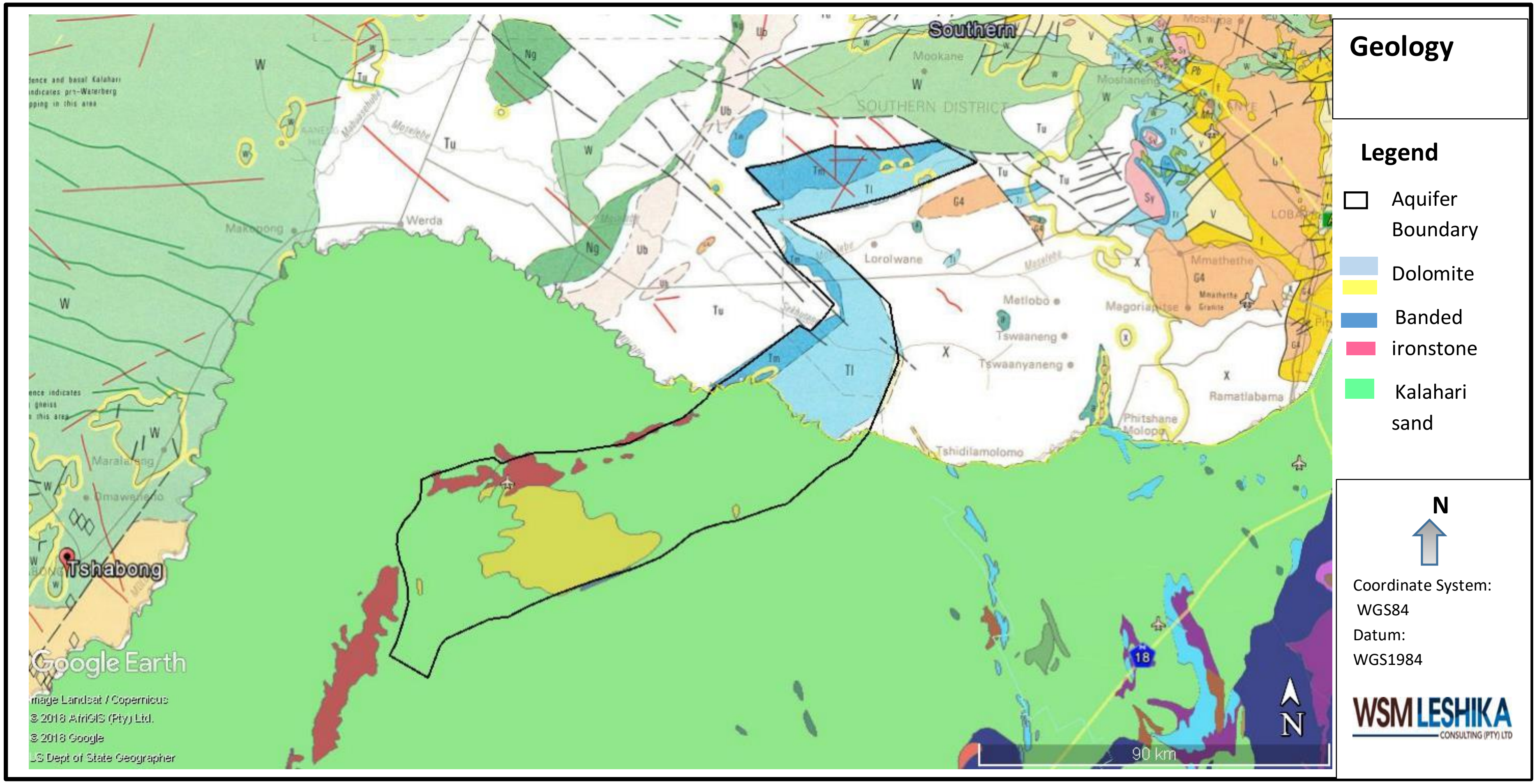


Figure 3-5 Geological map

Table 3-3 Stratigraphy

Group	Formation	Lithology
Kalahari	Gordonia	Red brown aeolian sand
	Eden	Calcareous sandstone and clay
	Budin	Red clay
	Wessels	Sandstones and gravels
Late Karoo intrusions		Dolerite dykes
Griquatown	Asbestos Hills	Banded ironstone and chert
Campbell Rand/ Taupone	Ghaap Plateau	Dolomite, chert and limestone
	Schmidtsdrift	Dolomite and shale
	Vryburg/ Kanye	Quartzite

An era of intense weathering and erosion followed the deposition of the Griqualand West Sequence, carving a north-east trending U-shaped valley into the dolomite. The depth of the valley below the present surface increases towards the Molopo river where a depth in excess of 150 meters is reached. This valley is filled with younger (Quaternary – Tertiary) clastic and clayey fluvial sediments of the Kalahari Group.

At the base of the valley gravels and sandstones of the Wessels Formation were deposited. These gravels are poorly sorted and range in size from less than 1 mm to 25 mm.

On top of the gravels red-brown clay of the Budin Formation were deposited, followed by fine grained sandstone of the Eden Formation. The Budin Clay Formation (a red clay) is restricted to valleys or depressions in the pre-Kalahari surface and may be fluvial or lacustrine in origin. The Kalahari sandstones (Eden Formation) have a much wider distribution than the clays and gravels and may have been in part deposited in a braided river system.

The sequence is covered by red-brown aeolian sand which covers most of the area. The surface Aeolian sands, named the Gordonia Sand Formation, are up to 20m thick and are underlain by a duricrust horizon of silcrete and calcrete.

Partridge et al, (2006) divide the Kalahari Group into six Formations, namely the basal Wessels, overlying Budin, Eden, Mokalanen, Obobogorop and Gordonia Formations. The calcretes at the base of the Gordonia Formation are assigned to the Mokalanen Formation and can be divided into a lower, sandy limestone and an overlying conglomerate with a calcareous matrix. The Obobogorop Formation, lying above the calcretes, comprise pebble and boulder clasts believed to have been derived from erosion of Dwyka tillite and, in places, form the cappings of flat erosional remnants. This Formation is unlikely to be present in the study area.

The thickness of Kalahari sands varies across the area from less than 15 m near the dolomitic outcrops in the west, to up to 120 m of thickness in proximity to the Molopo river (figure 3-6). The thickness of the Kalahari succession is largely a function of pre-Kalahari Group topography, with the gravels being largely confined to palaeovalleys and channels. In in excess of 220m of Kalahari deposits has been proven in the Bray area and in adjoining Northern Cape Province.

Along the Molopo river and tributaries, very recent river deposits are present. The channel of the Molopo river meandered within a 4 km wide band from the present channel to build up a riverbed deposit up to 30 m in depth. These deposits consist of gravels of 1 to 10 mm, sandbars, and fine-grained sand and to a lesser extent silt.

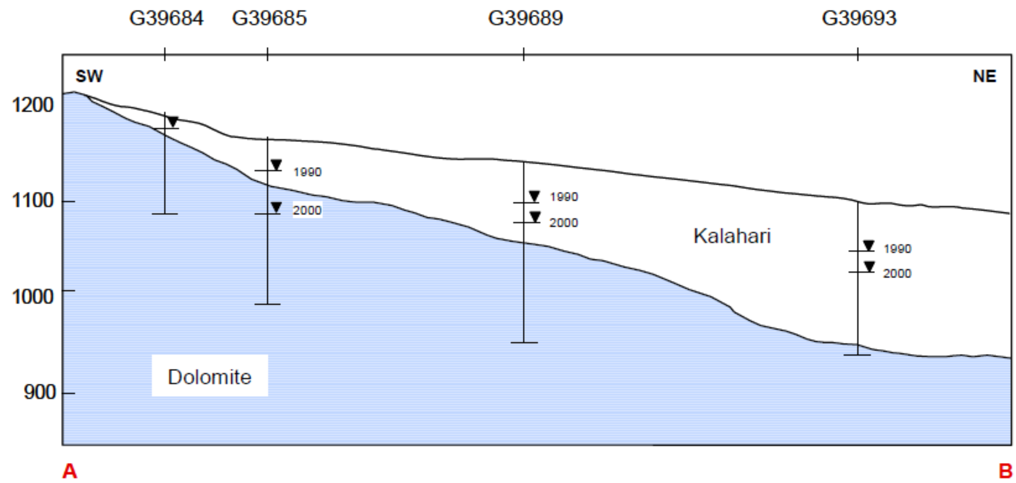


Figure 3-6 Cross section across the study area

3.4.2 Structure

In view of the extensive cover of unconsolidated sands, both the sub-Kalahari lithologies and their related structures are poorly exposed on surface, if at all. Structural studies in the area are, therefore, heavily dependent on geophysical methods, coupled with drilling or trenching, to establish critical relationships and the structural nature of the sub-Kalahari geology.

High-density aeromagnetic and gravity data has been generated by the Council for Geoscience. Of relevance to the hydrogeology is the presence of dykes detected by such methods. A number of strong linear magnetic anomalies cross the study area. Owing to the general lack of outcrop, these are interpreted as dykes, with or without fault movement, that are generally near vertical.

In the dolomite aquifer intrusive dykes act as barriers that impede the underground leakage to adjacent compartments. These dykes constitute a unique characteristic of the dolomite aquifers as their low permeability restricts the underground outflow of groundwater. In this way they retain the recharge from abnormally high rainfall for longer periods and thus causes more sustained flow from the springs that drain compartments during periods of drought.

3.5 Hydrogeology

3.5.1 Dolomitic aquifers

The karstified fractured aquifers are represented by Transvaal dolomite and chert units of the Taupone Group in Botswana and Ghaap Plateau subGroup in South Africa. In the Chert breccia aquifer, yields range from 20 to 70 m^3/h. Within karstic dolomite aquifer, yields range from <10 to 90 m^3/h (DWA, 2006).

The dolomites of the Ghaap SubGroup in South Africa have generally good ground water potential and yields in excess of 7.20 m^3/hr (2.0 ℓ/s) are common. Groundwater occurs along the fractures, joints, and solution cavities commonly associated with faults and diabase dykes. More than 25 % of the boreholes yield from 1.80 m^3/hr to 7.20 m^3/hr (0.5 to 2.0 ℓ/s) and 13 % of the boreholes yield more than 18 m^3/hr (5 ℓ/s).

3.5.2 Kalahari Group Aquifers

The Kalahari aquifer(s) constitute an important water supply source in the region, having yields ranging from <1.0 m^3/hr to 8.6 m^3/hr.

The basal Kalahari gravels can constitute a useful aquifer. The Kalahari Group sediment thickness around Bray in Botswana and Vryburg in South Africa indicate a broad 15-30 km wide trough of these sediments (in excess of 180 m thickness) forming a paleo-valley. Steep gradients are observed on the northern and southern flanks of the paleo-valley. The northern flank shows several tributaries, which drain southwards into the paleo-valley. The paleo-valley crosses the international border and passes into the Molopo Farms area. Yields range from <1.0 m^3/hr to 8.6 m^3/hr.

Although groundwater can be found in small quantities all over the area, the best yields of potable groundwater are intersected in the areas where the Kalahari has a large saturated thickness. The groundwater levels remain fairly static because of the high storativity of the alluvial sediments, which without evidence of active recharge provides sufficient water to bridge periods of drought.

3.5.3 Hydrogeological delineation of the study area

The study area is defined as the sub-outcrop boundary of the Transvaal Group dolomites. The study area occupies part of quaternary catchments D41C, D, E and F in South Africa and catchment Z10D in Botswana. The dolomitic aquifer is currently overutilized in South Africa due to the abstraction of groundwater for agricultural activities. Due to the nature of the dolomitic aquifer, and the fact that the quaternary catchment boundaries do not form groundwater divides, the entire dolomitic aquifer was selected as the boundary of the study area and dykes were used to subdivide it into compartments.

Three Resource Units (RUs) are defined within the dolomitic aquifer (Godfrey and Van Dyk, 2002) in South Africa, identified from observed aquifer characteristics, from drilling logs, water level response, aquifer tests and the presence of regional dolerite dykes. One of the Resource Units extend into Botswana but was not considered by Godfrey and Van Dyk. A fourth Resource Unit was identified as the overlying, low yielding, Kalahari Group aquifer. This unit is only used extensively close to the Molopo river due to the good quality water available above the Budin clay Formation. Away from the river, very little groundwater is available in this Resource Unit.

For the purpose of calculating the available groundwater resource, RUs 1 and 3 were subdivided into two areas, (i) banded ironstone overlying dolomite, and (ii) outcrop and sub-outcrop dolomite.

These compartments have been kept, however the Tosca compartment was extended into Botswana. The fourth RU consisting of Kalahari sand cannot be accepted as a separate resource unit as it is in direct hydraulic connection with the underlying dolomite. On the Botswana side, the presence of faults and dykes suggests several other compartments (figure 3-7).

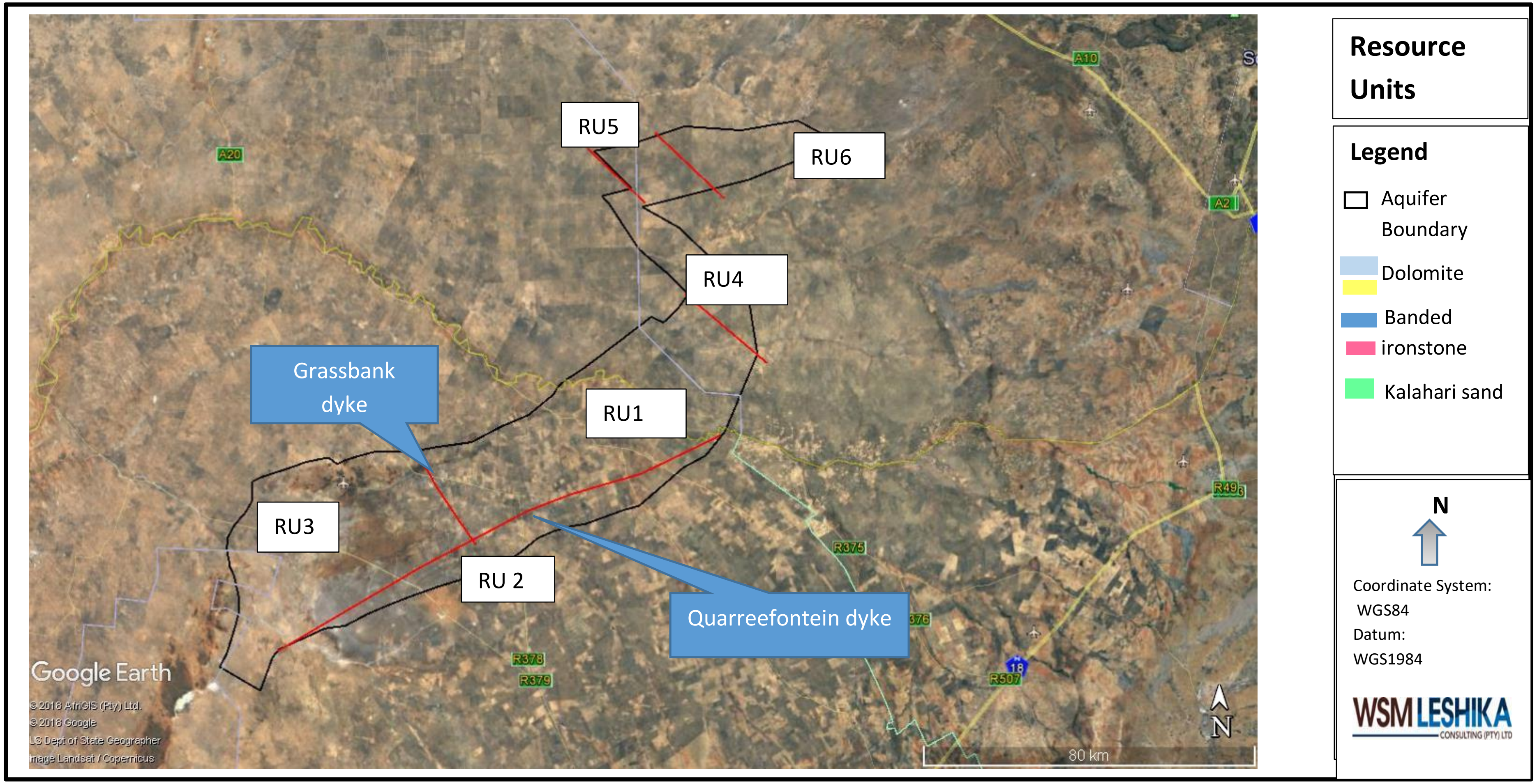


Figure 3-7 Geological map

Resource Unit 1, referred to as the Tosca - Vergelegen dolomitic aquifer, is bound by the Grassbank and Quarreefontein dykes to the west and south (Figure 3-7), and by a fault in Botswana, which appears to be filled by a dyke.

Groundwater occurrence is mainly within fault zones where fracturing, weathering and leaching have developed. The fault zones are meters to 10’s of meters in extent and stretch linearly north-south for kilometres. The brecciated fault zones consist of fractured dolomite, fractures, small solution cavities and Mg-rich wad material. Borehole yields within RU1 range between 0.01-126 l/s with an average yield of 6.32 l/s. In the northern part of the Resource Unit, the dolomite is overlain by banded ironstones.

Due to the shallow dip of these Formations, the majority of boreholes drilled into the banded ironstones, penetrate the underlying dolomite Formation. The water levels within RU1 vary between 5-10 m below ground level (mbgl) in the west to 50-60 mbgl north-east at the Molopo river. The Kalahari sands are 15 m thick at the western and southern boundaries, increasing to 120 m towards the Molopo. The thickness in Botswana is uncertain.

Resource Unit 2 consists of an area of east - west trending dykes, which have formed numerous small compartments within the dolomite. The groundwater occurrence is mainly along fracture zones associated with dolerite dykes, typically on the southern side of dykes. Borehole yields within RU2 are typically lower, ranging between 0.01-44 l/s with an average yield of 2.4 l/s. Water levels range between 15 to 25 mbgl. The Kalahari thickness increases from 0 m in the west to 90 m in the east at Mabule on the Molopo. The numerous dykes divide the area into many subcompartments.

In RU 1 and RU2, water levels in the northwest vary between 5 to 10m below surface, gradually deepening to 50 and 60 m to the north-east at the Molopo river. The hydraulic gradient is to the NE towards the Molopo, and presumably to the SW in Botswana. Elevated water levels along the Molopo River indicate recharge from the river.

Resource Unit 3 lies to the west and south-west the north-south Grassbank dyke. Dolomite outcrops within RU3, referred to as the Pomfret dolomitic aquifer. Groundwater occurs in similar fractured and weathered geological features. Groundwater levels are shallow at around 10 mbgl, with less dyke occurrence and compartmentalization than RU2. In RU3 groundwater occurs more in weathered zones and less in fractured zones, with good recharge due to calcrete cover and little sand cover. Borehole yields vary between 0.01-75 l/s with an average yield of 3.9 l/s. In the northern part of the Resource Unit, the dolomite is overlain by banded ironstones. Due to the shallow dip of these Formations, the majority of boreholes drilled into the banded ironstones, penetrate the underlying dolomite Formation. Water levels in the dolomitic aquifer vary between 10-70 mbgl. At least 13 subcompartments have been identified.

Resource Units 4, 5 and 6 consist of dolomites and banded ironstone in Botswana, separated by faults and dolerite dykes. These are covered by Kalahari sands, thinning to the Northeast from 180-30 m.

These units are overlain by gravels, sandstone, clay and sand. The Kalahari Group was originally saturated to the clays of the Budin Formation. In the Eden sandstones water sufficient to sustain stock watering is intersected. Along the Molopo river thicker saturation of the sandstones is present. The presence of the Budin clay Formation, which acts as an aquiclude or confining layer, is not continuous throughout the study area, resulting in some hydraulic connection between the dolomitic aquifer and the weak, overlying Eden Formation aquifer. This is evident from the fact that regional water levels within the Kalahari Group aquifer have also been impacted through over abstraction from the dolomite, resulting in a decline in the regional water level of 10-20m. From a use perspective the Kalahari Group aquifer may seem insignificant due to the low transmissivities, resulting in low yields. However, the storage capabilities of the Kalahari aquifer in combination with the high yielding underlying dolomites, is of particular significance. From aquifer testing it is estimated that the storage capabilities of the Kalahari Group aquifer are at least twice that of the dolomite.

Three main, geologically controlled, aquifers are therefore present within the aquifer. These include:

(i) Brecciated and leached zones along faults, a high yielding aquifer within the area.

(ii) Fracture zones associated with the intrusion of post-Karoo dolerite dykes and sills. Along these sills and dykes, relatively high yielding fractures are intersected. The extent of these fracture zones and compartmentalization impede the long-term, sustainable, yield from these zones. Pump testing and water level response to abstraction indicate poor recovery after pump testing, resulting in long-term water level declines.

(iii) Transition zone between the dolomite, shale bands and the banded ironstone.

3.6 Recharge

Due to the episodic nature of recharge, very long-term monitoring of water level is required to derive, among others, a mean annual recharge estimate. Moisture retention within the unsaturated zone in areas covered by the Kalahari sands can have a considerable influence on recharge. Only very high rainfall events can initiate recharge. If recharge occurs only once every 10 years, then not only is the volume of recharge of relevance, but also the period of time between recharge events. This is illustrated in figure 3-8, which is a probabilistic distribution of monthly rainfall. If 150 mm/month is required to initiate recharge, then recharge only occurs once every 140 months, or once every 11-12 years. It would require many years of water level data to establish an average recharge, if only water levels are utilised.

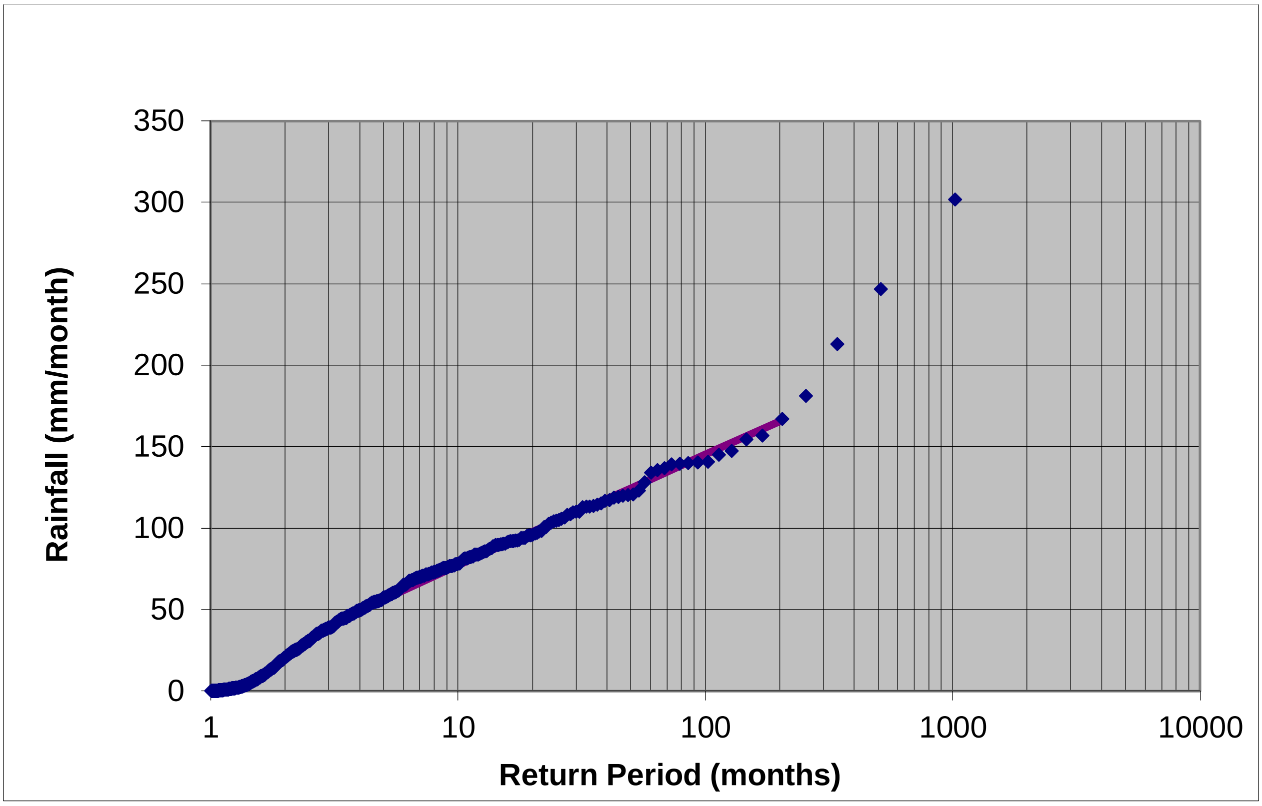


Figure 3-8 Return periods of monthly rainfall

Areas of higher recharge could occur near the Molopo river and its tributaries due to losses from infrequent floodwaters. This recharge however, will be small because of the retention of potential recharge in the unsaturated zone, from where it is lost by evapotranspiration.

This implies that methods based only on water level data cannot be easily applied. In addition, the wide spatial variation in recharge depending on runoff in channels and thickness of the Kalahari sediments, makes any point scale measurement unrepresentative.

The recharge in the areas covered by the Kalahari sediments is believed to be negligible in areas with less than 300 mm/year of rainfall and the quality of the groundwater being poor. Selaolo (2003) found that recharge in the Kalahari was 0.5 ± 0.1 mm/a where rainfall is < 400 mm/a using chloride profiles in the unsaturated zone. They suggested a critical seasonal precipitation threshold of 400 mm/yr is required. However, Isotopic evidence suggests that recharge to the karstic aquifers is taking place, with tritium values ranging from 0 to 0.9 TU. The higher tritium samples (> 0.9 TU) with depleted $\delta_{18}O$ signatures are indicative of more recent recharge, with groundwater flow within the karstic aquifers having responded quickly to precipitation. Verhagen using isotopes (2003) at Jwaneng found that recharge through the Kalahari was 3.7-4.7 mm/a from an MAP of 350 mm/a.

3.7 Groundwater levels

Water level monitoring level data is available only for boreholes in the vicinity of Pomfret in RU3, where dolomite and banded ironstone outcrop exist, and only for a limited period. These boreholes are not all in the same sub-compartments hence do not respond in the same way. Abstraction for Pomfret mine stopped in 1986, however, the only record covering this period was not in a compartment utilised by the mine. Abstraction began in 1989 by the South African Defence Force (SADF). Water use declined after 1994, then again after 1997, after the SADF withdrew from the military base.

Water levels clearly indicate declining levels due to over abstraction. From the general lack of annual water level rises, it is evident that recharge is not an annual event, or annual recharge is very low (Figure 3-9).

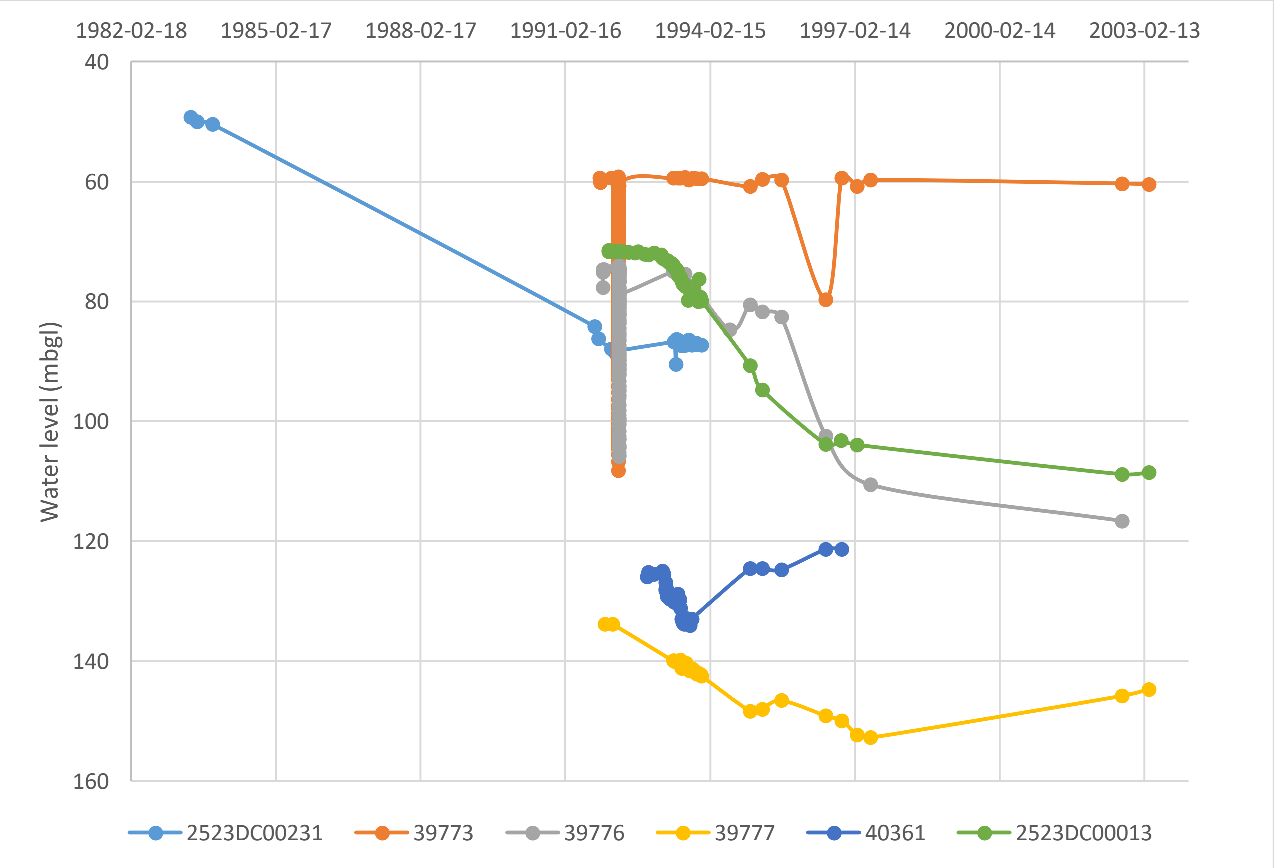


Figure 3-9 Water levels in RU3

3.8 Groundwater Use

According to Godfrey and Van Dyk (2002), Prior to 1990 groundwater use was limited to human consumption and stock watering. There was no industrial use and only limited irrigation use near Tosca and the Molopo River. The total irrigation of groundwater was less than 100 ha or equivalent to 0.77 Mm_3 per annum. The total stock consumption in the 220,000 ha was calculated as 60 l/d/stock unit at 12 ha per unit to be 0.5 Mm_3 per annum. Total human consumption was estimated at 0.5 Mm_3 per annum. The total water used in the area was therefore less than 1.8 Mm_3 per annum.

Since 1990 more high yielding boreholes were drilled and there was a steady increase in irrigation and a survey in 1994 reported 4.6 Mm_3/a of groundwater use. In April 2001, it had increased to 9.1 Mm_3/annum. By January 2002, it further increased to 11.1 Mm_3 of water. Calculations of groundwater usage made by the local irrigation farmers indicated that significantly more groundwater, 16-18 Mm_3 per annum, was being abstracted. In 2013 compulsory licensing allocated the total volume of 10.9 Mm3/a. In 2016 and additional 20% restriction was implemented reducing the total abstraction to 8.2 Mm3/a (table 3-4).

Groundwater is the sole source of water in the Pomfret area for both domestic and agricultural purposes. As with the Tosca aquifer, the Pomfret aquifer is currently under considerable strain.

Table 3-4 Estimated current groundwater use in the study area

	South Africa	Botswana
Groundwater use irrigation area (ha)	2000	90
Irrigation (Mm^3/a)	8.2	0.6
Stock watering	0.5	0.25
Domestic (Mm^3/a)	0.5	0.1?
Total	9,2	0.95

3.9 Recharge estimates

Smit (1977) calculated recharge as 2.2-3.8% of Rainfall in outcrop areas, 0.26-0.8% where the Kalahari cover is <15 m, and assumed no recharge where the Kalahari cover is greater than 15 m. The average recharge was 0.5%.

Godfrey and Van Dyk (2002) present recharge values for dolomitic areas and dolomite and Banded Ironstone Formation (BIF) based on 'professional judgement, based on experience within the catchment', with no further indication of how these values were derived (table 3-5). Given that abstraction was about 18 Mm^3/a and they list recharge as 19.6 Mm^3a, an average of 1.28% of rainfall, a balance should exist between recharge and abstraction. However, since large water level declines are evident, this estimate is almost certainly too high.

Table 3-5 Recharge values from Godfrey and Van Dyk (2002)

RU	Aquifer type	Area (km^2)	% Recharge/Rainfall	Recharge (Mm^3/a)	MAP (mm/a)	Recharge (mm/a)
1	BIF/dolomite	138	1.58	0.87	399	6.3

	Dolomite	863	1.75	6.02	399	7.0
2	Dolomite	624	0.69	1.72	399	2.8
3	BIF/dolomite	254	2.08	1.96	371	7.7
	Dolomite	1478	1.64	8.99	371	6.1
Total				19.57		5.8

Recharge to the aquifer was also estimated by Van Dyk (2005). Using the CMB method, he calculated recharge to be between 0.2 to 28 mm/a of the MAP in the different areas of the aquifer, with the higher values associated with outcrop areas, alluvial channels and structural features. The harmonic mean was 1.77 mm/a, or 0.4% of rainfall. The average was 4.9 mm/a.

The median percent recharge tabulated by Van Dyk was used to derive recharge volumes for the South African portion of the aquifer (table3-6). Recharge of 13.41 Mm/a is calculated. However, Van Dyk (2005) calculated a total volume of recharge of 12.1 Mm^3/a. The difference could perhaps be due to a slightly different area calculated for the compartments.

Table 3-6 Recharge modified from Van Dyk (2005)

RU	Aquifer type	Area (km^2)	% Recharge/Rainfall	Recharge (Mm^3/a)	MAP (mm/a)	Recharge (mm/a)
1	BIF/dolomite	138	1.06	0.58	399	4.2
	Dolomite	863	1.41	4.86	399	5.6
2	Dolomite	624	0.51	1.27	399	2.0
3	BIF/dolomite	254	1.7	1.60	371	6.3
	Dolomite	1478	0.93	5.10	371	3.5
Total				13.41		4.0

Based on a groundwater model, Van Dyk (2005) estimated that the average recharge was 1.75% of MAP or 9.7 mm/a. with the area covered by Kalahari sands 5.6 mm/a, the banded ironstones 1.9 mm/a and the strips along rivers being 7.5 mm/a.

Bredenkamp (2009) estimated recharge for the South African portion of the aquifer using regional rainfall-recharge relationships. The different recharge equations appear in table 3-7. Using average monthly rainfall, Bredenkamp obtains the values in table 3-7.

This study utilised the same equations but developed a time series using a 48-month moving average of rainfall. Using average monthly rainfall eliminates the effect of wet period and underestimates recharge during wet periods. When the equations are applied to 48-month average rainfall, this study achieves a higher average recharge. This stresses that recharge can only occur above of a monthly threshold rainfall value and that average time series data cannot be used to derive an average recharge.

Table 3-7 Recharge from rainfall – recharge relationships

Recharge estimate from regional rainfall equations					
Aquifer	**Equation from Which Recharge is Derived**	**Average Annual Rainfall (mm)**	**Average Monthly Rainfall (mm/mth)**	**Estimated Annual Recharge (mm/a) (Bredenkamp)**	**This Study Based on 48-Month Average (avg) Rainfall**
Dolomites					
Similar to Sishen	1) $Re = 0.898e^{0.032x1}$	390	32.5	0.44	2.48
Similar to Manyeding	2) $Re = 0.2744e^{0.0473x}$	390	32.5	1.00	1.24
Similar to Kuruman	4) $Re = 0.7425e^{0.0538x}$	390	32.5	3.52	4.16
Average				1.65	2.63

3.10 Recharge from the Cumulative Rainfall Departure Method

To apply this methodology, the following data are required:

- Aquifer size
- Monthly rainfall
- Abstraction volumes
- Storativity
- Monthly water level prior to and after abstraction

Only one borehole meets this requirement, 2523DC000231 (figure 3-9). This borehole is located in subcompartment 5 of GU3, which is overlain by banded ironstone. Fortunately, Van Dyk (1993), delineated this compartment and abstraction. Subcompartment 5 underlies the former asbestos mine, which was bought out by the South African Defence Force after the mine closed in 1985. Groundwater abstraction by the mine began in 1962. In 1982 abstraction was expanded and this borehole was drilled as a monitoring borehole.

Van Dyk gives the size of this compartment as 14.05 km^2 and abstraction as 284 692 m^3/a from 6 boreholes from 1990-1992 and from test pumping the S value is 0.005. By 1997 usage declined following the SADF withdrawing from the base.

The CRD method was applied and the following relationship was derived to match the water level decline to the CRD:

Recharge = (Rainfall – c) *b

Where Rainfall is monthly rainfall, c is the threshold rainfall to initiate recharge, calibrated to 100 mm/month, and b is the fraction of rainfall above the threshold generating recharge, calibrated to 0.1.

It was assumed that outflow from the compartment is equal to the mean monthly recharge when no abstraction occurs, and that inflow and outflow are zero when abstraction occurs.

The water level and simulated water level from the CRD method is given in figure 3-10, with abstraction terminated in 1993. The recharge time series for the CRD from 1920-2010 is shown in figure 3-11. Recharge is seen to be episodic and highly variable, with only 2 recharge events between 1983-1993 when water levels were monitored.

The mean annual recharge is 1.68 mm/a, or 0.44% of rainfall. The monthly recharge values were aggregated to derive an annual rainfall-recharge relationship (figure 3-12). The best-fit relationship for recharge is:

Recharge = (Rainfall -344) * 0.0372

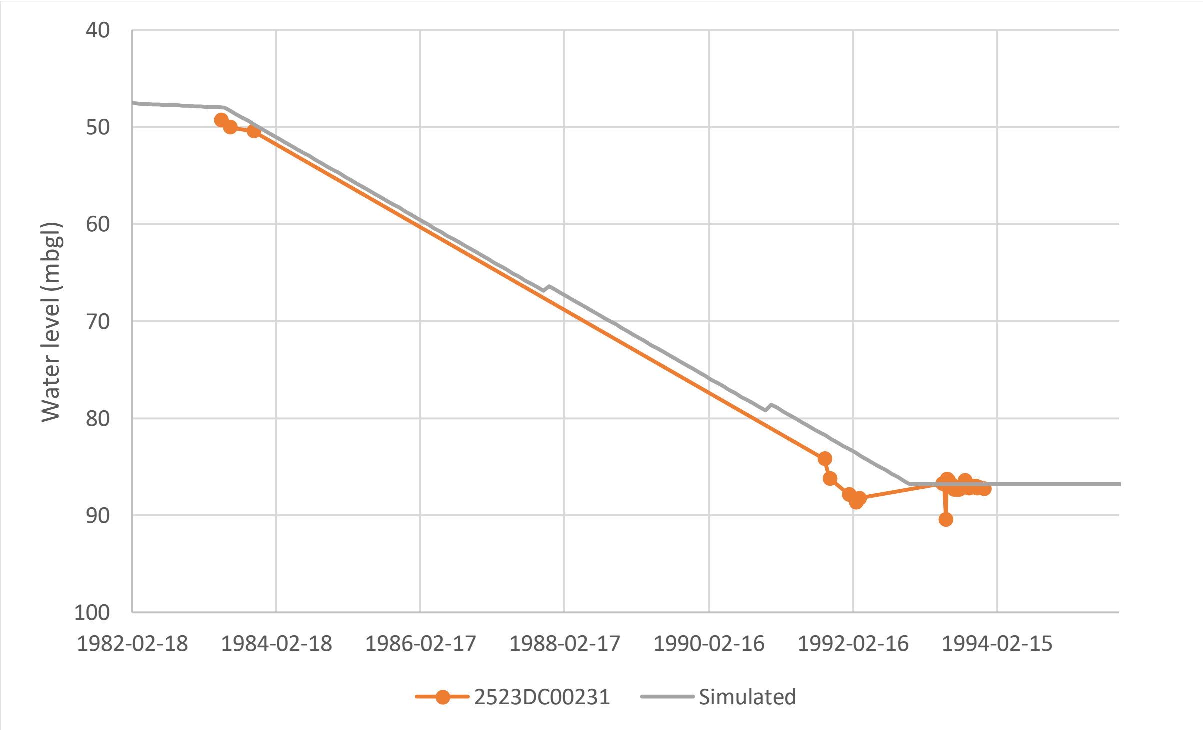


Figure 3-10 Observed water level and simulated water level

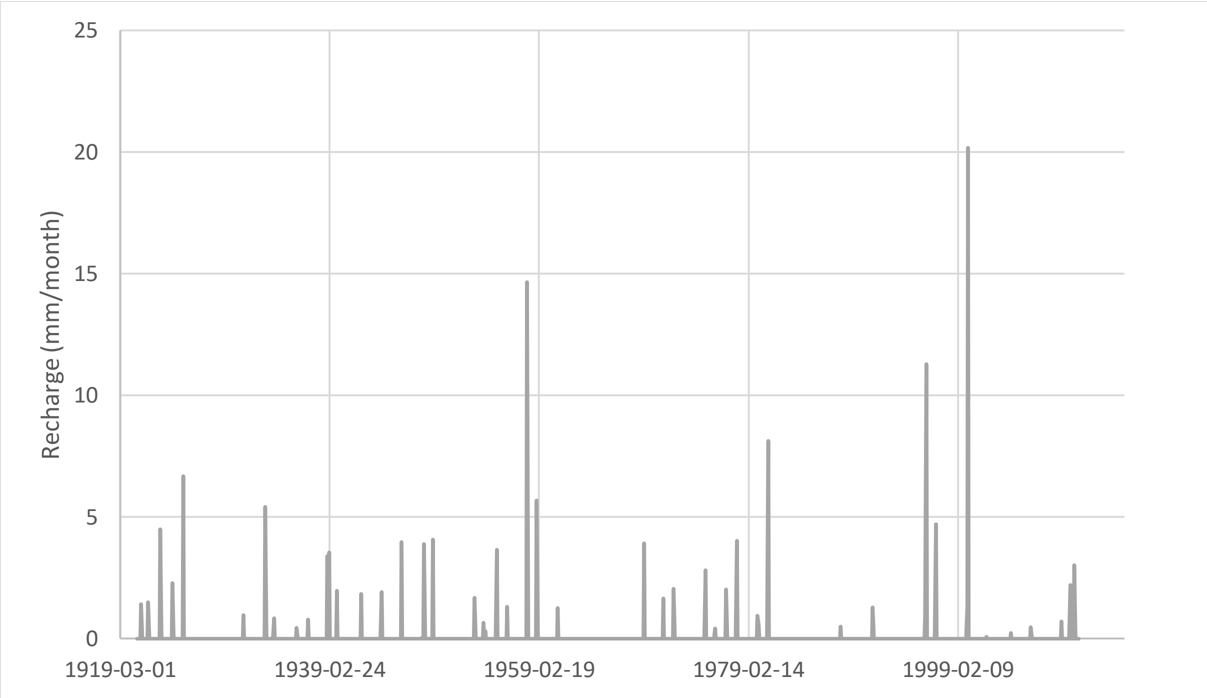


Figure 3-11 Time series of recharge

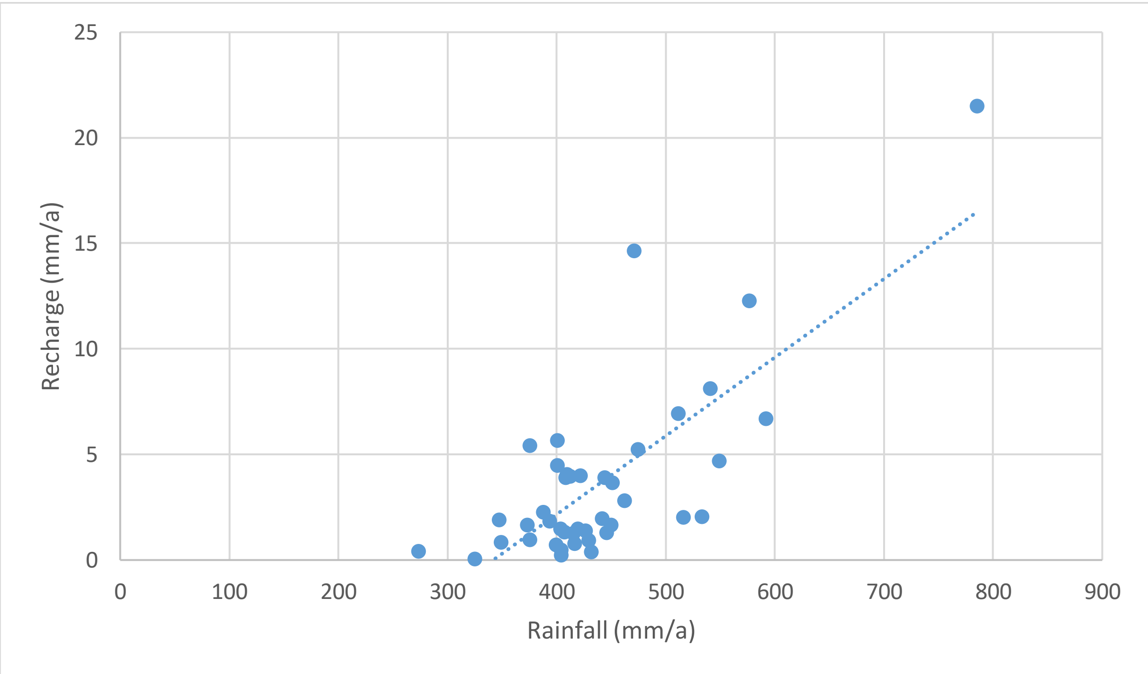


Figure 3-12 Rainfall Recharge Relationship

3.11 Proposed Recharge for the Khakhea- Bray Transboundary Aquifer

Based on water level data from Pomfret, recharge appears to be sporadic, only occurring when rainfall exceeds 100 mm/month. The recharge calculated for areas overlain by banded ironstone agrees with the figures from Van Dyk's modelling study (3.9) but are somewhat lower than Van Dyk's calculation based on the Chloride method. The calculated recharge also matches some of the relationships proposed by Bredenkamp (table 3-7), however such exponential relationships generate recharge in all years, hence may not be suitable for areas with the Kalahari cover.

It is proposed that the relationship developed in 3-10 be utilised. Calculated recharge is shown in table 3-8. RU1 is the one shared by South Africa and Botswana. 1220 km^2 lie within South Africa and the remainder i.e. 41%, in Botswana. Godfrey and Van Dyk (2002) estimated demand at 12.1 Mm^3/a, of which 11.1 Mm^3/a was for irrigation on the South African side and noted alarming declines in water level of up to 60 m. To this volume can be added 0.6 Mm^3/a of irrigation on the Botswana side along the Molopo river, and water use around Maloochna. The combined use of 12.7 Mm^3/a exceeded the calculated recharge of 6.21 Mm^3/a, hence the significant water level declines. Even the present combined irrigation use of 7.8 Mm^3/a exceeds the recharge volume.

It is likely that the recharge to RU2-6 also drains into RU1 as well as no natural outlets or springs exist. The current total abstraction total abstraction of 10.2 Mm^3/a, is less than recharge, but it remains to be seen whether water levels will recover.

Table 3-8 Estimated Recharge for the Dolomitic Transboundary Aquifer

Resource Unit	Area (km^2)	MAP (mm/a)	Recharge (mm/a)	Recharge (Mm^3/a)
RU1 (SA and Bots)	2061	425	3.01	6.21
RU2 (SA)	637	425	3.01	1.92
RU3 (SA)	1885	380	1.34	2.52
RU4 (Bots)	420	447	3.83	1.61
RU5 (Bots)	256	447	3.83	0.98
RU6 (Bots)	404	447	3.83	1.55
TOTAL	5663			14.79

4 KAROO SEDIMENTARY AQUIFER

4.1 Introduction

Groundwater resources play a crucial role in water supply for both rural villages and urban centres in Lesotho, as does the use of developed and undeveloped springs as well as handpumps, high capacity production boreholes and river abstraction. The Senqu / Orange River systems are also somewhat dependent on groundwater supplies. The importance of quantifying and protecting recharge in the Karoo sedimentary aquifer spanning Lesotho and South Africa is that recharge drives the baseflow which forms a large component of flow in the Orange-Senqu River system.

Two main aquifer types can be distinguished: The Highlands largely underlain by basalt, and where baseflow is interflow driven, and the Lowlands, which are drier and have a semi-arid to temperate climate, receiving annual rainfalls of 500 to 1 150 mm that fall mainly during October to April. The international boundary is marked by the perennial Caledon (Mohokare), Senqu (Orange), and Makhaleng rivers, many of whose tributaries are episodic or ephemeral.

TAMS (1996) estimated the renewable groundwater resources of Lesotho to be 10.84m_3/s (cumecs), of which 7.37m_3/s is available in the Lowland areas of the basin. Water balance studies indicate 2.5% of annual rainfall recharges to groundwater systems. There is unfortunately no water-level data to support these estimates.

The study area encompasses Tertiary catchments D11, D15-D18, which form the Senqu River basin, and D21-D23, which are the Upper Caledon River (Figure 4-1).

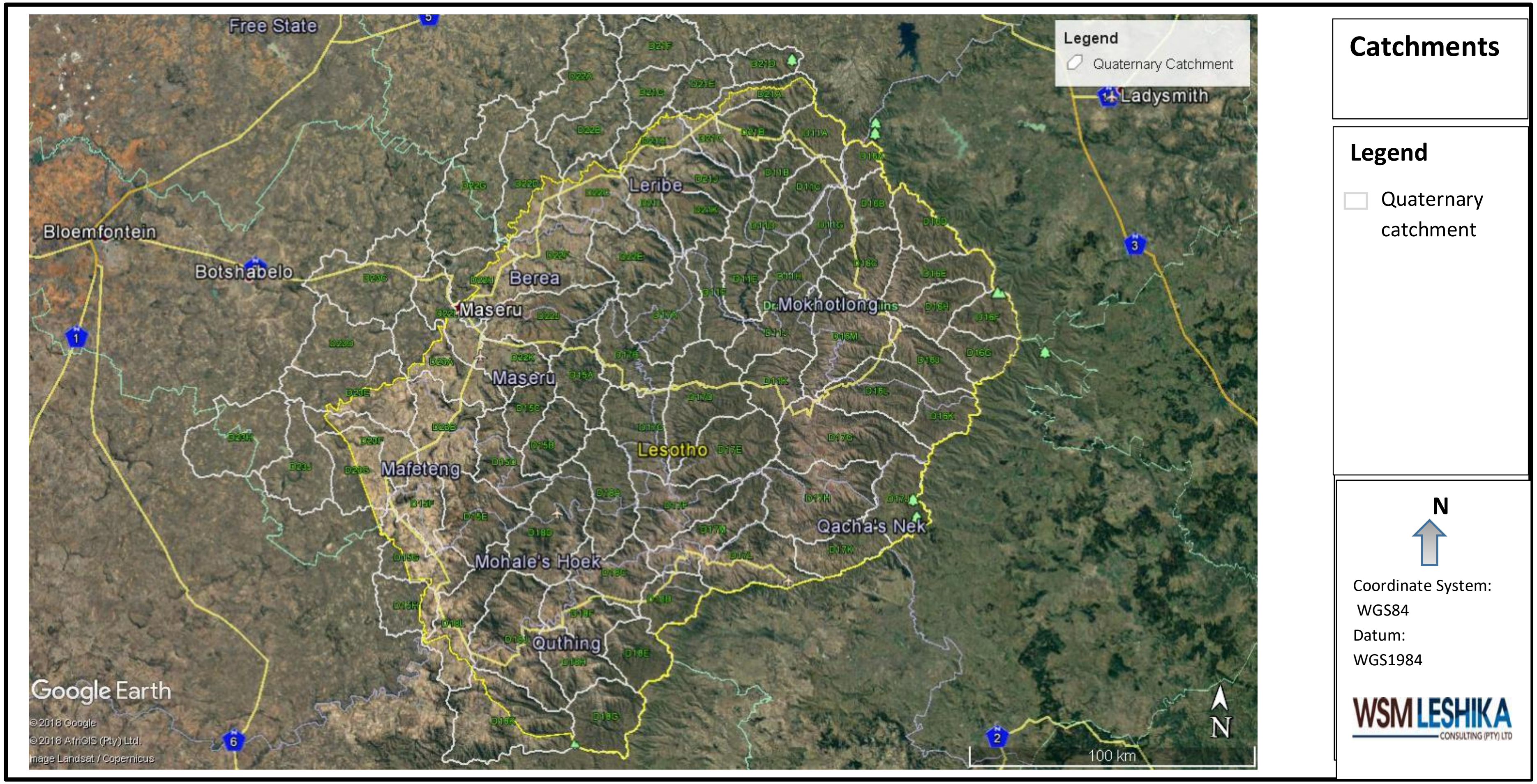


Figure 4-1 Quaternary catchments

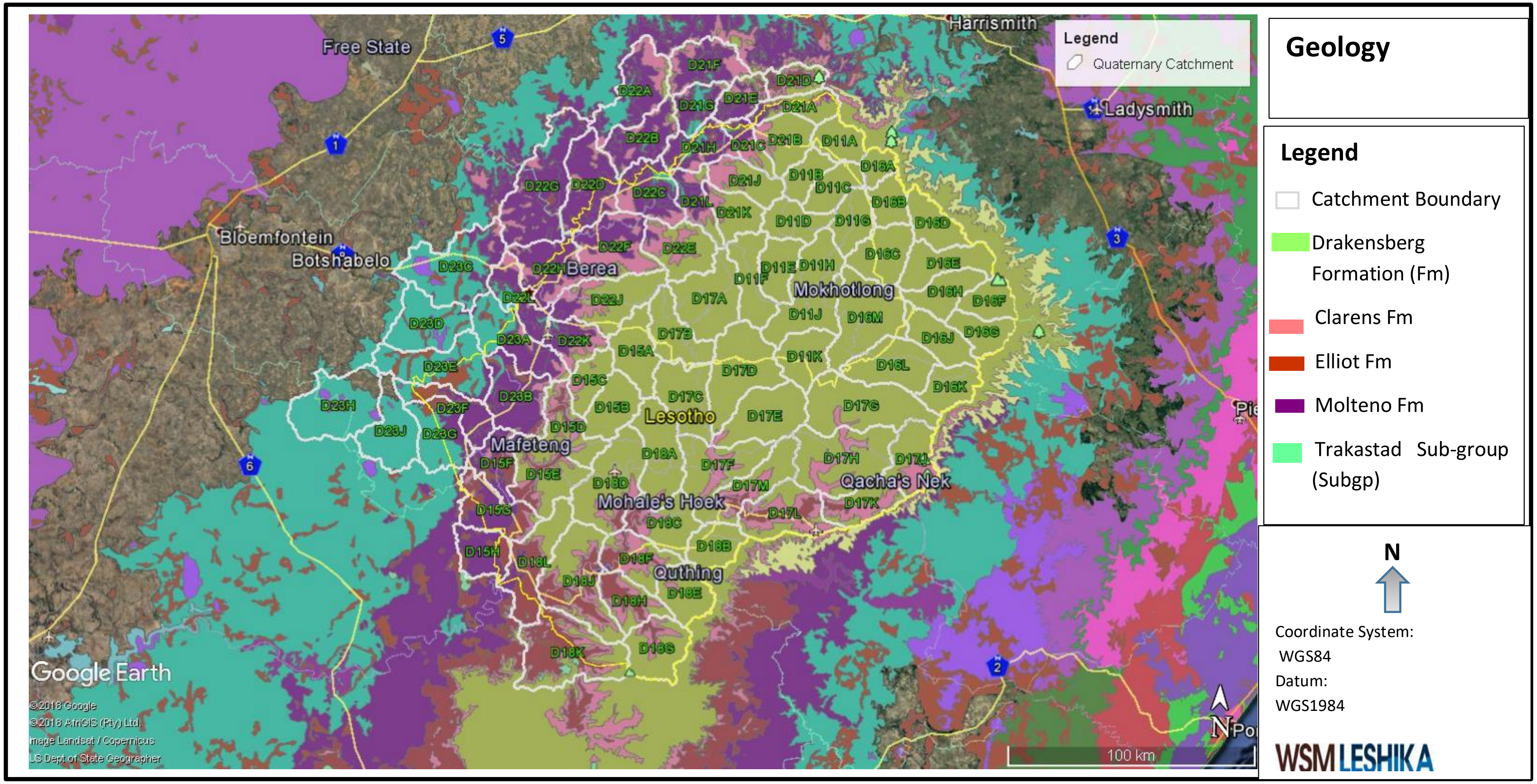


Figure 4-2 Geological map

4.2 Climate

The study area is characterised by variable rainfall (table 4-1). Rainfall is an average of 909 mm/a in tertiary catchment D11, with nearly 1200 mm/a in the headwaters. Rainfall declines to 745 mm/a in D18 where the Tertiary extends into South Africa at Oranjedraai. The rainfall in the headwaters of the Caledon River, catchment D21, is 867 mm/a, declining to 617 mm/a where the River reaches the Welbedacht dam between Smithfield and Wepener, catchment D23.

Table 4-1 Quaternary catchment rainfall in WR2012

QUATERNARY CATCHMENT	Catchment area		S-pan evaporation			Rainfall	
	Gross	Net	evap	MAE WR2005	MAE WR90	Rainfall	MAP
	(km^2)	(km^2)	zone	(mm)	(mm)	zone	(mm)
D11A	278	278	20B	1299	1300	D1A	1190
D11B	236	236	20B	1299	1300	D1A	1026
D11C	292	292	20B	1299	1300	D1A	1058
D11D	319	319	20B	1299	1300	D1A	914
D11E	322	322	20B	1299	1350	D1B	842
D11F	413	413	20B	1299	1350	D1B	951
D11G	320	320	20B	1299	1300	D1C	879
D11H	359	359	20B	1299	1300	D1B	852
D11J	440	440	20B	1299	1350	D1B	*774*
D11K	381	381	20B	1299	1350	D1B	759
Tertiary	***3360***	***3360***		***1299***	***1323***		***909***
D15A	437	437	20B	1449	1450	D1K	974
D15B	393	393	20B	1449	1450	D1K	961
D15C	276	276	20B	1449	1450	D1K	850
D15D	437	437	20B	1449	1450	D1K	927
D15E	619	619	20B	1526	1500	D1L	799
D15F	352	352	20B	1526	1500	D1L	750
D15G	485	485	20B	1526	1500	D1L	670
D15H	361	361	20B	1526	1525	D1L	609
Tertiary	***3360***	***3360***		***1491***	***1480***		***817***
D16A	159	159	20B	1299	1300	D1C	1186
D16B	249	249	20B	1299	1300	D1C	1088
D16C	438	438	20B	1299	1350	D1C	725
D16D	339	339	20B	1299	1300	D1D	994
D16E	434	434	20B	1350	1300	D1D	826
D16F	277	277	20B	1350	1300	D1D	997
D16G	290	290	20B	1350	1300	D1D	941
D16H	345	345	20B	1299	1300	D1D	763
D16J	374	374	20B	1350	1350	D1D	879
D16K	329	329	20B	1350	1350	D1E	871
D16L	533	533	20B	1350	1350	D1E	725
D16M	753	753	20B	1350	1350	D1E	646
Tertiary	***4520***	***4520***		***1333***	***1327***		***835***
D17A	638	638	20B	1299	1375	D1G	1000
D17B	442	442	20B	1299	1375	D1G	999
D17C	525	525	20B	1350	1400	D1G	876

D17D	748	748	20B	1299	1450	D1G	899
D17E	605	605	20B	1299	1450	D1G	899
D17F	582	582	20B	1299	1450	D1G	717
D17G	849	849	20B	1299	1400	D1F	717
D17H	852	852	20B	1299	1400	D1F	710
D17J	437	437	20B	1350	1375	D1F	871
D17K	383	383	20B	1350	1375	D1F	711
D17L	590	590	20B	1350	1400	D1F	679
D17M	528	528	20B	1350	1450	D1F	716
Tertiary	***7179***	***7179***		***1316***	***1411***		***810***
D18A	599	599	20B	1376	1475	D1H	819
D18B	327	327	20B	1376	1475	D1H	736
D18C	466	466	20B	1401	1475	D1H	691
D18D	766	766	20B	1449	1475	D1H	788
D18E	376	376	20B	1449	1475	D1H	792
D18F	446	446	20B	1449	1475	D1H	678
D18G	492	492	20B	1401	1500	D1J	800
D18H	384	384	20B	1404	1500	D1J	714
D18J	859	859	20B	1376	1500	D1J	712
D18K	935	935	20B	1376	1525	D1J	774
D18L	610	610	20B	1376	1525	D1J	663
Tertiary	***6260***	***6260***		***1400***	***1494***		***745***
D21A	309	309	20B	1276	1275	D2A	978
D21B	394	394	20B	1276	1275	D2A	1021
D21C	212	212	20B	1276	1275	D2A	833
D21D	252	252	20B	1299	1300	D2A	839
D21E	268	268	20B	1299	1300	D2A	784
D21F	480	480	20B	1325	1325	D2B	725
D21G	278	278	20B	1325	1325	D2B	751
D21H	381	381	20B	1325	1325	D2B	782
D21J	359	359	20B	1299	1300	D2C	991
D21K	326	326	20B	1299	1300	D2C	960
D21L	304	304	20B	1325	1325	D2C	860
Tertiary	***3563***	***3563***		***1304***	***1304***		***867***
D22A	636	636	20B	1376	1375	D2D	682
D22B	457	457	20B	1376	1375	D2D	725
D22C	486	486	20B	1376	1375	D2D	786
D22D	628	628	20B	1401	1400	D2D	694
D22E	498	498	20B	1475	1475	D2E	817
D22F	633	633	20B	1475	1475	D2E	758
D22G	969	969	20B	1449	1450	D2D	688
D22H	541	541	20B	1449	1450	D2E	730
D22J	652	652	20B	1401	1400	D2E	772
D22K	324	324	20B	1401	1400	D2E	750
D22L	376	376	20B	1401	1475	D2E	705
Tertiary	***6200***	***6200***		***1420***	***1424***		***733***
D23A	608	608	20B	1475	1475	D2F	688
D23B	597	597	20B	1475	1475	D2F	705
D23C	861	861	20B	1499	1500	D2F	638
D23D	565	565	20B	1526	1525	D2F	607
D23E	702	702	20B	1526	1525	D2F	615
D23F	352	352	20B	1526	1525	D2G	638

D23G	512	512	20B	1526	1525	D2G	622
D23H	776	776	20B	1600	1600	D2G	519
D23J	534	534	20B	1547	1550	D2G	541
Tertiary	***5507***	***5507***		***1523***	***1523***		***617***

4.3 Drainage

All the Quaternary catchments are perennial. According to GRAII, the MAR of the Senqu Basin is 4012.1 Mm^3/a, of which 1680.44 Mm^3/a originates as baseflow (table 4-2). This implies 42% of runoff is via groundwater. For the Caledon river, MAR is 1243 Mm^3/a, of which 442.15 Mm^3/a, or 36% is from baseflow. This highlights the importance of recharge in maintaining flow in these rivers, both in terms of low flows and total volumetric discharge.

Table 4-2 Runoff and Baseflow from GRAII

QUAT	AREA	MAP	MAR	Baseflow	GW %Contribution to MAR
Senqu River Basin					
	km2	mm	Mm3/a	Mm3/a	%
D11A	278	1190	118.29	46.36	39
D11B	236	1026	72.63	29.42	41
D11C	292	1058	96.28	38.98	40
D11D	319	914	74.57	30.26	41
D11E	322	842	57.33	23.31	41
D11F	413	951	99.81	40.13	40
D11G	320	879	64.19	27.70	43
D11H	359	852	69.42	29.09	42
D11J	440	774	62.84	26.79	43
D11K	381	759	51.63	22.15	43
D15A	437	974	108.67	43.75	40
D15B	393	961	94.70	38.09	40
D15C	276	850	49.55	20.06	40
D15D	437	927	96.62	38.80	40
D15E	619	799	105.06	38.75	37
D15F	352	750	27.71	7.79	28
D15G	485	670	26.01	7.29	28
D15H	361	609	13.59	3.84	28
D16A	159	1186	64.90	26.14	40
D16B	249	1088	83.82	33.70	40
D16C	438	725	49.90	23.50	47
D16D	339	994	94.72	35.41	37
D16E	434	826	76.65	31.24	41
D16F	277	997	77.96	30.29	39
D16G	290	941	71.09	27.81	39
D16H	345	763	49.04	20.06	41
D16J	374	879	73.52	28.98	39
D16K	329	871	62.50	26.21	42
D16L	533	725	62.08	28.16	45
D16M	753	646	64.12	31.34	49
D17A	638	1000	165.16	71.85	44

D17B	442	999	114.14	49.66	44
D17C	525	876	95.43	42.67	45
D17D	748	899	138.22	61.33	44
D17E	605	920	118.75	52.54	44
D17F	582	717	59.51	28.60	48
D17G	849	710	92.05	41.11	45
D17H	852	691	85.97	38.80	45
D17J	437	871	84.26	34.50	41
D17K	383	711	42.94	18.70	44
D17L	590	679	56.73	25.80	45
D17M	528	716	55.39	24.70	45
D18A	599	819	88.57	38.75	44
D18B	327	736	36.54	16.77	46
D18C	466	691	43.99	20.65	47
D18D	766	788	102.37	45.16	44
D18E	376	792	50.92	22.44	44
D18F	446	678	40.06	18.93	47
D18G	492	800	79.02	31.77	40
D18H	384	714	46.14	18.96	41
D18J	859	712	102.54	42.17	41
D18K	935	774	135.01	54.40	40
D18L	610	663	59.20	24.79	42
	24679		4012.10	1680.44	42
Caledon Basin					
D21A	309	978	62.76	25.46	41
D21B	394	1021	90.37	36.27	40
D21C	212	883	31.80	13.35	42
D21D	252	839	31.26	13.45	43
D21E	268	784	26.84	12.18	45
D21F	480	725	33.32	9.31	28
D21G	278	751	21.91	6.37	29
D21H	381	782	39.74	17.39	44
D21J	359	991	76.00	30.18	40
D21K	326	960	63.15	25.21	40
D21L	304	860	41.39	17.00	41
D22A	636	682	36.47	10.48	29
D22B	457	725	32.75	9.43	29
D22C	486	782	50.24	21.41	43
D22D	628	694	37.60	10.82	29
D22E	498	817	52.34	22.00	42
D22F	633	758	52.91	23.46	44
D22G	969	688	54.06	16.06	30
D22H	541	730	36.82	10.74	29
D22J	652	772	63.34	27.55	43
D22K	324	750	28.83	12.82	44
D22L	376	705	22.10	6.47	29
D23A	608	688	39.07	10.92	28
D23B	597	705	41.67	11.67	28

D23C	861	638	41.78	11.70	28
D23D	565	607	22.51	6.33	28
D23E	702	615	29.32	8.24	28
D23F	352	638	20.03	5.48	27
D23G	512	622	26.81	7.34	27
D23H	776	519	20.07	1.68	8
D23J	534	541	16.42	1.37	8
	15270.00		1243.67	442.15	36

4.4 Geology

The stratigraphy and lithology of the basin is shown in table 4-3.

The geology of Lesotho comprises horizontal to sub-horizontal dipping sedimentary rocks of the Beaufort and Stormberg Groups of the Karoo Supergroup overlain by up to 1600 m of Drakensburg Group basalt. Sedimentary rocks belonging to the Burgersdorp, Molteno, Elliot and Clarens Formations include fluvio-deltaic mudstones, siltstones, and sandstones that underlie and crop out in the western lowlands. The Clarens Formation is overlain by a thick sequence of (up to 1600 m) compact and amygdaloidal basalt flows of the Drakenberg/Lesotho Formation. Numerous dykes, ring dykes and sills intrude the sediment and basalt formations. The doleritic and basaltic dykes mainly trend north-west – south-east and north-north-east – south-south-west, forming either resistant ridge or eroded trench features. The ring dyke complexes form characteristic circular low hills surrounded by Burgersdorp sediments, where they occur in western Lesotho. The sedimentary formations have low angles of dip with limited folding and faulting.

Table 4-3 Stratigraphy

Group	Formation	Lithology
Quaternary and Tertiary		Alluvium, colluvium and residual deposits of Clays, silts and gravels
Drakensberg	Lesotho	Basaltic lava with subordinate tuff and lenses of sandstone near the base
Stormberg	Clarens	Sandstone and siltstone
	Elliot	Mudstones and shales with subordinate feldspathic sandstone
	Molteno	Sandstones, grits, mudstones, shales and coals
Beaufort Group	Burgersdorp	Mudstones and siltstones, sandstone intercalations common

4.5 Hydrogeology

4.5.1 Alluvial aquifers

There are a small number of unconsolidated aquifers in Lesotho in which boreholes can yield from 10 l/s to 40 l/s. These aquifers consist of gravels and sands along the banks of major rivers or on former river courses. One well known is the Maputsoe-Nyenye aquifer in the north of Lesotho.

4.5.2 Lesotho Formation

This basalt aquifer is of low permeability. Numerous springs occur at almost all levels, originating from weathered sections of the basalt near dykes, interflow zones and at the contact zone between the basalts and the metamorphosed top of the underlying, very low permeability Clarens Formation. These springs generate interflow from perched aquifers when above the regional water level, or groundwater baseflow, where the ground surface intersects the regional groundwater water level.

Boreholes have low sustainable yields due to limited interconnection and storage, however, they can have yields of up to 1.5 l/s. This information aquifer recharge is quite low.

4.5.3 Dolerite dykes

The wider dolerite dykes (wider than 50m) act as a barrier to flow. The narrower dykes are often fractured to depths of 30m to 40m and consequently have high permeability compared with surrounding strata, hence contact zones are a preferred target. The most hydrogeologically significant feature of the dykes is the contact zone between dyke and parent rock. This is because the intrusion of the dykes caused some induration and fracturing of the surrounding country rock along the contact zone. Boreholes can give blow yields of up to 10 l/s and sustainable yields of up to 4 l/s. Numerous pumping test results have shown that, although dykes are very permeable, their storage capacity is generally low.

Dyke-related springs are usually perennial.

4.5.4 Clarens Formation

This is a minor aquifer due to the fine grain size and correspondingly low porosity. Groundwater discharge occurs via many seasonal springs as interflow at the base of the cliffs, derived from groundwater flows through fractures in the Clarens Formation that emerge at the junction with the shales and even lower permeability sandstones of the underlying Elliot Formation.

Boreholes drilled in this formation, if not dry, have low yields of ~0.1 l/s.

4.5.5 Elliot Formation

This Formation is a poor aquifer, with yields of 0.1 l/s to 0.2 l/s. Very few springs occur in this formation, and any springs have low yields: wet season spring discharges may be 0.05 l/s and are more likely to form wetlands due to slow seepage.

4.5.6 Molteno Formation

This formation is the best aquifer in Lesotho. The Molteno Formation sandstone aquifer has good groundwater development potential. The quality of this aquifer varies according to the sand / shale ratio and degree of cementation of the component sandstone layers. This aquifer has been developed at Roma and Teyateyaneng, where wellfields with individual yields of greater than 3 litres/s have been installed. The Molteno aquifer can have both limited primary intergranular permeability as well as secondary fracture permeability. The most productive boreholes are located adjacent to dolerite dykes where secondary permeability has been developed by the baking and jointing of the formation during periods of contact metamorphism.

The Molteno outcrops also form an important spring line with individual spring discharges as high as 0.5 l/s. Statistical analysis of available borehole data suggest an average borehole yield in the Molteno aquifer of 1.6 litres/sec, average borehole depth of 61m and average depth to water table of 24m.

Average transmissivity of $20m_2/d$ and a storativity of 0.001.

4.5.7 Burgersdorp Formation

This mainly argillaceous formation has low productivity with borehole yields of less than 0.5 litres/sec. Boreholes drilled adjacent to dolerite intrusions, especially ring dykes, tend to display higher yields of 1-2 litres/sec obtained from baked sediments. An average borehole yield for the Burgersdorp Formation is 1.6 litres/sec, reflecting the large number of boreholes drilled adjacent to dolerite intrusions. Average transmissivity of $20m_2/d$ and storativity of 0.00117 indicate semi-confined to confined conditions within a low permeability aquifer.

4.6 Recharge

TAMS (1996) estimated the renewable groundwater resources of Lesotho to be $10.84m_3/s$ (cumecs), of which $7.37m_3/s$ is available in the Lowland areas of the basin. Water balance studies indicate 2.5% of annual rainfall recharges to groundwater systems. There is unfortunately no water-level data to support these estimates.

Groundwater recharge data is given in GRAII, calculated using the chloride method (table 4-4). Recharge in the Senqu river basin is 1415 Mm^3/a and 725 Mm^3/a in the Caledon river basin.

Table 4-4 Groundwater use and recharge

Quaternary Catchment	Abstraction	Recharge	
	Mm^3/a	Mm/a	Mm^3/a
D11A	0.00	142.94	39.77
D11B	0.00	126.35	29.86
D11C	0.00	114.77	33.45
D11D	0.00	94.04	29.96
D11E	0.00	62.72	20.21
D11F	0.00	72.50	29.94
D11G	0.00	76.03	24.31
D11H	0.00	65.11	23.33
D11J	0.00	51.86	22.80
D11K	0.00	48.75	18.57
D15A	0.00	72.39	31.62
D15B	0.00	73.48	28.90
D15C	0.00	65.33	18.02

D15D	0.00	70.79	30.93
D15E	0.00	57.62	35.65
D15F	0.00	37.27	13.14
D15G	0.00	32.77	15.88
D15H	0.10	23.66	8.53
D16A	0.00	128.28	20.42
D16B	0.00	108.37	26.88
D16C	0.00	51.59	22.56
D16D	0.00	92.71	31.43
D16E	0.00	56.58	24.53
D16F	0.00	68.47	18.93
D16G	0.00	63.57	18.39
D16H	0.00	46.21	15.90
D16J	0.00	54.17	20.24
D16K	0.00	58.34	19.18
D16L	0.00	40.84	21.76
D16M	0.00	49.83	37.51
D17A	0.00	79.11	50.47
D17B	0.00	81.43	35.97
D17C	0.00	62.77	32.93
D17D	0.00	53.81	40.25
D17E	0.00	50.41	30.48
D17F	0.00	40.26	23.43
D17G	0.00	39.70	33.68
D17H	0.00	42.21	35.92
D17J	0.00	52.32	22.85
D17K	0.00	48.04	18.41
D17L	0.00	48.96	28.89
D17M	0.00	38.13	20.14
D18A	0.00	45.88	27.49
D18B	0.00	47.05	15.39
D18C	0.00	48.28	22.47
D18D	0.00	51.93	39.77

D18E	0.00	52.45	19.70
D18F	0.00	42.97	19.15
D18G	0.00	61.97	30.47
D18H	0.00	53.12	20.38
D18J	0.00	50.15	43.06
D18K	0.00	58.68	54.86
D18L	0.00	42.71	26.04
Total	0.10		1424.81
D21A	0.00	86.41	26.73
D21B	0.00	95.46	37.58
D21C	0.00	70.75	14.97
D21D	0.00	63.35	15.93
D21E	0.03	47.26	12.68
D21F	0.03	42.31	20.29
D21G	0.03	45.59	12.68
D21H	0.00	51.96	19.79
D21J	0.00	91.14	32.75
D21K	0.00	94.50	30.80
D21L	0.00	69.08	21.02
D22A	0.00	37.82	24.03
D22B	0.06	45.41	20.75
D22C	0.00	52.14	25.31
D22D	0.03	39.08	24.53
D22E	0.00	74.34	37.03
D22F	0.00	52.13	32.99
D22G	0.27	37.46	36.31
D22H	0.01	52.31	28.30
D22J	0.00	60.65	39.53
D22K	0.00	53.78	17.41
D22L	0.00	46.01	17.32
D23A	0.02	45.45	27.63
D23B	0.00	44.84	26.76
D23C	0.78	34.80	29.97

D23D	0.78	30.85	17.43
D23E	0.08	29.58	20.77
D23F	0.00	27.67	9.73
D23G	0.36	22.78	11.66
D23H	0.77	15.59	12.10
D23J	0.19	18.78	10.02
Total	3.45		714.78

4.7 Recharge Derived from Surface-Subsurface Modelling

4.7.1 Objectives and Methods

Since the requirements from a recharge study are twofold: calculating recharge to determine its relevance to baseflow protection, and calculating the groundwater resource, two types of information are required:

- Recharge which drives both groundwater baseflow and interflow from springs
- Aquifer recharge which reaches the regional aquifer and is available to boreholes

There must also be a water balance so that all of recharge is accounted for. Due to the large size of the study area and the variable rainfall, point estimate of recharge would not be useful.

The GRAII data provides areal data on total recharge, however, the Cl method does not provide a water balance regarding the fate of recharge to verify recharge volumes. In addition, the large volumes of recharge shown by the Cl method cannot be substantiated by the limited groundwater resources present in the basin.

To derive a water balance for recharge and its eventual discharge, the WRSM2000 model was utilised with the hydrology network for ORAECOM Phase 2 (2011). The original ORASECOM hydrology did not include the Sami surface-subsurface groundwater module. This was included, and the model was recalibrated against observed flows with groundwater, also ensuring that the accepted surface water hydrology characteristics did not change significantly from the 2011 study. This involved recalibrating 5 existing networks of the ORASECOM hydrology (figure 4-3 and 4-4), the Katse subsystem, the Senqu system to the Oranjedraai gauging weir, the D21A, D21B, D22 & D23 networks to Welbedacht dam.

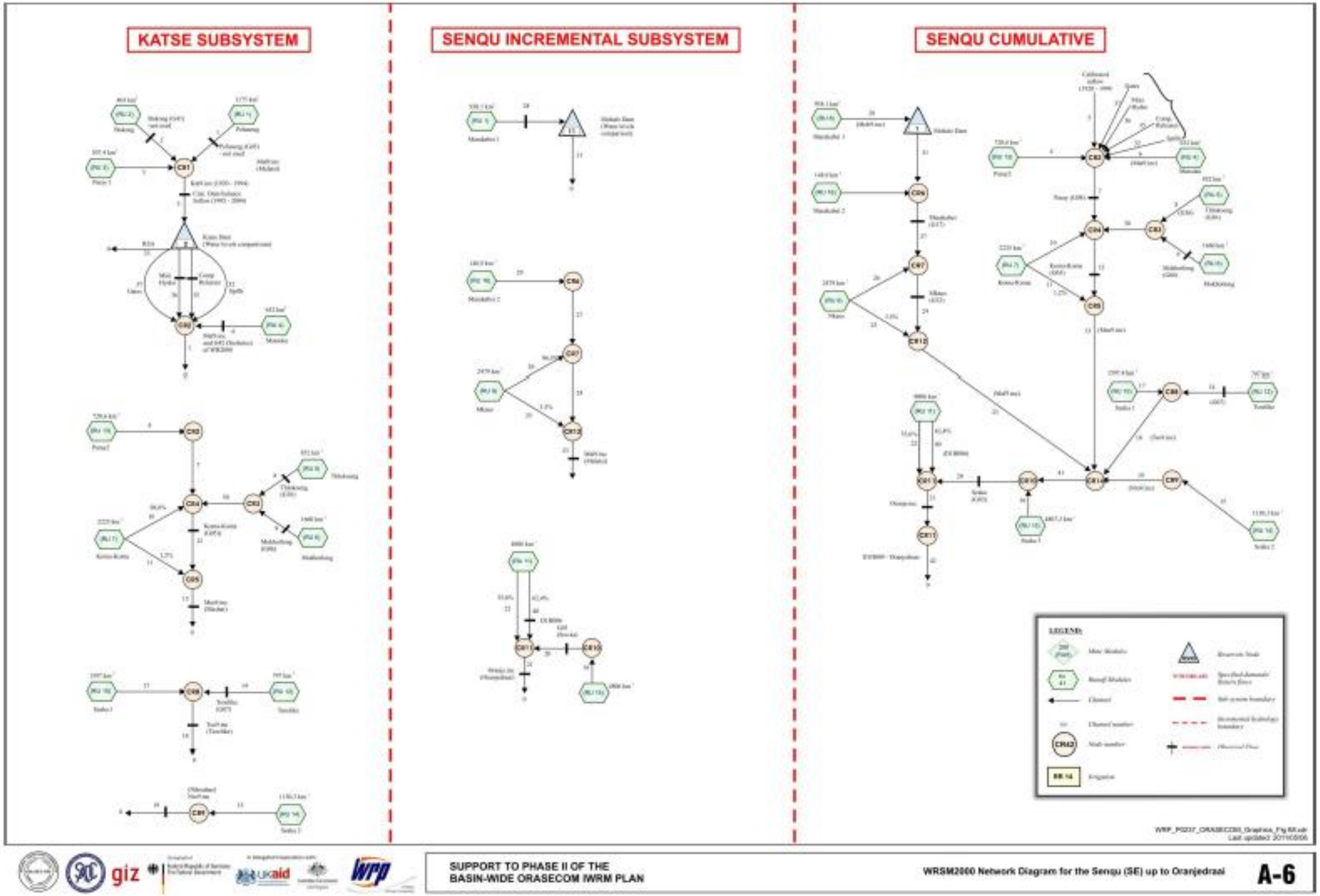


Figure 4-3 Senqu river network diagram

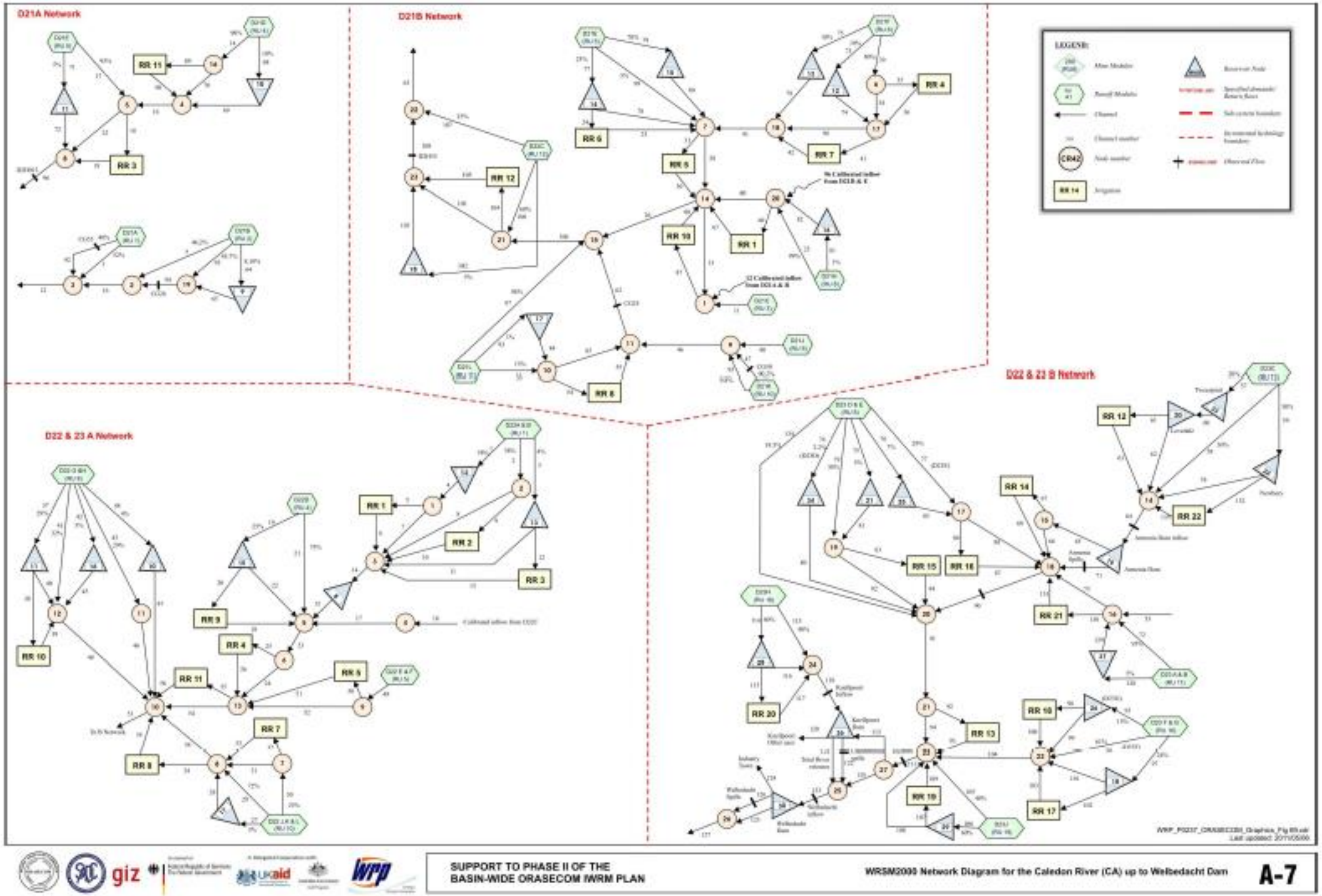


Figure 4-4 Upper Caledon River network diagram

4.7.2 Calibration

When calibrating groundwater in the model, calibration targets include matching recharge to accepted values, and matching baseflow volumes and temporal distribution, so that calibration of baseflows fit for the correct reasons.

The following describes the calibration methods used:

Recharge calibration: Recharge figures given in databases like GRAII include recharge contributing to interflow and to the regional aquifer. For example, mountainous wet regions have a large recharge flux, yet little of it reaches the regional aquifer; most being lost as interflow and not accessible to boreholes in valley bottoms. To compare modelled results to established recharge values, the volumetric mean annual interflow must be converted to mm and added to aquifer recharge to obtain a comparable recharge.

Baseflow calibration: Once the correct recharge is achieved, calibration is achieved my matching low flows to observed flows and comparing baseflow volumes under naturalised conditions to other baseflow data such as Hughes and Pitman (DWAF, 2006).

Calibration statistics: Calibration is undertaken against observed MAR, the log of MAR, which is more strongly weighted to low flows, the standard deviation of flow, the seasonality index.

Graph of mean monthly flow: this graph assists with calibrating flow volumes in dry months and the shape of the baseflow recession.

Monthly flow histogram: this graph ensures the correct distribution of very low flows are obtained, which calibrates groundwater baseflow in terms of volumes and recession.

Cumulative frequency of flow: This graph calibrates a wide range of low to medium flows.

The calibration results compared to observed from data are given in Appendix 1. The calibration curves show that simulated recharge and baseflow volumes were able to reproduce low flows according to the above method calibration targets.

Simulated mean annual recharge, baseflow, the interflow component of baseflow and total runoff is given in table 4-5 for the Senqu River and in table 4-6 for the Caledon River. These were derived from monthly values. For comparison, runoff simulated during ORASECOM Phase II is also provided. The results show that the GRAII recharge is a much higher than the simulated results. Recharge volumes calculated by GRAII would not be able to be calibrated against observed flows.

The GRAII results are believed to be a large over estimate. The observed baseflows do not support such large recharge volumes. This can be attributed to the GRAII results being based on the Chloride method, which assumes that all Cl from precipitation ends up in groundwater. This assumption is not valid in the area as surface runoff is high. The Cl method therefore overestimates the Cl load to groundwater, hence overestimates recharge.

To demonstrate the error that arises when applying the Cl method when surface runoff is significant, the percent of runoff from surface origin (Runoff – (Baseflow/ Runoff)) was compared to the difference between GRAII recharge and this study (GRAII recharge – WRSM2000 recharge/GRII recharge) (figure 4-5). It is evident that as the proportion of runoff that doesn't pass through groundwater increases, the increasing export of chloride by surface runoff results in an increasing error in the recharge estimate. It can be concluded that the Cl method cannot be applied in catchments where surface runoff is significant.

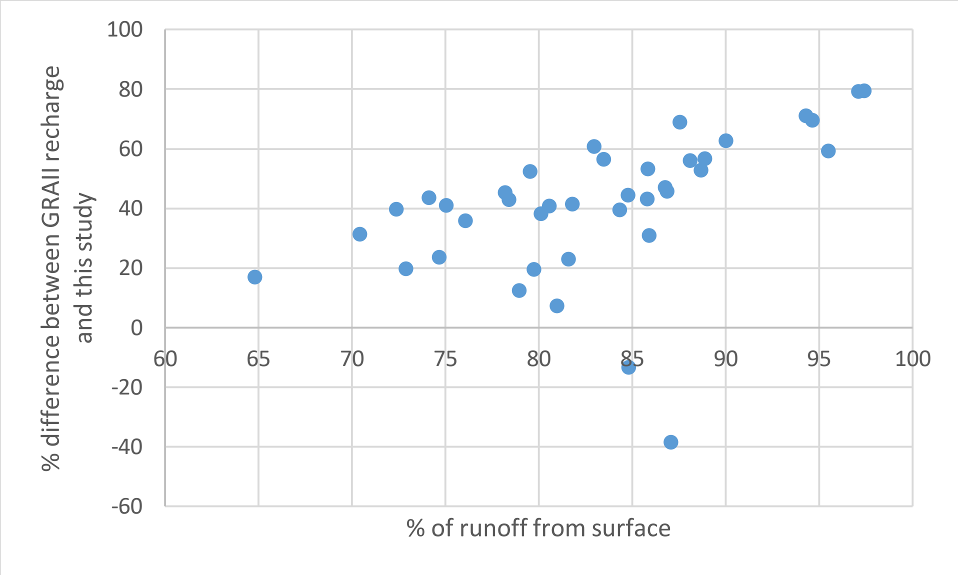


Figure 4-5 Error in recharge with increasing surface runoff

The total recharge (aquifer recharge and recharge generating interflow) in the Senqu River Basin is 945.03 Mm^3/a. The baseflow component is 760.76 Mm^3/a, of a total of 4165 Mm^3/a of discharge from the basin. This therefore means groundwater contributes 18% of discharge. Aquifer recharge is 221.1 Mm^3/a. Of this volume, 36.83 M^3/a (17%), generates baseflow from groundwater. Total Rainfall is 19279 Mm^3/a; hence aquifer recharge is only 1.1% of rainfall.

Total recharge in the Upper Caledon River basin is 337.10 Mm^3. Annual baseflow in the basin is 196.13 Mm^3 of 1241.62 Mm^3/a of runoff, therefore groundwater contributes 16% of discharge from the basin. Aquifer recharge is 176.11 Mm^3/a. Of this volume, 35.13 M^3/a (20%) generates groundwater baseflow. Total Rainfall is 11037.79 Mm^3/a; hence aquifer recharge is only 1.6% of rainfall.

Table 4-5 Simulated recharge and baseflow for the Senqu River

Runoff Unit	Quaternaries	Gauging Station	Dominant Geology	MAP (mm/a)	Area (km^2)	GRAII Recharge (mm/a)	Total Recharge (mm/a)	Aquifer recharge (mm/a)	Interflow (Mm^3/a)	Total Baseflow (Mm^3/a)	Runoff (Mm3/a)	ORASECOM Phase II Runoff (Mm^3/a)
Pelaneng	D11A-D	SG45	Basalt	962	1157	120	56.03	9.06	54.34	55.42	391.55	
Bokong	D11F	SG41	Basalt	930	403	72.5	50.11	10.28	16.05	16.37	116.17	
Paray	D11E	None	Basalt	763	307.4	62.72	34.81	7.61	8.36	8.6	56.42	
Total									78.75	80.39	564.14	559.4
Matsoku	D11G&H	SG42	Basalt	721	652	70	38.24	7.44	20.08	20.97	96.18	98.1
Paray2	D11J&K	None	Basalt	763	720.6	50	38.57	7.86	22.13	23.05	125.2	
Tlokoeng	D16A-C	SG36	Basalt	813	852	82.57	46.67	10.14	31.12	32.54	125.77	
Mokhotlong	D16D-E	Sg06	Basalt	872	1660	72.39	44.78	10.2	57.41	60.04	302.08	
Koma Koma	D16F-M	SG05	Basalt	718	2225	52.36	29.83	7.65	49.34	53.1	245.96	
Total									160	168.73	799.01	792.1
Marakabei1	D17A&B	Mohale	Basalt	944	938.1	50.47	57.23	10.22	44.1	45.08	296.72	
Marakabei2	D17B	SG17	Basalt	944	148.9	35.97	49.83	10.14	5.91	6.02	46.59	
total									50.01	51.1	343.31	303.2
Nkaus	D17C-F	SG32	Basalt	678	2479	51.67	33.11	8.35	61.38	65.49	273.82	291.7
Tsoelike	D17J-K	SG07	Basalt	763	797	50.31	26.62	6.68	15.89	17.14	129.6	
Seaka1	D17G-H	None	Basalt	796	1497.4	40.92	37.96	10.11	41.7	44.37	233.1	
Total									57.59	61,51	362.7	362.6
Seaka2	D17L-M	None	Basalt	796	1130.3	43.85	38.44	10.79	31.25	33.11	157.14	154.5
Seaka3	D18A-J	SG03	Basalt	796	4807.3	50.45	40.65	11.18	141.69	149.08	736.2	

Runoff Unit	Quaternaries	Gauging Station	Dominant Geology	MAP (mm/a)	Area (km²)	GRAII Recharge (mm/a)	Total Recharge (mm/a)	Aquifer recharge (mm/a)	Interflow (Mm³/a)	Total Baseflow (Mm³/a)	Runoff (Mm3/a)	ORASECOM Phase II Runoff (Mm³/a)
Oranjedraai	D15A-H, D18L-M	D1H009	Basalt	742	4806	53.74	32.46	6.83	123.18	130.38	832.68	
total									264.87	279.46	1568.88	1557.7
BASIN TOTAL											4165.18	4120.1

Table 4-6 Simulated recharge and baseflow for the Caledon River

Quaternaries	Gauging Station	Dominant Geology	MAP (mm/a)	Area (km²)	GRAII Recharge (mm/a)	Total Recharge (mm/a)	Aquifer recharge (mm/a)	Interflow (Mm³/a)	Total Baseflow (Mm³/a)	Runoff (Mm3/a)	WR2012 Runoff (Mm³/a)	ORASECOM Phase II Runoff (Mm³/a)
D21A	CG55	Basalt	978	309	86.41	69.38	13.72	17.2	17.65	65.08	65.50	56.9
D21B	CG26	Basalt	1021	394	95.46	72.99	14.31	23.12	23.66	93.4	93.92	78.30
D21D	D2h012	Sedimentary	839	252	63.35	30.22	13.59	4.19	4.75	23.2	22.59	
D21E		Sedimentary	784	268	47.26	27.85	12.4	4.14	4.58	18.36	18.60	
Total								8.33	9.33	41.56	41.19	47.0
D21C	D2H035	Sedimentary	883	212	70.75	48.51	11.2	7.91	8.32	28.12	33.62	
D21F		Sedimentary	725	480	42.31	25.07	15.19	4.74	6.56	33.76	33.04	
D21G		Sedimentary	751	278	45.59	26.75	16.03	2.98	4.02	22.06	20.97	

Quaternaries	Gauging Station	Dominant Geology	MAP (mm/a)	Area (km²)	GRAII Recharge (mm/a)	Total Recharge (mm/a)	Aquifer recharge (mm/a)	Interflow (Mm³/a)	Total Baseflow (Mm³/a)	Runoff (Mm3/a)	WR2012 Runoff (Mm³/a)	ORASECOM Phase II Runoff (Mm³/a)
D21H		Sedimentary	782	381	51.96	43.16	10.09	12.6	13.39	38.05	41.62	
Total								28.23	32.29	121.99	129.25	128.1
D21K	Cg50	Basalt	960	326	94.50	44.50	15.73	9.38	10.02	88.44	67.16	91.80
D21J	CG25	Basalt	991	359	91.14	49.47	17.27	11.56	12.27	93.26	80.55	
D21L		basalt	860	304	69.08	39.24	14.7	7.46	8.15	57.34	44.18	
Total								19.02	20.42	150.60	124.73	158.2
D22A+B		Sedimentary	700	1093	40.97	17.98	13.25	5.17	8.09	67.91	68.25	
D22C	D2H35 (D2C+D21)	Sedimentary	786	486	52.14	31.44	9.84	10.5	11.7	42.35	50.26	
D22D		Sedimentary	694	628	39.08	16.96	12.68	2.69	4.12	37.03	37.08	
D22E+F		Sedimentary	784	1131	66.43	26.09	13.56	14.17	18.15	106.5	108.22	
D22G+H		Sedimentary	703	1510	42.79	15.93	12.1	5.79	8.96	89.76	90.21	
D22J+K+L		Sedimentary	748	1352	54.92	23.87	13.39	14.17	18.86	114.06	122.81	
Total								52.49	69.88	457.61	476.83	446.2
D23A+B		Sedimentary	696	1205	45.14	13.06	11.65	1.7	4.15	72.94	76.60	
D23C	D2R002	Sedimentary	638	861	34.8	10.84	10.26	0.5	3.39	27.23	26.19	30.1
D23D+E		Sedimentary	611	1267	30.15	9.20	8.82	0.48	2.48	46.33	50.01	

Quaternaries	Gauging Station	Dominant Geology	MAP (mm/a)	Area (km^2)	GRAII Recharge (mm/a)	Total Recharge (mm/a)	Aquifer recharge (mm/a)	Interflow (Mm^3/a)	Total Baseflow (Mm^3/a)	Runoff (Mm3/a)	WR2012 Runoff (Mm^3/a)	ORASECOM Phase II Runoff (Mm^3/a)
D23F+G	D2H037 Incremental D21-D23G	Sedimentary	629	864	24.75	10.09	9.52	0.49	1.93	42.7	44.59	
D23H	D2R006	Sedimentary	519	776	15.59	3.20	3.17	0.02	0.48	18.59	26.25	17.6
D23J		Sedimentary	541	534	18.78	3.91	3.85	0.03	0.44	15.15	21.18	
TOTAL	D2H001 D2R004									1241.62		1236.7

4.8 Proposed recharge for the Karoo Sedimentary Aquifer

The results from the surface-subsurface modelling study were utilised to derive rainfall-recharge relationships. Figure 4-6 shows that catchments underlain by basalt generate proportionally more runoff than those underlain by sedimentary rocks. This is to be expected given the steep slopes and shallow soils of the basalt catchments. Figure 4-7 shows that the basalt aquifers also generate a higher proportion of baseflow.

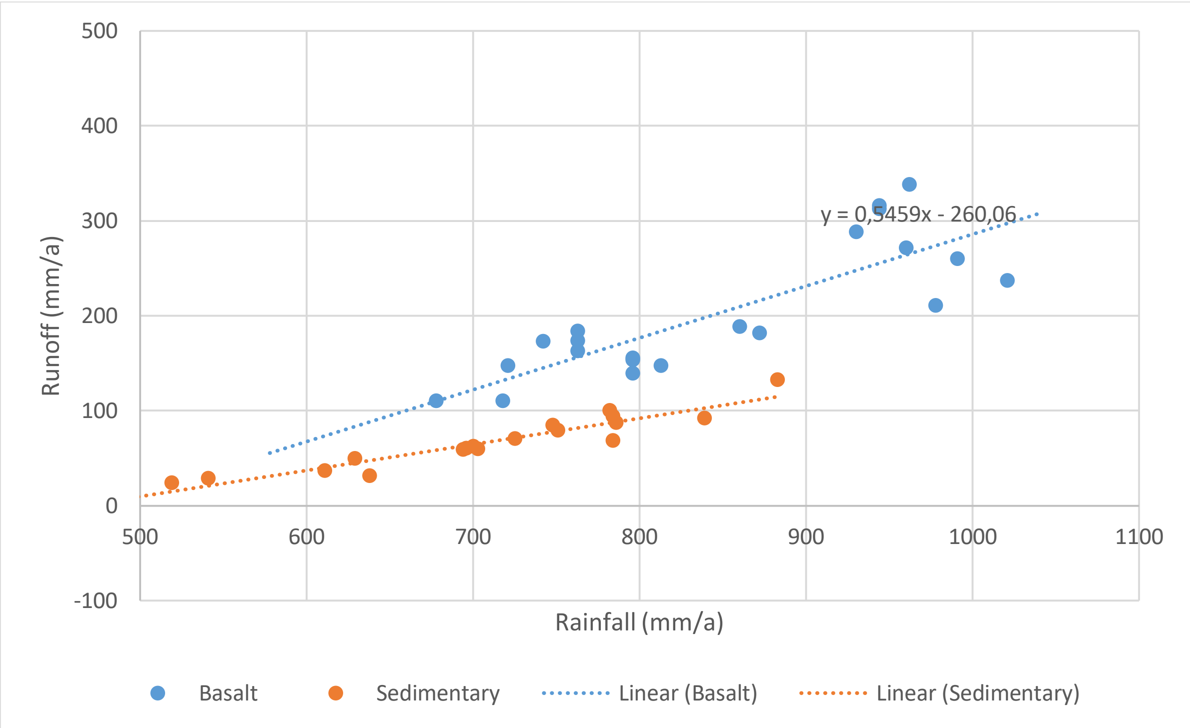


Figure 4-6 Relationship between rainfall and runoff

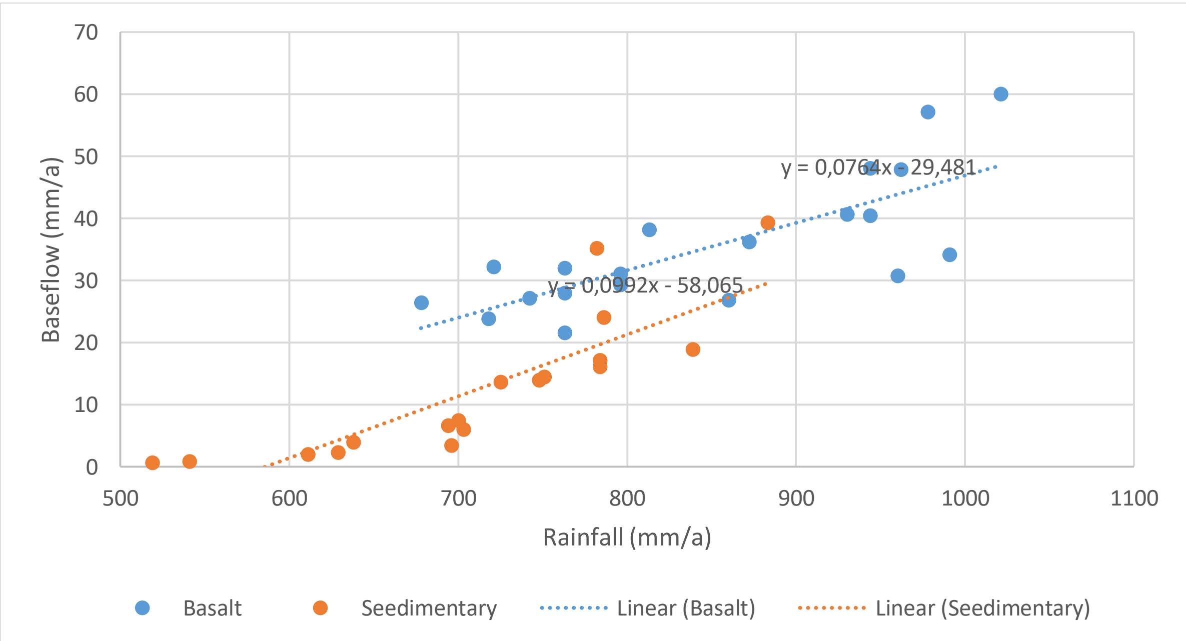


Figure 4-7 Relationship between Rainfall and baseflow

Figure 4-8 shows that in the basalts, over 90% of baseflow originates as interflow, and doesn't pass through the regional aquifer. This implies that over 90% of recharge is not accessible as a groundwater resource, resulting in the low borehole yields and limited groundwater resources in the basaltic Highlands. In the drier sedimentary lowlands, the bulk of recharge percolates to the regional aquifer.

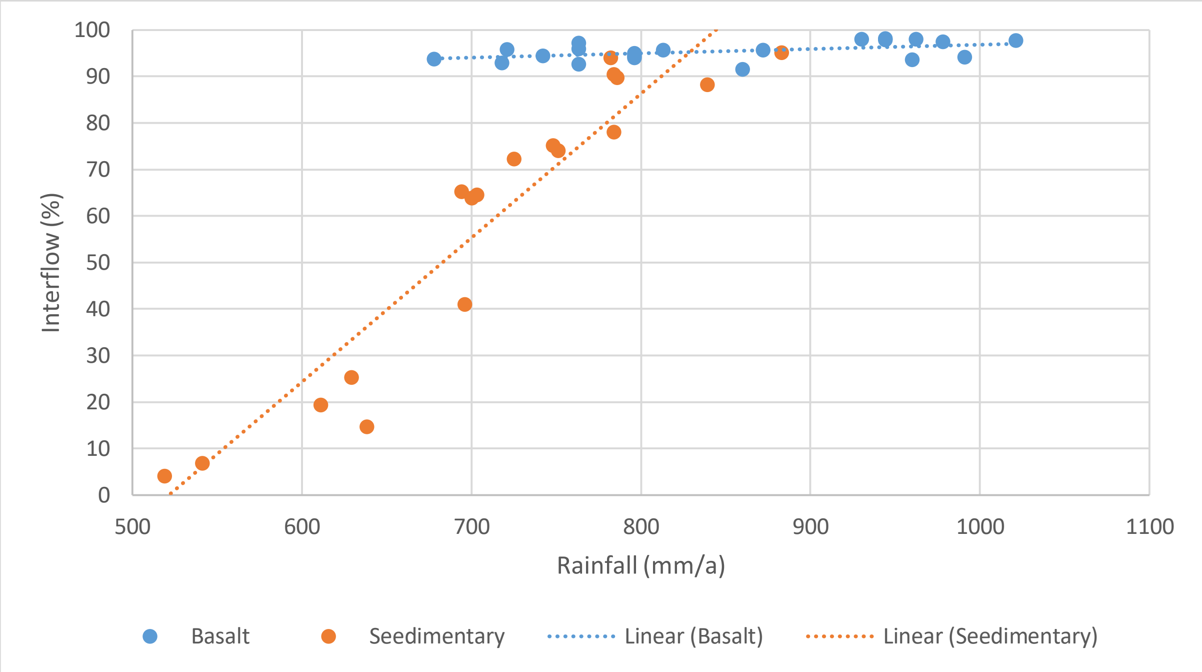


Figure 4-8 Interflow as percent of baseflow

The regional rainfall-recharge relationships are shown in figure 4-9. For basalts, recharge can be defined by:

Recharge mm/a = (Rainfall – 396) *0.098

For the Karoo sedimentary aquifer:

Recharge mm/a = (Rainfall – 532) *0.12

In terms of quantifying aquifer recharge to the regional aquifer, the groundwater available to boreholes, recharge to the Karoo sedimentary aquifer is proportionally higher than the basalt aquifer (figure 4-10), since much of the recharge to the basalts is lost as interflow.

Aquifer recharge for the Karoo sedimentary aquifer can be defined by:

Recharge (mm/a) = 17.72 * LN Rainfall -105

For the basalt aquifer:

Recharge (mm/a) = 17.87 * LN Rainfall -110

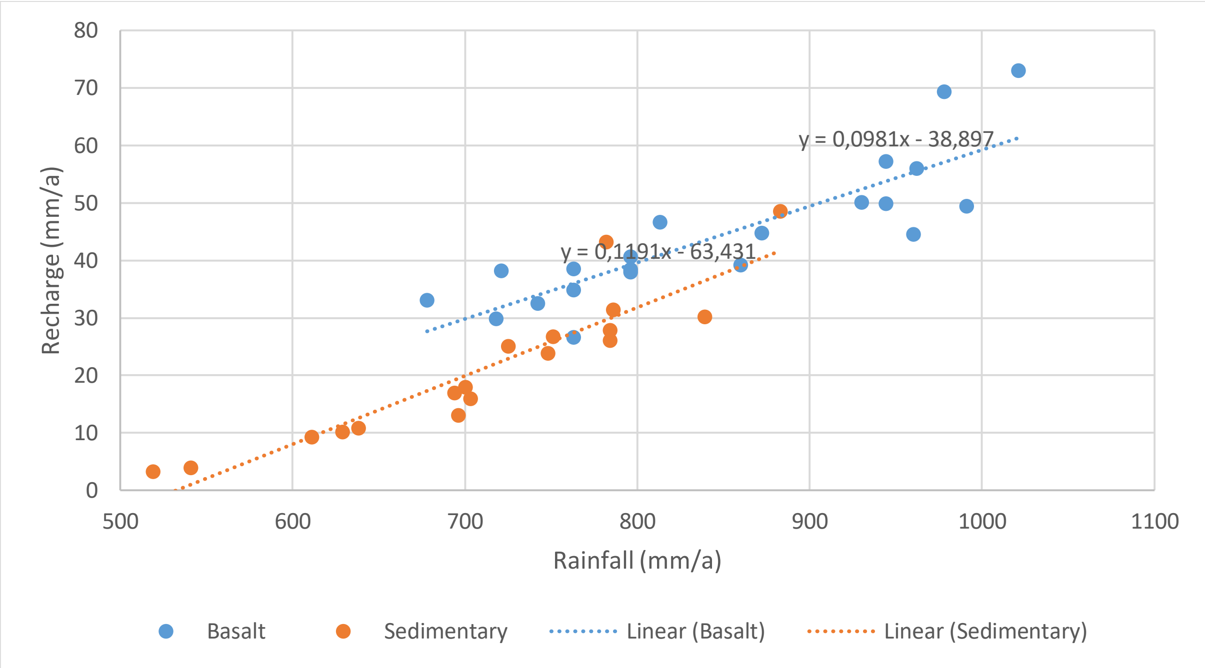


Figure 4-9 Relationship between rainfall and recharge

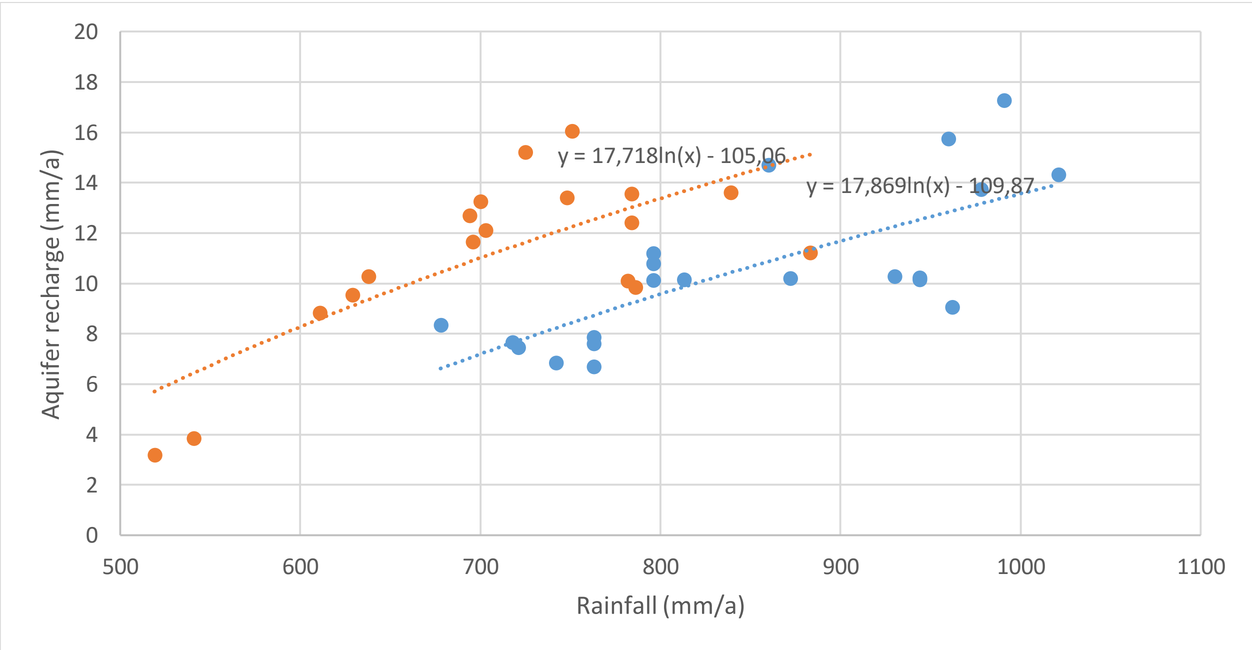


Figure 4-10 Relationship between rainfall and aquifer recharge

5 SUMMARY AND CONCLUSIONS

5.1 Khakhea Bray Aquifer

In the Khakhea/Bray area, two main aquifer types can be identified: porous sedimentary and karstic. The porous aquifer, that stores and transmits water via the interstitial pore space in the sedimentary formations is represented by alluvial and Kalahari Bed aquifers. The karstic fractured aquifer is of carbonate rocks where solution weathering along joints, fractures, and bedding has enhanced the water-bearing capabilities of the rock.

The study area is characterised by low annual rainfall. The average for all stations is 376 mm/a.

The mean annual rainfall was used to statistically derive drought rainfall based on the General Extreme Value Distribution (GEV). The 100-year drought rainfall is 155 mm/a. The 10- year drought rainfall is 231 mm/a.

The Geology of the aquifer consists of 2 units of interest: Kalahari Group: Quaternary and tertiary sediments, pan sediments (sand and clay), diatomaceous limestone and aeolian sand, with extensive coverage all over the area; and the Griqualand west/ Kanye basin: Predominantly carbonate rocks such as limestone, and dolomite with interbedded chert. They lie conformably on the Vryburg Formation, which is the base of the dolomite and consists of quartzite, flagstone and grit.

The study area is defined as the sub-outcrop boundary of the Transvaal Group dolomites. The study area occupies part of quaternary catchments D41C, D, E and F in South Africa and catchment Z10D in Botswana. The dolomitic aquifer is currently overutilized in South Africa due to the abstraction of groundwater for agricultural activities. Due to the nature of the dolomitic aquifer, and the fact that the quaternary catchment boundaries do not form groundwater divides, the entire dolomitic aquifer was selected as the boundary of the study area and dykes were used to subdivide it into compartments.

Three Resource Units (RUs) are defined within the dolomitic in South Africa, identified from observed aquifer characteristics, from drilling logs, water level response, aquifer tests and the presence of regional dolerite dykes. One of the Resource Units extend into Botswana. 3 other Resource Units can be identified in Botswana.

The recharge in the areas covered by Kalahari sediments is sometimes believed to be negligible in areas with less than 300 or 400 mm/year of rainfall. However, Isotopic evidence suggests that recharge to the karstic aquifers is taking place. Isotopes have suggested that recharge through the Kalahari was 3.7-4.7 mm/a from an MAP of 350 mm/a.

The only available continuous water levels are around Pomfret between the mid-80s-90s. Water levels clearly indicate declining levels due to over abstraction. From the general lack of annual water level rises, it is evident that recharge is not an annual event, or annual recharge is very low.

Calculations of groundwater usage indicated a usage of nearly 21 Mm3/a, of which 19.5 Mm^3/a was for irrigation.

Smit (1977) calculated recharge as 2.2-3.8% of Rainfall in outcrop areas, 0.26-0.8% where the Kalahari cover is <15 m, and assumed no recharge where the Kalahari cover is greater than 15 m. The average recharge was 0.5%.

Godfrey and Van Dyk (2002) present recharge values based on 'professional judgement, based on experience within the catchment', with no further indication of how these values were derived. They list recharge as 19.6 Mm^3a for the South African Portion, yet large water level declines are evident, hence this estimate is almost certainly too high.

Recharge to the aquifer was also estimated by Van Dyk (2005). Using the CMB method, he calculated recharge to be between 0.2 to 28 mm/a of the MAP in the different areas of the aquifer, with the higher values associated with outcrop areas, alluvial channels and structural features. The harmonic mean was 1.7 mm/a, or 0.4% of rainfall. The average was 4.9 mm/a. A total recharge of 13.41 Mm/a is calculated.

Based on a groundwater model, Van Dyk (2005) also estimated that the average recharge was 1.75% of MAP or 9.7 mm/a. with the area covered by Kalahari sands 5.6 mm/a, the banded ironstones 1.9 mm/a and the strips along rivers being 7.5 mm/a.

Bredenkamp (2009) estimated recharge for the South African portion of the aquifer using regional rainfall-recharge relationships. He estimated an average recharge of 1.65 mm/a.

This study utilised the same equations as Bredenkamp but developed a time series using a 48-month moving average of rainfall. Using average monthly rainfall eliminates the effect of wet period and underestimates recharge during wet periods. When the equations are applied to 48-month average rainfall, this study achieves a higher average recharge of 2.63 mm/a. This stresses that recharge can only occur above a monthly threshold rainfall value and that average time series data cannot be used to derive an average recharge.

This study also applied the CRD to one of the boreholes and subcompartments at Pomfret. The threshold rainfall to initiate recharge was found to be 100 mm/month, above which 10% of rainfall contributes to recharge. The mean annual recharge is 1.68 mm/a, or 0.44% of recharge. The monthly recharge values were aggregated to derive an annual rainfall-recharge relationship:

Recharge = (Rainfall -344) * 0.0372

Based on water level data from Pomfret, recharge appears to be sporadic, only occurring when rainfall exceeds 100 mm/month. This rainfall has a return period of 22 months.

Calculated recharge for the entire aquifer is 14.79 Mm^3/a. In the Resource Unit directly shared between South Africa and Botswana it is 6.21 Mm^3/a. 1220 km^2 of the 2061 km^2 lie within South Africa and the remainder in Botswana. It is likely that the recharge from the other Resource Units drain into this transboundary unit.

In 2016 a restriction was implemented reducing the total abstraction to 8.2 Mm^3/a on the South African side. Demand from this resource unit is currently 10.2 Mm^3/a, of which 8.2 Mm^3/a, is for irrigation on the South African side.

5.2 Karoo Sedimentary Aquifer

Two main aquifer types can be distinguished: The Highlands largely underlain by basalt, and where baseflow is interflow driven, and the Lowlands, which are drier and have a semi-arid to temperate climate, receiving annual rainfalls of 500 to 1 150 mm that fall mainly during October to April. The international boundary is marked by the perennial Caledon, (Mohokare), Senqu (Orange) and Makhaleng rivers, many of whose tributaries are episodic or ephemeral.

TAMS (1996) estimated the renewable groundwater resources of Lesotho to be 10.84m_3/s (cumecs), of which 7.37m_3/s is available in the Lowland areas of the basin. Water balance studies indicate 2.5% of annual rainfall recharges to groundwater systems. There is unfortunately no water-level data to support these estimates.

The study area encompasses Tertiary catchments D11, D15-D18, which form the Senqu River basin, and D21-D23, which are the Upper Caledon River (Figure 4-1).

The study area is characterised by variable rainfall. Rainfall is an average of 909 mm/a in tertiary catchment D11, with nearly 1200 mm/a in the headwaters. Rainfall declines to 745 mm/a in D18 where the Tertiary extends into South Africa to Oranjedraai. The rainfall in the headwaters of the Caledon River, D21 is 867 mm/a, declining to 617 mm/a where the River reaches the Welbedacht dam between Smithfield and Wepener, D23.

All the Quaternary catchments are perennial. According to GRAII, the MAR of the Senqu Basin is 4012.1 Mm^3/a, of which 1680.44 Mm^3/a originates as baseflow. This implies 42% of runoff is via groundwater. For the Caledon river, MAR is 1243 Mm^3/a, of which 442.15 Mm^3/a, or 36% is from baseflow.

The geology of Lesotho comprises horizontal to sub-horizontal dipping sedimentary rocks of the Beaufort and Stormberg Groups of the Karoo Supergroup overlain by up to 1600 m of Drakensburg Group basalt.

Groundwater recharge data is given in GRAII, calculated using the chloride method. Recharge in the Senqu river basin is 1415 Mm^3/a and 725 Mm^3/a in the Caledon river basin.

Since the requirements from a recharge study are twofold: calculating recharge to determine its relevance to baseflow protection, and calculating the groundwater resource, two types of information are required: Recharge which drives both groundwater baseflow and interflow from springs; and Aquifer recharge which reaches the regional aquifer and is available to boreholes. There must also be a water balance so that all of recharge is accounted for. Due to the large extent of the study area and the variable rainfall, point estimate of recharge would not be useful.

To derive a water balance for recharge and its eventual discharge, the WRSM2000 model was utilised with the hydrology network for ORASECOM Phase 2 (2011). The original ORASECOM hydrology did not include the Sami surface-subsurface groundwater module. This was included, and the model was recalibrated against observed flows with groundwater, also ensuring that the accepted surface water hydrology characteristics did not change significantly from the 2011 study. This involved recalibrating 5 existing networks of the ORASECOM hydrology (figure 4-3 and 4-4), the Katse subsystem, the Senqu system to the Oranjedraai gauging weir, the D21A, D21B, D22 & D23 networks to Welbedacht dam.

The study shows that existing GRAII recharge area large over estimate. The observed baseflows do not support such large recharge volumes. This can be attributed to the GRAII results being based on the Chloride method, which assumes that all Cl from precipitation ends up in groundwater. This assumption is not valid in the area as surface runoff is high. The Cl method therefore overestimates the Cl load to groundwater, hence increasingly overestimates recharge with increasing volumes of surface runoff. The error was found to increase from 10-80% with increasing proportions of surface runoff. It can be concluded that the Cl method cannot be applied in catchments where surface runoff is significant.

The results show that catchments underlain by basalt generate proportionally more runoff than those underlain by sedimentary rocks. The basalt aquifers also generate a higher proportion of baseflow. In the basalt catchments, over 90% of baseflow originates as interflow, and doesn't pass through the regional aquifer. This implies that over 90% of recharge is not accessible as a groundwater resource, resulting in the low borehole yields and limited groundwater resources in the basaltic Highlands. In the drier sedimentary lowlands, the bulk of recharge percolates to the regional aquifer.

Catchments underlain by basalt generate proportionally more runoff than those underlain by sedimentary rocks. In the basalts, over 90% of baseflow originates as interflow, and doesn't pass through the regional aquifer. This implies that over 90% of recharge is not accessible as a groundwater resource, resulting in the low borehole yields and limited groundwater resources in the basaltic Highlands. In the drier sedimentary lowlands, the bulk of recharge percolates to the regional aquifer.

The regional rainfall-recharge relationships developed are, for basalts, recharge can be defined by:

Recharge mm/a = (Rainfall – 396) *0.098

For the Karoo sedimentary aquifer:

Recharge mm/a = (Rainfall – 532) *0.12

In terms of quantifying aquifer recharge to the regional aquifer, the groundwater available to boreholes, recharge to the Karoo sedimentary aquifer is proportionally higher than the basalt aquifer, since much of the recharge to the basalts is lost as interflow. Aquifer recharge for the Karoo sedimentary aquifer can be defined by:

Recharge (mm/a) = 17.72 * LN Rainfall -105

For the basalt aquifer:

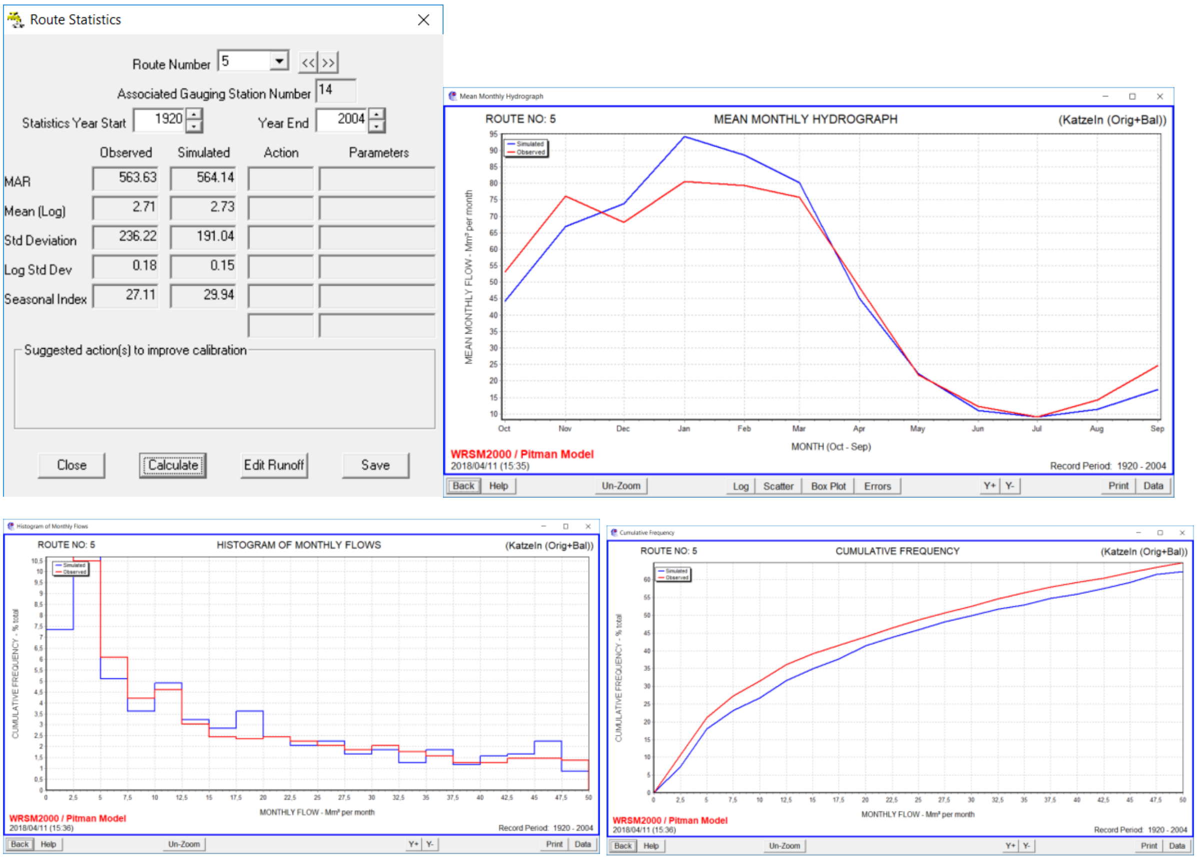
Recharge (mm/a) = 17.87 * LN Rainfall -110

The total recharge (aquifer recharge and recharge generating interflow) in the Senqu River Basin is 945.03 Mm^3/a. The baseflow component is 760.76 Mm^3/a, of a total of 4165 Mm^3/a of discharge from the basin. This therefore means groundwater contributes 18% of discharge. Aquifer recharge is 221.1 Mm^3/a. Of this volume, 36.83 M^3/a (17%), generates baseflow from groundwater. Total Rainfall is 19279 Mm^3/a; hence aquifer recharge is only 1.1% of rainfall.

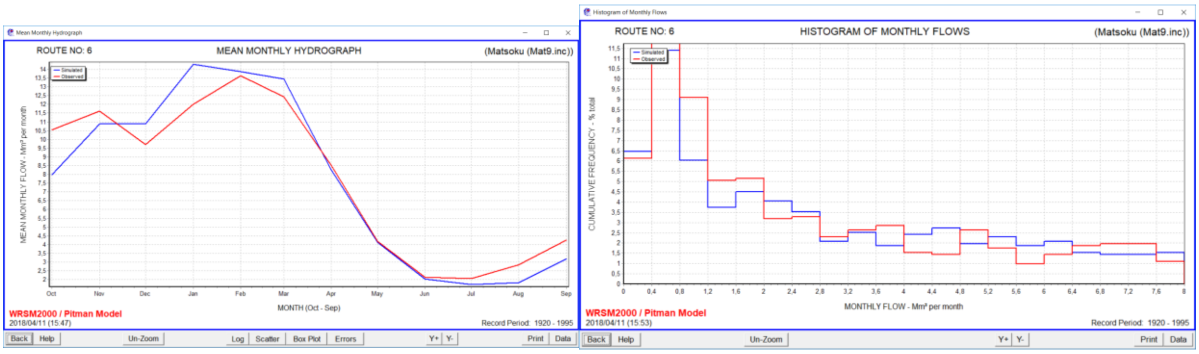
Total recharge in the Upper Caledon River basin is 337.10 Mm^3. Annual baseflow in the basin is 196.13 Mm^3 of 1241.62 Mm^3/a of runoff, therefore groundwater contributes 16% of discharge from the basin. Aquifer recharge is 176.11 Mm^3/a. Of this volume, 35.13 M^3/a (20%) generates groundwater baseflow. Total Rainfall is 11037.79 Mm^3/a; hence aquifer recharge is only 1.6% of rainfall.

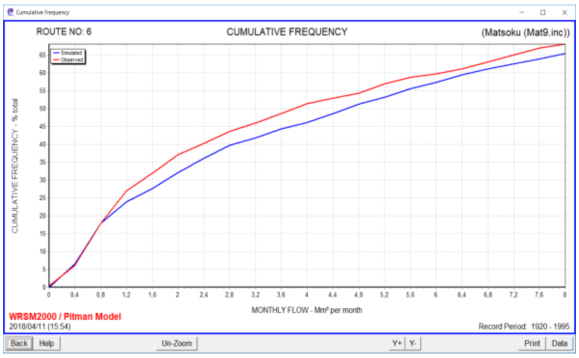
6 APPENDIX 1 CALIBRATION RESULTS

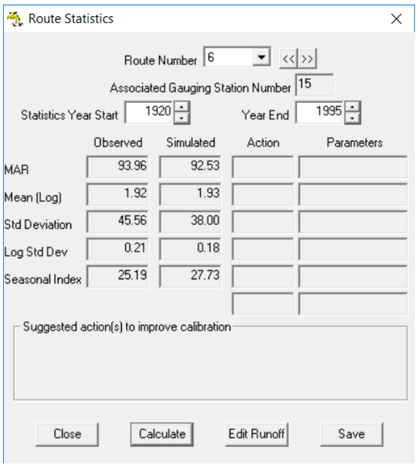
Katse Subsystem



Matsoku






Route Statistics

Route Number 6

Associated Gauging Station Number 15

Statistics Year Start 1920 Year End 1995

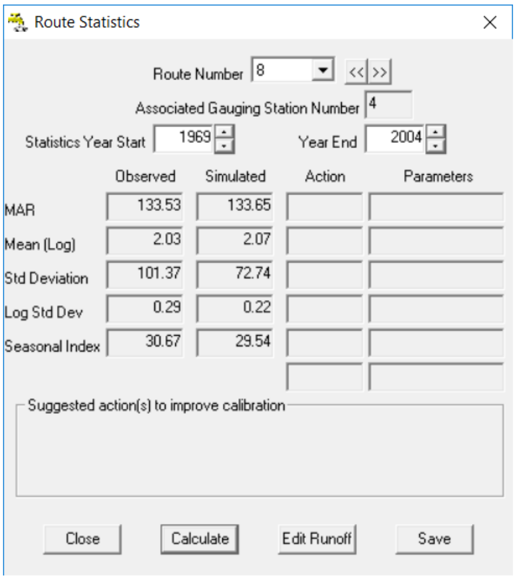
	Observed	Simulated	Action	Parameters
MAR	93.96	92.53		
Mean (Log)	1.92	1.93		
Std Deviation	45.56	38.00		
Log Std Dev	0.21	0.18		
Seasonal Index	25.19	27.73		

Suggested action(s) to improve calibration

Close Calculate Edit Runoff Save

Paray

Tlokeng


Route Statistics

Route Number 8

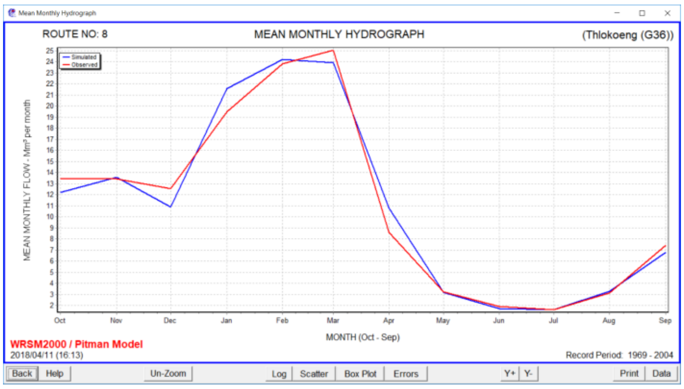
Associated Gauging Station Number 4

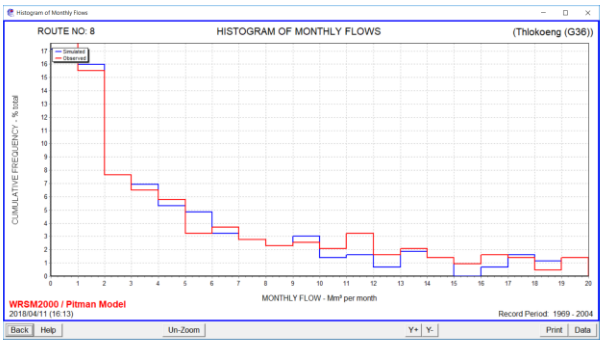
Statistics Year Start 1969 Year End 2004

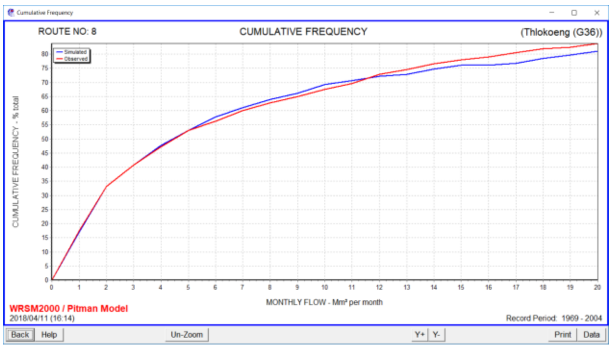
	Observed	Simulated	Action	Parameters
MAR	133.53	133.65		
Mean (Log)	2.03	2.07		
Std Deviation	101.37	72.74		
Log Std Dev	0.29	0.22		
Seasonal Index	30.67	29.54		

Suggested action(s) to improve calibration

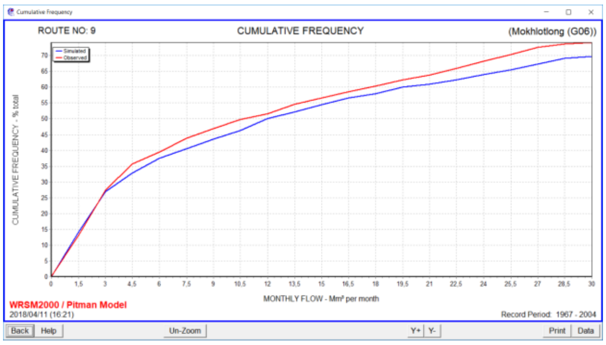
Close Calculate Edit Runoff Save

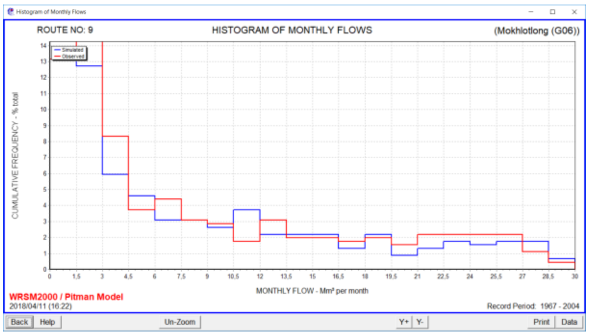


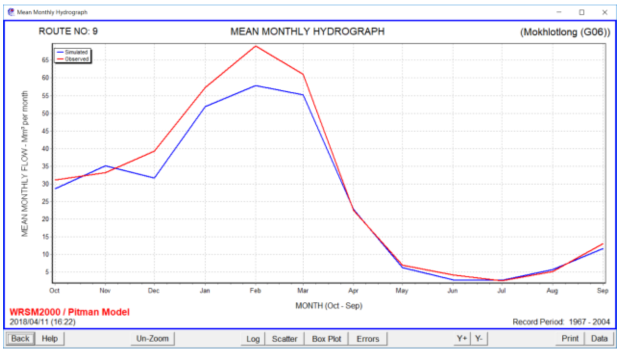


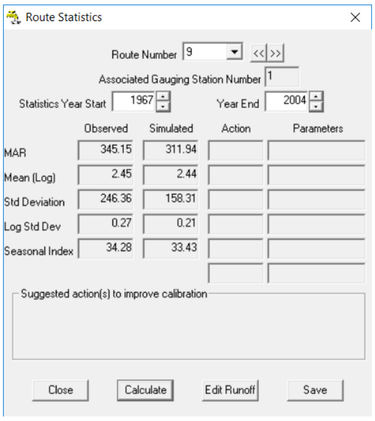


Mokhotlong








Route Statistics

Route Number 9

Associated Gauging Station Number 1

Statistics Year Start 1967 Year End 2004

	Observed	Simulated	Action	Parameters
MAR	345.15	311.94		
Mean (Log)	2.45	2.44		
Std Deviation	246.36	158.31		
Log Std Dev	0.27	0.21		
Seasonal Index	34.28	33.43		

Suggested action(s) to improve calibration

Close Calculate Edit Runoff Save

Marakabei


Route Statistics

Route Number 27

Associated Gauging Station Number 5

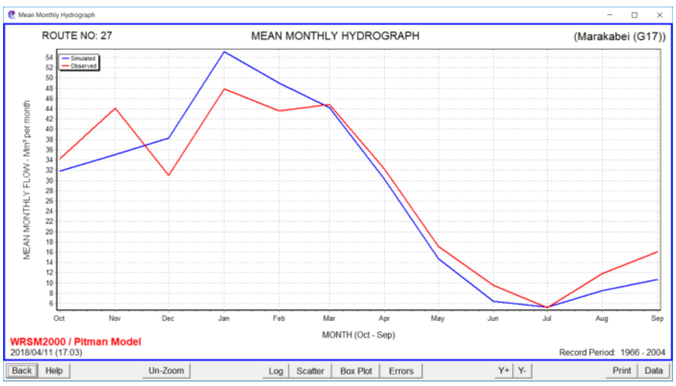
Statistics Year Start 1966 Year End 2004

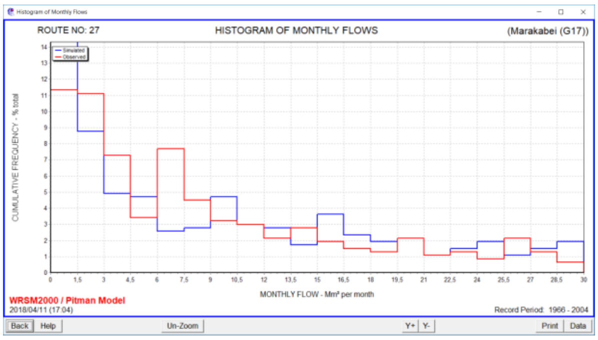
	Observed	Simulated	Action	Parameters
MAR	337.71	329.25		
Mean (Log)	2.45	2.44		
Std Deviation	181.29	148.38		
Log Std Dev	0.30	0.31		
Seasonal Index	23.94	27.84		

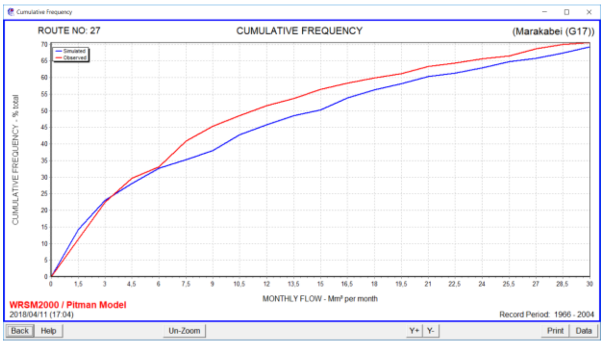
Suggested action(s) to improve calibration

No further suggestions.

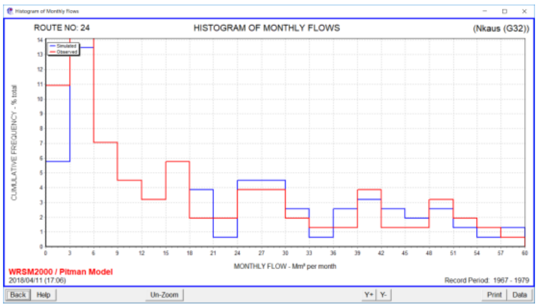
Close Calculate Edit Runoff Save

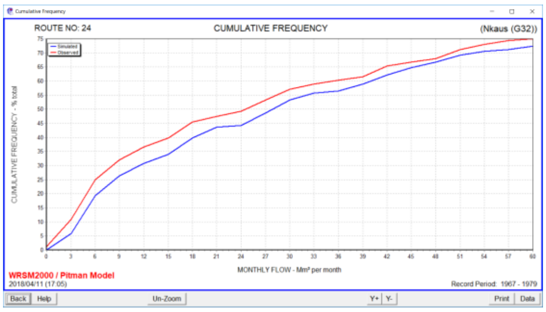


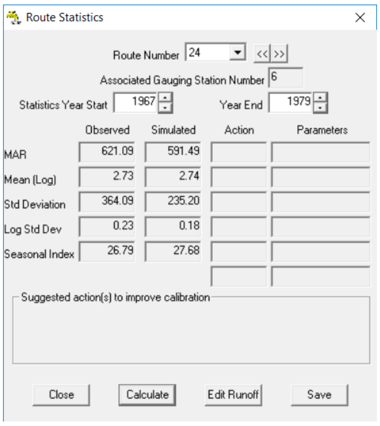


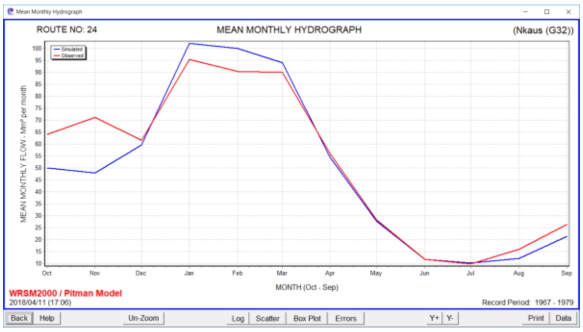


Mkaus

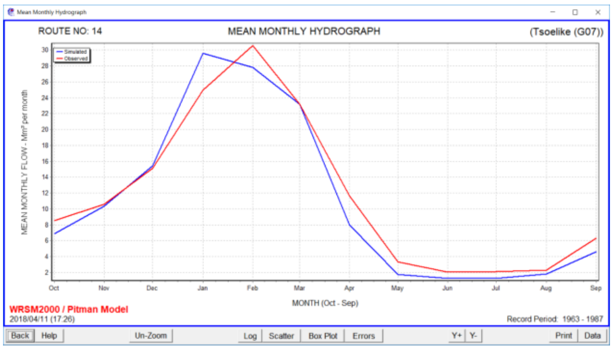


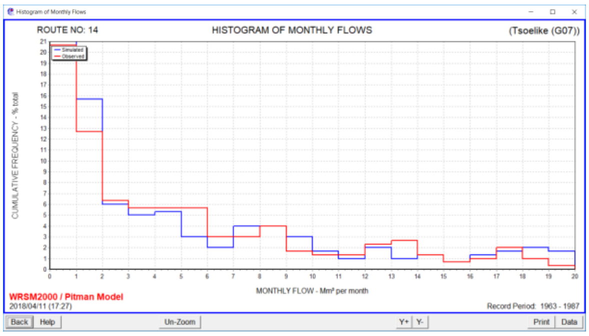


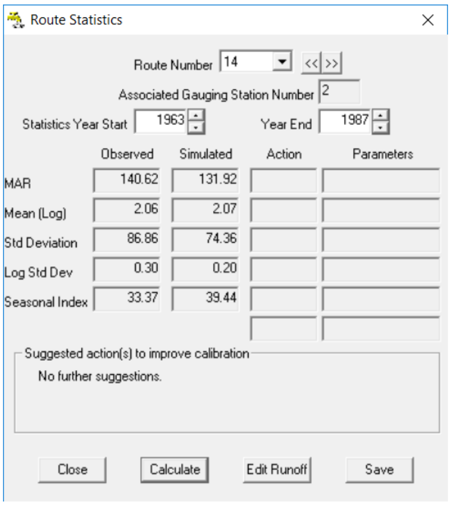


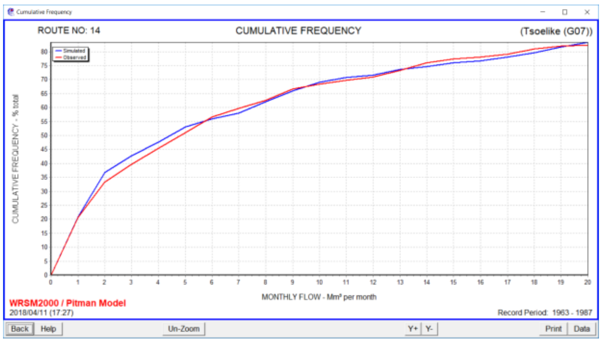


Tsoelike

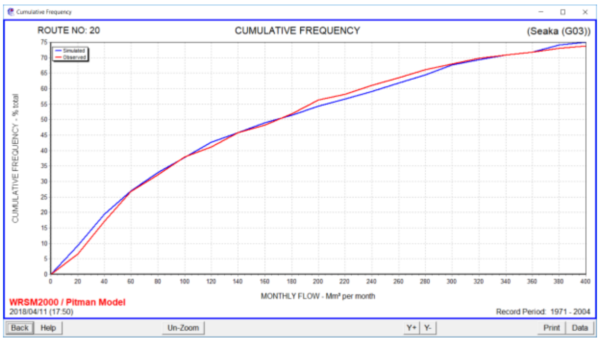

Mean Monthly Hydrograph
ROUTE NO: 14
MEAN MONTHLY HYDROGRAPH
(Tsoelike (G07))
Simulated
Observed
MEAN MONTHLY FLOW - Mm³ per month
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
MONTH (Oct - Sep)
WRSM2000 / Pitman Model
2018/04/11 (17:26)
Record Period: 1963 - 1987
Back Help Un-Zoom Log Scatter Box Plot Errors Y+ Y- Print Data

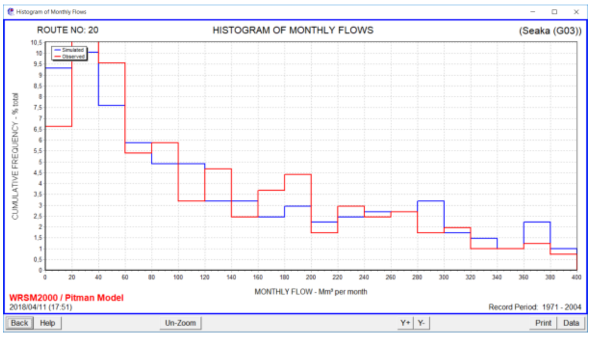

Histogram of Monthly Flows
ROUTE NO: 14
HISTOGRAM OF MONTHLY FLOWS
(Tsoelike (G07))
Simulated
Observed
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
2018/04/11 (17:27)
Record Period: 1963 - 1987
Back Help Un-Zoom Y+ Y- Print Data

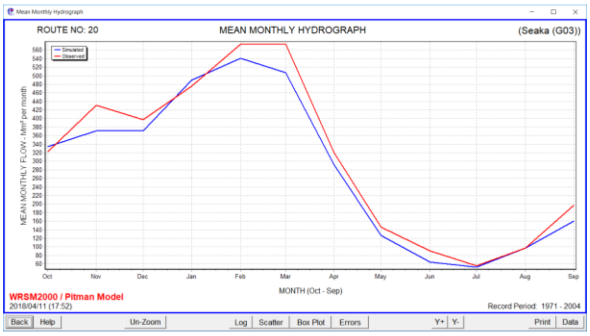

Route Statistics
Route Number 14
Associated Gauging Station Number 2
Statistics Year Start 1963
Year End 1987
Observed Simulated Action Parameters
MAR 140.62 131.92
Mean (Log) 2.06 2.07
Std Deviation 86.86 74.36
Log Std Dev 0.30 0.20
Seasonal Index 33.37 39.44
Suggested action(s) to improve calibration
No further suggestions.
Close Calculate Edit Runoff Save

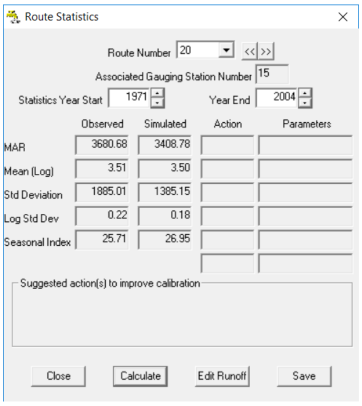

Cumulative Frequency
ROUTE NO: 14
CUMULATIVE FREQUENCY
(Tsoelike (G07))
Simulated
Observed
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
2018/04/11 (17:27)
Record Period: 1963 - 1987
Back Help Un-Zoom Y+ Y- Print Data

Seaka

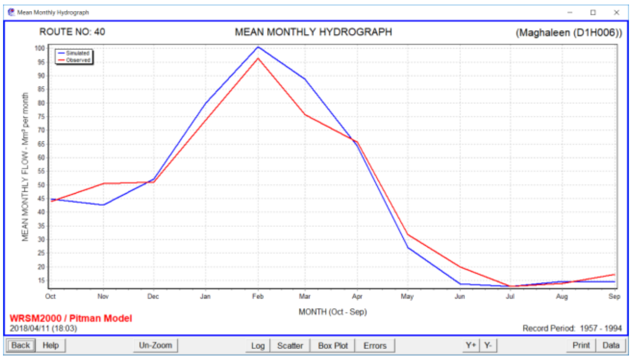

Cumulative Frequency
ROUTE NO: 20
CUMULATIVE FREQUENCY
(Seaka (G03))
Simulated
Observed
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
2018/04/11 (17:50)
Record Period: 1971 - 2004
Back Help Un-Zoom Y+ Y- Print Data

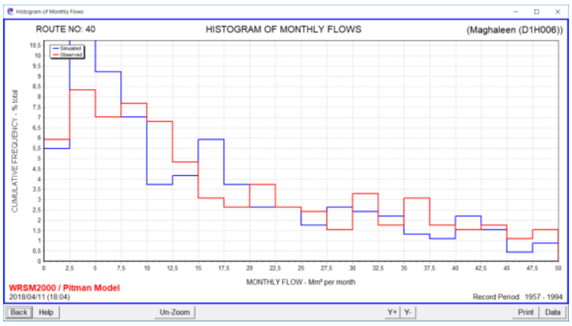

Histogram of Monthly Flows
ROUTE NO: 20
HISTOGRAM OF MONTHLY FLOWS
(Seaka (G03))
Simulated
Observed
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
2018/04/11 (17:51)
Record Period: 1971 - 2004
Back Help Un-Zoom Y+ Y- Print Data

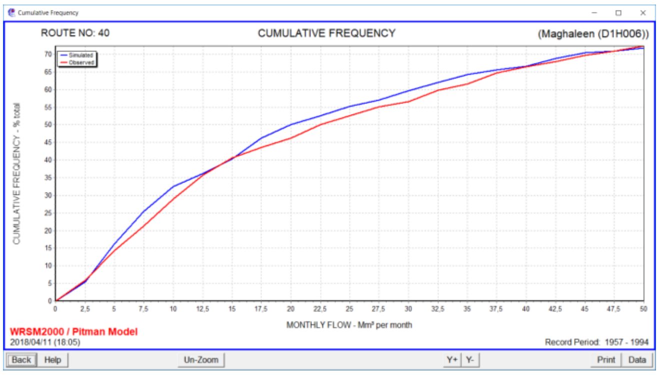

Mean Monthly Hydrograph
ROUTE NO: 20
MEAN MONTHLY HYDROGRAPH
(Seaka (G03))
Simulated
Observed
MEAN MONTHLY FLOW - Mm³ per month
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
MONTH (Oct - Sep)
WRSM2000 / Pitman Model
2018/04/11 (17:52)
Record Period: 1971 - 2004
Back Help Un-Zoom Log Scatter Box Plot Errors Y+ Y- Print Data

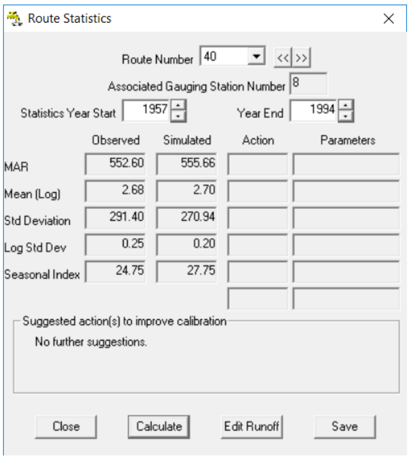

Route Statistics
Route Number 20
Associated Gauging Station Number 15
Statistics Year Start 1971
Year End 2004
Observed Simulated Action Parameters
MAR 3680.68 3408.78
Mean (Log) 3.51 3.50
Std Deviation 1885.01 1385.15
Log Std Dev 0.22 0.18
Seasonal Index 25.71 26.95
Suggested action(s) to improve calibration
Close Calculate Edit Runoff Save

Magaleen D1H006

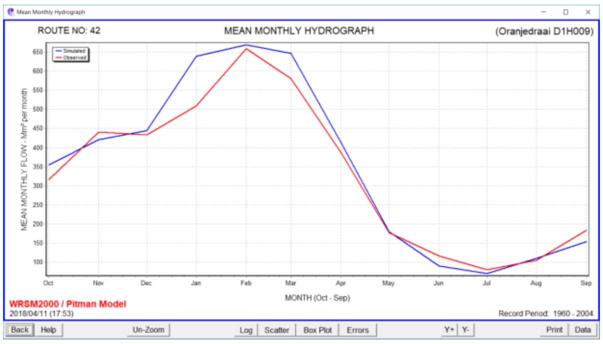


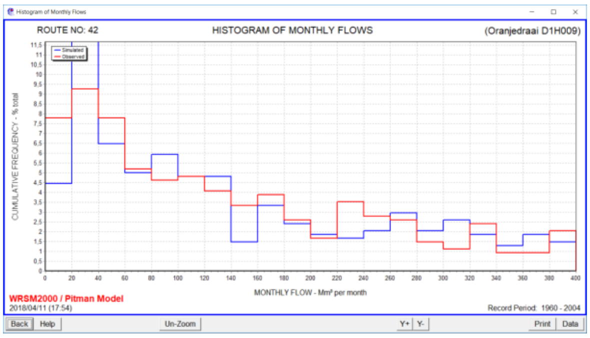


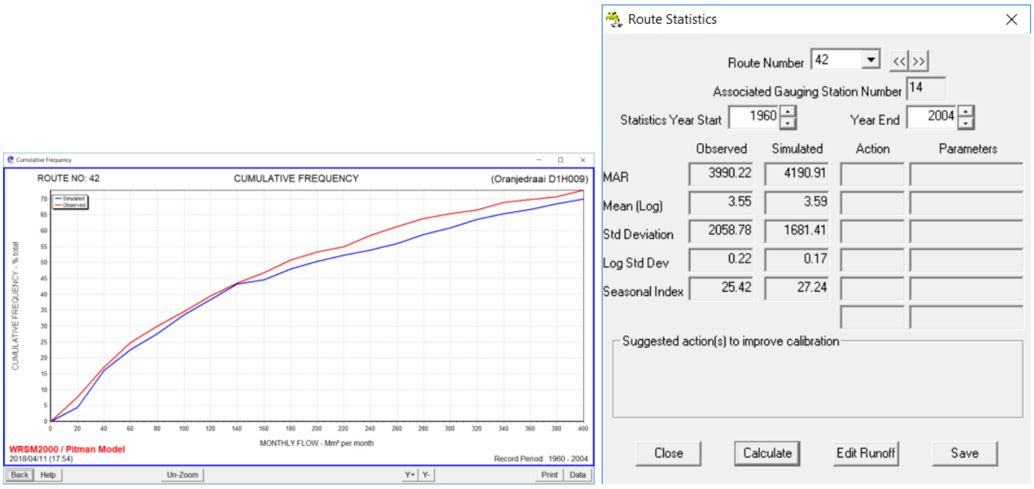




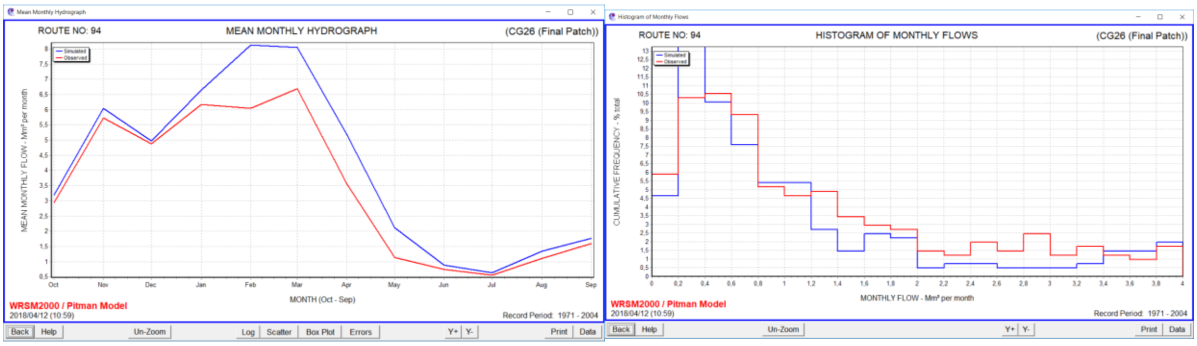
Oranjedraai

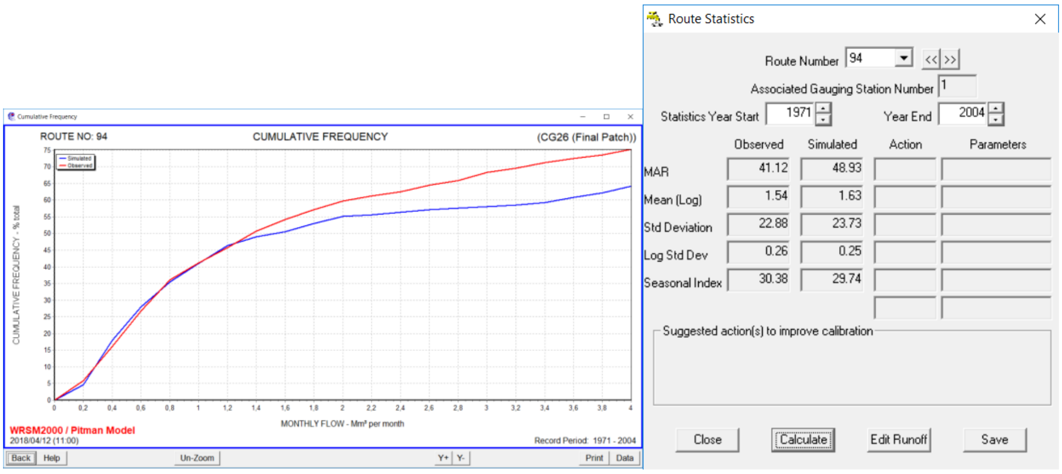




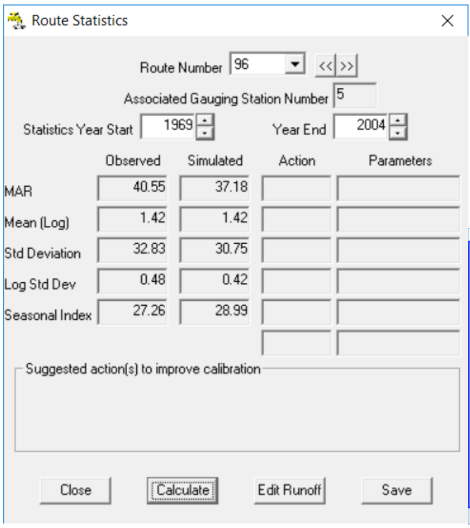

ROUTE NO: 42
CUMULATIVE FREQUENCY
(Oranjedraai D1H009)
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
Record Period: 1960 - 2004
Route Statistics
Route Number 42
Associated Gauging Station Number 14
Statistics Year Start 1960
Year End 2004
Observed Simulated Action Parameters
MAR 3990.22 4190.91
Mean (Log) 3.55 3.59
Std Deviation 2058.78 1681.41
Log Std Dev 0.22 0.17
Seasonal Index 25.42 27.24
Suggested action(s) to improve calibration
Close Calculate Edit Runoff Save

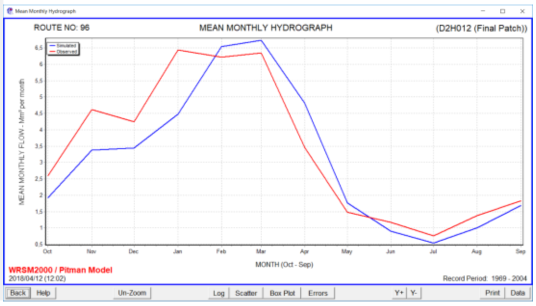
CG26

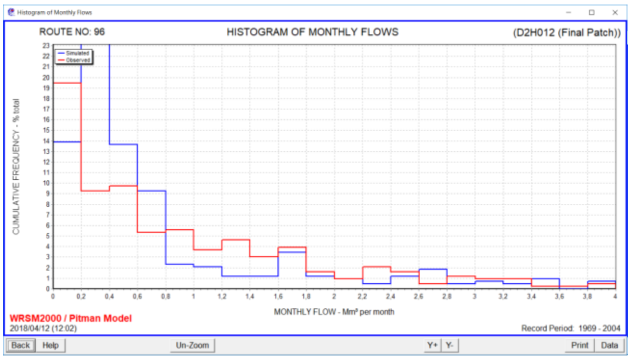

ROUTE NO: 94
MEAN MONTHLY HYDROGRAPH
(CG26 (Final Patch))
MEAN MONTHLY FLOW - Mm³ per month
MONTH (Oct - Sep)
WRSM2000 / Pitman Model
Record Period: 1971 - 2004
ROUTE NO: 94
HISTOGRAM OF MONTHLY FLOWS
(CG26 (Final Patch))
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
Record Period: 1971 - 2004

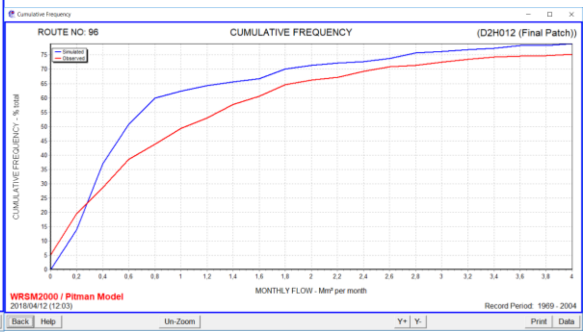

ROUTE NO: 94
CUMULATIVE FREQUENCY
(CG26 (Final Patch))
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
Record Period: 1971 - 2004
Route Statistics
Route Number 94
Associated Gauging Station Number 1
Statistics Year Start 1971
Year End 2004
Observed Simulated Action Parameters
MAR 41.12 48.93
Mean (Log) 1.54 1.63
Std Deviation 22.88 23.73
Log Std Dev 0.26 0.25
Seasonal Index 30.38 29.74
Suggested action(s) to improve calibration
Close Calculate Edit Runoff Save

D2H012

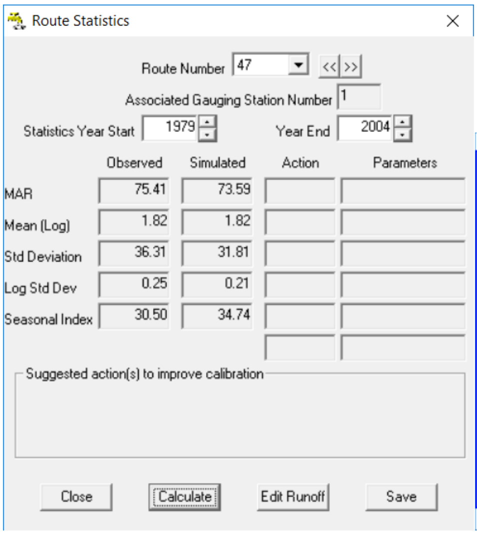

Route Statistics
Route Number 96
Associated Gauging Station Number 5
Statistics Year Start 1969
Year End 2004
Observed
Simulated
Action
Parameters
MAR 40.55 37.18
Mean (Log) 1.42 1.42
Std Deviation 32.83 30.75
Log Std Dev 0.48 0.42
Seasonal Index 27.26 28.99
Suggested action(s) to improve calibration
Close
Calculate
Edit Runoff
Save

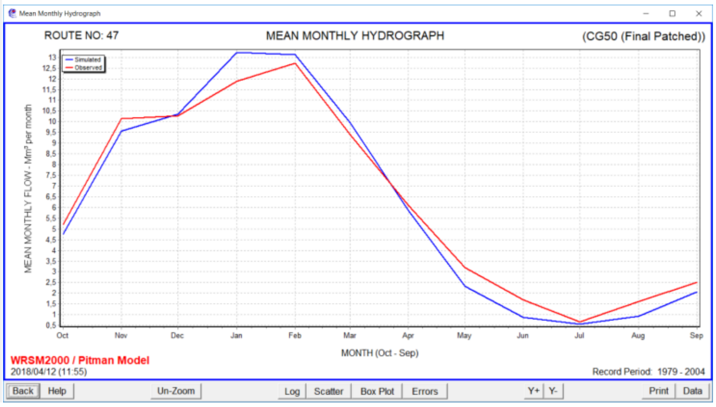

ROUTE NO: 96
MEAN MONTHLY HYDROGRAPH
(D2H012 (Final Patch))
MONTH (Oct - Sep)
WRSM2000 / Pitman Model
Record Period: 1969 - 2004

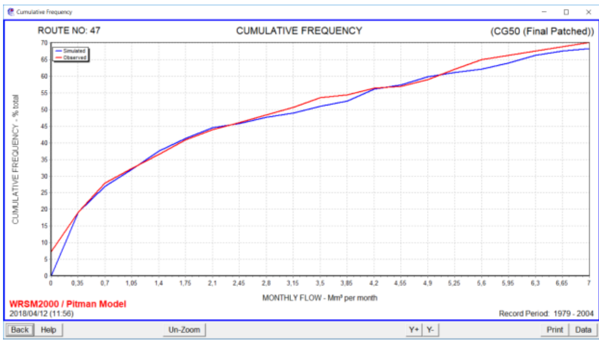

ROUTE NO: 96
HISTOGRAM OF MONTHLY FLOWS
(D2H012 (Final Patch))
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
Record Period: 1969 - 2004

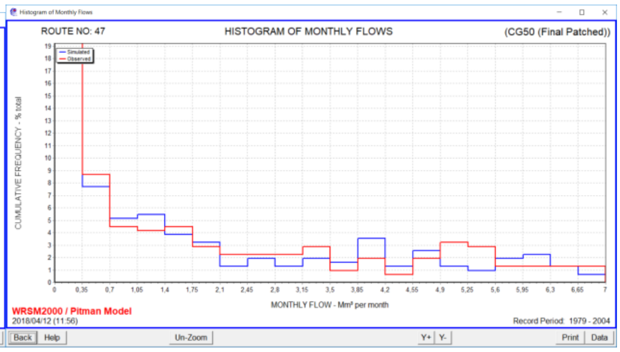

ROUTE NO: 96
CUMULATIVE FREQUENCY
(D2H012 (Final Patch))
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
Record Period: 1969 - 2004

CG50

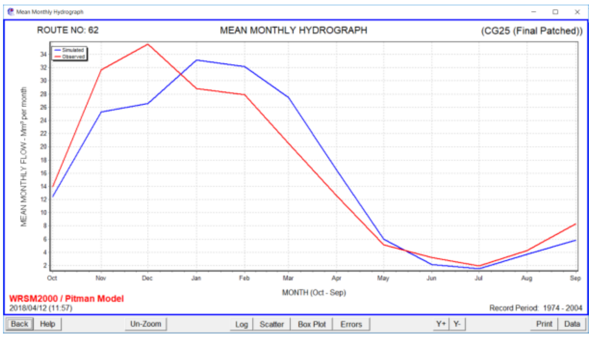

Route Statistics
Route Number 47
Associated Gauging Station Number 1
Statistics Year Start 1979
Year End 2004
Observed
Simulated
Action
Parameters
MAR 75.41 73.59
Mean (Log) 1.82 1.82
Std Deviation 36.31 31.81
Log Std Dev 0.25 0.21
Seasonal Index 30.50 34.74
Suggested action(s) to improve calibration
Close
Calculate
Edit Runoff
Save

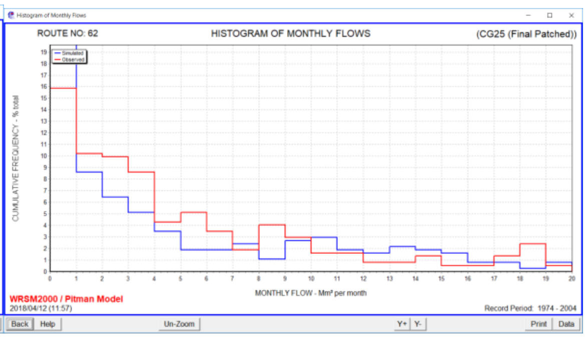

ROUTE NO: 47
MEAN MONTHLY HYDROGRAPH
(CG50 (Final Patched))
MEAN MONTHLY FLOW - Mm³ per month
MONTH (Oct - Sep)
WRSM2000 / Pitman Model
Record Period: 1979 - 2004

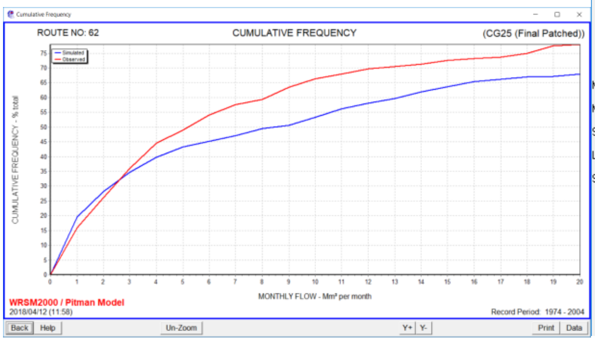


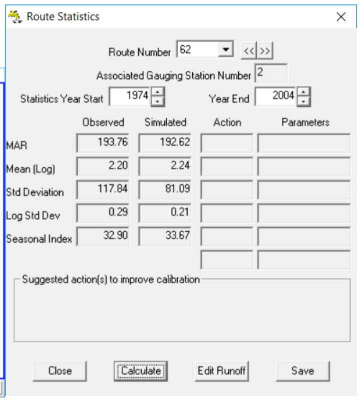


CG25








Route Statistics

Route Number 62

Associated Gauging Station Number 2

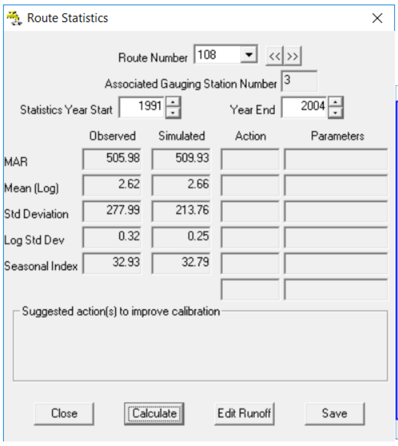
Statistics Year Start 1974 Year End 2004

	Observed	Simulated	Action	Parameters
MAR	193.76	192.62		
Mean (Log)	2.20	2.24		
Std Deviation	117.84	81.09		
Log Std Dev	0.29	0.21		
Seasonal Index	32.90	33.67		

Suggested action(s) to improve calibration

Close Calculate Edit Runoff Save

D2H035



Route Statistics

Route Number 108

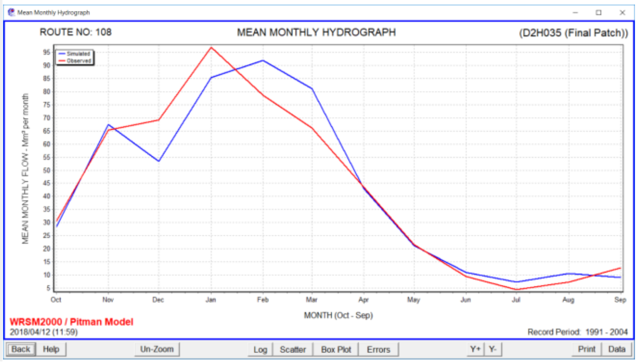
Associated Gauging Station Number 3

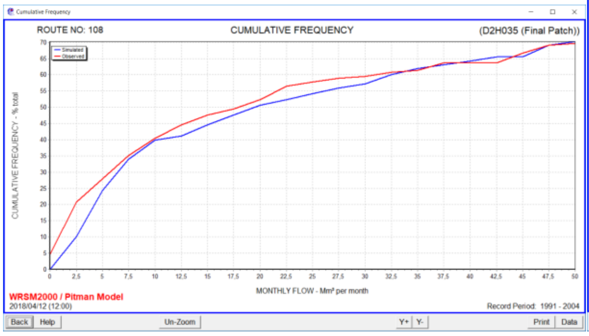
Statistics Year Start 1991 Year End 2004

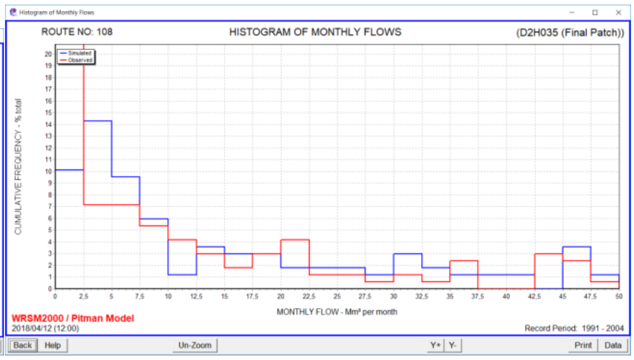
	Observed	Simulated	Action	Parameters
MAR	505.98	509.93		
Mean (Log)	2.62	2.66		
Std Deviation	277.99	213.76		
Log Std Dev	0.32	0.25		
Seasonal Index	32.93	32.79		

Suggested action(s) to improve calibration

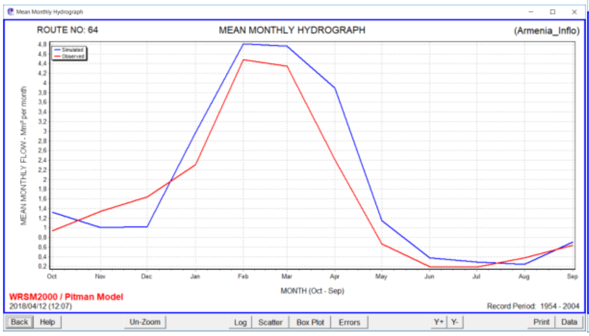
Close Calculate Edit Runoff Save

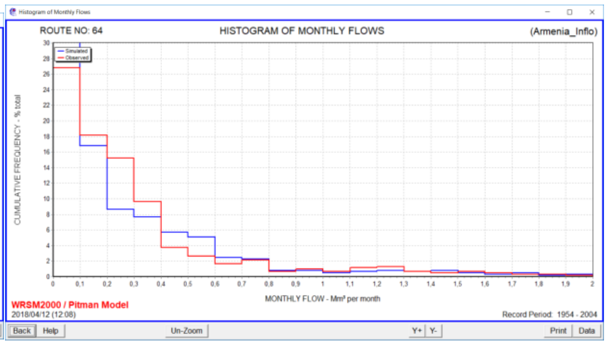


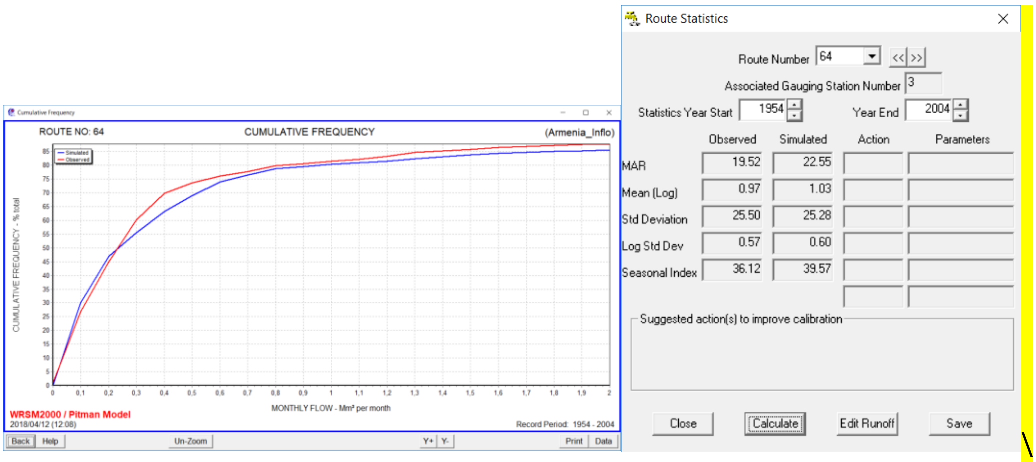




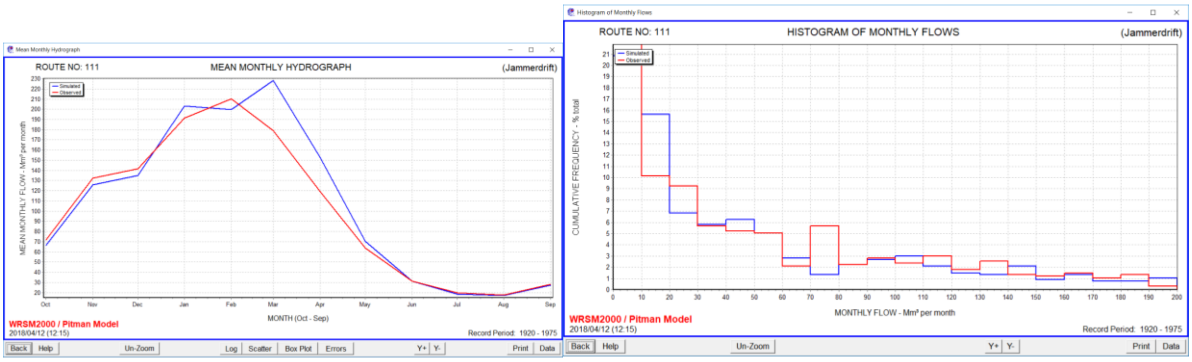
Amenia Dam

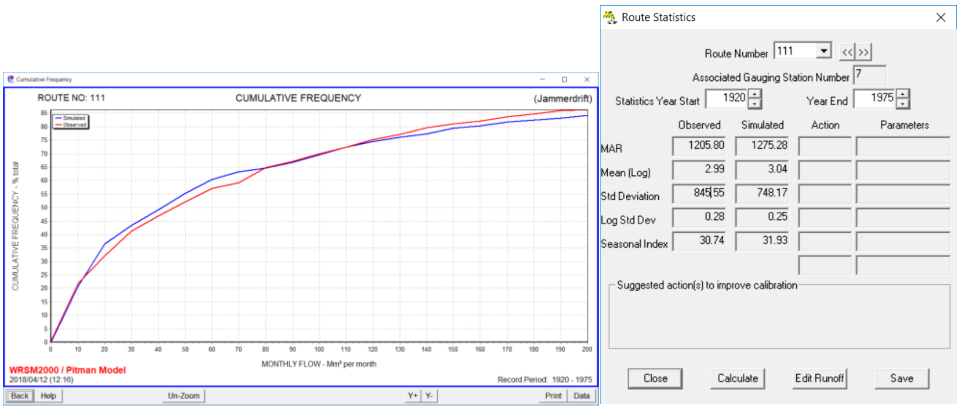




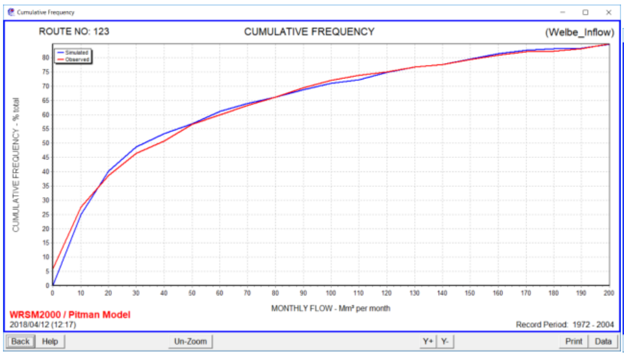


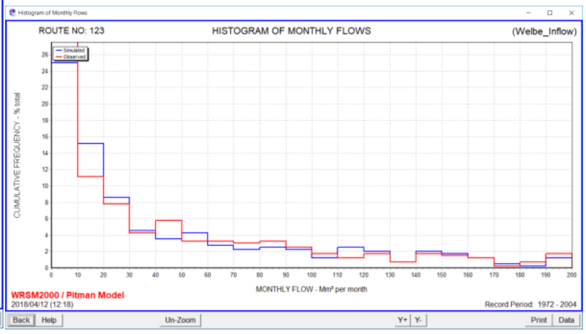
D2H001

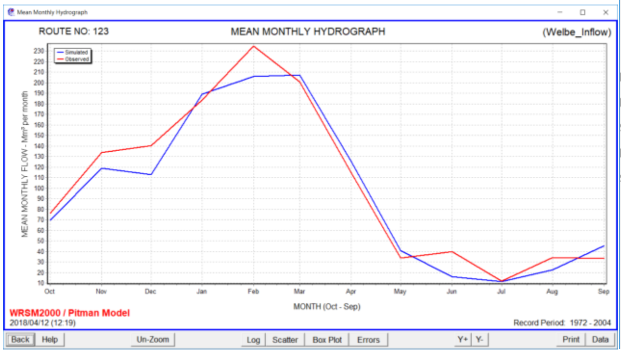


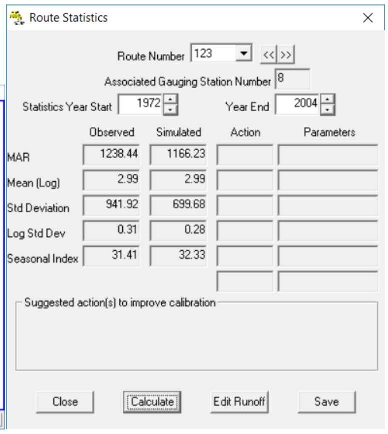


Welbedacht dam inflows


Cumulative Frequency
ROUTE NO: 123
CUMULATIVE FREQUENCY
(Welbe_Inflow)
Simulated
Observed
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
2018/04/12 (12:17)
Record Period: 1972 - 2004
Back
Help
Un-Zoom
Y+
Y-
Print
Data


Histogram of Monthly Flows
ROUTE NO: 123
HISTOGRAM OF MONTHLY FLOWS
(Welbe_Inflow)
Simulated
Observed
CUMULATIVE FREQUENCY - % total
MONTHLY FLOW - Mm³ per month
WRSM2000 / Pitman Model
2018/04/12 (12:18)
Record Period: 1972 - 2004
Back
Help
Un-Zoom
Y+
Y-
Print
Data


Mean Monthly Hydrograph
ROUTE NO: 123
MEAN MONTHLY HYDROGRAPH
(Welbe_Inflow)
Simulated
Observed
MEAN MONTHLY FLOW - Mm³ per month
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
MONTH (Oct - Sep)
WRSM2000 / Pitman Model
2018/04/12 (12:19)
Record Period: 1972 - 2004
Back
Help
Un-Zoom
Log
Scatter
Box Plot
Errors
Y+
Y-
Print
Data


Route Statistics
Route Number 123
Associated Gauging Station Number 8
Statistics Year Start 1972
Year End 2004
Observed
Simulated
Action
Parameters
MAR 1238.44 1166.23
Mean (Log) 2.99 2.99
Std Deviation 941.92 699.68
Log Std Dev 0.31 0.28
Seasonal Index 31.41 32.33
Suggested action(s) to improve calibration
Close
Calculate
Edit Runoff
Save

7 APPENDIX B – COMMENTS REGISTER

Section	Report statement	Comments	Changes made?	Comment

Section	Report statement	Comments	Changes made?	Comment