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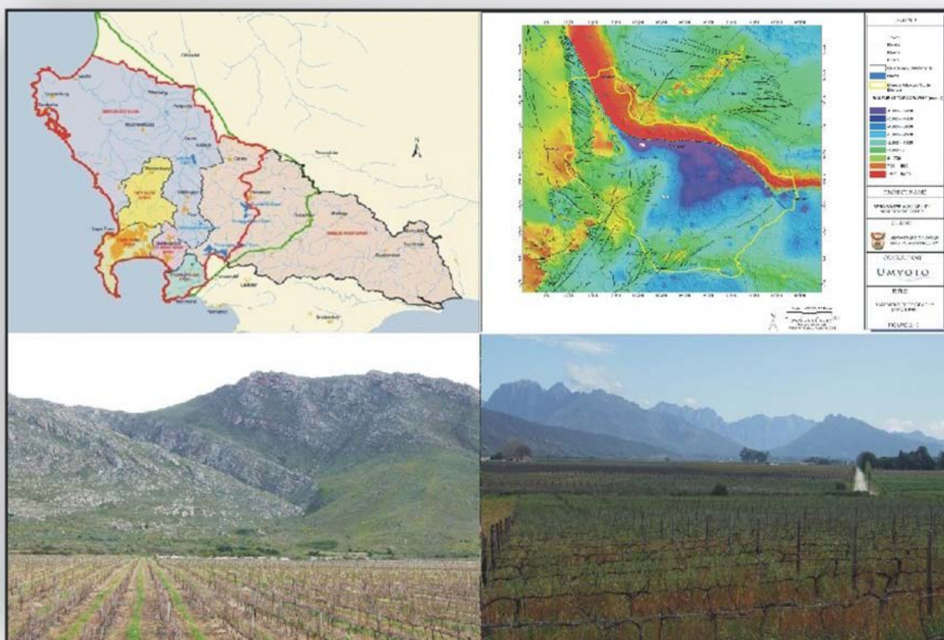
Department of Water Affairs and Forestry

Directorate: National Water Resource Planning

The Assessment of Water Availability in the Berg Catchment (WMA 19) by means of Water Resource Related Models

GROUNDWATER MODEL REPORT VOL. 9
BREEDE RIVER ALLUVIUM AQUIFER MODEL



Final **December 2008**

Submitted by
Umvoto Africa (Pty) Ltd
in Association with
Ninham Shand (Pty) Ltd

NINHAM SHAND CONSULTING SERVICES

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DEPARTMENT OF
WATER AFFAIRS AND FORESTRY

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THE ASSESSMENT OF WATER AVAILABILITY IN THE BERG CATCHMENT (WMA 19) BY MEANS OF WATER RESOURCE RELATED MODELS

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APPROVAL

TITLE	:	The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models : Groundwater Model Report Volume 9 Breede River Alluvium Aquifer Model
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CONSULTANTS	:	Umvoto Africa in association with Ninham Shand
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REPORT No	REPORT TITLE	VOLUME No.	VOLUME TITLE
1	Final Summary Report		
2	Rainfall Data Preparation and MAP Surface		
3	The Assessment of Flow Gauging Stations		
4	Land Use and Water Requirements	Vol 1	Data in Support of Catchment Modelling
		Vol 2	Invasive Alien Plant Mapping
		Vol 3	Water Use and Water Requirements
5	Update of Catchment Hydrology	Vol 1	Berg River
		Vol 2	Upper Breede River
		Vol 3	Peripheral Rivers
6	Water Quality	Vol 1	A Literature Review of Water Quality Related Studies in the Berg WMA, 1994 - 2006
		Vol 2	Updating of the ACRU Salinity Model for the Berg River
		Vol 3	Update Monthly FLOSAL Model to WQT
7	(Report No Not Used)		
8	System Analysis Status Report		
9	Groundwater Model	Vol 1	Overview of Methodology and Results
		Vol 2	Data Availability and Evaluation
		Vol 3	Regional Conceptual Model
		Vol 4	Regional Water Balance Model
		Vol 5	Cape Flats Aquifer Model
		Vol 6	Langebaan Road and Elandsfontein Aquifer System Model
		Vol 7	TMG Aquifer, Piketberg Model
		Vol 8	TMG Aquifer, Witzenberg – Nuy Model
		Vol 9	Breede River Alluvium Aquifer Model
10	Berg and Mhlathuze Assessment Studies (Refer to Report No.1)		
11	Applicability of the Sami Groundwater Model to the Berg WAAS Area		

THE ASSESSMENT OF WATER AVAILABILITY IN THE BERG CATCHMENT (WMA 19) BY MEANS OF WATER RESOURCE RELATED MODELS

GROUNDWATER MODEL REPORT VOLUME 9
BREEDE RIVER ALLUVIUM AQUIFER MODEL

EXECUTIVE SUMMARY

INTRODUCTION

The Berg Water Availability Assessment Study (WAAS) forms part of five studies commissioned nationally by DWAF to set up models that will support, *inter alia*, allocable water quantification as a prerequisite for compulsory licensing. The main objectives of the Study are to (DWAF, 2005):

- Reconfigure the existing Water Resources Yield Model (WRYM) configurations at a spatial resolution suitable for allocable water quantification to support compulsory licensing.
- Use reconfigured existing models or newly configured models for allocable water quantification for both surface water and groundwater, where applicable.

The Study comprises two phases: Phase 1 (Inception) and Phase 2 (Model configurations for assessment of current water availability and selected augmentation options). Phase 2 comprises several distinct components that can be grouped into:

- Surface water hydrology
- Groundwater hydrology
- Surface water quality
- Water resources analysis
- Reconciliation options analysis
- Study management and review.

Based on the hydrogeological analysis and the requirements for modelling as well as the over-arching strategic management intent established for the Berg Catchment, a number of models are considered for evaluating the groundwater availability on a regional scale.

After finalizing all tasks, a combined modelling report will be prepared, comprising separate volumes for each task. Each report documents model development and model scenarios, as well as recommendations for implementation and model upgrade. These volumes are:

Volume 1: Overview of Methodology and Results

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer Model

Volume 6: Langebaan Road and Elandsfontein Aquifer System Model

Volume 7: Table Mountain Group Aquifers – Piketberg area

Volume 8: Table Mountain Group Aquifers - Witzenberg-Nuy Valley area

Volume 9: Breede River Alluvium Aquifer Model

This report is Volume 9 in the project series. Volumes 2 and 3 can be read as a background to this report as the available data has informed the regional conceptual model, and the regional conceptual model has informed the delineation of individual model domains, data selection for model input and calibration.

BREEDE RIVER ALLUVIUM AQUIFER MODEL

The Breede River Alluvium is located in the valley south of Worcester, adjacent to Brandvlei. The upper Breede River valley between Wolseley and Nuy is filled with sand and gravel deposits, which constitute an extensive aquifer (Van Zijl et al, 1981). The agricultural community in the valley utilises groundwater from this aquifer for irrigation as well as for domestic use in some of the towns. The upper Breede River and the existing dams (e.g. Greater Brandvlei Dam) are considered for further augmentation towards the Berg River Water Management Area. Since the aquifer is already utilised, the water balance in this area and its split between surface water and groundwater needs to be reconciled. Additionally, the impact of further groundwater development on stream flow, the impact of river diversion on the groundwater level and quality, and the cumulative impact of both activities need to be simulated prior to decisions about upgrading of schemes. This model is seen as a first step towards quantifying the water balance in the valley and understanding the various aquifer interactions which are present.

The main aims in development of the model are:

- Model different scenarios under different hydrological conditions (e.g. flood, drought, surface water abstraction)
- establish at least first order estimates of the rate and volume of exchange between the water in the alluvium and that in the river, and between groundwater in various aquifers
- test the possibility for an aquifer storage and recovery scheme to store surplus flood water.

CONCEPTUAL MODEL

The Table Mountain Group (TMG) discharges to springs and perennial rivers, which flow from the steep mountain sides into alluvial fans within the Breede valley. The alluvial fans and the alluvium which underlies the central Breede River, together make up the heterogeneous Breede River Alluvial Aquifer. The alluvial fans are coarsest at the fan heads and act as sponges to the perennial surface waters. The surface waters recharge the aquifer on entrance to the valley, and then these alluvial fans discharge to the Breede River in the centre of the valley. At the regional scale the groundwater movement is towards the centre of the valley, discharging at the Breede River, and also along the valley southwards. The alluvium overlies TMG aquifers and the aquitards of the Malmesbury and Cape Granite Suite. Lateral recharge from the TMG to the alluvium occurs where these units are juxtaposed. The third form of recharge to the alluvium is from rainfall.

The aquifer discharges to the Breede River along its length and groundwater also flows southwards through the valley, though ultimately discharging to the Breede as the alluvium reduces in volume and therefore capacity to carry the water south of Greater Brandvlei Dam and west of Robertson.

NUMERICAL MODEL

The mountains bounding the Breede valley are comprised of TMG rocks which also underlie the valley. The deep flows in the TMG are investigated in the Brandvlei hot spring numerical model. The model shows that discharge from the TMG aquifer into the alluvium and into the TMG-fed surface waters, is relatively constant. Therefore the Breede Alluvium model can be simplified to represent the Alluvium only, with the TMG-derived fluxes incorporated as constant fluxes.

Based on the conceptual model a 3-dimensional finite difference model is developed for the Breede River Alluvium Aquifer. The modelled area covers 486 km^2. The Modflow software functions on a square grid and the model contains 7,778 grid squares or cells in each layer, 23,334 grid squares in total.

MODEL RESULTS

The modelled water levels are compared to the observed water levels based on a comparison with mapped data. The major features of the flow regime are replicated in the model. Groundwater flows from the valley sides towards the Breede River, and also through the valley towards the southeast. The observed groundwater gradients are also broadly replicated. The model replicates the flow regime at a regional scale and gives expected mass balance numbers.

Model runs showed that the equivalent hydraulic conductivity in the valley must be in the range of 10-100 m/d. The seasonal variation of the aquifer was simulated in transient modelling. The modelled groundwater fluxes are shown in **Table E.1**.

Table E.1 Modelled groundwater fluxes

	Influx		Discharge	
	Recharge	Constant heads	Rivers	Balance
m^3/day	62 982	8 144	-71 062	64
Mm^3/annum	23	3	-25	0

Scenario testing on the transient model suggests that the aquifer is relatively fast to respond to major changes in the influxes or outfluxes applied to the aquifer. Inputting the assumed current abstraction to the transient model shows that the system re-adjusts to the lower net recharge conditions and achieves stability after 10 years of this continued abstraction. The modelled system responds within 1 year to maximum and minimum surface water levels taken from flood and low flow records, suggesting a short time lag between groundwater storage and surface water. The relationship does suggest that the alluvium can readily take up excess surface water, and that this time lag could be optimised to store winter flood water for use within the following summer dry period. The ASR scenario showed that there is a potential for significant storage within the aquifer, away from the centre of the valley. Local-scale mapping of water levels as depth to water is required to quantify such available storage.

RECOMMENDATIONS

Recommendations are made for the acquisition of monitoring data (including surface water data, hydrogeological data, and hydroclimatic monitoring) and to address model uncertainty and for further scenario testing. These recommendations can be summarised as discrete projects:

1. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the Upper and Middle Breede to obtain time-series data on fluvial aquifer response to vertical and lateral recharge (short-term priority).
2. Map and understand the time lag between surface water and groundwater in the Breede to identify preferred sites for establishing a pilot ASR scheme as well as to upgrade the hydrological models that are input to the WRYM (medium-term priority).
3. Hydraulic testing of the aquifer at selected sites to determine aquifer properties including storage potential and quantification of preliminary design of an ASR scheme (medium to long-term priority).
4. Undertake model upgrade based on extensive testing and field confirmation of selected assumptions in the formal model test process, such that it can be used predictively and thereby realise medium to long-term upgrade of the hydrological data and WRYM (short-term priority and ongoing)
5. Evaluate use of heat flow modelling of TMG aquifers (short-term priority).

THE ASSESSMENT OF WATER AVAILABILITY IN THE BERG CATCHMENT (WMA 19) BY MEANS OF WATER RESOURCE RELATED MODELS

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ABBREVIATIONS

ASR	Aquifer Storage Recovery
BAA	Breede River Alluvium Aquifer
BRBS	Breede River Basin Study
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
EIA	Environmental Impact Assessmernt
FD	Finite Difference
FE	Finite Element
GIS	Geographical Information System
GRA	Groundwater Resources Assessment
IFR	Instream Flow Requirements
IWR	Integrated Water Resources
IWRM	Integrated Water Resources Management
K	Hydraulic conductivity
km	kilometre
Kx	Hydraulic conductivity in the horizontal x direction
Ky	Hydraulic conductivity in the horizontal y direction
Kz	Hydraulic conductivity in the vertical z direction
m	metre
Ma	Millions of years ago
MAE	Mean annual evaporation
mamsl	metres above mean sea level
MAP	Mean annual precipitation
MAR	Mean annual runoff
mbgl	metres below ground level
m/d	metres per day
mm/a	milimeters per year
Mm^3/a	million metres cubed per year
mS/m	mili siemens per metre
NEMA	National Environmental Management Act (Act 107 of 1998)
NGDB	National Groundwater Database
NWRS	National Water Resources Strategy
NWA	National Water Act (Act 36 of 1998)

PAJA	Promotion of Administrative Justice Act (Act 3 of 2000)
RDM	Resource Directed Measures
RQO	Resource Quality Objectives
Sy	Specific Yield [dimensionless]
Ss	Specific Storativity [L^{-1}]
TMG	Table Mountain Group
TMGA	Table Mountain Group Aquifer
WAA	Water Availability Assessment
WAAS	WAA Study
WARMS	Water-use Authorisation and Management System
WCWSS	Western Cape Water Supply System
WMA	Water Management Area
WRC	Water Research Commission
WRYM	Water Resources Yield Model

1. INTRODUCTION

1.1 THE WAAS PROJECT

1.1.1 Project Background

The Berg River Catchment forms the heart of the Western Cape Water Supply System (WCWSS), whose supply area constitutes the economic hub of the Western Cape and serves a primary export industry based on agricultural produce. The WCWSS serves the City of Cape Town, both urban water users and irrigators along the Berg, Eerste, Lourens, Steenbras and Palmiet Rivers, domestic and industrial users on the West Coast, as well as irrigators and urban users in the Riviersonderend catchment of the Breede Water Management Area (WMA).

The Department of Water Affairs and Forestry (DWAF) have initiated two major water resource management and planning undertakings in the environment of the WCWSS:

a) Compulsory licensing in terms of the National Water Act (NWA) - Act 36 of 1998 - is due to be piloted in the Berg WMA, in response to concerns that growing water user demands, as well as streamflow salinity increases, might place parts of the WCWSS in a water-stress condition during the foreseeable future.

b) A Reconciliation Strategy Study has been completed, which reviewed the future water requirements and the options for meeting these demands. The Study identified the most favourable augmentation options and recommended a programme of feasibility studies and other investigations to improve the operation and planning of the system, and to ensure that the necessary infrastructure or other interventions are implemented timeously so as to reconcile the supplies with the future demands.

The Berg Water Availability Assessment Study (WAAS) forms part of five studies commissioned nationally by the DWAF to set up the models that will support, *inter alia*, allocable water quantification as a prerequisite for compulsory licensing. The objectives of the Study are to (DWAF, 2005):

- Reconfigure the existing Water Resources Yield Model (WRYM) configurations at a spatial resolution suitable for allocable water quantification to support compulsory licensing.
- Use reconfigured existing models or newly configured models for allocable water quantification for both surface water and groundwater, where applicable.
- Incorporate changes in concepts, models and approaches, as derived from pilot studies initiated by DWAF elsewhere, if these become available in time.
- Support the Reconciliation Strategy and feasibility studies with model-based assessment of water resource augmentation options.

Ninham Shand (Pty) Ltd is the Lead Consultant and is responsible for the surface water components of the Study, as well as study management, while Umvoto Africa (Pty) Ltd is responsible for the groundwater components. Both Consulting Firms contribute either conceptually or directly to certain shared tasks.

1.1.2 Study area delineation

The study area shown in **Figure 1-1** comprises the following drainage systems and bulk water infrastructure:

- The Berg River catchment from its source in the Groot Drakenstein Mountains to its estuary at Laaiplek on the Atlantic West Coast.
- The Cape Town Basin, which includes the Eerste, Lourens and Sir Lowry's Pass rivers – all of which drain into False Bay.

- The Diep River, which flows westerly from its source in the Riebeeck Kasteel mountains to its mouth in the northern suburbs of Cape Town.
- The Palmiet and Steenbras catchments in the south of the study area, which flow in a south-westerly direction to the south of False Bay.
- The Breede River, which flows easterly to the Indian Ocean and of which the Upper and Middle Breede and the Upper Riviersonderend catchments are focus areas for this Study.

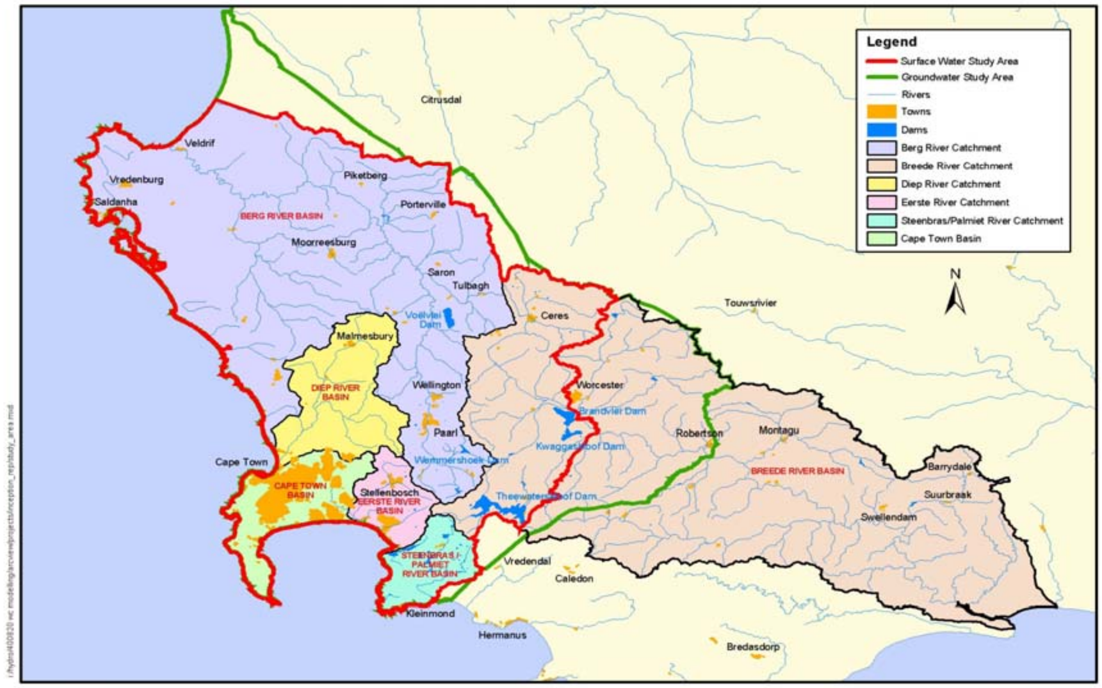


Figure 1-1 Study Area Locality

The Western Cape Water Supply System (WCWSS) is an integrated system of reservoirs, linked via a complex network of tunnels, pump stations and pipelines that stores and reticulates the runoff from rivers for use in the greater Cape Town Metropolitan area. Surface water inter-basin transfers take place between the Berg, Riviersonderend and Eerste catchments, while water from the existing Steenbras Scheme is supplied from the Lower Steenbras water treatment works into the Cape Town Water Undertaking network. The Palmiet Scheme is a dual hydro-electric pumped-storage and water transfer scheme (to the Steenbras pumped-storage scheme), of which the water transfer component has not yet been fully implemented.

The study domain for the groundwater component extends beyond the boundary of the Berg WMA and includes the upper part of the Breede WMA as well as southern portions of the Olifants/Doorn WMA. This extended area between Tulbagh-Ceres, Kleinmond and Robertson approximately coincides with the "syntaxis" zone of north-south and east-west cross- or interference folding in the Cape Fold Belt. The high mountain exposures of the Table Mountain Group (TMG) in the anticlinal folds, the confined TMG fractured-rock aquifers in the synclinal folds and the hydrotects are the main structural elements forming natural boundaries of groundwater flow. These structures would therefore build the conceptual basis of any sound groundwater models in the TMG terrain of the Berg WMA.

1.1.3 Project Components

The Study comprises two phases: Phase 1 (Inception) and Phase 2 (Model configurations for assessment of current water availability and selected augmentation options). Phase 2 comprises several distinct components that can be grouped into:

- Surface water hydrology
- Groundwater hydrology
- Surface water quality
- Water resources analysis
- Reconciliation options analysis
- Study management and review.

1.1.4 Terms of reference for groundwater

In 2001 it was estimated that a minimum of 30 Mm^3/a of water was available to augment supply to the WCWSS from the confined Peninsula Aquifer alone (City of Cape Town, 2001). More recent evaluations of both the confined Peninsula and the Skurweberg Aquifers suggest that between 20 and 400 Mm^3/a can be abstracted from the TMG within the Breede River basin area of the WCWSS domain (City of Cape Town, 2004a), if these aquifers are drawn down by 1 and 20 m respectively.

DWAF, as the custodian of the water resources in South Africa, has several tools available under the NWA for ensuring that the goals of IWRM are met within the boundaries of the WMAs, of which compulsory licensing is one. The aim of compulsory licensing is to equitably and sustainably distribute the available supply of water (i.e. current yield, not potential yield) within the catchment between all potential users, without compromising future needs or foreclosing on certain water resource development options, either for individuals or for rural or urban supply.

Allocation of future surface water involves a two-dimensional analysis of the hydrology and current use. This can easily be simplified to one dimension without losing significant physical reality. The impact of future groundwater use on current users and therefore the sustainable utilisation of water in aquifer storage by both user groups can only be assessed if the potential yield rather than the current yield is analysed with appropriate spatial and time series detail. In the Berg WAAS domain this is mostly a fully 3-dimensional problem, which cannot be simplified to one dimension.

In order to achieve this, the regulatory authority needs to have knowledge of the following:

- total quantity of water available within the catchment;
- temporal and spatial distribution of water availability;
- current and future water demand;
- impact of water abstraction at any point and time on the environment and other users;
- scenario for optimal development of the aquifer and
- scenario for best possible development and management of the aquifer given the status quo.

The contrast between the latter two scenarios will indicate the extent to which *ad hoc* aquifer development and management impacts on the resource, from a source-directed and a water quality-directed perspective.

The Promotion of Administrative Justice Act (PAJA) - Act 3 of 2000 – suggests that it is necessary that any water resource modelling undertaken to support administrative or regulatory decisions be based on all available data and uses the most appropriate models and methodologies available (and/or notes the limitations and uncertainties thereof). Water resource quantification or allocation models need to be configured, sequenced or linked in such a way that different scenarios may be assessed for aligning water supply and demand to best meet the Reserve and the Resource Quality Objectives (RQOs) in a given catchment (DWAF, 2003). Where limited data is available it is good practise to establish an agreed-upon set of scenarios which reflect a composite range in likely model input parameters. As improved data become available the range in model input or scenario testing is narrowed down.

The manner in which surface and groundwater model usage can be integrated will likely vary between catchments. Sound modelling outcomes would depend, not only on the impact of groundwater abstraction on baseflow and on the ecology, but also on the temporal relationship/operating rules for groundwater storage and surface water storage and the impact of surface water storage and reduced streamflows on groundwater levels and on the ecology.

Based on the hydrogeological analysis and the requirements for modelling as well as the over-arching strategic management intent established for the Berg Catchment, the following models are considered the *minimum* requirement to address the Terms of Reference and to evaluate the groundwater availability on a regional scale:

- Task 7a:GIS database for groundwater component
- Task 7b: Digitising geological maps
- Task 12: Regional model development:
  - Conceptual model for study domain
  - GIS based water balance model for study domain
- Task 13: Configuration of a numerical model for the Cape Flats Aquifer:
  - Quantification of surface water – groundwater interaction
  - Calibration of recharge estimation and water balance
  - Scenario for augmentation of the bulk water supply to Cape Town (in support of the Western Cape Reconciliation Strategy and feasibility studies)
  - Scenario for flood management (as support of Western Cape Reconciliation Strategy)
- Task 14: Review and update conceptual model for the West Coast Aquifers:
  - Review of the conceptual model
  - Quantification of surface water – groundwater interaction
  - Review and revision of recharge estimation and water balance
- Task 14a: Configuration of a numerical groundwater model for the Langebaan Road Aquifer :
  - Refinement of surface water – groundwater interaction
  - Refinement of recharge and yield estimation
  - Scenario for artificial recharge schemes (is support of the Western Cape Reconciliation Strategy)
- Task 15: Water balance and storage model for the TMG Aquifer:
  - Recharge estimation and water balance on a regional scale
- Task 15a: Configuration of a numerical TMG groundwater model for Worcester:

  - Quantification of surface water – groundwater interaction
  - Refinement of recharge and yield estimation
  - Scenario for Aquifer Storage Recovery (ASR) schemes (is support of the Western Cape Reconciliation Strategy
- Task 15b: Configuration of a numerical TMG groundwater model for Tulbagh – Ceres:
  - Quantification of surface water – groundwater interaction
  - Refinement of recharge and yield estimation
- Task 15c: Configuration of a numerical TMG groundwater model for the Hexriver Mountains:
  - Quantification of surface water – groundwater interaction
  - Refinement of recharge and yield estimation
  - Scenario for Aquifer Storage Recovery (ASR) schemes (is support of the Western Cape Reconciliation Strategy)
- Task 15d: Configuration of a numerical TMG groundwater model for Piketberg:
  - Quantification of surface water – groundwater interaction
  - Refinement of recharge and yield estimation.

After finalizing all tasks, a combined modelling report will be prepared, comprising separate volumes for each task. Each report documents model development and model scenarios, as well as recommendations for implementation and model upgrade. Volume 2 and 3 are to be read in conjunction with each other volume as the available data has informed the conceptual model and the conceptual model has informed the selection of data for model input and calibration.

The volumes making up the groundwater report are:

Volume 1: Overview of Methodology and Results

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer Model

Volume 6: Langebaan Road and Elandsfontein Aquifer System Model

Volume 7: Table Mountain Group Aquifers – Piketberg area

Volume 8: Table Mountain Group Aquifers - Witzenberg-Nuy Valley area

Volume 9: Breede River Alluvium Aquifer Model.

This report is Volume 9 in the project series. Volumes 2 and 3 form a basis to this report as the available data has informed the regional conceptual model upon which conceptual modelling at the smaller scale of the Breede River Alluvium Aquifer is based and refined, and the conceptual model has informed the selection of data for model input and calibration.

1.2 BREEDE RIVER ALLUVIUM AQUIFER MODEL

1.2.1 Background and report purpose

The ultimate purpose of the present Water Availability Assessment and groundwater modeling study is to provide a sound quantitative basis for resource assessment into the future. A regional conceptual model and Geographical Information System (GIS) water balance model has been developed in order to further the understanding of the hydrogeology of the TMG system (Volume 3 and Volume 4 of this series). In addition to the regional-scale model, smaller scale modelling is undertaken in selected areas, to characterise and quantify the available water resource with greater confidence at a smaller spatial scale for specific aquifers (DWAF; 2005). The conceptual understanding on the regional scale is iteratively reviewed based on the understanding and knowledge gained from the smaller scale modelling and, if available, on the basis of monitoring data and analysis.

The upper Breede River Valley between Wolseley and Nuy is filled with sand and gravel deposits, which constitute an extensive aquifer (Van Zijl et al, 1981). The agricultural community in the valley utilises groundwater from this aquifer for irrigation as well as for domestic use in some of the towns. The upper Breede and the existing dams (e.g. Greater Brandvlei Dam) are considered for further augmentation of the Berg River WMA`s. Since the aquifer is already utilised, the water balance in this area and its split between surface water and groundwater need to be reconciled. Additionally, the impact of further groundwater development on stream flow, the impact of river diversion on the groundwater level and quality, and the cumulative impact of both activities need to be simulated prior to decisions about upgrading of schemes.

There are very few complete groundwater point -source data sets, i.e. which include geology, time-series water levels, water quality and where relevant, pump rates and periods. The surface flows are sparsely monitored and a number of flow gauges on tributary rivers are not calibrated. Thus robust assumptions on boundary conditions and relatively coarse calibration criteria are necessary and the direction of flow is assumed to be perpendicular to the river at the local scale, towards and parallel to the river on the regional scale (See **Figure 2-18**). The alluvial aquifer geometry is basin shaped and defined by the relatively smooth valley infill of eroded Bokkeveld Shales and the dip slope of the TMG on the valley sides. The position and slope of the alluvial basin sides are obtained directly from the 1:250 000 geology map and the base is inferred from balanced cross-sections at the same scale (see **Figure 2-15**). A quasi-three dimensional Finite Difference (FD) model was considered adequate to model the groundwater flow in the Breede River Alluvium Aquifer (BAA). The flow patterns generated are realistic and the temporal changes in surface-groundwater exchange do reflect expected seasonal patterns.

The model and data available are adequate to use with a relatively coarse mesh to:

- Model different scenarios under different hydrological conditions (e.g. flood, drought, water abstraction)
- Evaluate lateral and vertical inflow/recharge and discharge into open water bodies.

The model, however, will not support the spatial detail needed to:

- Model different abstraction scenarios under different actual and predicted rainfall conditions
- Evaluate the impact of the preferred abstraction scenario on existing wetlands, open water bodies and areas of natural/indigenous/protected vegetation.
- The model is seen as a first step to understand the temporal and spatial patterns of surface and groundwater in the Upper Breede Valley. The purpose is to establish at least first order estimates of the rate and volume of exchange between the water in the alluvium and that in the river, the resultant impact on calibration of the hydrological models and the possibility for an ASR scheme to store surplus flood water - thereby upgrading the management of the water that is stored in the extensive and relatively thick alluvium that fills the Upper Breede

Valley between Ceres and the Greater Brandvlei Dam. To do so would help avoid double counting as well as double allocation of the same water to surface users and to groundwater users.

The Inception Report states that the modelling of the Breede River Alluvium Aquifer has the following objectives:

- Calibration of:
  - Vertical and lateral recharge
  - Natural aquifer discharge into rivers
  - Specific yield
- Rainfall dependency of surface - groundwater interaction, recharge and yield
- Identification of key data gaps and uncertainties in quaternary scale resource evaluation
- One scenario for Aquifer Storage Recovery (ASR) schemes within the primary aquifer, using surplus winter flood water in the Upper Breede
- Identification of areas and quantification of high impact of aquifer abstraction on stream flow.

The above have been addressed in variable detail based on the dependence upon model coarseness, e.g. abstraction was modelled by reducing the recharge by the value of total abstraction, and the possibility to use ASR was assessed at conceptual to pre-feasibility level by evaluating the volume of unsaturated alluvium but did not do so with the design of an ASR scheme.

1.2.2 Summary of Conceptual Model

The outline of the conceptual model for the smaller scale model domains is given in Volume 3 of this series. It is summarised below as an introduction to developing the conceptual model through detailed analysis of relevant features in chapters 2 and 3 of this report.

The Breede Alluvium is the infill of a curiously L-shaped valley floor through which the Upper Breede River flows in a north-north-west to east-south-east direction from Wolseley towards the Greater Brandvlei Dam, after which it flows easterly towards Robertson. The valley shape is controlled by large scale faulting in the Table Mountain Group (TMG) strata that form the valley sides (See **Figure 1-2**). The TMG forms characteristic rugged mountain chains that reflect the valley L-shape as far south as the Greater Brandvlei Dam. The valley changes its shape east of the Greater Brandvlei Dam as the Modder River, a major tributary, enters from the south while the Breed River itself flows in an east-west direction through the broad Worcester Valley. This valley closes as the Langeberg on the northern side converge with the north-east/south-west trending Ouhagsberg on the southern side and the river exits the valley to flow through Robertson becoming the Lower Breede as it flows to the sea at St Sebastian Bay.

Other than the Modder River mentioned above, fast flowing perennial streams in narrow valleys flow from these mountainous areas across alluvial fans formed where the valley sides abruptly change slope and then flow on toward the Breede River. On the northern side, from west to east, the significant fans are on the Wabooms, the Jan du Toit and the Hex rivers. The Breede River itself flows across an alluvial fan as it exits the Ceres valley at Ceres and flows towards Wolseley. On the southern side of the valley, from west to east, the dominant fans are the Molenaars and the Holsloot. The fans are named after the rivers flowing across them. The Wit and Wabooms rivers enter the Breede River just south of the Tulbagh-Ceres Valley. The Slanghoek River enters into the Breede River east of the Slanghoek Mountains. The Molenaars and Holsloot rivers traverse the Breede Alluvium alluvial fan from the Du Toitsberge in the south, while the Jan Du Toit River enters the Breede River from the southern extension of the Hex

River Mountains. The Hex, Nuy and Doring rivers all enter the Breede River channel downstream the Greater Brandvlei Dam (see **Figure 1-2**).

Conceptually, these various sedimentary features coalesce to form the Breede River Alluvium Aquifer (BAA) between Wolseley and Robertson. The BAA is recharged by rain, by surface water runoff as well as perennial spring flow discharging on both the northern side and the southern side, by flood recharge along the Breede channel itself. It is laterally recharged by overspill ("rejected recharge") from the Peninsula and Skurweberg aquifers on both valley sides, these being of a seasonal nature while perennial hot springs, at Goudini and Brandvlei in particular, discharge from the deeper confined Peninsula Aquifer.

Discharge from the alluvial system occurs in an easterly direction along the main channel of the Breede River, depending on the relative elevation of the water table with respect to river level (effluent or influent condition) (see **Figure 1-3**).

1.2.3 Structure of this Report

The report is structured into a number of chapters with sections and sub-sections each.

Chapter 1 describes the background to the project, determines the terms of reference for the groundwater component and gives the purpose of this specific report.

Chapter 2 describes the data and information available on and describes the relevant physical features such as topography and geology.

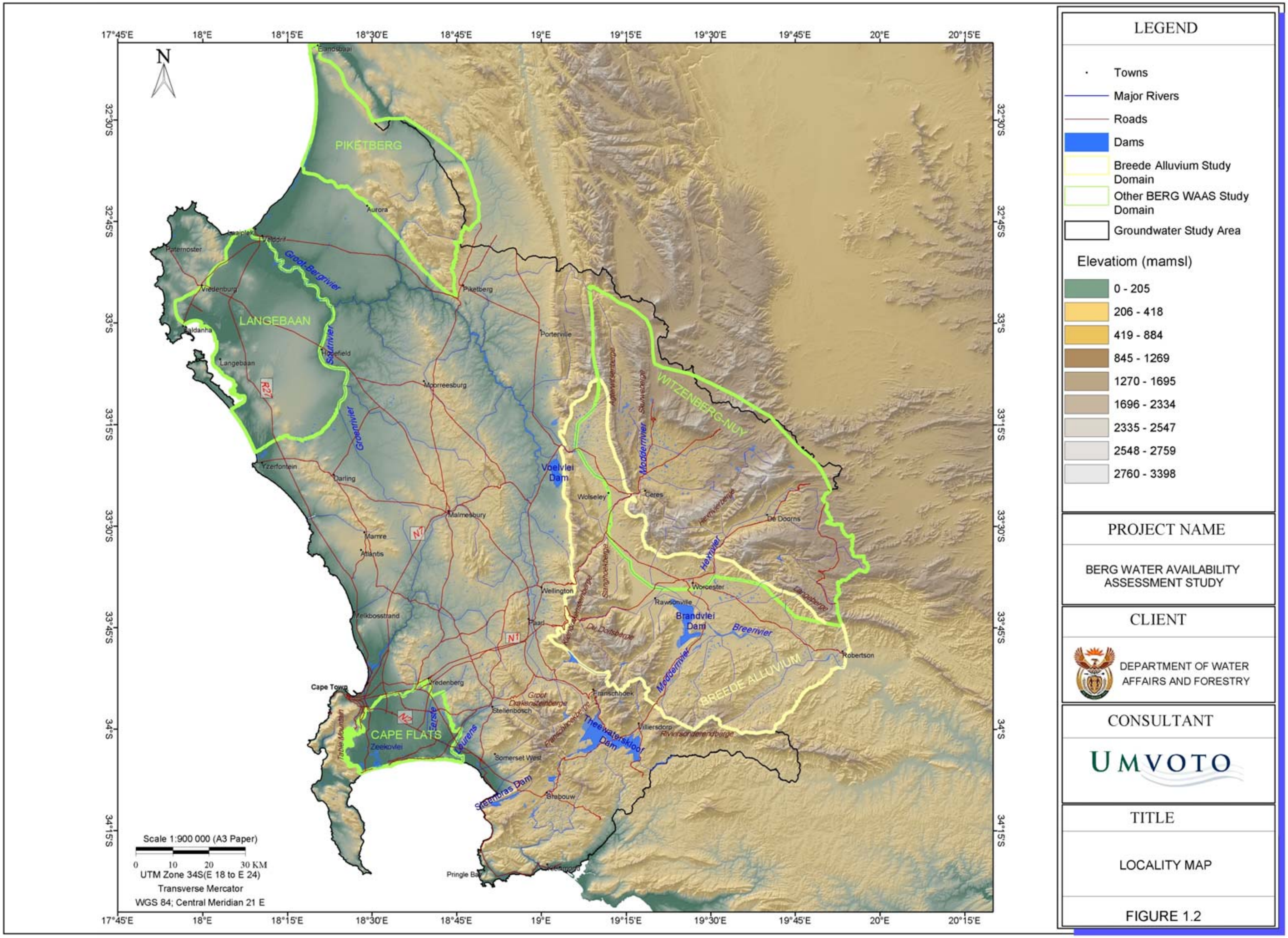
Chapter 3 provides a conceptual model for the groundwater flow regime based on the available data and information and the translation into a numerical model.

Chapter 4 details available relevant data and model input data.

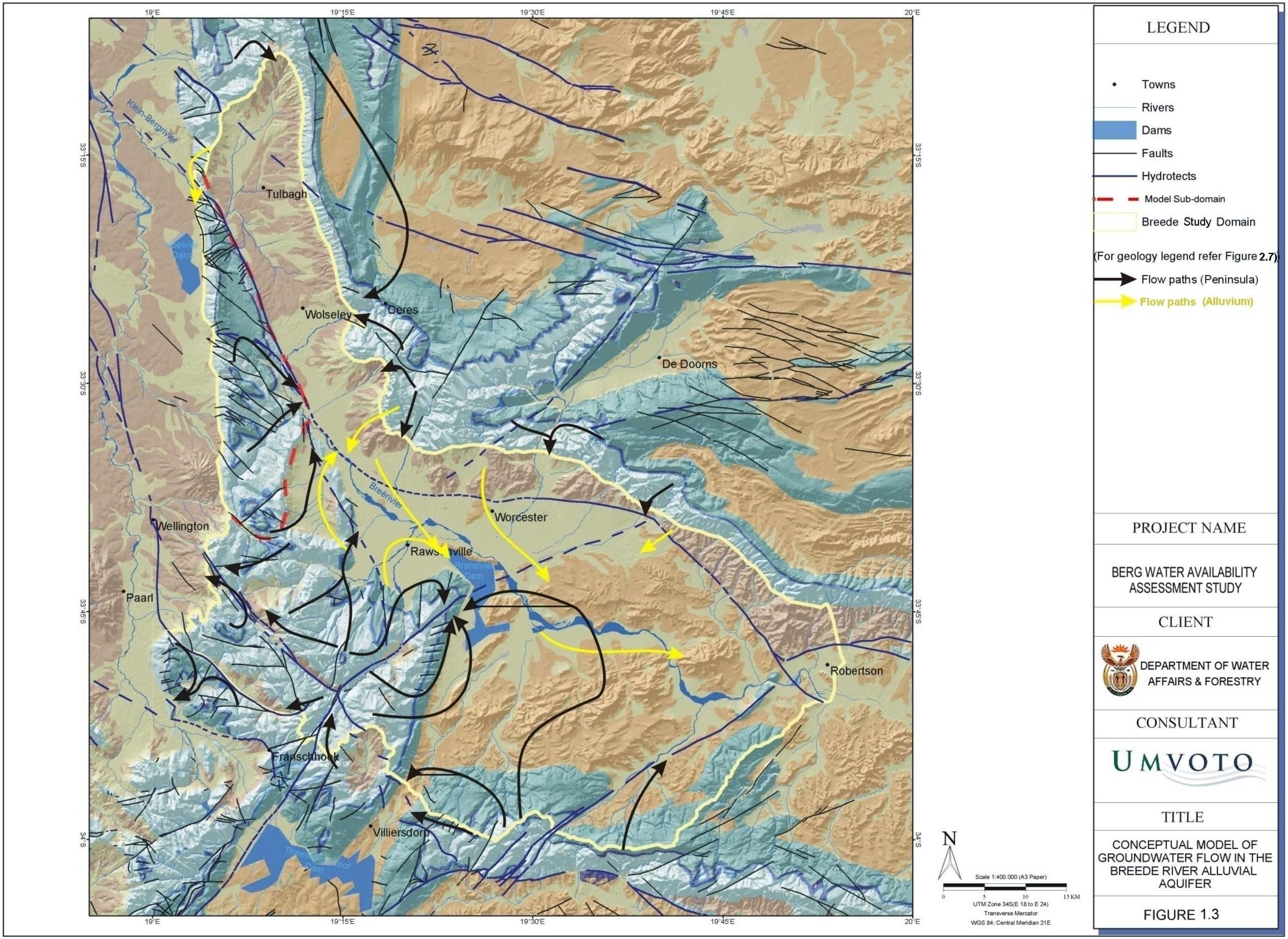
Chapter 5 presents the numerical model results of the steady state and transient model.

Chapter 6 presents the results of scenario testing

Chapter 7 states the interpretations drawn from the modelling and details recommendations.



LEGEND
Towns
Major Rivers
Roads
Dams
Breede Alluvium Study Domain
Other BERG WAAS Study Domain
Groundwater Study Area
Elevatiom (mamsl)
0 - 205
206 - 418
419 - 884
845 - 1269
1270 - 1695
1696 - 2334
2335 - 2547
2548 - 2759
2760 - 3398
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS AND FORESTRY
CONSULTANT
UMVOTO
TITLE
LOCALITY MAP
FIGURE 1.2
N
17°45'E
18°E
18°15'E
18°30'E
18°45'E
19°E
19°15'E
19°30'E
19°45'E
20°E
20°15'E
32°30'S
32°45'S
33°S
33°15'S
33°30'S
33°45'S
34°S
34°15'S
PIKETBERG
LANGEBAAN
WITZENBERG-NUY
BREEDE ALLUVIUM
CAPE FLATS
Elandsbaai
Aurora
Velddrif
Paternoster
Vredenburg
Saldanha
Langebaan
Hopefield
Piketberg
Porterville
Moorreesburg
Yzerfontein
Darling
Malmesbury
Mamre
Atlantis
Wellington
Paarl
Melkbosstrand
Cape Town
Stellenbosch
Somerset West
Franschhoek
Villiersdorp
Grabouw
Pringle Bay
Kleinmond
Wolseley
Ceres
De Doorns
Worcester
Rawsonville
Robertson
Groot-Bergrivier
Sout-rivier
Groenrivier
Modderrivier
Hexrivier
Breerivier
Voelvlei Dam
Brandvlei Dam
Theewaterskloof Dam
Steenbras Dam
Zeekovlei
Table Mountain
R27
N7
N1
N2
Scale 1:900 000 (A3 Paper)
0 10 20 30 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E



LEGEND
Towns
Rivers
Dams
Faults
Hydrotects
Model Sub-domain
Breede Study Domain
(For geology legend refer Figure 2.7)
Flow paths (Peninsula)
Flow paths (Alluvium)
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS & FORESTRY
CONSULTANT
UMVOTO
TITLE
CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE BREEDE RIVER ALLUVIAL AQUIFER
FIGURE 1.3
19°E
19°15'E
19°30'E
19°45'E
20°E
33°15'S
33°30'S
33°45'S
34°S
Tulbagh
Wolseley
Ceres
De Doorns
Wellington
Worcester
Rawsonville
Paarl
Robertson
Franschhoek
Villiersdorp
Klein-Bergrivier
Breerivier
Brandvlei Dam
N
Scale 1:400 000 (A3 Paper)
0
5
10
15 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21E

2. DESCRIPTION OF STUDY AREA

2.1 DEFINITION OF STUDY AREA

The Breede River Alluvium is located in the valley south of Worcester, adjacent to Greater Brandvlei Dam. The original study domain, as delineated in the Conceptual Model (Volume 3), included the Brandvlei and Robertson IWRM domains, and the Kleinberg catchment G10E, which forms part of the Voëlvlei-Tulbagh IWRM Domain (see **Figure 2-1**). A detailed description of the IWRM domains is given in Volume 3 of this report.

The term study domain refers to the area on which the conceptual model is based; it is the area over which groundwater and surface water flows must be considered in order to build a conceptual model. It is not necessarily the same as the area entered to the numerical model. The latter is termed model domain or model area.

The delineation of the study domain was revised after detailed mapping and field work and initial modelling indicated that the Riviersonderend Mountains comprise the main recharge area for the Peninsula Aquifer underneath the middle portion of the Breede River valley. The revised study domain excludes the G10B catchment (Wemmershoek) and G10E catchment (Klein Berg), but includes the southern slopes of the Riviersonderend Mountains, which forms part of the Theewaterskloof IWRM Domain.

The revised boundary follows the contact between the Peninsula Formation and the Malmesbury sediments to the north along the Worcester Fault. The northern and western boundary coincides with the boundary of the Brandvlei IWRM Domain, while the eastern boundary coincides with the boundary of the Robertson IWRM Domain. The southern boundary extends beyond the boundary of the Robertson IWRM Domain towards the fault, so that the southern slopes of the Riviersonderend Mountains in the Theewaterskloof IWRM Domain become part of the study domain.

The Brandvlei IWRM Domain is located in the central eastern portion of the Berg WAAS area. It has a total area of 1 582 km^2. The Robertson IWRM Domain is located in the eastern portion of the Berg WAAS study area. It has a total area of 1 385 km^2. The Theewaterskloof IWRM Domain is located south of the Brandvlei and Robertson domains.

The concept of IWRM is necessary to model surface and groundwater interaction and is different to the inclusion of groundwater in the WRYM, which models scheme(s) yield in the context of a river basin at different scales. The IWRM defines the scale at which it is possible to model the natural processes without artificially partitioning either a surface or a groundwater flux. Given that aquifers extend over and between surface water divides the IWRM concept facilitates mapping, evaluation of data sets and modelling of the processes at the correct spatial and temporal scales. As the models are refined and improved data sets obtained, it will improve how different groundwater management issues for example the impact of abstraction on low flows, impact of abstraction on other users are evaluated.

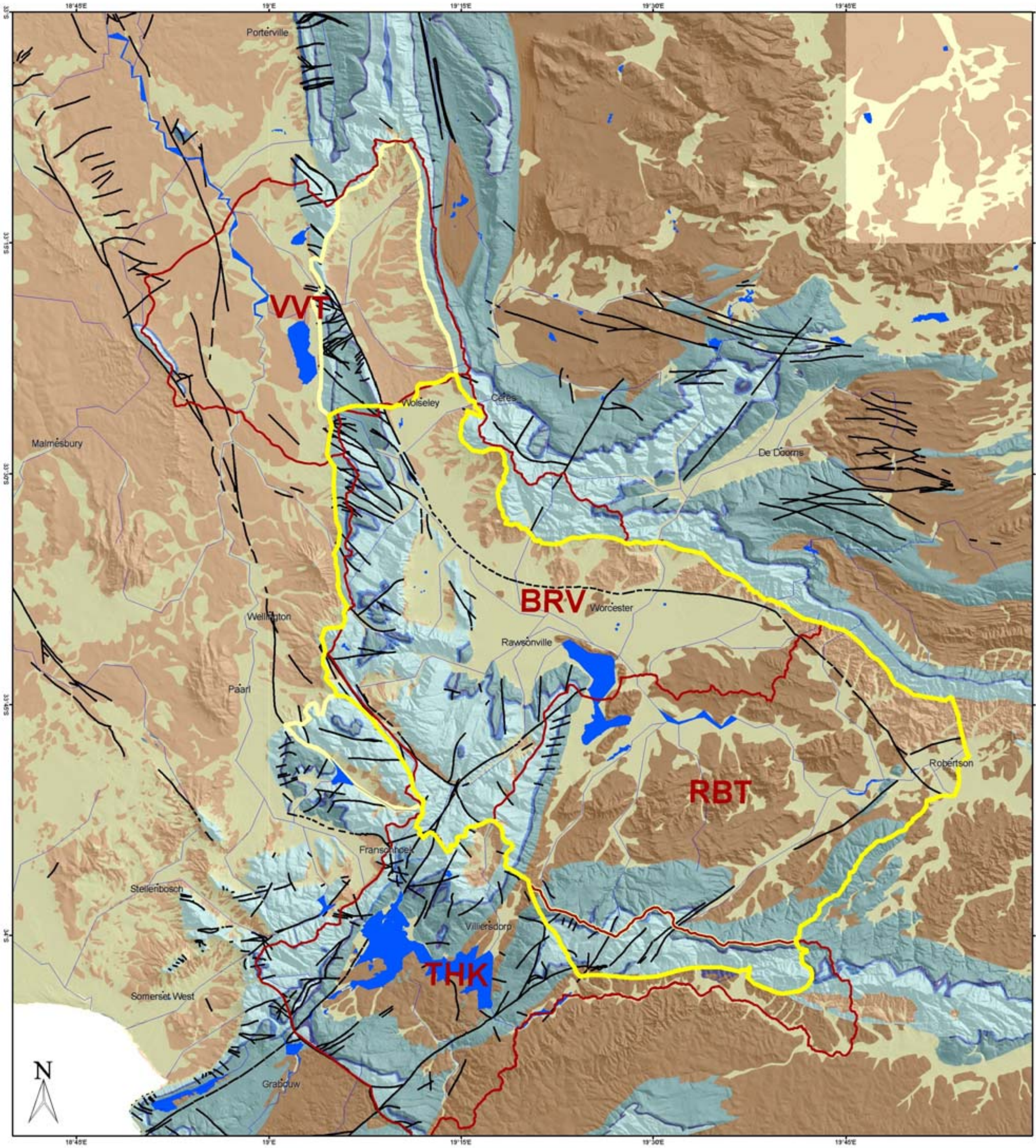
The conceptual model is based on a three-dimensional insight of aquifers, recharge and discharge processes at the IWRM scale in order to define the boundaries of a numerical model, within which the process to be modelled and the data selected for input or inference is relevant to the scale of the process being modelled as well as to the model purpose. The spatial and hydrological cycle process information relevant to the Breede Alluvium Aquifer model purpose and the dominant processes to be modelled are summarised below.

2.2 TOPOGRAPHY & DRAINAGE

The Breede River basin is divided into six sub-basins (DWAF; 2002), viz.

- The Ceres basin from the source of the Breede River to the Michell`s Pass
- The Upper Breede from Michell`s Pass to Greeter Greater Brandvlei Dam, mainly coinciding with the Brandvlei IWRM Domain;
- The Middle Breede from Greater Brandvlei Dam to the confluence with the Riviersonderend, mainly coinciding with the Robertson IWRM Domain,
- The Lower Breede from the confluence with Riviersonderend to the mouth,
- The Hex River basin, and
- The Riviesonderend basin.

The Upper Breede , upper parts of the Middle Breede and lower parts of the Hex basin form part of the study domain for this model and report.



Scale 1:500 000 (A3 Paper)

0 5 10 15 20 KM

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

Towns
Rivers
Faults
Dams
BRV IRWM Domains
Revised Breede Alluvium Study Domain
Original Alluvium Study Domain

SIMPLIFIED GEOLOGY

Quaternary
Post_TMG
Nardouw Group
Cedarberg/Pakhuis Formation
Peninsula Formation
Pre_Cape

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

DELINEATION OF STUDY DOMAIN

FIGURE 2.1

2.2.1 Topography

The Breede River basin from Wolseley in the west to Robertson in the east is a wide, flat valley surrounded by high mountain peaks (see **Figure 2-2**). The elevation of the valley floor decreases from about 300 m at Wolseley to about 180 m around Robertson.

In contrast the valley sides are formed by rugged steep mountain chains. The northern mountains from immediately east of Ceres to west of Robertson are the Waaihoek Mountains (up to 2030 m), the Hex River Mountains (up to 2250 m), the Meiring's Ridge (up to 1990 m), the Kwadousberg (up to 2072 m) and the Langeberg (up to 1698 m).

The mountains bounding the other side of the valley (from west to east) are, the Elandskloof and Limiet mountains (up to 1517 m), which trend north-south, and the Slanghoek Mountains (up to 1694 m) which are L-shaped trending north-south and also east- west. At the Greater Brandvlei Dam the mountains abruptly change orientation to north-south again and continue as the Wabooms Mountains (~1300 m) and Stettyns Mountains (up to 1820 m). A key tributary of the Upper Breede, the Holsloot, emerges from the Du Toits Mountains (up to 1995 m) which lie in the centre of what, together with the Wabooms and the Stettyns mountains are also commonly known as the Haweqwas mountain range.

East of the Greater Brandvlei Dam the valley widens, trends east-west and is known as the Worcester Valley. Here the northern valley side comprises the Lange Mountain while the southern limit is formed by the lower lying north-east south-west trending Klip and Ouhangs mountains with elevations of 700 m – 900 m, beyond which are the Riviersonderend Mountains (1400 m – 1654 m).

2.2.2 Drainage basins

The H10-H70 secondary catchments cover the Breede River basin, the largest river in the Western Cape. The Breede River originates in the Ceres Valley and flows in a south-westerly direction towards Wolseley. It turns southwards after the Michell's Pass and then flows in a south-easterly direction until its confluence with the Hex River near Worcester. The flow continues in a south-easterly direction to join the Riviersonderend before it reaches the Indian Ocean at St Sebastian Bay.

The study area comprises the following quaternary catchments:

- Upper Breede from Wolseley to Greater Brandvlei Dam, including tributaries (H10E, H10F, H10G, H10H, H10J, H10K, H10L),
- Confluence of Hex River and Breede River (H20g, H20H),
- Middle Breede from Greater Brandvlei Dam to Robertson, including tributaries (H40C, H40D, H40E, H40F,H40G, H40H,H40J)
- Riviersonderend Mountains (northern parts of H60C, H60D, H60E, H60F,H60H)

It further straddles the eastern Peninsula outcrops of the Middle Berg catchments (G10C and G10D).

Several tributaries contribute to the flow in the Breede River (see **Figure 2-2**). The most relevant in the Upper and Middle Breede basins, coming from the north, are:

- The **Wabooms River** (south-eastern part of H10F) drains the Waaihoek Mountain and joins Breede River downstream of Wolseley, where the Breede River exits the Elandskloof.
- The **Jan Du Toits River** (H10H) drains the southern end of the Hex River Mountains, the Waaihoek Mountain and the Meiring`s Ridge, and joins the Breede River just upstream of Rawsonville.
- The **Hex River** (H20A,B,G and H) has its source in the Hex River Mountains and flows through the Hex River valley, joining with several mountain streams from the high mountains

on either side. Downstream of Sandhills, the Hex River flows south through the Hex River Poort int Breede River valley, passes east of Worcester to its confluence with the Breede River just north of Greater Brandvlei Dam.

- The **Nuy River** (H40B and C) comes from the Koo valley north of the Langeberge and flows southwest towards the Breede River just below Greater Brandvlei Dam.

The most relevant streams entering the Breede River from the west and south are:

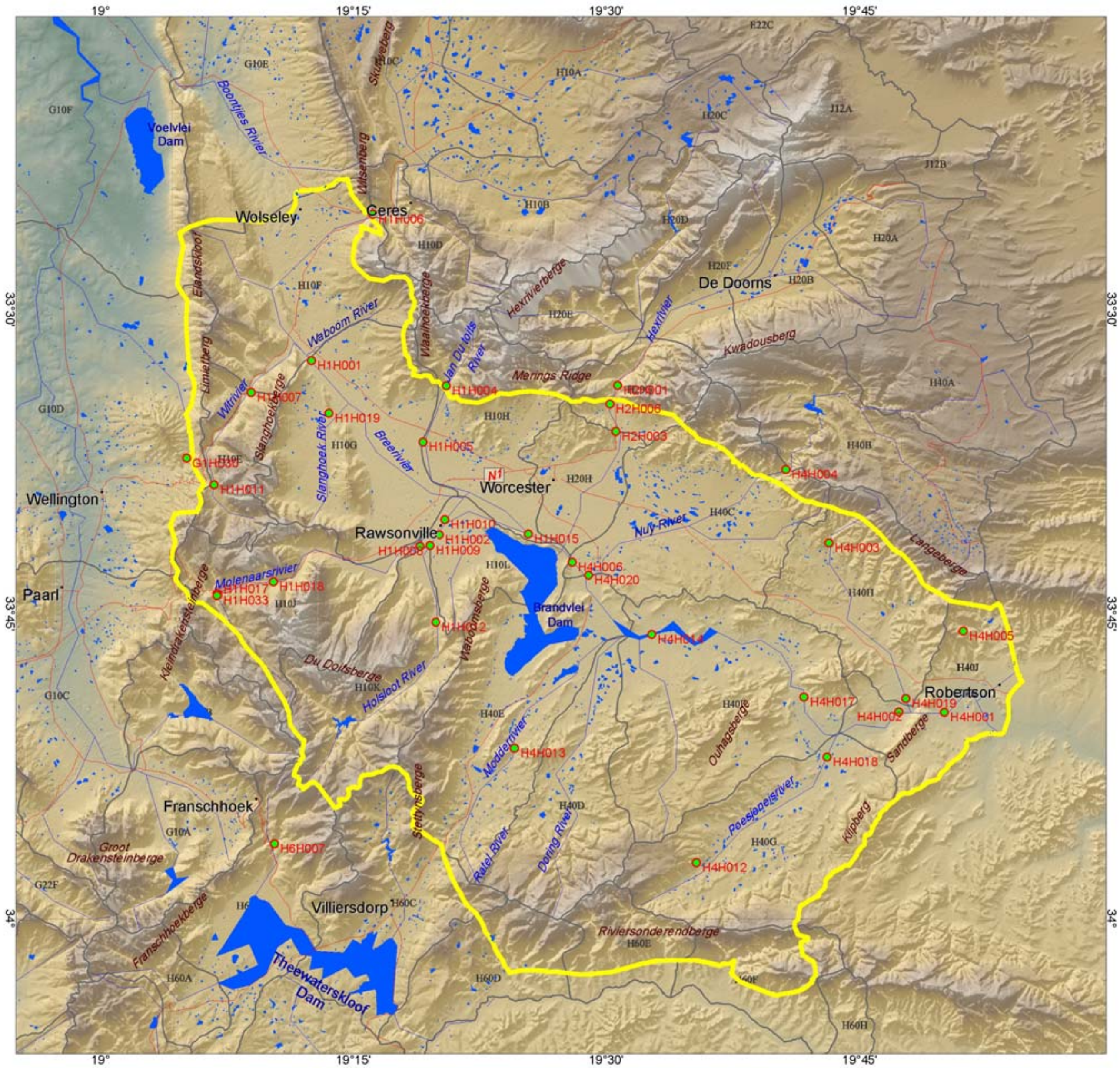
- The **Wit River** (H10E and south-western part of H10F) drains the Limiet Mountains and the south-western slopes of the Slanghoek Mountains and joins the Breede River opposite the Wabooms River
- The **Slanghoek River** (western part of H10G) drains the eastern slopes of the Slanghoek Mountains
- The **Molenaars River** (H10J) originates in the Haweqwas Mountain range and is fed by streams on the northern Du Toits Mountains and the south-eastern slopes of the Slanghoek Mountain. The Molenaars River joins the Breede River just north of Rawsonville.
- The **Holsloot River** (H10K), draining the southern slopes of the Du Toitskloof Mountain and the northern slopes of the Stetteyns Mountain joins the Breede River just upstream of the Papenkuils Wetland and Greater Brandvlei Dam.

Several smaller streams join the Breede River downstream of the Greater Brandvlei Dam:

- The **Modder** and **Ratel rivers** (H40E), draining the Stettyns Mounatin flow in the northerly direction, passing the Kwaggaskloof Dam and joining the Breede River just downstream of the Dam.
- The **Doring River** (H40D) drains the western part of the Riviersonderend Mountains and joins with the Modder and Ratel rivers before reaching the Breede River.
- The **Poesjenels River** (H40G) originates in the Riviersonderend Mountains and flows in a north-easterly direction, joining the Breede River upstream of Robertson.

:

N



Scale 1:400 000 (A3 Paper)

0 5 10 15 KM

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Flow Gauges
- Major Rivers
- Roads
- Dams
- Breede Alluvium Study Domain
- Quarternary Catchments
- Groundwater Study Area

Elevatiom (mamsl)

- 0 - 370
- 371 - 750
- 751 - 1130
- 1131 - 1510
- 1511 - 1890
- 1891 - 2270
- 2271 - 2640
- 2641 - 3020
- 3021 - 3400

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

TOPOGRAPHY AND DRAINAGE

FIGURE 2.2

2.3 HYDROCLIMATOLOGY AND HYDROLOGY

2.3.1 Climate

The study area falls within the winter rainfall region of South Africa. Rainfall is strongly seasonal, with roughly 80% of the annual precipitation falling between the months of April and September (see **Figure 2-3**), resulting from north-westerly frontal systems. This figure showing the average monthly rainfall illustrates the marked difference in winter rainfall between the mountainous area on the southern side of the valley (Slanghoek and Stettyns Mountains) and the valley itself (Worcester and Greater Brandvlei Dam). The annual rainfall is significantly higher in the mountainous areas although the mountains to the north of the valley receive less rainfall than those to the south (see **Figure 2-4**).

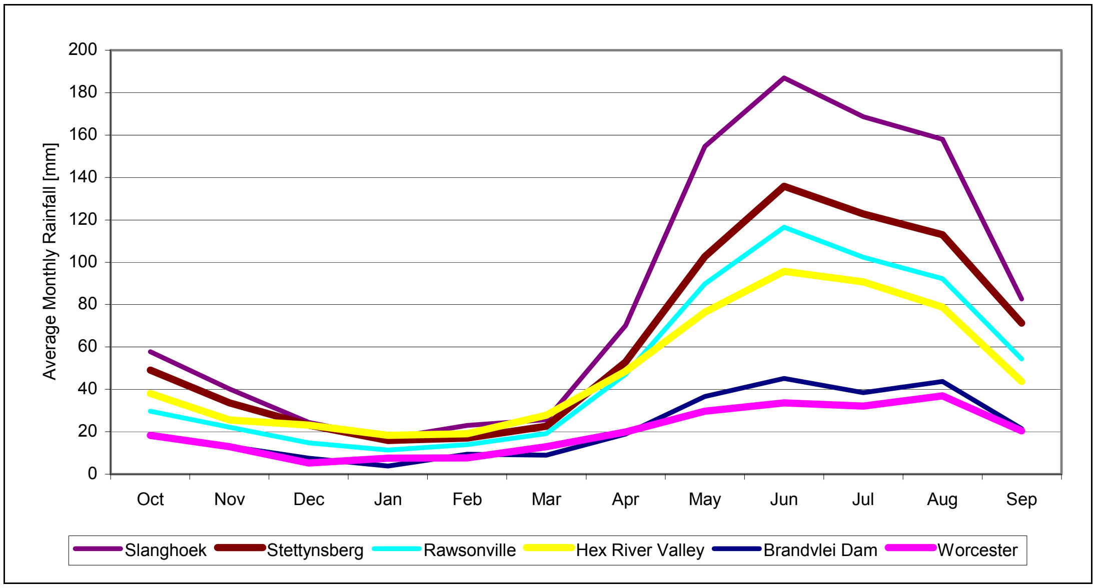


Figure 2-3 Average monthly rainfall at different weather stations in Breede River Basin

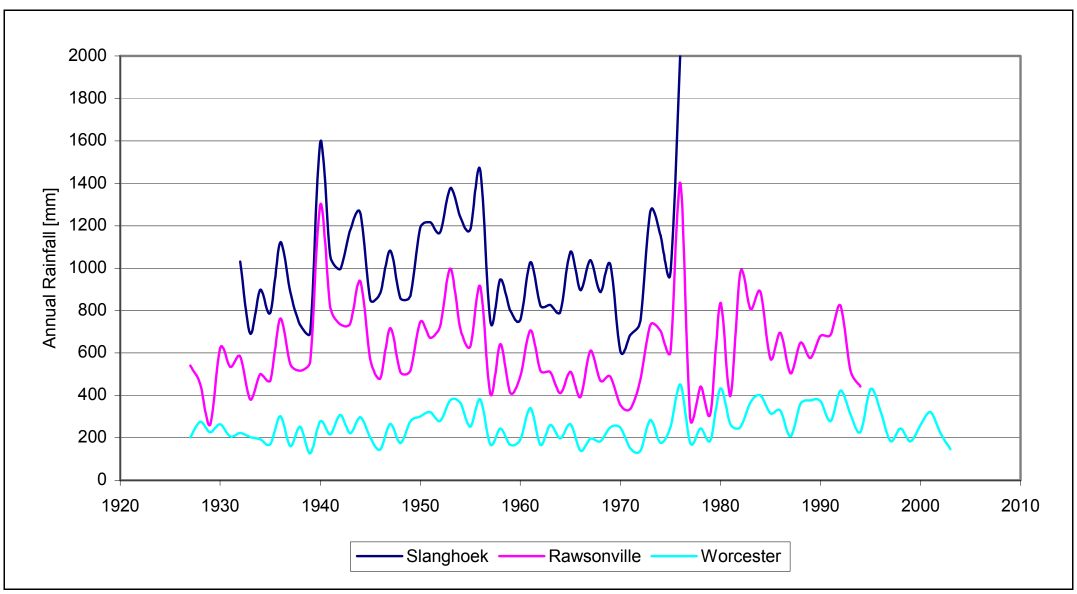


Figure 2-4 Annual rainfall from 1926 to 2002 for three selected weather stations in the Breede River Basin

The variation in rainfall pattern over the study area is due mainly to variation in altitude arising from the topographic extremes and the different, often abrupt change in orientation of the mountain chains that form the valley sides in relation to the prevailing north westerly winter winds. The highest rainfall of about 2 300 mm/a occurs in the high mountainous areas in the west while the low-lying middle reaches of the Breede River Valley and the area north of the Langeberg mountain range receives the lowest rainfall. In these regions, the average rainfall is about 400 mm/a. In the south of the Breede River Basin along the Riviersonderend and lower reaches of the Breede River, the rainfall varies between about 2 300 mm/a in the upper Riviersonderend to about 400 mm/a in the lower reaches (see **Figure 2-6**).

It appears that the Middle Breede basin, downstream of the Greater Brandvlei Dam, receives significantly less rain than the Upper Breede basin and the Hex River basin. The “climate divide” between these two zones runs east of the Stettyns and Wabooms mountains, crosses the Greater Brandvlei Dam and runs through the Hex River Valley (see **Figure 2-6**).

Summers tend to be dry and hot with generally high evaporation. The mean annual S-Pan evaporation is estimated to vary from about 1 800 mm/a in the Upper and Middle Breede Valley down to about 1000 mm/a in the Hawequas mountain range. Temperatures vary between a minimum of –1°C in the winter and maximums in the mid to high 30°s in the summer months (see **Figure 2-5**).

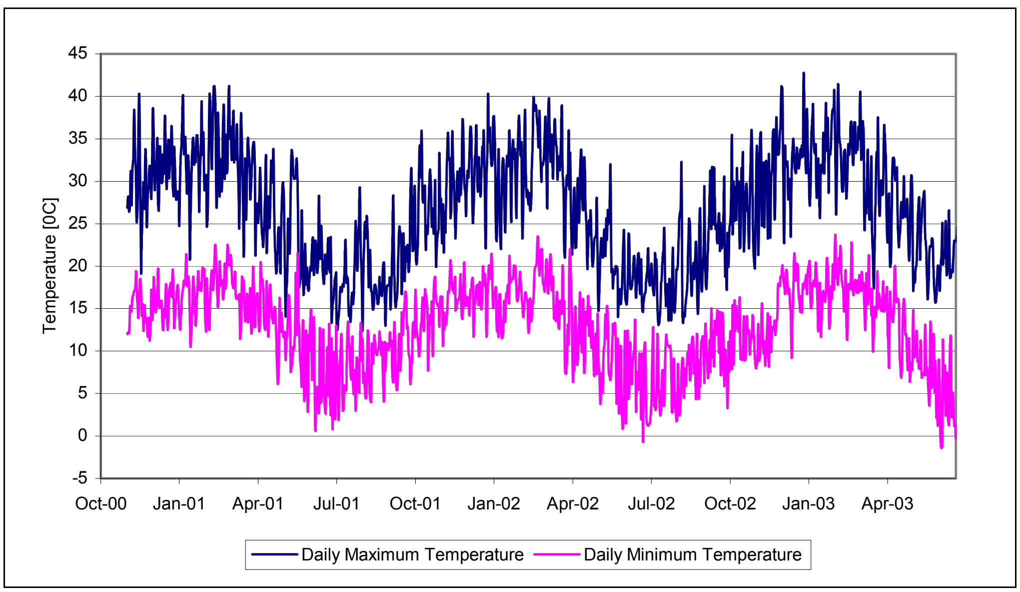
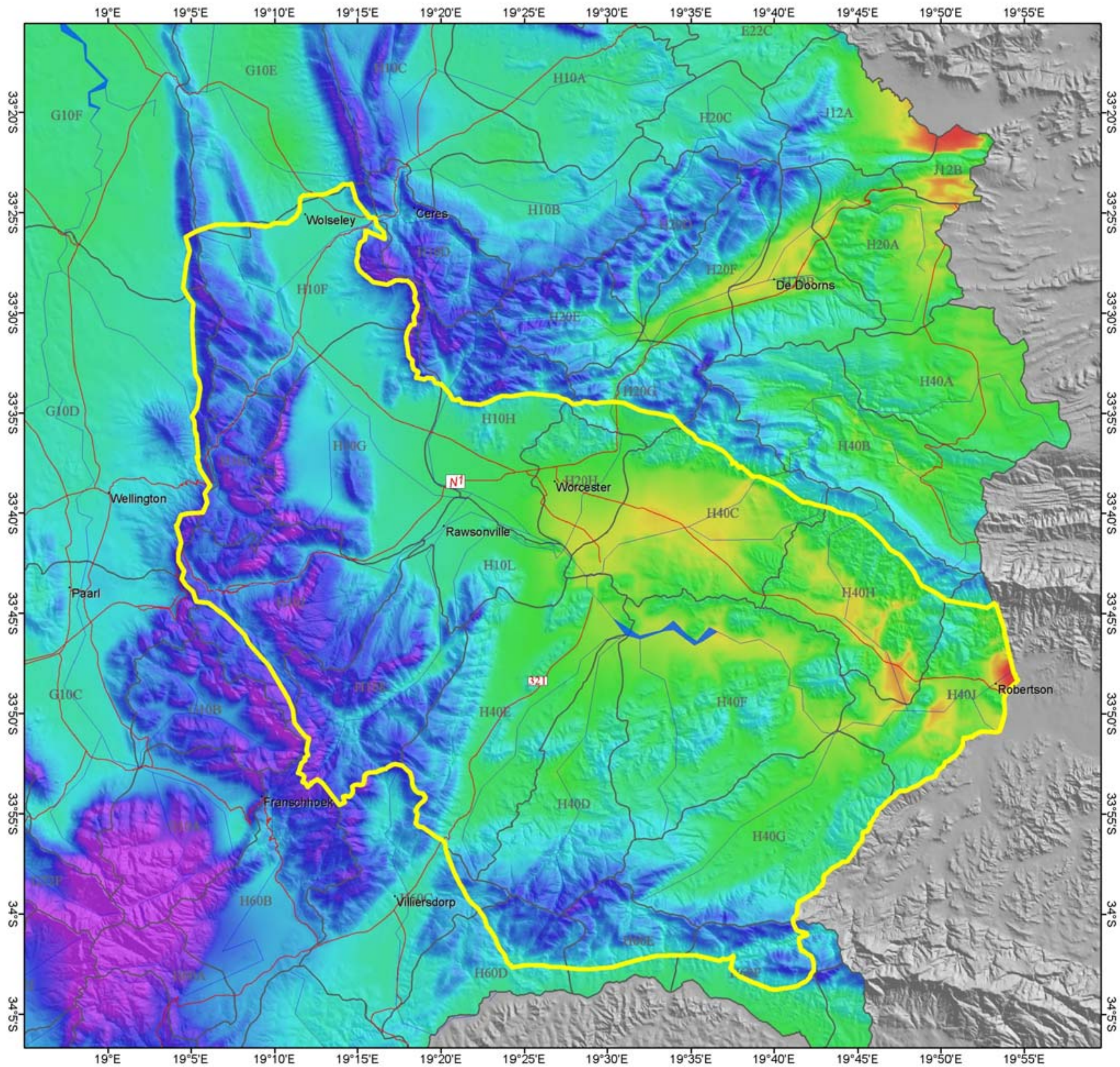


Figure 2-5 Daily minimum and maximum temperature at Worcester weather station from November 2000 to June 2003



LEGEND

- Towns
- Rivers
- Roads
- Dams
- Quartenary Catchments
- Breede Alluvium Study Domain

MEAN ANNUAL PRECIPITATION (mm/a)

- 100 - 190
- 190 - 220
- 220 - 230
- 230 - 300
- 300 - 500
- 500 - 700
- 700 - 820
- 820 - 1000
- 1000 - 1150
- 1150 - 1440
- 1440 - 1770
- 1770 - 2620
- 2620 - 3238

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

MEAN ANNUAL PRECIPITATION (DWAF, 2007)

FIGURE 2.6

Scale 1:400 000 (A3 Paper)

0 5 10 15 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

2.3.2 Hydrology

The drainage basins of the study domain are described in Section 2.2.2. The spatial pattern of surface runoff and runoff response to rainfall parallels the differences in climatic conditions across the study domain, varying widely between the mountainous catchments in the south and west as compared to the north of the study domain and the wider valley catchments in the centre and east of the study domain.

The naturalised mean annual runoff (MAR) per catchment, as estimated in the WR90 project (Midgley et al, 1994) and in the WR2005 project (Ninham Shand, unpubl.), are compared in **Table 2-1**, with the mean annual precipitation (MAP). The calculated runoff efficiency varies between 0.08 and 0.76.

Table 2-1 Catchment area, MAP, MAR and Run-off efficiency for selected catchments, indicating the range of hydroclimatic and hydrologic conditions in the study domain

Quaternary catchment	Area	MAP *WR90*	MAP *Berg WAAS*	MAR *WR90*	MAR *WR2005*	Run-off Efficiency *WR90*
	km^2	*mm*	*mm*	*mm*	*mm*	
H10E	85	1404	1241	1064	1495	0.76
H10F	248	784	883	349	235	0.45
H10G	270	788	816	353	239	0.45
H10H	187	886	753	423	216	0.48
H10J	214	1595	1226	859	897	0.54
H10K	194	1225	1106	573	621	0.47
H10L	96	476	542	94	7.6	0.20
H20G	85	680	765	55	259	0.08
H20H	89	300	365	29	1.2	0.10
H40C	272	375	380	52	66	0.14
H40D	182	557	672	136	114	0.24
H40E	285	539	590	126	27	0.23
H40F	340	293	427	27	24	0.09
H40G	263	417	554	66	26	0.16
H40H	208	461	415	88	46	0.19
H40J	152	417	372	52	229	0.12
H60C	217	891	869	386	197	0.43
H60D	138	652	809	184	158	0.28
H60E	85	640	849	174	148	0.27
H60F	116	582	731	141	119	0.24
Total	3725	679	697	250	221	0.37

2.4 GEOLOGY

The topography, drainage, hydroclimate, land-use and even the agricultural crops are largely determined by the underlying rock type and its structural character. The strong correlation between geology and terrain, illustrated on the Digital Elevation Model (DEM) topographic base (see **Figure 2-7**), implies a strong geological control also of local climate and land-use potential, through orographic control over precipitation and the widely variable geochemical composition of the different formations.

2.4.1 Stratigraphy

The full geological stratigraphy present in the Berg WAAS area is also present in the Breede River basin (See **Figure 2-7**).

The oldest rocks in the study area, namely the **Malmesbury Group** (>555 Ma) and the **Cape Granite Suite** (555-510 Ma), are exposed on the northern side of the Breede River Valley and on the flanks of the Slanghoek valley. Further outcrops are found in anticlinal valleys in the TMG dominated Du Toits Mountains and Stettyns Mountains.

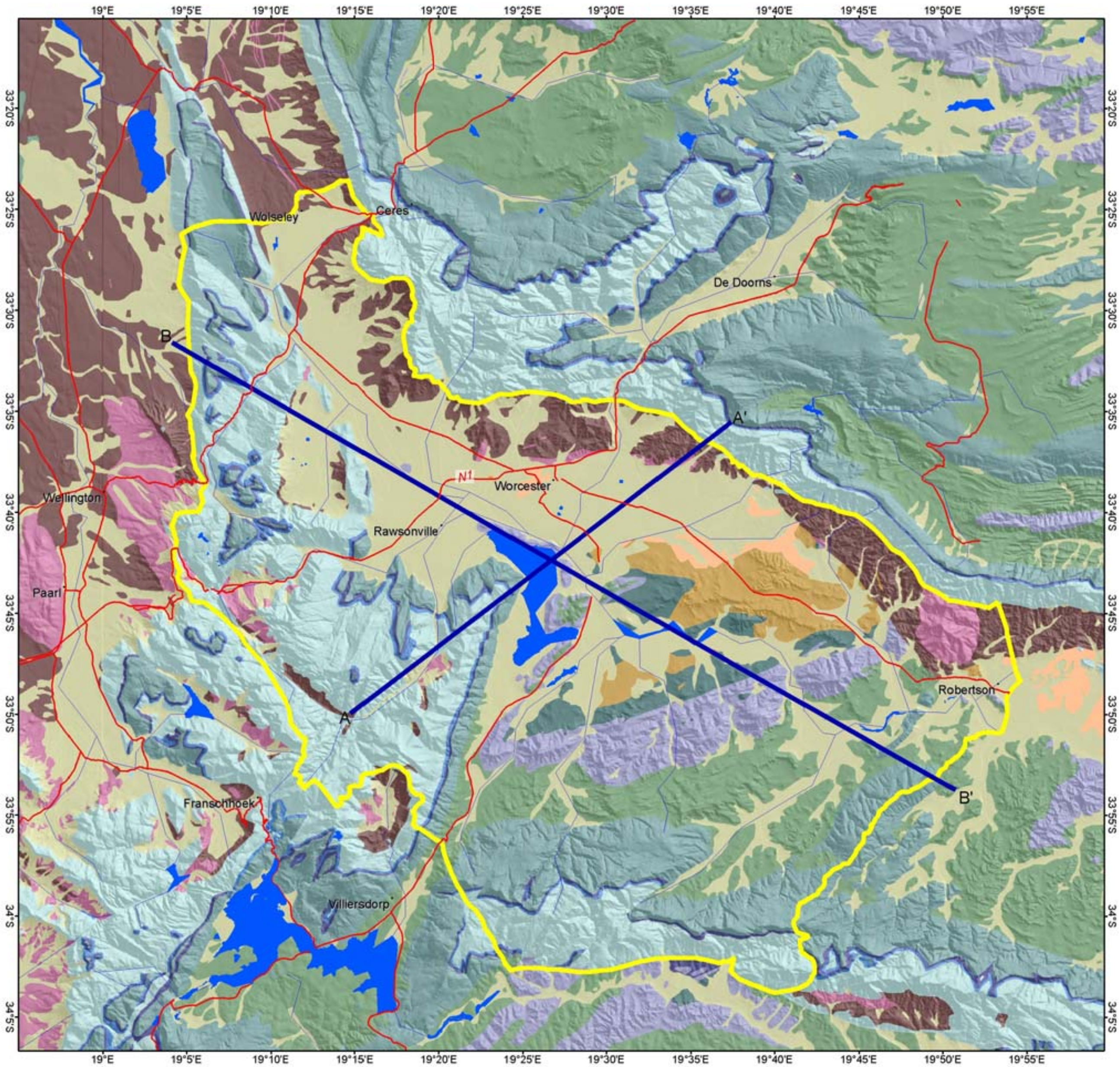
The mountainous character of the study area is determined by the extremely resistant and fractured rocks that constitute the **Table Mountain Group** (the lower part of the **Cape Supergroup; Table 2-2**) which are, in terms of Western Cape geological history, middle-aged (~400 Ma).

The valleys in this region are infilled by slightly younger (~350 Ma) and more easily erodable rocks of the **Bokkeveld Group,** which consist largely of shales with a few relatively thin sandstone strata. The **Witteberg Group** and the lower parts of the **Karoo Supergroup** (**Table 2-2**) appear centrally in the eastern half of the study area between the towns of Worcester and Robertson, and extend southwest to just north of Villiersdorp.

The relatively young **Uitenhage Group** is exposed in a downfaulted syncline to the south of the Worcester Fault.

The flat-lying and younger semi- to unconsolidated sediments of the fluvial **Alluvium** (0 – 2.5 Ma) fill the valley bottoms in the central part of the study area and occur along the watercourses and flood plains of the larger rivers of the Breede River basin. The main alluvium deposits are found along the Breede, Riviersonderend and Hex rivers and their tributaries.

These major lithostratigraphic groups are summarised in **Table 2-2** below.



Scale 1:400 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Rivers
- Roads
- Regional Cross Section lines
- Dam
- Breee Alluvium Study Domain

GEOLOGY

- Quaternary Sediments
- Uitenhage Group
- Ecca Group
- Dwyka Group
- Witteberg Group
- Bokkeveld Group
- Nardouw Subgroup
- Cedarberg Formation
- Pakhuis Formation
- Peninsula Formation
- Cape Granite Suite
- Klipheuwel Group
- Malmesbury Group

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

GEOLOGY IN THE BREEDE RIVER ALLUVIUM MODEL AREA

FIGURE 2.7

Table 2-2 Stratigraphy of the Study Area

Age range (Ma)	Supergroup	Group	Formation	Thickness (m)
0 – 2.5		Alluvium		
~~ Major unconformity ~~~~~				
65 - 144		Uitenhage		
			Enon	
		False Bay Suite	(dolerite swarm)	
~~ Major unconformity ~~~~~				
248 - 290	Karoo	Ecca		
		Dwyka		
290 - 354	Cape	Witteberg	(various)	
354 - 417		Bokkeveld	(various)	
		Table Mountain	Rietvlei	
417 - 443			Skurweberg	
			Goudini	
			Cedarberg	
			Pakhuis	
			Peninsula	
443 - 495			Graafwater	
			Piekenierskloof	
~~ Major unconformity ~~~~~				
495 - 545	(Saldanian)	Klipheuwel		
		Cape Granite Suite		
545 – >750				
		Malmesbury		

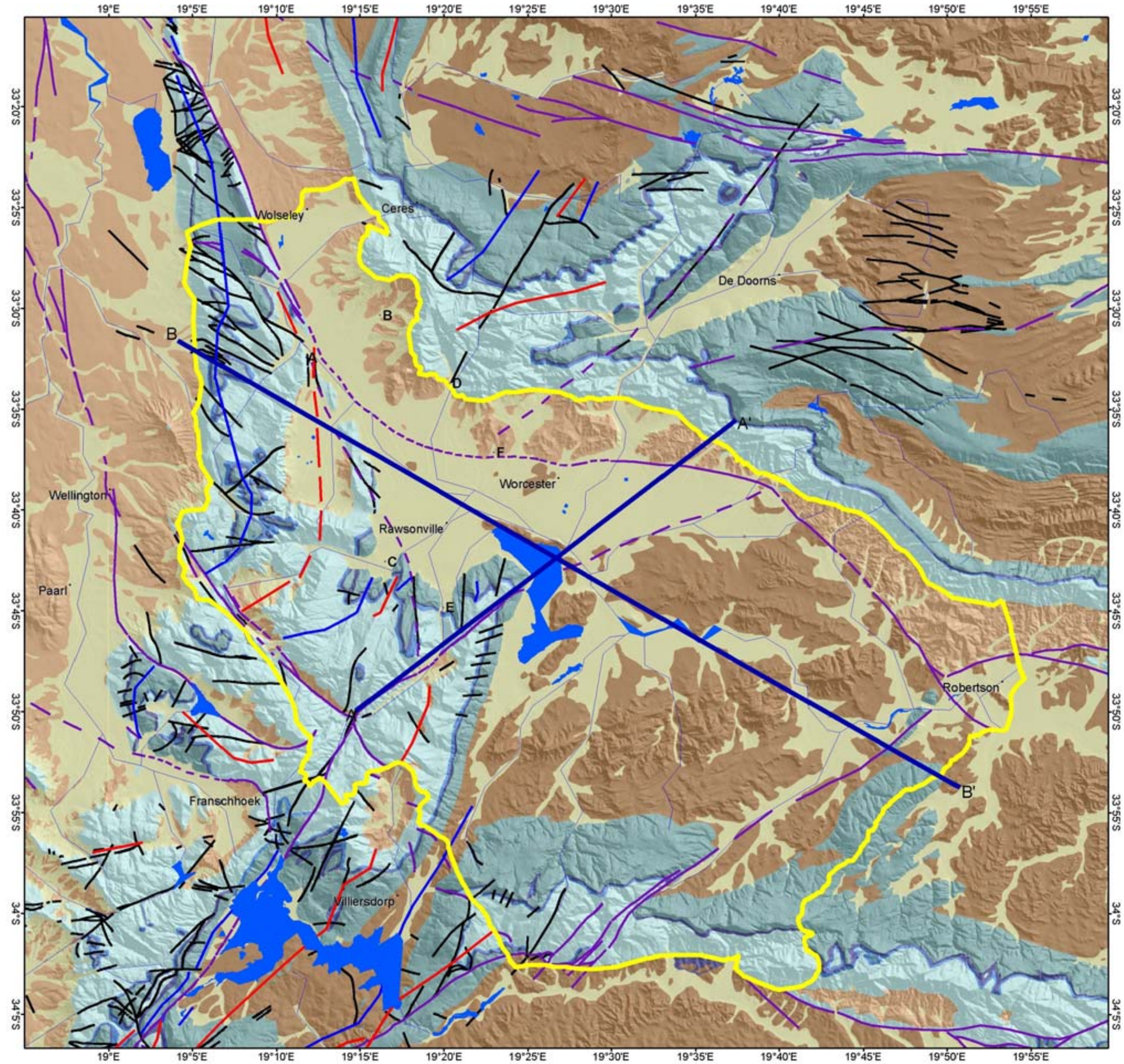
2.4.2 Geological history and structural geology

The Western Cape has undergone two periods of compressional deformation, pre and post ~500 Ma (viz. the Saldanian and Cape orogenies respectively). The Cape orogeny was followed by extensional faulting due to the fragmentation of Gondwanaland in the late Jurassic (205-141Ma).

The Cape and Karoo Supergroups, as well as the pre-Cape rocks, underwent compressional deformation during the Cape Orogeny (Gresse and Theron, 1992), to form the Cape Fold Belt. The Cape Fold Belt can be divided into three units; the western branch, where the folds trend in a northwesterly direction, the southern branch, with westerly trending overturned folds, and the syntaxis domain, where the two branches converge (De Beer, 2002; Gresse and Theron, 1992, Meyer, 2001).

The Breede River Valley is situated within the syntaxis domain, which is characterized by northeasterly trending folds and the merging of the major branch folds in arcuate fold structures (De Beer, 2002). The area was cut by thrust and strike-slip faults, which generally also trend in a northeasterly direction (Gresse and Theron, 1992). It is considered likely that the folds and faults were formed simultaneously (De Beer, 2002); although there was some reactivation of original Saldanian thrust faults.

During the late Jurassic extensional event several major northwesterly trending normal faults developed. The largest of these is the Worcester Fault, located in the Breede River Valley, which has a down throw of at least 6 km in this area (Gresse and Theron, 1992). The Riversonderend Mountain Fault also has a large down throw and runs to the south of the area under investigation. Two cross-sections showing the large-scale structural deformations are presented in **Figure 2-9**. It is this complex pattern of folding and faulting that determine the shape and changes in orientation of the Breede River Valley sides, the drainage patterns and the preferred groundwater flow paths. The time sequence of structural features can be a significant factor in hydraulic connectivity between different TMG aquifers as well as those overlying them.



Scale 1:400 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Rivers
- Faults
- Hydrotects
- Anticline
- Syncline
- Regional Cross Section Lines
- Dams
- Breede Alluvium Study Domain

SIMPLIFIED GEOLOGY

- Quaternary Sediments
- Post-TMG
- Nardouw Subgroup
- Cedarberg/Pakhuis Formation
- Peninsula Formation
- Pre-Cape

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

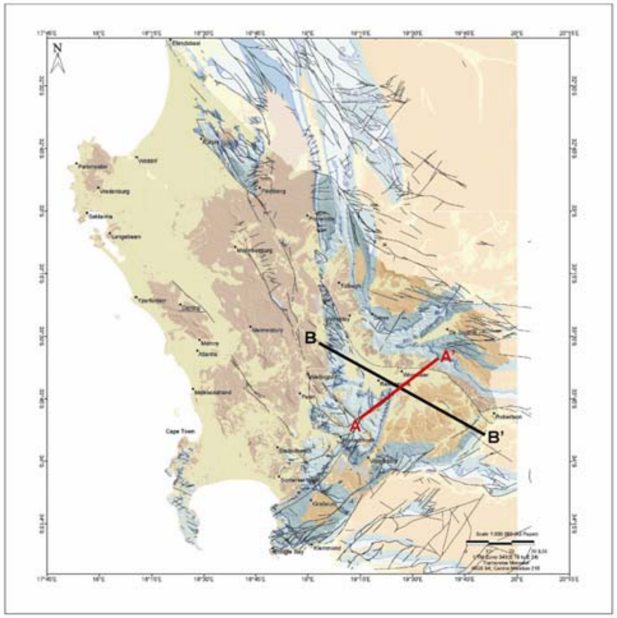
CONSULTANT

UMVOTO

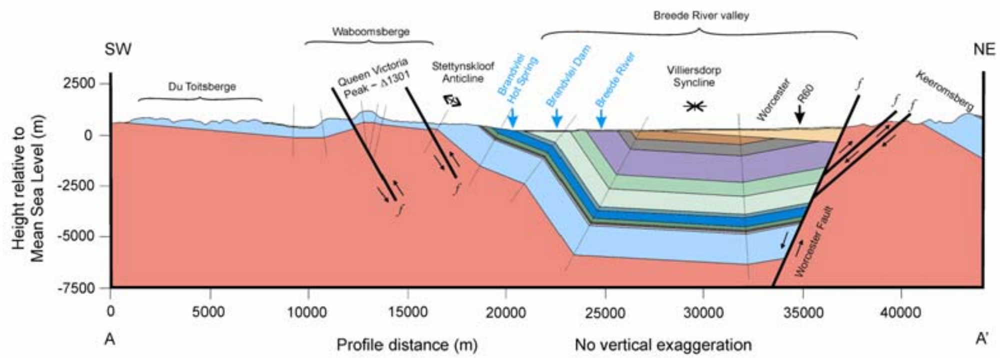
TITLE

SIMPLIFIED GEOLOGY WITH MAJOR FOLD AND FAULT STRUCTURES

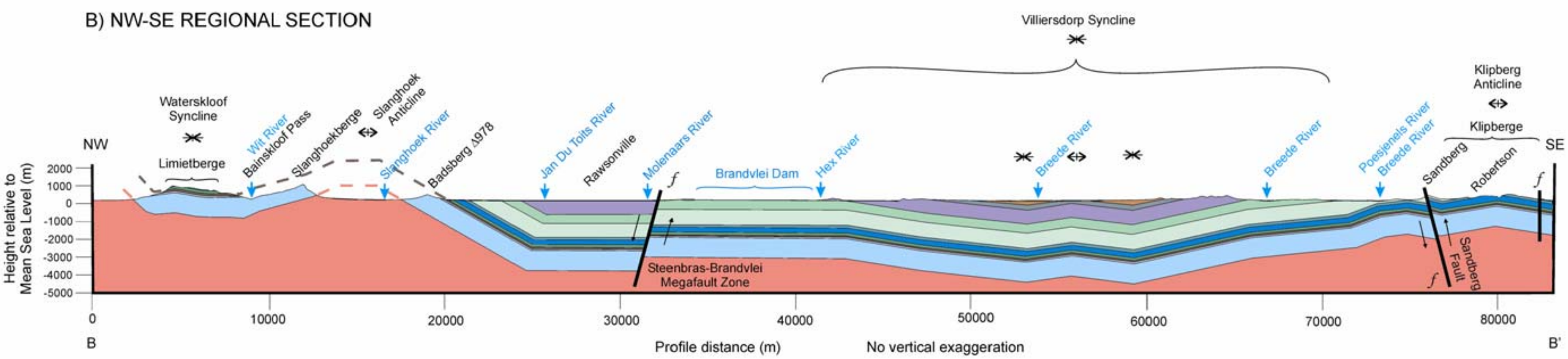
FIGURE 2.8



A) NE-SW BALANCED SECTION



B) NW-SE REGIONAL SECTION



LEGEND

Anticline
Syncline
Fault
Surface water bodies

GEOLOGY

Alluvium
Enon Formation
Ecca Group
Dwyka Group
Witteberg Group
Bidouw Subgroup — Bokkeveld Group
Ceres Subgroup — Bokkeveld Group
Rietvlei Formation
Skurweberg Formation — Table Mountain Group
Goudini Formation — Table Mountain Group
Cedarberg Formation — Table Mountain Group
Pakhuis Formation — Table Mountain Group
Peninsula Formation — Table Mountain Group
Basement

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

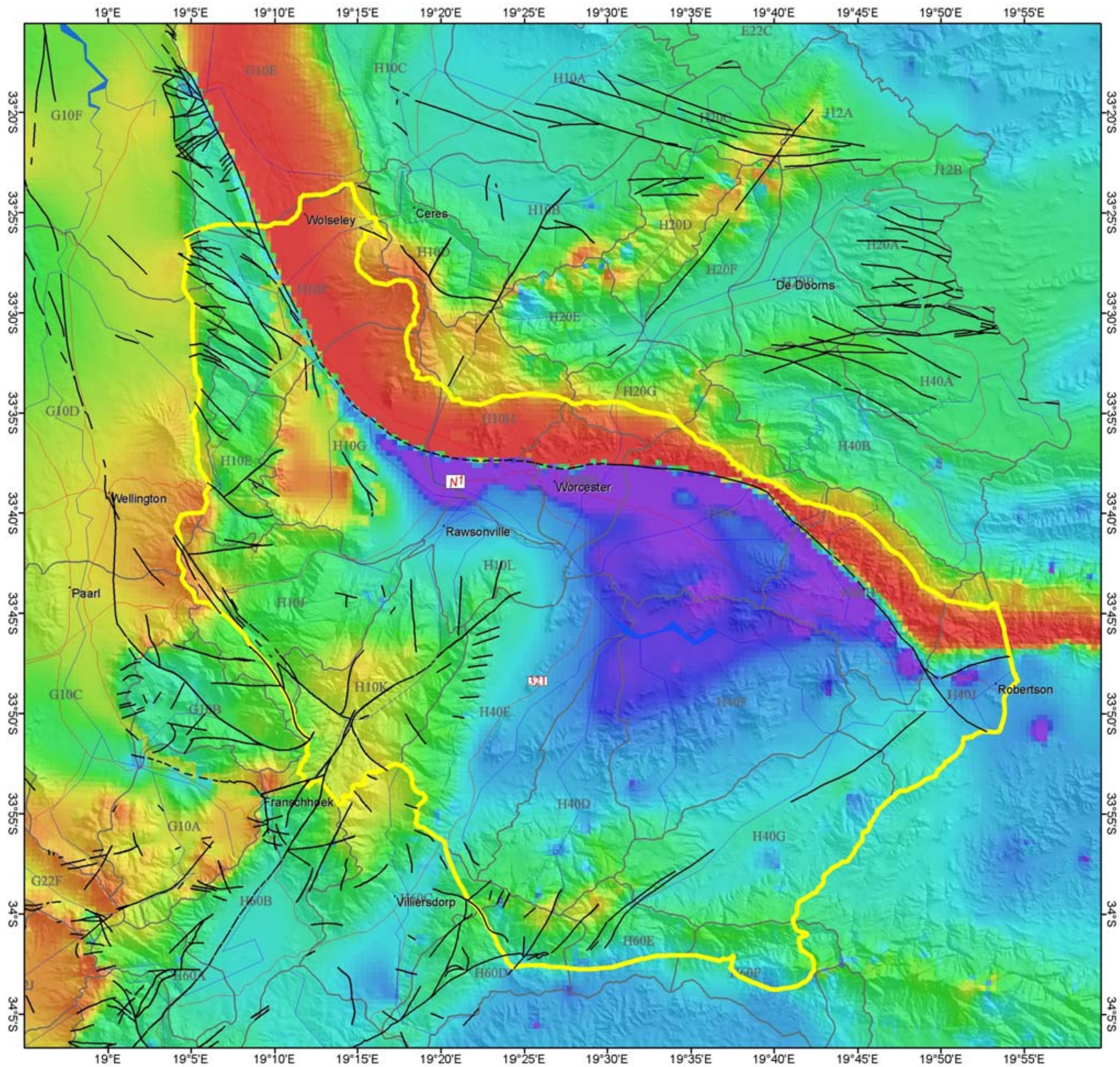
CONSULTANT

UMVOTO

TITLE

REGIONAL CROSS SECTIONS THROUGH THE BREEDE RIVER VALLEY

FIGURE 2.9



LEGEND

· Towns
Roads
Rivers
Faults
Quartenary Catchments
Dams
Breede Alluvium Study Domain

BASEMENT TOPOGRAPHY (mamsl)

- -6000 - -5000
- -5000 - -4000
- -4000 - -3000
- -3000 - -2000
- -2000 - -1000
- -1000 - 0
- 0 - 700
- 700 - 1600
- 1600 - 5320

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

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CONSULTANT

UMVOTO

TITLE

BASEMENT TOPOGRAPHY (TMG Base)

FIGURE 2.10

N

Scale 1:400 000 (A3 Paper)

0 5 10 15 KM

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

2.4.3 Alluvial deposits

Gresse and Theron (1992) distinguish several cenozoic deposits that are present in the study domain:

- Scree (T-Qt),
- Loam and sandy loam (T-Ql)
- River terrace gravels,
- Light-grey to pale-red sandy soil (Qg), and
- Alluvium.

The alluvium sediments vary from fine loam and silty soil to sand, gravely sands and boulders. The boundary between alluvium, terrace gravel, pediment gravel and scree is not always clear. Around Worcester a distinction is made between gravely alluvium and sandy alluvium but the deposits usually consist of a mixture of sand, silt and gravel. The composition of the alluvium depends on the provenance and varies from quartzose sands in the Table Mountain sandstones (the Upper Breede) to silty soil in areas underlain by Malmesbury, Bokkeveld and Karoo rocks (Middle Breede). Old alluvium-filled channels, overlain by younger alluvium have been intersected in boreholes near mountains.

Where the tributaries leave the steep mountain ranges and enter the Breede River Valley, alluvium fans are developed where the slope change is abrupt. “An alluvium fan is a body of detrital sediments built up by a mountain stream at the base of a mountain front and commonly having the shape of a segment of a cone” (Heward, 1978). They are generally areas in the alluvium layer of the highest thickness and form, together with the deposits of the Breede River itself, the alluvium aquifer. Deposits at the fanhead are mostly coarse (boulders), while decreasing in grain size further downstream. The distal facies is a lower energy environment and deposits of sand and mud are common, depending on the provenance. The typical settings of fluvial deposits are shown in **Figure 2-11**.

The most prominent alluvial fans are at the entry of the Wabooms River, Jan Du Toits River, Hex River, Molenaars River, Holsloot River, similarly, the entry of the Breede River itself, where it crosses the Michell’s Pass (see **Figure 2-12**).

The known thickness of the alluvium varies between 10 m and +50 m, with the thickest areas found in the Rawsonville area (Molenaars and Holsloot alluvial fans) and east of Worcester (Hex River alluvial fan) (see **Figure 2-14**). The available National Groundwater Database (NGDB) logs for the BAA record maximum thicknesses of 57 m of boulders drilled in the Hex River Valley, 25 m deep boulders in the Rawsonville area, 46 m deep boulders in the Jan Du Toit fan and a maximum of 28 m deep in the central valley of the Upper Breede.

The composition of the alluvium between Wolseley, Worcester and Rawsonville was investigated by means of geophysical tools (van Zyl et.al, 1981). The results showed that the Molenaars and Holsloot alluvial fans comprise thick layers of boulders in the upper parts and thick sand deposits in the lower parts of the alluvial deposits. It further indicated the inferred bedrock geology below the alluvium (see **Figure 2-15**), showing the extent of the TMG sub-outcrop and the traces of the Worcester Fault and other relevant faults in the area. Van Zyl et al. (1981) noted “the alluvium often attains its maximum thickness where it is underlain by softer Bokkeveld rocks close to the contact with the Table Mountain Sandstone”.

Between the alluvium and the underlying bedrock is often a layer of weathered, decomposed bedrock, which creates a clayey layer of about 10 m thick, especially in areas underlain by Bokkeveld or Malmesbury Group. In areas that are underlain by the TMG, no weathered bedrock is developed (van Zyl et al, 1981).

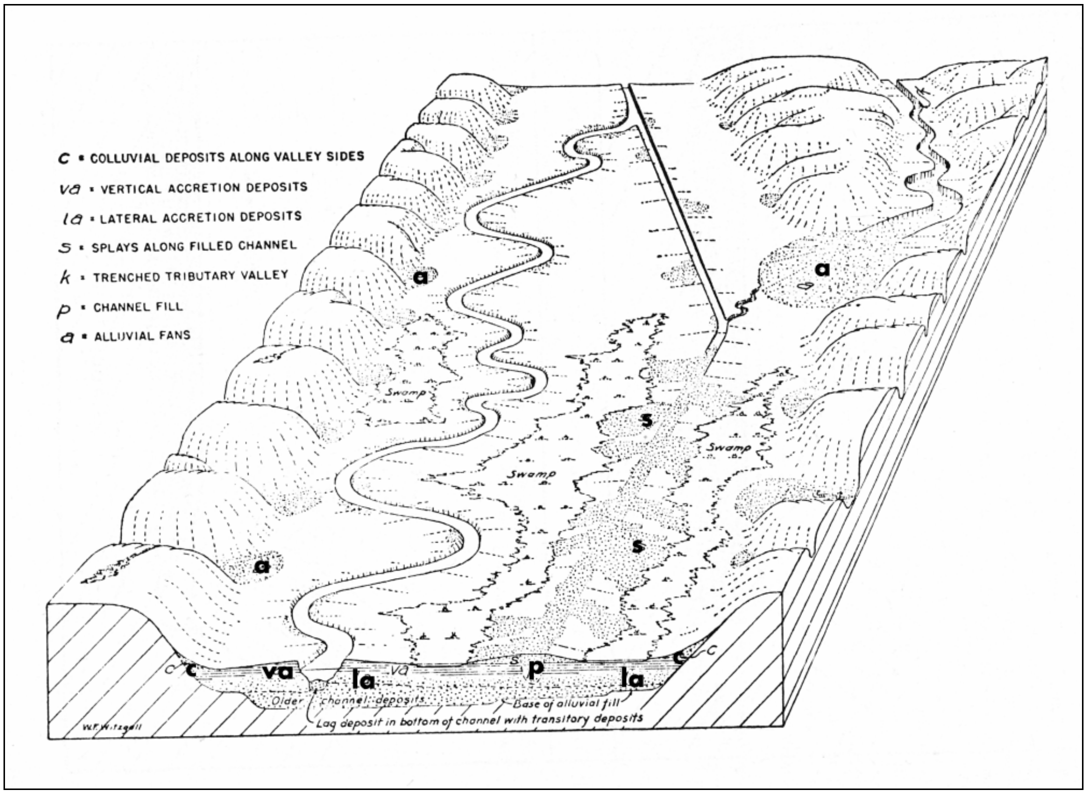
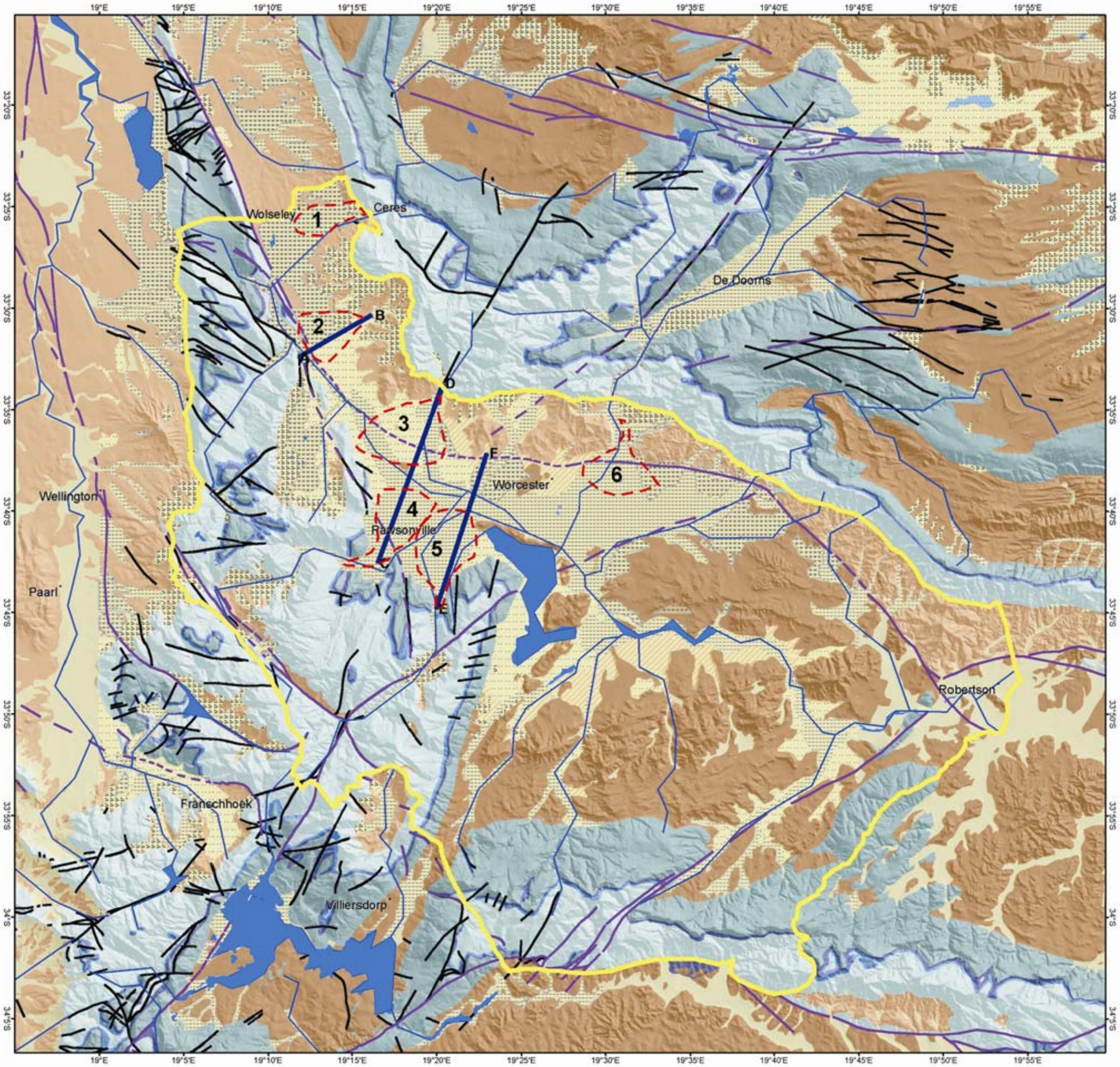


Figure 2-11 A fluvial block diagram model, illustrating typical relations of the various types of deposits in the valley accumulation (from Happ et.al., 1940; taken from Miall, 1978)



Scale 1:900 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Rivers
- Faults
- Hydrotects
- Dams
- Breede Alluvium Study Domain

QUATERNARY GEOLOGY

- Alluvium
- Loam and sandy loam
- Brackish, calcareous soil
- Gravel on river-terrace
- Light-grey to pale-red sandy soil
- Scree grading into piedmont gravel

SIMPLIFIED GEOLOGY

- Quaternary
- Post_TMG
- Nardouw Group
- Cedarberg/Pakhuis Formation
- Peninsula Formation
- Pre_Cape

A B Alluvium sections (Figure 2.13)

Alluvial fans
1. Breede
2. Wabooms
3. Jan Du Toit
4. Molenaars
5. Holsloot
6. Hex

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

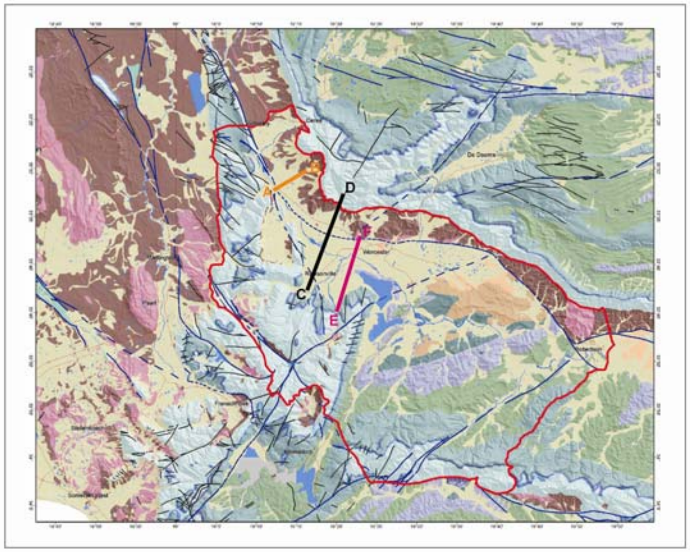
CONSULTANT

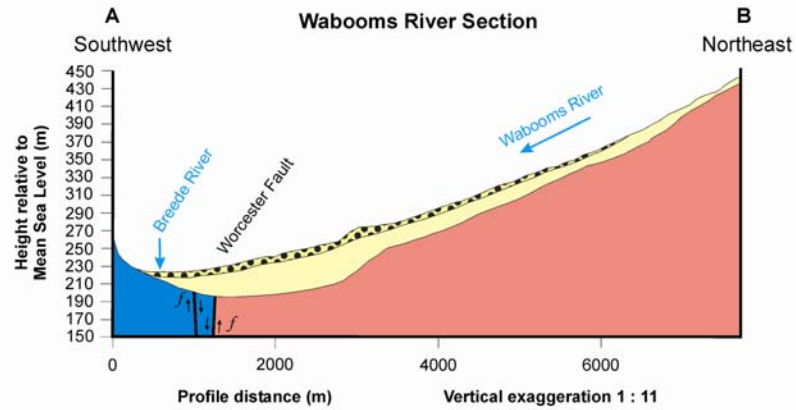
UMVOTO

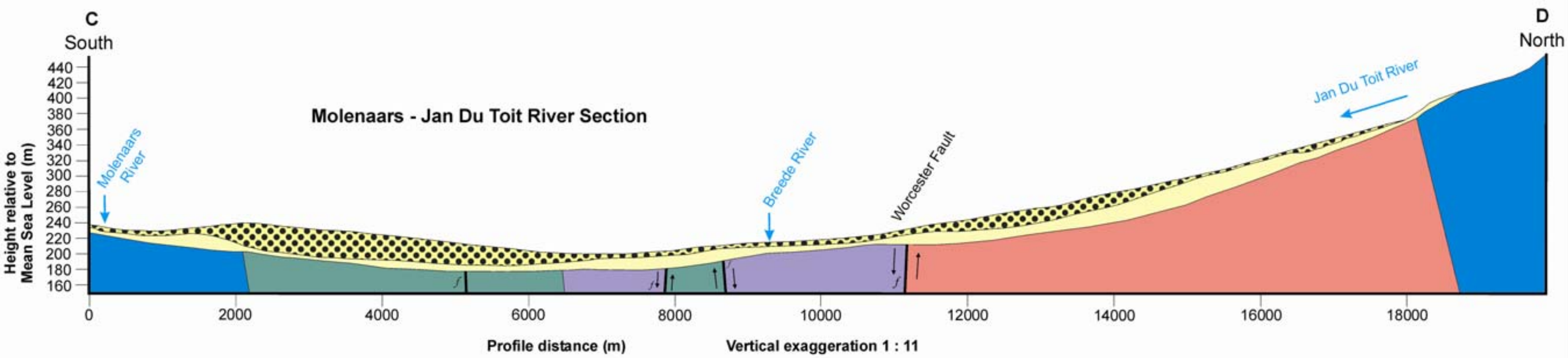
TITLE

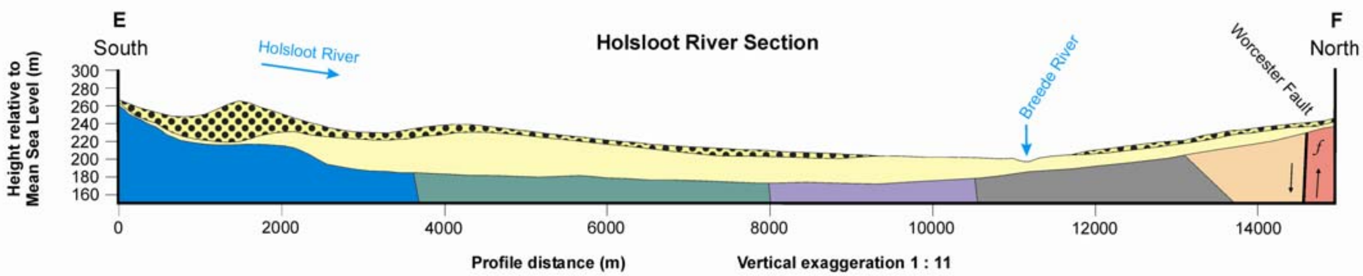
GEOMORPHOLOGY AND ALLUVIAL DEPOSITS IN BREEDE RIVER VALLEY

FIGURE 2.12









LEGEND

Fault

GEOLOGY

- Boulder and gravel layer
- Alluvial sand
- Enon Formation
- Karoo Supergroup
- Witteberg Group
- Bokkeveld Group
- Table Mountain Group
- Malmesbury Group

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

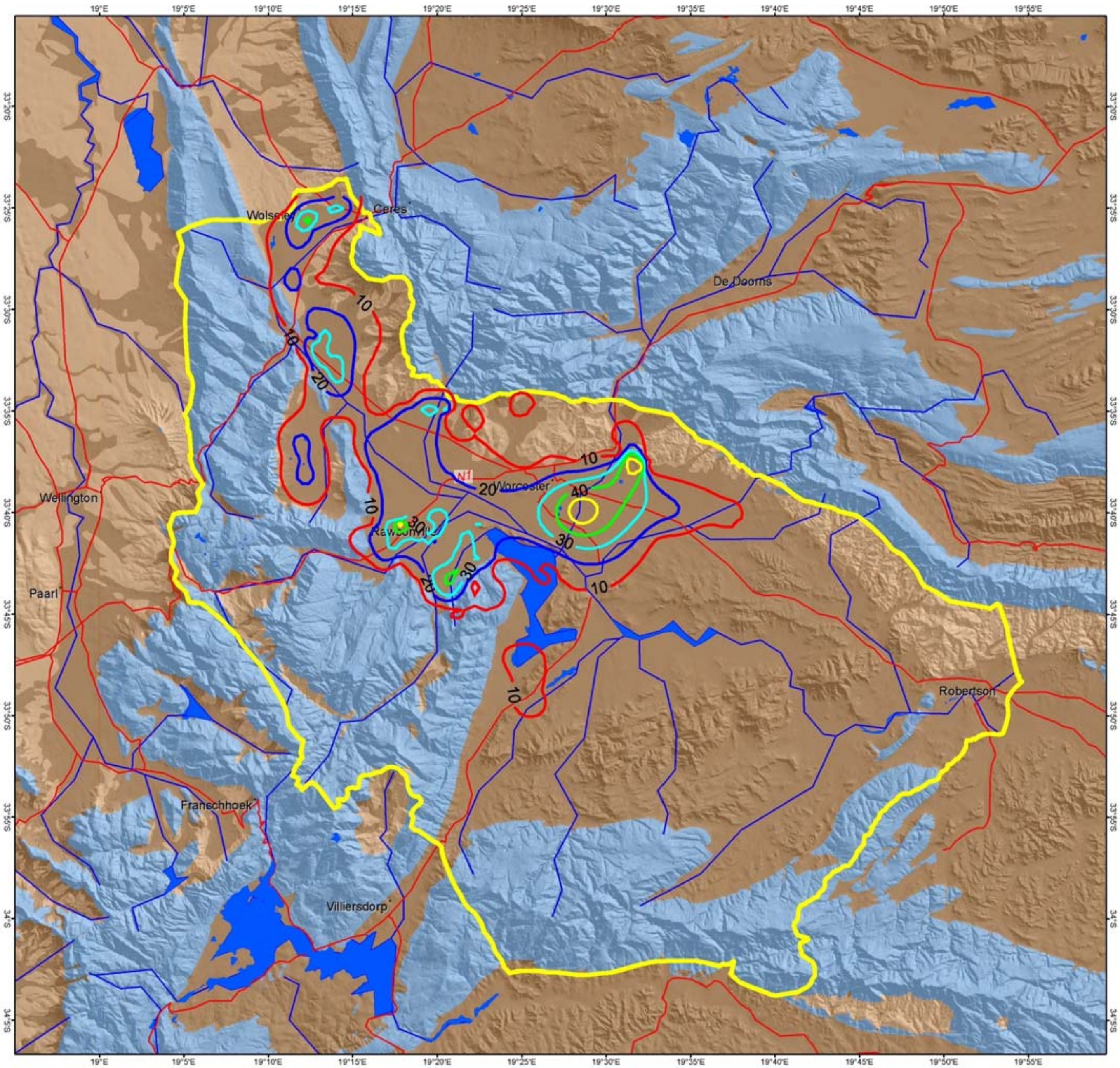
CONSULTANT

UMVOTO

TITLE

CROSS SECTIONS THROUGH THE BREEDE RIVER VALLEY ALLUVIUM (AFTER VAN ZIJL ET AL., 1981)

FIGURE 2.13



Scale 1:400 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

Towns

Roads

Rivers

Dam

Breede Alluvium Study Domain

SIMPLIFIED GEOLOGY

Post_TMG

TMG

Pre_Cape

Alluvium thickness (m)

10

20

30

40

50

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

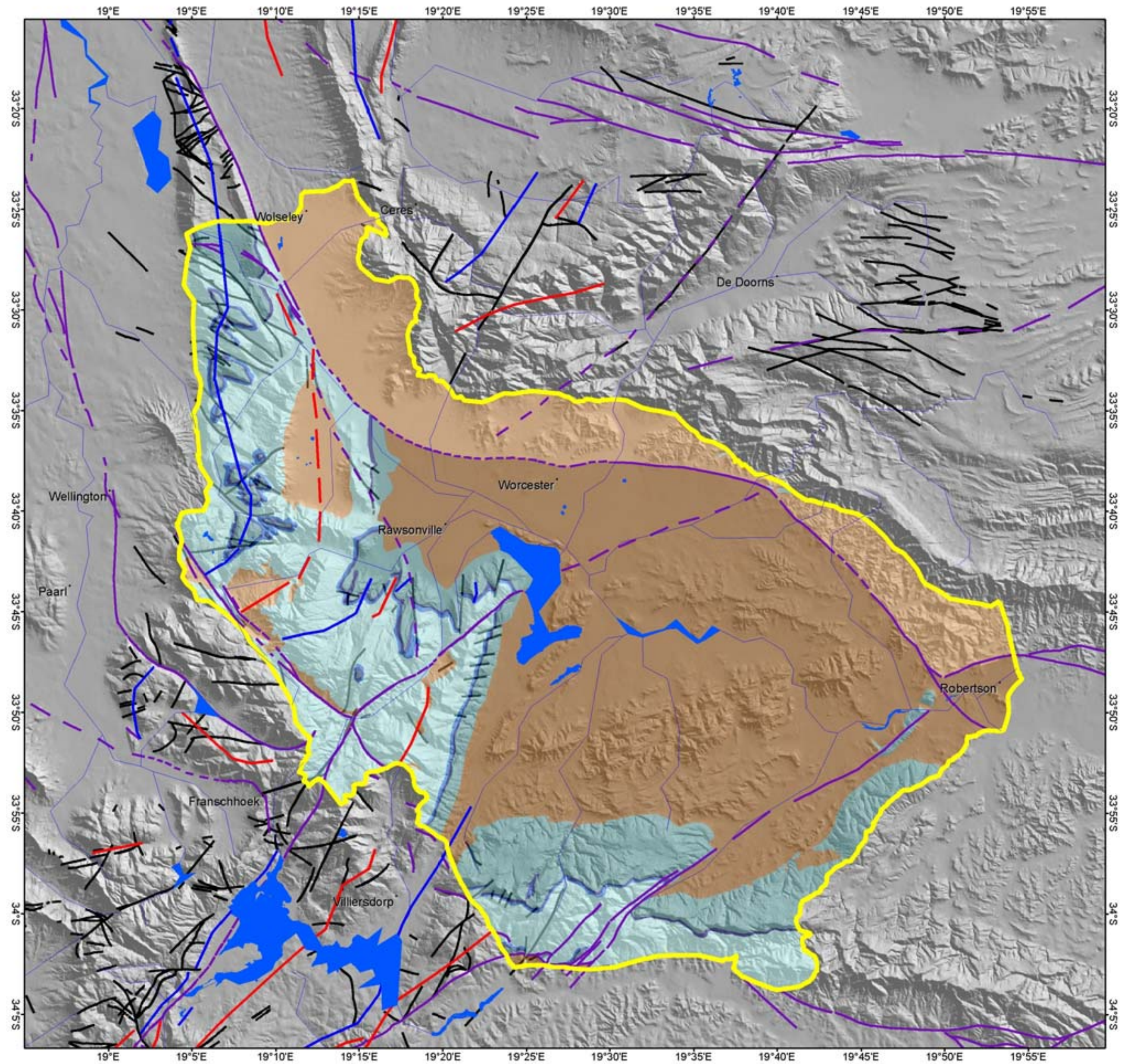
CONSULTANT

UMVOTO

TITLE

ALLUVIUM THICKNESS
(After van Zijl et al., 1981)

FIGURE 2.14



Scale 1:400 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Rivers
- Faults
- Hydrotects
- Anticline
- Syncline
- Dams
- Breede Alluvium Study Domain

SIMPLIFIED GEOLOGY

- Quaternary
- Post_TMG
- Nardouw Group
- Cedarberg/Pakhuis Formation
- Peninsula Formation
- Pre_Cape

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

INFERED BEDROCK GEOLOGY (AFTER VAN ZIJL et al 1981)

FIGURE 2.15

2.5 HYDROGEOLOGY

2.5.1 Aquifer types

The Cape Town hydrogeological map (DWAF, 2000) distinguishes three types of aquifer (see Volume 3), namely,

- type a – intergranular ("primary" or porous sandy aquifers),
- type b – fractured ("secondary" aquifers), and
- type d – intergranular-and-fractured (also termed "regolith" aquifers, in which porosity and permeability is related to a combination of near-surface fracturing and chemical weathering).

The aquifer classification used in this study differs in selected areas of the study relative to the different previous study areas in which they were defined. The reasons for the differences in aquifer classification have been discussed in the Conceptual Model Report (Volume 3 DWAF; 2007). The aquifer classification impacts on the hydrostratigraphic classification as well as the flow path definition, the mass balance and on the definition of boundary conditions within local-scale model domains.

Fractured-rock aquifers

Fractured-rock aquifers are by far the most important in the Breede River catchment and cover a large portion of the catchment area, either as surface outcrop or as sub-outcrop overlain by other aquifer types. Of the fractured aquifers, the Peninsula Aquifer and Skurweberg Aquifer of the TMG are the most important. Although rocks of the Malmesbury, the Bokkeveld groups and the Karoo Supergroup can also yield water under fractured conditions, they are rather considered regolith or fractured-weathered aquifers for the purposes of this report.

Fractured and intergranular aquifers

The fractured and intergranular aquifers consist mainly of moderately weathered, medium to coarse-grained granite of the Cape Granite Suite. Groundwater is contained within intergranular interstices in the saturated zone and in jointed and occasionally fractured bedrock. This aquifer type comprises the Cape Granites and Malmesbury Group, found primarily north of the Worcester Fault, and the Bokkeveld Group and Karoo Supergroup, south of the Worcester Fault. This aquifer type is not considered to be an important regional aquifer in the Breede Basin, as it only yields significant water in very localised settings.

Intergranular aquifers

The unconsolidated intergranular aquifers consist of the Tertiary to Quaternary alluvial deposits. They are occasionally semi-consolidated but groundwater occurs within granular interstices in the porous medium. Although the intergranular aquifers cover large areas of the Breede and Hex River valleys they have variable thickness and may be largely unsaturated where they are poorly developed (< 10 m). Areas where there is extensive development of alluvium and where the intergranular aquifers comprise an important resource include:

- Wolseley to Goudini (including the Slanghoek River valley),
- The Rawsonville area,
- Worcester to Nuy,
- The Modder River valley, and
- The Robertson area.

2.5.2 Hydrostratigraphy

The division and sub-division of the stratigraphic units into aquifer and aquitard units is shown in **Table 2-3**. More detailed lithostratigraphic descriptions can be obtained from previous works (e.g., Gresse and Theron, 1992). The spatial distribution of the hydrostratigraphic units present in the study area is shown in **Figure 2-16**.

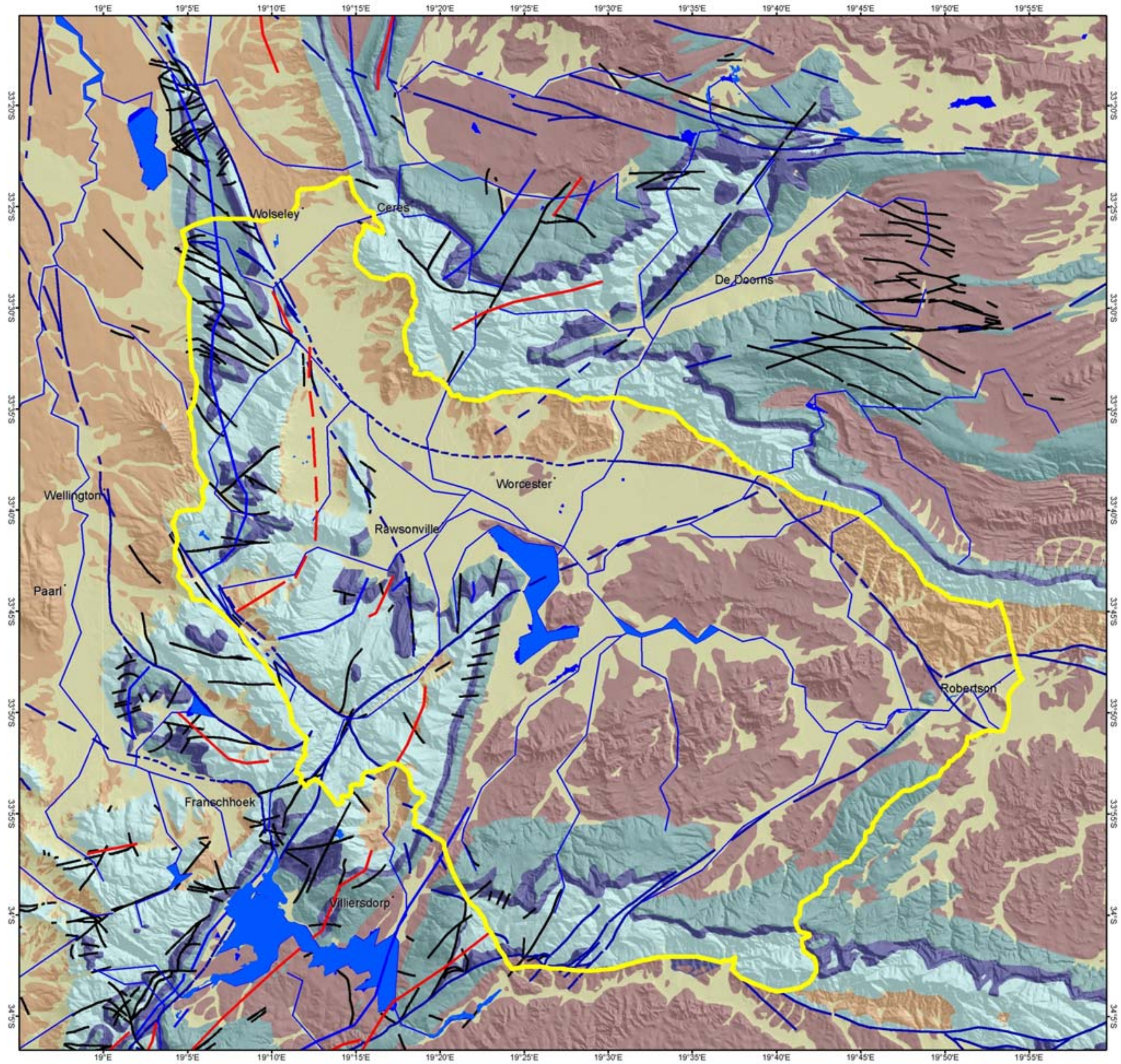
The scale of interest of the model investigation is regional. At this scale the Malmesbury and Cape Granite Suite can be considered aquicludes. Locally however these rocks may yield significant supplies, and at the scale of water supply to an individual farm, their interaction with the Breede Alluvium would have to be considered.

Table 2-3 Coincident hydrostratigraphic units of the study area

Superunits	Units	Subunits	Aquifer Type
	Breede Alluvium Aquifer	Various discrete alluvial aquifers	Intergranular
Underlain by aquicludes of Malmesbury Group and or Cape Granite Suite north of Worcester Fault (northern part of Study Domain); *Underlain by TMG and higher units south and west of Worcester Fault*			
	Karoo Mega-aquitard		Regolith
	Witteberg Aquifer		Fractured
	Gydo Mega-aquitard		Regolith
Table Mountain Superaquifer	Nardouw Aquifer	Rietvlei Subaquifer	Fractured
		Verlorenvalley Mini-aquitard	
		Skurweberg Subaquifer	Fractured
	Winterhoek Mega-aquitard	Goudini Meso-aquitard	
		Cedarberg Meso-aquitard	
		Pakhuis Mini-aquitard	
	Peninsula Aquifer	Platteklip Subaquifer ?	Fractured
		Leeukop Subaquifer ?	
		Graafwater Meso-aquitard	
		Piekenierskloof Subaquifer (localized)	Fractured
	Aquicludes	[Klipheuwel Group] [Cape Granite Suite] [Malmesbury Group]	Regolith

2.5.3 Water level

The piezometric map for the TMG Aquifer, as shown in **Figure 2-17**, shows the water flow from the high lying recharge areas towards the confining parts of the aquifer in the Breede River Valley. The map was generated based on the assumption that where rivers cross TMG outcrops the surface water and groundwater are hydraulically connected and so this topographical elevation is the elevation of the groundwater head. Any NGDB data points from the TMG were also included. Similarly, the piezometric map for the alluvium in **Figure 2-18** shows the general water flow from the edges of the valley towards the river and along the river eastwards. The alluvium map is based on NGDB data.



Scale 1:400 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Rivers
- Faults
- Hydrotects
- Anticline
- Syncline
- Dams
- Breede Alluvium Study Domain

AQUIFER TYPES

- Intergranular: Alluvium
- Regolith: Gydo Mega-aquitard
- Fractured: Nardouw Aquifer
- Regolith: Winterhoek Mega-aquitard
- Fractured: Peninsula Aquifer
- Regolith: Basement Aquiclude

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

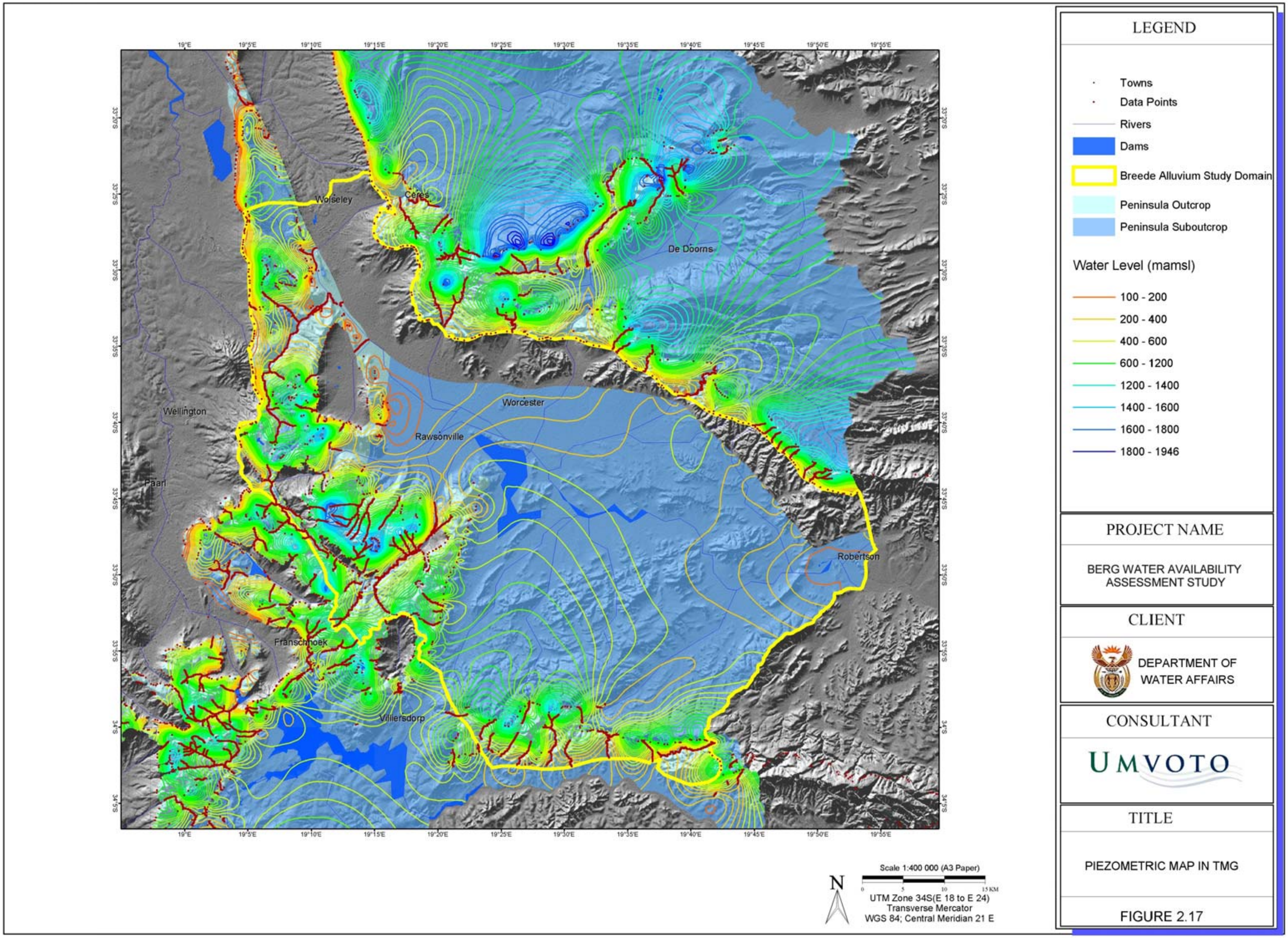
CONSULTANT

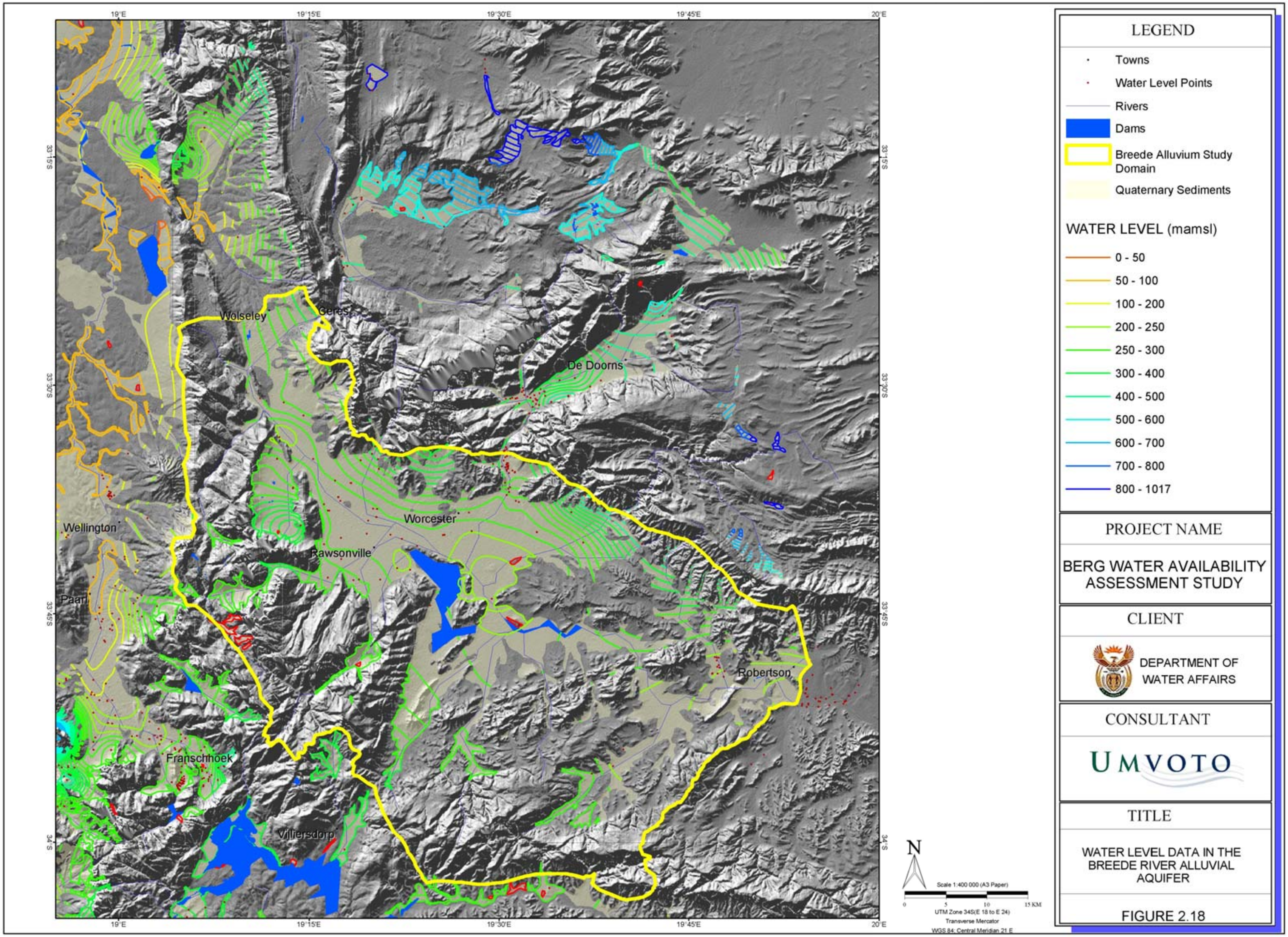
UMVOTO

TITLE

HYDROSTRATIGRAPHY AND AQUIFER TYPES IN MODEL DOMAIN

FIGURE 2.16


LEGEND
Towns
Data Points
Rivers
Dams
Breede Alluvium Study Domain
Peninsula Outcrop
Peninsula Suboutcrop
Water Level (mamsl)
100 - 200
200 - 400
400 - 600
600 - 1200
1200 - 1400
1400 - 1600
1600 - 1800
1800 - 1946
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS
CONSULTANT
UMVOTO
TITLE
PIEZOMETRIC MAP IN TMG
FIGURE 2.17
Wolseley
Ceres
De Doorns
Wellington
Worcester
Rawsonville
Paarl
Robertson
Franschhoek
Villiersdorp
Scale 1:400 000 (A3 Paper)
N
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E


19°E
19°15'E
19°30'E
19°45'E
20°E
33°15'S
33°30'S
33°45'S
34°S
Wolseley
Ceres
De Doorns
Wellington
Worcester
Rawsonville
Paarl
Robertson
Franschhoek
Villiersdorp
N
Scale 1:400 000 (A3 Paper)
0
5
10
15 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E
LEGEND
Towns
Water Level Points
Rivers
Dams
Breede Alluvium Study Domain
Quaternary Sediments
WATER LEVEL (mamsl)
0 - 50
50 - 100
100 - 200
200 - 250
250 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 800
800 - 1017
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS
CONSULTANT
UMVOTO
TITLE
WATER LEVEL DATA IN THE BREEDE RIVER ALLUVIAL AQUIFER
FIGURE 2.18

2.5.4 Springs

Numerous perennial and seasonal flowing springs exist along the Breede River Valley and are used by farmers, but no comprehensive record of springs or of spring usage and flow rate is available. Most of these springs originate from the TMG. Perennial springs usually discharge from the Peninsula Aquifer and springs and seep zones of a more seasonal character from the Skurweberg Aquifer.

There are more than ten thermal springs that originate from the TMG (Diamond, 1997), four of which are located in the Breede Basin (see **Table 2-4**). The temperature of the water in these springs ranges from 27°C to 64 °C. The occurrence of the Brandvlei hot spring, the strongest flowing and hottest spring in South Africa (> 125 ℓ/s and 64°C) is evidence of the existence of open fissures extending to great depths (at least 2 - 3 km), which can transmit groundwater to the surface. Oxygen and hydrogen isotope ratios of thermal spring waters indicate that the springs are recharged from a colder weather system, such as during a previous colder climate regime, or at high altitude (Diamond, 1997), with high altitude rain being the probable source.

Table 2-4 Some thermal springs in the Breede River catchment

Locality	Flow	Temperature	Use
Brandvlei	125 l/s	57-61 (DWAF 2002)	Prison domestic supply
Goudini	4 l/s	30-47 (Grant 2007)	Irrigation of gardens and spa

2.5.5 Papenkuils Wetland

The Papenkuils Wetland is a 900 ha seasonal floodplain palustrine scrub-shrub wetland located next to the Greater Brandvlei Dam, downstream of the confluence of the Molenaars and Breede River (see **Figure 2-2**). Both rivers normally bypass the wetland to the north-west and north-east, respectively, but may overflow into the wetland during high flow conditions. The Holsloot River drains into the wetland from the west, and provides most of the surface runoff to the wetland.

The aquifer underlying the wetland is part of the alluvial fan of the Rawsonville aquifer. The cultivated areas south of Rawsonville comprise the proximal facies of the fan and consist largely of gravel and boulders, whereas the wetland comprises the distal facies made up of sand and mud. The sedimentology and morphology of the wetland has been influenced by the Breede River, which flows perpendicular to the axis of the fan. Detailed investigations indicate that the stream channels and the annual inundation of the wetland from flooding of the Breede River and Holsloot River are likely to contribute a major source of recharge to the alluvium aquifer (DWAF, 2002).

2.5.6 Surface water – groundwater interaction

There are two relevant processes of surface water – groundwater interaction in the study area, viz. the groundwater contribution to stream flow and *vice versa* in the wider valleys, and the groundwater recharge from stream flow where the mountain streams widen into alluvial fans and enter the bottom valley.

According to Vegter (1995), the groundwater component of mean annual run-off (MAR) in the Breede catchment under current abstraction conditions is:

- 20 – 30% in the Breede catchment
- 0 – 10% in the Hex River Valley

- Negligible in the Middle Breede Valley
- 10 – 20% of MAR in the Lower Breede catchment

DWAF (2002) undertook a comparison between different techniques of baseflow separation for a number of selected catchments to identify catchments in which there is a significant connection between surface and groundwater during the Breede River Basin Study.

The results of the hydrograph separation methods are shown in **Table 2-5**, indicating a groundwater contribution to stream flow of 4% to 28% of MAR. The naturalised mean annual run-off from the WR90 Study (Midgley et al, 1994) have been used, which are based on Pitman's run-off model and represent run-off from undeveloped catchments.

Table 2-5 Comparison of Baseflow in selected catchments (after DWAF, 2002)

CATCHMENT	MAR	BASEFLOW					
		SEMI-LOG PLOT		Linear Interpolation		Herold's Model	
	Mm^3/a	Mm^3/a	% MAR	Mm^3/a	% MAR	Mm^3/a	% MAR
Wit H10E	101	16	16	6	6	28	28
Molenaars H10J	206	32	16	11	5	58	28
Holsloot H10K	125	22	17	7	6	35	28
Hex H20A – G	140	24	17	6	4	39	28

The following comments were made relating to the baseflow separation techniques (DWAF, 2002):

- Herold's method gives an indication of the baseflow component of stream hydrographs. This incorporates the interflow as well as the groundwater contribution to stream flow. Herold's method provides a baseflow volume of approximately 30% for most sub-catchments in the upper Breede Basin for both gauged DWAF and WR90 data.
- The semi-log plot method gives an estimate of the interflow component and groundwater contribution to baseflow but incorporates a greater component of the groundwater recession as baseflow... The baseflow as a percentage of MAR resulting from baseflow is 5% – 10% less than that using Herold's method.
- The linear interpolation method provides a low estimate baseflow (3% – 15% of MAR) and is thought to constitute the groundwater contribution to stream flow when compared to other hydrograph separation methods. The linear interpolation therefore provides a more realistic indication of the groundwater component to surface flow.

This comparison gives an indication of the amount of groundwater contribution to baseflow that can be expected within the model domain. However, these estimates cannot be attributed to specific aquifers and therefore cannot be used for an impact assessment of groundwater abstraction in the alluvium. The approach, followed in this report to estimate the aquifer-specific groundwater contribution to baseflow, was described in detail in Volume 4.

Table 2-6 below shows the distribution of the baseflow contribution between different aquifer types in the Study Domain, based on proportional recharge. A significant baseflow contribution is calculated from the Peninsula Aquifer (60 – 70% of total baseflow, depending upon the recharge method).

Table 2-6 Aquifer-specific discharge estimation in Study Domain, groundwater contribution to baseflow disaggregated according to recharge

Recharge method	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	Total groundwater contribution to baseflow	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
ISP	23.37	2.61	0.01	1.64	5.29	32.93	20
Map-centric	18.05	2.32	0.02	4.18	5.67	33.23	21

The magnitude of the various published surface water - groundwater fluxes vary greatly and are lumped for large areas, and upgrade of these estimates is the focus of this modelling. What is clear from the data is that the Breede River is a dominant sink to the Alluvium. This is evident in the contours in **Figure 2-18**. The deep TMG flow however shows no connection to the surface water of the Breede River and the piezometric map suggests flow to the north towards the Worcester fault and towards spring discharge (**Figure 2-17**). It is therefore assumed that the Breede River gains water from the aquifer over most of it's length.

The surface water and groundwater interaction in the TMG-fed tributaries that flow over alluvial fans is more complex. As described in section 2.4.3, the fan heads are coarse (boulders) and the deposits decrease in grain size along the fan, i.e. towards the centre of the valley and the Breede River itself. Where the tributaries leave the steep mountain ranges and enter the alluvium fans, the slope change is abrupt and the tributaries are considered to lose water to the fans (i.e. recharge them). Further downstream where the topographic slope lessens the tributaries themselves will drain the aquifer.

2.5.7 Recharge

The dominant recharge processes and volumes differ between the fractured aquifers and the alluvial aquifers. While the vertical recharge due to infiltration from rain is the dominant process for the fractured aquifers, recharge to alluvial aquifers may take place by a combination of the following mechanisms:

- Direct rainfall infiltration on the surface
- Infiltration of irrigation water,
- Influent seepage from rivers entering the alluvial plain from the bordering mountains.
- Upward leakage into alluvial aquifers from the limited area where the TMG is the underlying bedrock and lateral flow of groundwater from the mountain fronts.

The recharge areas also differ between the aquifers. The conditions for the infiltration of rainfall on the high mountains surrounding the Breede River Valley are favourable as the TMG has a fractured, 'blocky' surface, with limited soil cover resulting in quick seepage through the unsaturated zone. The main recharge areas for the Peninsula Aquifer are listed below in order of relevance, based on outcrop area and proportion of infiltrating rainfall:

- Haweqwas Mountain range between Wellington, Rawsonville and Villiersdorp, including the Du Toits, Stettyns, Slanghoek and Limiet mountains, receiving an MAP of up to 3400 mm/a
- Hex River Mountain range north of Worcester, including Waaihoek Mountain, Hex River Mountains, Meiring`s Ridge , Kwadous and Lange mountains, with an average MAP of 2000 mm/a
- Riviersonderend Mountain, with an average MAP of 800mm/a.

The recharge areas for the Skurweberg Aquifer are listed below. They receive less rainfall than the Peninsula Aquifer outcrop areas and are more scattered, often forming the hillslopes of higher Mountains of sandstones from the Peninsula Formation. The main areas of relevance are:

- Northern and western parts of the Riviersonderend Mountain
- Water valley between Elandsfontein and Watervals Mountains.

The recharge pattern for the Alluvium Aquifer differs in that direct vertical recharge from rain infiltration accounts only for part of the recharge, which component would be less than that in the TMG terrain due to a significantly lower rainfall and higher evaporation in the valleys (see above). However, the conditions for rainfall infiltration to the alluvium are favourable over large areas of the Upper and Middle Breede basins, which have high permeable surface horizons and therefore a significant amount of the rainfall will recharge the aquifer. Additional recharge occurs through surface run-off from surrounding bedrocks, infiltrating the alluvial deposits, and through periodical flood events of the main rivers intersecting the alluvium aquifers. High groundwater levels (<10mbgl) are found in the Upper to Middle Breede seasonally being above ground in places.

DWAF (2002) estimated the spatial distribution of recharge to the different aquifers, indicating the high recharge areas being the mountainous regions in the south (Haweqwas ranges, more specifically the Du Toits and Stettyns) and north (Hex and Kwadous ranges) of the Breede River catchment (see **Figure 2-19**). In these areas, the mean annual recharge varies from 100 mm - 400 mm and comprises approximately 50% of the total volume of groundwater recharge in the basin.

Areas of moderate recharge (40 to 100 mm/a) indicated in green in **Figure 2-19**, correspond to the base of the mountainous areas in the west and north of the Breede catchment (including the alluvial valleys around Rawsonville and north of Goudini) as well as the Riviersonderend and Langeberg ranges. Areas of moderate recharge account for approximately 35% of annual recharge. The high and moderate recharge areas combined receive in excess of 80% of the total recharge in the study domain.

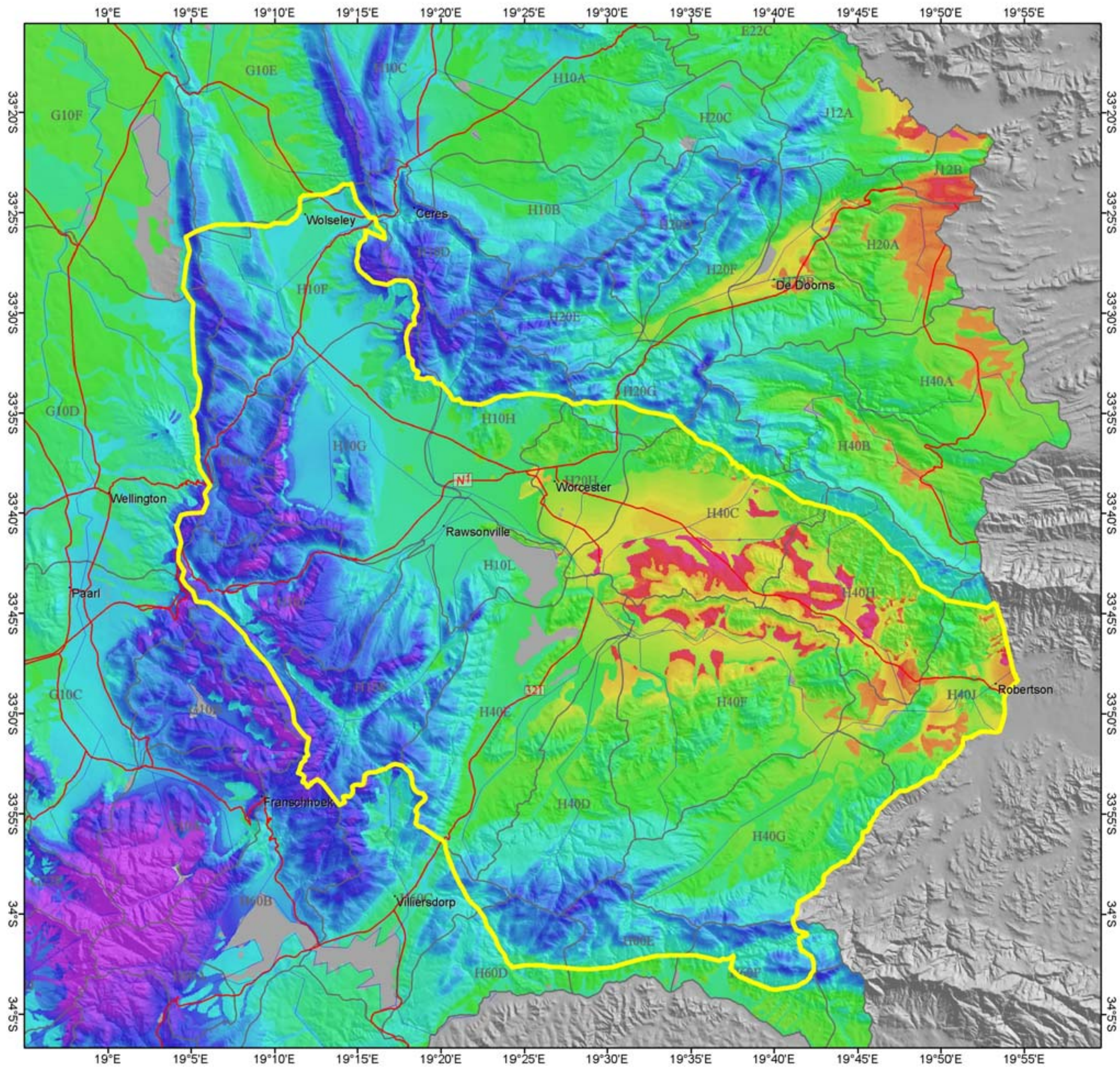
Areas of low recharge (0 – 40 mm/a) are depicted in orange and red on the map and represent the valley areas, especially in the eastern part of the study domain. Although comprising around 40% of the catchment area, only 10% of the total recharge is estimated to occur in these areas.

A similar distribution of recharge (see **Figure 2-20**) was estimated during the Groundwater Resource Assessment Project, Phase II (GRA II; DWAF, 2004).

Aquifer specific recharge was estimated with different methods for the Regional Water Balance (Volume 4) and are summarised below for the study domain. **Table 2-7** confirms that the Peninsula Aquifer receives nearly 50% of the total recharge in the study domain, while the intergranular aquifer receives about 20%.

Table 2-7 Aquifer-specific recharge estimation in Study Domain, with different recharge methods (per year)

Recharge method	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Total recharge**	
	Mm^3	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*mm*
GRA II	115.37	19.42	0.45	29.25	42.19	206.68	70
BRBS	97.65	27.37	1.41	24.27	46.96	198.51	67
ISP	109.15	35.93	2.12	15.97	32.86	196.03	66
Map-centric	54.71	32.94	4.29	64.76	58.96	215.66	73
Average	94.22	28.92	2.07	33.56	45.22	204.22	69



LEGEND

- Towns
- Rivers
- Roads
- Quartenary Catchments
- Breede Alluvium Study Domain

RECHARGE (mm/a)

- 2 - 8
- 8 - 15
- 15 - 40
- 40 - 50
- 50 - 70
- 70 - 100
- 100 - 120
- 120 - 140
- 140 - 270
- 270 - 290
- 290 - 310
- 310 - 415
- 415 - 980

Scale 1:400 000 (A3 Paper)

N

0 5 10 15 KM

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

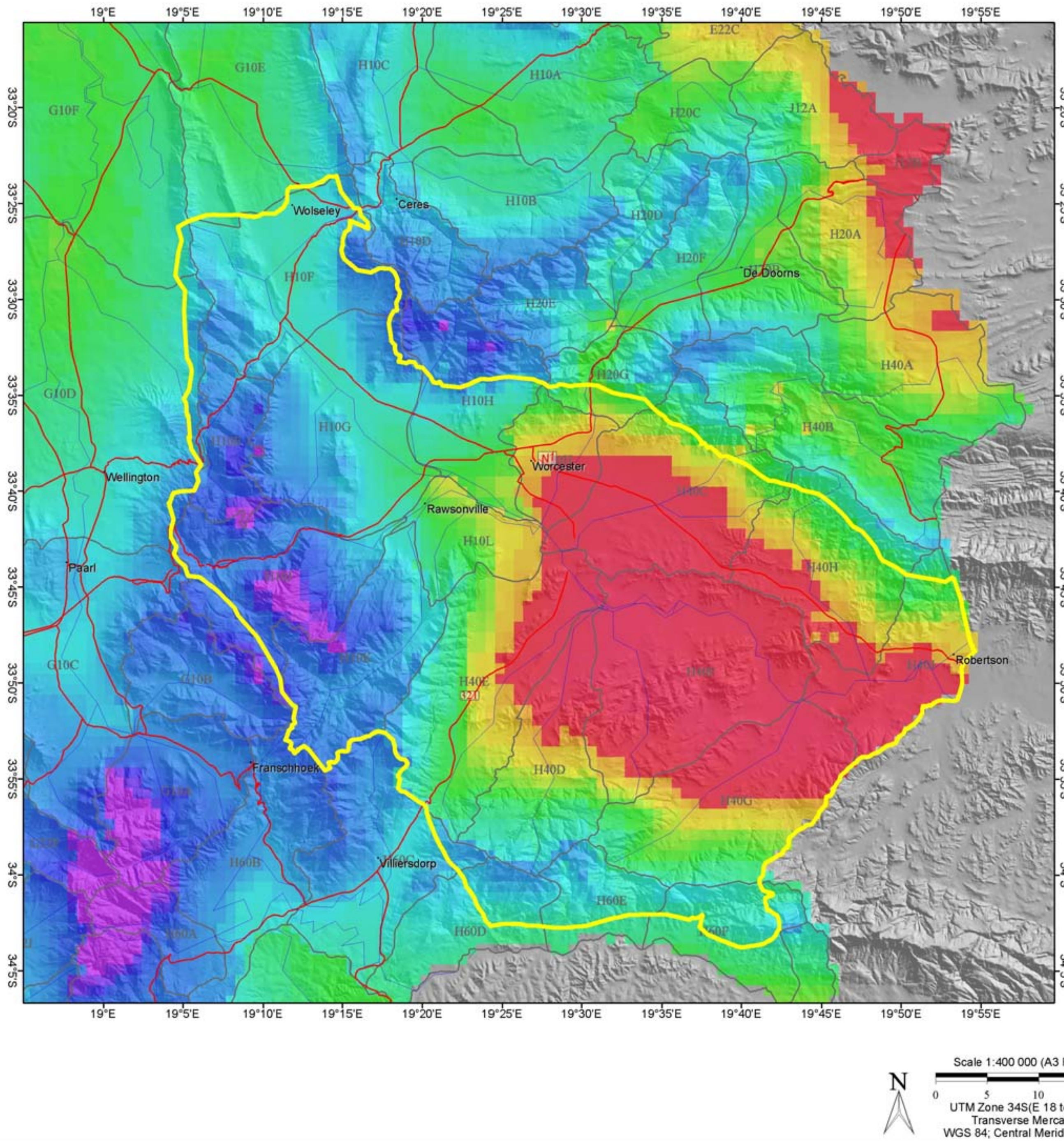
CONSULTANT

UMVOTO

TITLE

MODIFIED RECHARGE (DWAF, 2002)

FIGURE 2.19



LEGEND

- Towns
- Roads
- Rivers
- Quartenary Catchments
- Breede Alluvium Study Domain

RECHARGE (mm/a)

- 0 - 8
- 8 - 16
- 16 - 40
- 40 - 60
- 60 - 70
- 70 - 105
- 105 - 190
- 190 - 420
- 430 - 460
- 460 - 820

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

RECHARGE (GRA II)

FIGURE 2.20

2.5.8 Groundwater use

Significant groundwater abstraction takes place in the Upper Breede catchment and approximately 95% of it is used for irrigation. The Breede River Basin Study estimated that in quaternary catchments H10A - K (Ceres to Greater Brandvlei Dam) approximately 44 Mm^3/a is abstracted from aquifers whereas in the quaternary catchments H20A – H (Hex Valley to Worcester including Nuy and Noona – H40C), abstraction is approximately 20 Mm^3/a (DWAF, 2002).

Approximately 30% of farmers' irrigation requirements are estimated to come from groundwater in the Upper Breede. In the Hex River and Rawsonville areas, the percentages are around 50% and 32% respectively. Therefore, although the usage volume is less in the Middle Breede, this usage represents a larger proportion of the total. The estimated groundwater use in different sub-regions is listed in **Table 2-8**.

Table 2-8 Groundwater use in the Breede Basin (after DWAF, 2002)

SUB-REGION	QUATERNARY CATCHMENTS	GROUNDWATER USE
		Mm^3/a
Wolseley-Goudini	H10D, E, F, G, H	17
Rawsonville	H10, J, K, L	15
Hex Valley	H20A – F	20
Worcester/ Nuy / Moordkuil	H20G, H, H40C, E	9

The TMG aquifer is not extensively used in this area due to the limited access for drilling in the rugged mountainous terrain. However, extensive use is made of the alluvial aquifer, particularly during summer in the central part of the study domain around Rawsonville. Further north, towards Wolseley, groundwater abstraction from the alluvium is also significant and is frequently from shallow pits adjacent to the Breede River. Groundwater abstraction also takes place from fractured Malmesbury aquifers in the Hartbees, Jan du Toits and Wabooms River Valleys.

The groundwater abstraction per aquifer was estimated for the Regional Water Balance Model (Volume 4), based on recent estimates of groundwater abstraction per quaternary catchment (GRA II; DWAF, 2004), the registered groundwater use (WARMS) and the spatial distribution of boreholes (NGDB) (see **Figure 2-21**). The results are summarised in **Table 2-9**, indicating that only a small fraction is currently abstracted from the TMG, while more than 50% is taken from the alluvium aquifer. The registered groundwater use (WARMS) is in the same order as the estimates from the Breede River Basin Study (~41 Mm^3/a), while the estimates from the GRA II are ~25% lower (~31 Mm^3/a).

Table 2-9 Estimated groundwater use per aquifer in the Study Domain (after DWAF,2007C)

IWRM Domain	Peninsula Aquifer *Mm^3/a*	Nardouw Aquifer *Mm^3/a*	Other Fractured Aquifers *Mm^3/a*	Intergranular fractured Aquifers *Mm^3/a*	Intergranular Aquifers *Mm^3/a*	**Total Groundwater use** *Mm^3/a*
WARMS	2.28	3.94	0.09	9.29	28.11	43.71
GRA II	6.35	2.77	0.35	7.25	14.47	31.18

Table 2-10 Groundwater use per catchment after (DWAF, 2007e)

Quaternary Catchment	Groundwater Use [Million m^3/a]							
	Total	Rural	Municipal	Agric. Irrigation	Agric. Livestock	Mining	Industry	Aqua
G10C	0.5832	0.0030	0.0000	0.0000	0.0012	0.0000	0.5790	0.0000
G10D	1.7538	0.0040	0.0000	1.3551	0.0262	0.0000	0.2070	0.1615
H10E	0.0017	0.0000	0.0000	0.0000	0.0017	0.0000	0.0000	0.0000
H10F	8.9360	0.0000	0.0000	8.7940	0.0220	0.0000	0.1200	0.0000
H10G	8.4146	0.0000	0.0000	8.4110	0.0036	0.0000	0.0000	0.0000
H10H	1.4186	0.0000	0.0000	1.0500	0.0026	0.0000	0.3660	0.0000
H10J	0.4807	0.0000	0.0000	0.4600	0.0047	0.0000	0.0160	0.0000
H10K	0.3938	0.0000	0.0000	0.3901	0.0037	0.0000	0.0000	0.0000
H10L	2.5953	0.0000	0.1040	2.4170	0.0013	0.0000	0.0730	0.0000
H20G	0.4916	0.0080	0.0000	0.4825	0.0011	0.0000	0.0000	0.0000
H20H	0.7075	0.0000	0.0000	0.4863	0.0012	0.0000	0.2200	0.0000
H40C	4.2137	0.0140	0.0000	4.1960	0.0037	0.0000	0.0000	0.0000
H40D	1.5695	0.0000	0.0000	1.5671	0.0024	0.0000	0.0000	0.0000
H40E	1.6816	0.0000	0.0000	1.6778	0.0038	0.0000	0.0000	0.0000
H40F	1.7010	0.0110	0.0000	1.6801	0.0099	0.0000	0.0000	0.0000
H40G	0.2355	0.0000	0.0000	0.0000	0.0155	0.0000	0.2200	0.0000
H40H	0.0424	0.0070	0.0000	0.0000	0.0104	0.0240	0.0010	0.0000
H40J	0.0193	0.0000	0.0000	0.0000	0.0113	0.0000	0.0080	0.0000
H60C	0.5261	0.0120	0.4682	0.0333	0.0046	0.0000	0.0080	0.0000
H60D	0.0065	0.0020	0.0000	0.0000	0.0045	0.0000	0.0000	0.0000
H60E	0.0297	0.0260	0.0000	0.0000	0.0037	0.0000	0.0000	0.0000
H60F	0.3497	0.0000	0.3428	0.0000	0.0069	0.0000	0.0000	0.0000
H60H	0.0069	0.0000	0.0000	0.0000	0.0069	0.0000	0.0000	0.0000
Total	**36.16**	**0.087**	**0.915**	**33.00**	**0.153**	**0.024**	**1.818**	**0.162**

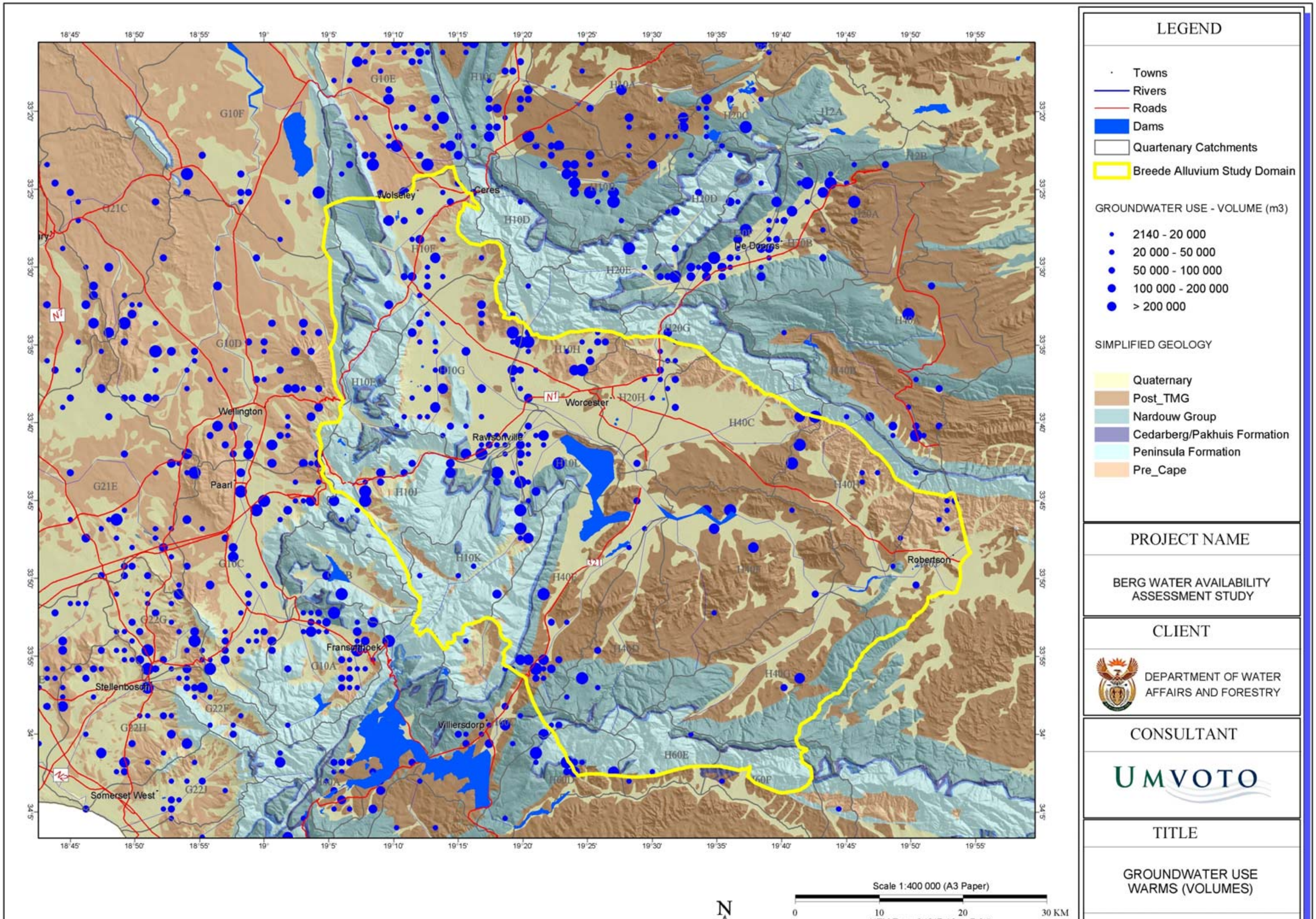

LEGEND
Towns
Rivers
Roads
Dams
Quartenary Catchments
Breede Alluvium Study Domain
GROUNDWATER USE - VOLUME (m3)
2140 - 20 000
20 000 - 50 000
50 000 - 100 000
100 000 - 200 000
> 200 000
SIMPLIFIED GEOLOGY
Quaternary
Post_TMG
Nardouw Group
Cedarberg/Pakhuis Formation
Peninsula Formation
Pre_Cape
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS AND FORESTRY
CONSULTANT
UMVOTO
TITLE
GROUNDWATER USE WARMS (VOLUMES)
Scale 1:400 000 (A3 Paper)
0
10
20
30 KM
N
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E
Wolseley
Ceres
De Doorns
Wellington
Worcester
Rawsonville
Paarl
Robertson
Franschhoek
Stellenbosch
Villiersdorp
Somerset West
G10E
G10F
G21C
G10D
G21E
G10C
G22G
G10A
G22F
G22H
G22J
H10C
H10A
H20C
H12A
H10B
H10D
H20A
H20E
H10E
H10F
H20B
H20G
H40A
H10H
H10G
H20H
H40C
H40B
H10L
H10J
H10K
H40E
H40D
H40G
H60E
H60F

FIGURE 2.21

2.6 WATER QUALITY

Groundwater quality is generally excellent in the TMG sandstones and in other aquifers in proximity to recharge areas. This includes the Upper Breede Valley, the Rawsonville – Goudini area and the Villiersdorp area where the Electric Conductivity (EC) is generally < 70 mS/m (**Figure 2-22**). An area of brackish water is present (EC > 150 mS/m) in the Worcester, Brandwacht and eastern Jan Du Toits areas where the groundwater is not suitable for irrigation. This brackish water is confined to the Uitenhage, Karoo and Malmesbury rocks and, in places, the overlying alluvium.

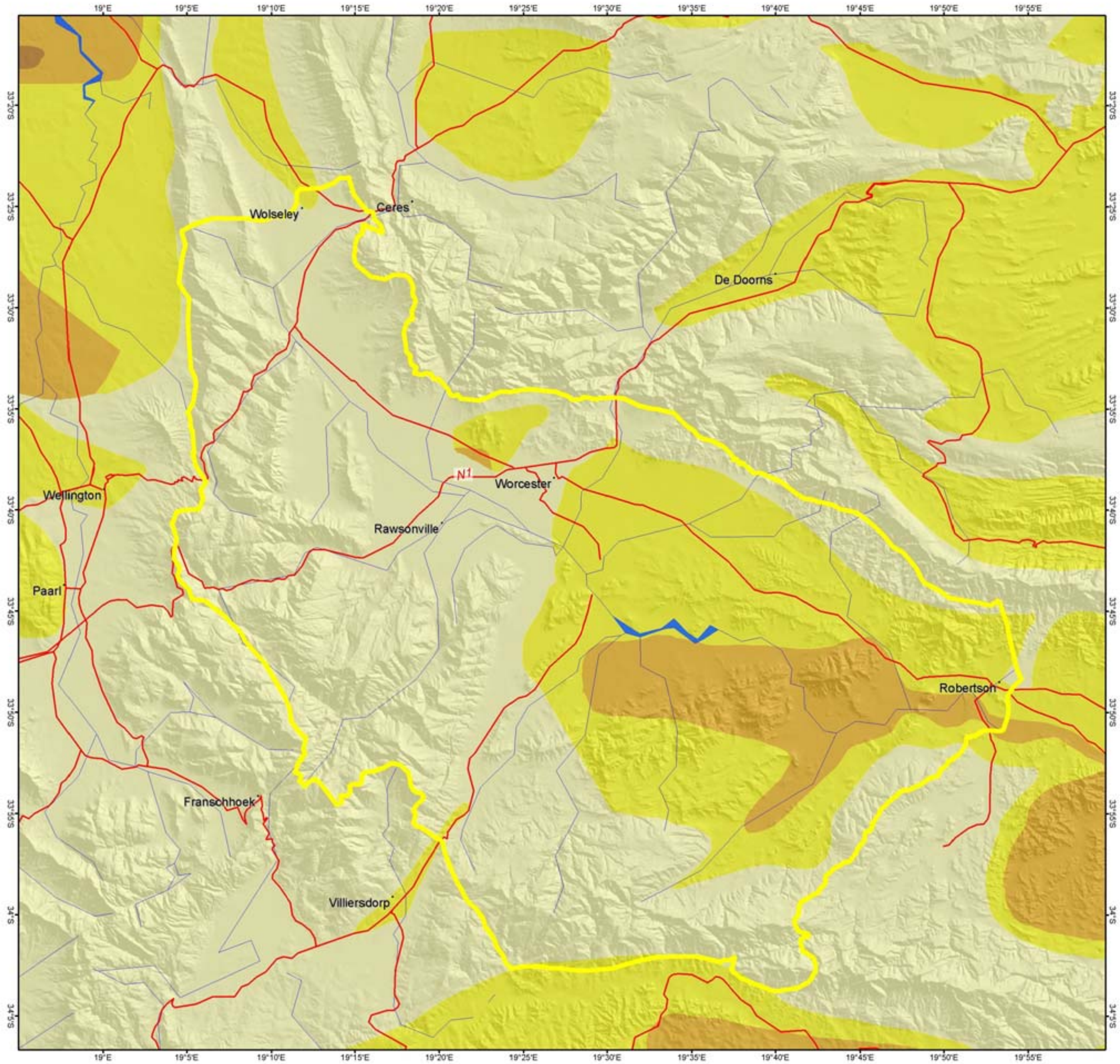
Most TMG boreholes have EC less than 30 mS/m, whereas the greatest number of boreholes in the Bokkeveld Group have EC predominantly in the 70 – 300 mS/m range (DWAF, 2002). In the Upper and Middle Breede basin areas, only 2% of Bokkeveld Group boreholes have EC values above 300 mS/m. Below Robertson, 30% of Bokkeveld Group boreholes have EC above 300 mS/m.

Alluvial groundwater quality changes along the length of the Breede River Valley: the water from the alluvium from Wolseley to Rawsonville being of significantly better quality than in the Robertson area. The salinity (measured as the water's electrical conductivity EC) is less than 30 mS/m between Wolseley and the Greater Brandvlei Dam (Rosewarne, 2002) but around Robertson the EC varies from 600 – 1200 mS/m. The deterioration in the quality of alluvial groundwater is partly due to leaching of salts (primarily Na and Cl) from the Bokkeveld and Karoo Group rocks into the alluvial aquifer.

The alluvial aquifers are vulnerable to pollution and the main source of salinity in the alluvium is thought to originate from return flows from irrigated land, primarily those east of the Greater Brandvlei Dam. Other relevant sources of pollution are the disposal of and irrigation with treated effluent from domestic and industrial waste water treatment plants, e.g. in the Worcester area, which impacts negatively on the water quality in both the Breede River and the alluvium aquifer.

2.7 LANDUSE

The pre-dominant land-use in the catchment is agriculture (see **Figure 2-23**), mainly focussing on the production of fruit and wine. Irrigation occurs along the flatter areas between mountain ranges, particular along river reaches in valleys. Afforestation occurs mainly in the upper Riviersonderend catchment, with small areas of afforestation scattered over the remainder of the catchment. Invasive alien plants are scattered throughout the catchment, with the highest level of infestation occurring in the Riviersonderend and Lower Breede catchments.



LEGEND

Towns
Roads
Rivers
Breede Alluvium Study Domain

GROUNDWATER QUALITY (mS/m)

< 70
70 - 300
300 - 1000
> 1000

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

GROUNDWATER QUALITY (DWAF Hydrogeological Map Series)

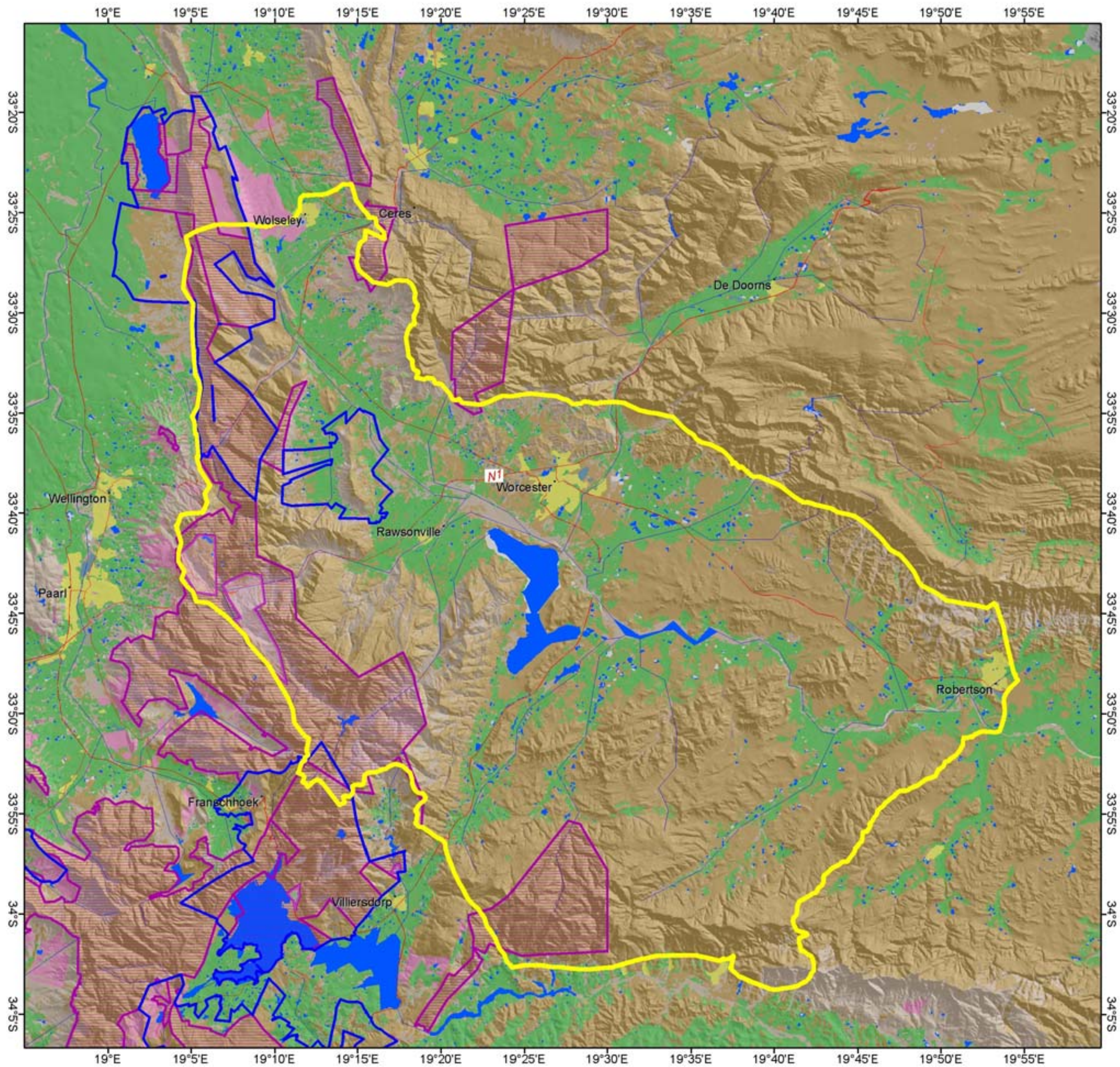
FIGURE 2.22

Scale 1:900 000 (A3 Paper)

N

0 5 10 15 20 KM

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E



Scale 1:400 000 (A3 Paper)

N

0 5 10 15 KM

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Rivers
- Roads
- Dams
- Breede Alluvium Study Domain
- Conservancies
- Nature Reserve

LANDUSE - NLC 2000

- Cultivated, commercial
- Shrubland & Low Fynbos
- Bushland,High Fynbos
- Forest Plantations
- Improved Grassland
- Mines & Quarries
- Built-up residential
- Wetlands

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

LANDUSE (NLC 2000)

FIGURE 2.23

3. CONCEPTUAL MODEL

3.1 MODELLING APPROACH

The focus of this model is the Breede River Alluvium Aquifer (BAA). To understand and conceptualise the groundwater flow into and through this unconfined primary aquifer, it is necessary to understand the relationships with the underlying and surrounding aquifers, especially the TMG aquifers. The TMG discharges via springs into the BAA and also supplies the perennial tributaries with summer and winter flow, hence the need to model both systems for improved water balance results and in particular surface-groundwater exchange fluxes into and out of the Breede catchment in summer and winter.

It was not feasible, given the available data, for this project to include all possible aquifers and aquitards, including weathered zones, of the TMG, the Karoo Group as well as the Breede River alluvium in one numerical model. The model configuration and testing of different mesh designs would be exhaustive and, given the available data, unwarranted. It is possible to calibrate 3 separate aquifers in one model, if appropriately spaced and reliable input and calibration data are available. It can, however, be an unpredictably iterative process, which could not be undertaken within the relatively tight project tight lines. Furthermore the groundwater flow process in the three key aquifers, viz. the Peninsula, the Skurweberg and the BAA aquifers, differ in scale, in aquifer volumes and in character, making a combined model unnecessarily complex. The TMG is unconfined on the Breede Valley walls but confined below the BAA, while the BAA itself is unconfined to semi- and confined as the percentage and thickness of clay and finer sediment horizons varies laterally and vertically.

The hydrostratigraphic relationship between these aquifers is shown in

Table 3-1 and the complex hydraulic connections that define the spatial and temporal scale of the processes to be modelled for the Alluvium Aquifer, is illustrated in two dimensions in **Figure 3-4**. The different stratigraphic layers are represented as discreet layers in a numerical model, each layer having the physically correct thickness and volume. The large differences in depth, aerial extent and implied volume between all the aquifers are evident in **Figure 3-4**. It is clear that the scale of the processes to be modelled would range between 5-10 years and possibly 1 000 years.

The decision to develop the BAA model in discreet steps was taken. A separate model was developed for the Brandvlei hot spring to understand the factors driving flow and discharge in the TMG, the use of temperature measurements as a potential calibration tool and to estimate the hydraulic properties for the TMG aquifers. Being outside the scope of work, the model was undertaken in-house by Umvoto.

The model set up and results are contained in some detail in Appendix 1. Key elements that impact significantly on the boundary conditions selected for the BAA model are summarised below under the Section 3.2 (Conceptual Understanding of Flow Systems in the TMG). Thereafter follows a detailed discussion of the model assumptions that underpin the BAA model itself. Both models use the Groundwater Vistas software with the quasi-three dimensional Finite Difference (FD) Modflow code.

Table 3-1 Coincident hydrostratigraphic units and TMG model layers

<table>
<tr><th>Superunits</th><th>Units</th><th>Subunits</th><th colspan="2">Model Layers</th></tr>
<tr><td></td><td>Breede Alluvium Aquifer
(10 – 75 m thick)</td><td>Various discrete alluvial aquifers</td><td>Alluvium Aquifer</td><td>1</td></tr>
<tr><td></td><td>Gydo Mega-aquitard</td><td></td><td rowspan="3">Karoo / Bokkeveld Aquitard</td><td rowspan="3">2</td></tr>
<tr><td rowspan="10">Table Mountain Superaquifer</td><td rowspan="3">Nardouw Aquifer</td><td>Rietvlei Subaquifer</td></tr>
<tr><td>Verlorenvalley Mini-aquitard</td></tr>
<tr><td>Skurweberg Subaquifer</td><td>Skurweberg Aquifer</td><td>3</td></tr>
<tr><td rowspan="3">Winterhoek Mega-aquitard</td><td>Goudini Meso-aquitard</td><td rowspan="3">Winterhoek Mega-aquitard</td><td rowspan="3">4</td></tr>
<tr><td>Cedarberg Meso-aquitard</td></tr>
<tr><td>Pakhuis Mini-aquitard</td></tr>
<tr><td rowspan="2">Peninsula Aquifer</td><td>Platteklip Subaquifer ?</td><td rowspan="2">Peninsula Aquifer</td><td rowspan="2">5</td></tr>
<tr><td>Leeukop Subaquifer ?</td></tr>
<tr><td></td><td>Graafwater Meso-aquitard</td><td rowspan="2">N/a</td><td rowspan="2"></td></tr>
<tr><td></td><td>Piekenierskloof Subaquifer (localized)</td></tr>
<tr><td></td><td>Aquicludes</td><td>[Klipheuwel Group]
[Malmesbury Group]
[Cape Granite Suite]</td><td>Basement (impermeable boundary)</td><td>Base</td></tr>
</table>

3.2 CONCEPTUAL UNDERSTANDING OF GROUNDWATER FLOW SYSTEM IN THE TMG

3.2.1 General flow in the TMG

The TMG aquifers are recharged both north and south of the Breede River Valley. On the southern side they are recharged in the high mountainous areas of the Hawequas Mountains in the west and south-west of the model domain. The Hawequas mountains comprise a number of different ranges but it is the Limiet, Slanghoek and the duToits mountains whose rivers drain into the Breede Valley and which form the southern valley sides.

Further south are the Riviersonderend mountains, whose northern slopes drain into the eastern end of the valley via the Poesjeneisrivier. The lower lying mountains between the Riviersonderend mountains and the Breede River itself are known as the Ouhags mountains. Between the Riviersonderend and the Hawequas mountains is a narrow north-south valley in which the Modder River flows north, joining the Breede just below the Greater Brandvlei Dam.

On the northern side of the Breede River Valley the TMG aquifers are recharged by rainfall in the Hex River, Kwadous Mountain and at the eastern end the Lange mountains. However the

Worcester Fault is considered an impermeable boundary in the TMG model concept and this recharge is not considered in the mass balance of the Brandvlei hot spring model, as groundwater cannot flow from the unconfined portions of the aquifers north of the fault to the confined portions to the south.

However, the unconfined aquifers do reject recharge on the southern slopes of these mountains and there are perennial springs discharging from the confined Peninsula aquifer that feeds the tributaries that flow southwards into the BAA and Breede River itself. Thus these TMG aquifers are considered in the BAA model.

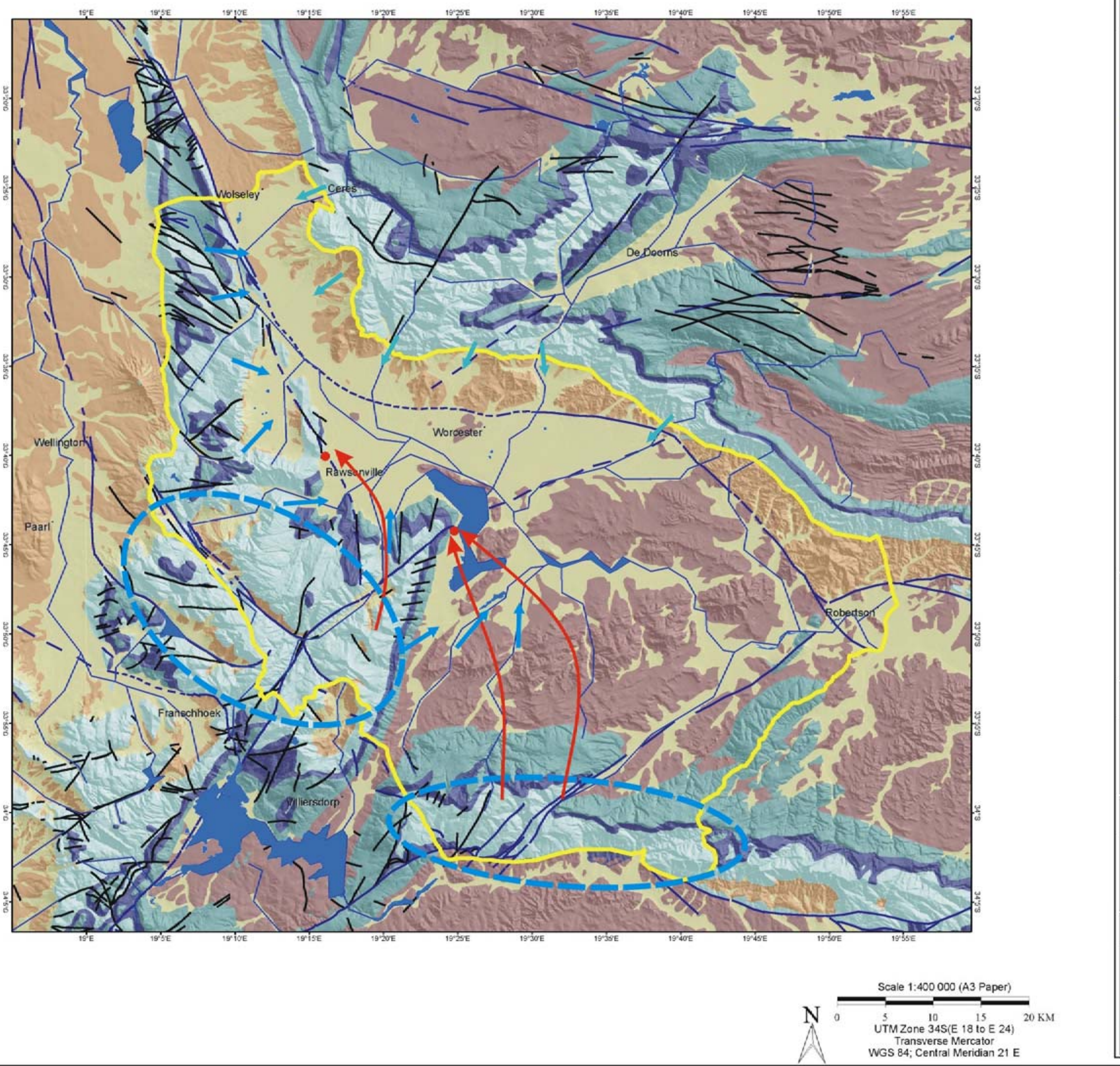
The perennial rivers that flow into the BAA and also to the Breede River, are fed by springs discharging from the confined Peninsula aquifer as well as more seasonal springs discharging from the unconfined Peninsula and Skurweberg aquifers. Some of these rivers discharge to alluvial fans (section 2.4.3), some are not associated with fan development and discharge straight to the Breede River. The alluvial fans play a significant role in the overall interaction between surface and groundwater patterns as well as comprising significant available aquifer storage.

As described in the Regional Conceptual Model Report (Volume 3 (DWAF, 2007b)) and shown in **Figure 1-3** the general groundwater flow within the TMG aquifers is directed both towards springs and streams in the mountainous areas and along the major fault zones towards the Worcester Fault. The Worcester Fault is considered part of a hydrotect (i.e. Tulbagh Road / Worcester Megafault), along which groundwater flows over long distances northwestwards, i.e. it is both a preferred flow path for groundwater flowing along the strike, but a hydraulic barrier to groundwater flowing perpendicular to it.

The purpose of the Brandvlei Numerical Model is:

- to understand preferred TMG flow paths orientated along the hydraulically conductive structural features that dominate flow in the TMG aquifers discharged at the Brandvlei hot spring;
- to support reasonable assumptions being made in the BAA model with respect to discharge from TMG to perennial springs, which discharge to the BAA;
- to establish reasonable and calibrated hydraulic parameters for the TMG that could be used as BAA model input and relevant to the region; and
- to test different model assumptions about TMG flow prior to simplifying the flow patterns and interaction with the BAA in that model.

The groundwater flow that results in the Brandvlei and Goudini hot springs are complex and arise from groundwater moving in the deep confined Peninsula and Skurweberg aquifers below the rocks of the Bokkeveld and Witteberg groups in the Villiersdorp Syncline. Key elements of the model developed to better understand the flow paths and heat flow patterns and the impact on our understanding of the Breede Alluvium is next addressed more specifically.



PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

TMG CONCEPTUAL FLOW MODEL

FIGURE 3.1

3.2.2 Brandvlei Numerical Model

In order to understand the potential interactions between the TMG aquifers and the BAA and especially the fluxes from the TMG to the BAA, and to test prevailing and alternative concepts as to why the Brandvlei hot spring is where it is, a groundwater flow model of the Brandvlei hot spring was undertaken by Grant (2007) supervised by Dr Chris Hartnady of Umvoto and Dr Rae Mackay of Birmingham University, UK.

In the Brandvlei Model only the most relevant units are modelled as separate layers and the other units are combined together and assigned averaged values representing the average hydraulic properties of the whole unit (see

Table 3-1). The actual model boundaries are defined by key regional structures but the orientation is roughly perpendicular to facilitate mesh generation and the use of the FD code (see **Figure 3-1**). The regional structures are modelled as No Flow boundaries and the model dimension is very close to the study area dimensions, as are the aquifer dimensions.

Figure 3-2 describes the translation of the conceptual model of flow around the Greater Brandvlei Dam into the numerical model. The model consists of four layers representing the Peninsula Formation, the Winterhoek Aquitard, the Nardouw Aquifer and the overlying confining sediments (lumping layers 1 and 2 from

Table 3-1). The layers dip towards the Worcester Fault, which constitutes the no-flow northern model boundary. The groundwater flow in the Peninsula Aquifer originates from recharge in the Riviersonderend mountains at the southern model boundary (see **Figure 3-2**).

The Brandvlei Fault extends towards the Worcester Fault in the north and is considered both a flow barrier of low permeability and a preferred flow path with a zone of high permeability along the fault.

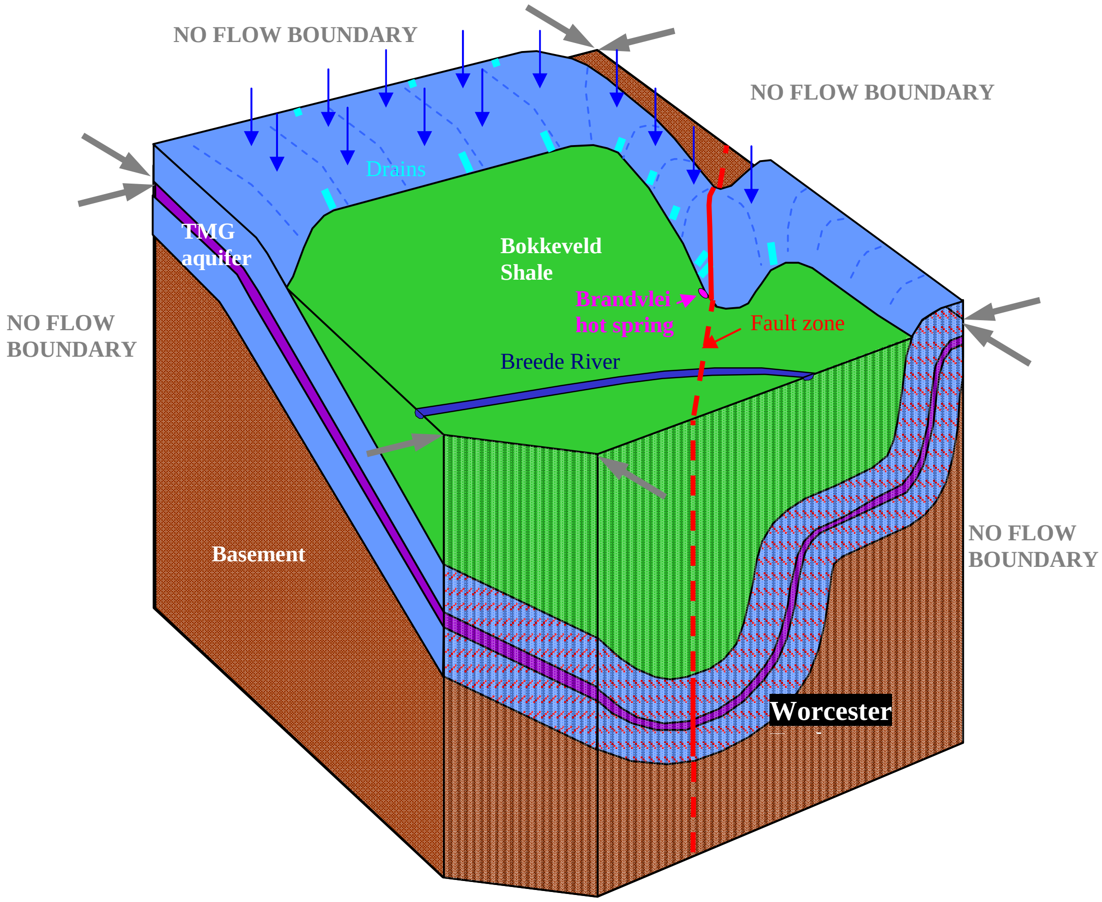


Figure 3-2 Translation of the conceptual model for the Brandvlei hot spring into model conditions (Grant, 2007)

It is considered likely that the structure of the Brandvlei hot spring is similar to the “Pipe Model” type described by Donaldson (1982), where cool water infiltrates to depth through cracks and fractures, is heated in an extensive fracture system and rises to the surface through a single fracture due to head differences between the deep hot water and the cold surface water (Diamond, 1997). Although this system has generally been considered for geothermal waters of magmatic origin, it is applicable in a modified form to deep circulation in non-volcanic fractured rock settings (Manga, 2001).

The detailed results of the Brandvlei model, developed using Modpath software, are given in **Appendix 1.** Elements that are input or used in development of the Breede Alluvium model are summarised below. The flow rate calculated by Modpath indicates that the water takes approximately 400 years to travel through the aquifer to the Brandvlei hot spring, which is similar to that estimated from the mass balance calculations (375 years). The catchment area for the spring is approximately 280 km^2, which is similar to the value obtained from the mass balance calculations and the thermal modelling (300 km^2). Most significantly the TMG model showed that discharge from the TMG to the drains (corresponding to spring/surface discharge) is relatively insensitive to recharge. Therefore, over the short time scales in question for the Breede Alluvium model (i.e. <100’s years not 10,000 yrs), the TMG could be considered a constant input to the Breede Alluvium model.

The modelling showed that recharge over the Riviersonderend Mountains to the south flows down through the synclinal Peninsula Aquifer until it encounters the fault zone, where it is deflected along the high permeability fracture zone (see

Figure 3-3). The water is likely to migrate to the top of the Peninsula Formation where it will be contained by the low permeability Cedarberg Shales.

The water must rise up rapidly through the Cedarberg Shales and overlying quartzite formations to discharge at such high temperatures. This suggests that there is a fault in the vicinity of the Brandvlei hot spring, which provides a pathway through the aquitard. However, the inspection of the surface geology in the area gave no indication of the presence of a fault (Grant, 2007). The nearby northwest-southeast trending normal faults are near vertical and as such are unlikely to pass to the south of the spring at depth.

The main fault zone passes to the south of the spring, so it is possible that there will be further north-south trending reverse faults, approximately paralleling those seen in the area. This is suggested by the topography along the eastern edge of the Brandvlei mountain range, but any possible direct evidence for this is concealed by the prison development. Although it remains unclear as to why Brandvlei hot spring exists precisely at this location, it is suggested that the heated groundwater encounters a break in the Cedarberg Shales, due to faulting, where it rises rapidly to the surface due to density and head differences through one of the northwest - southeast trending fractures, that are common in this area.

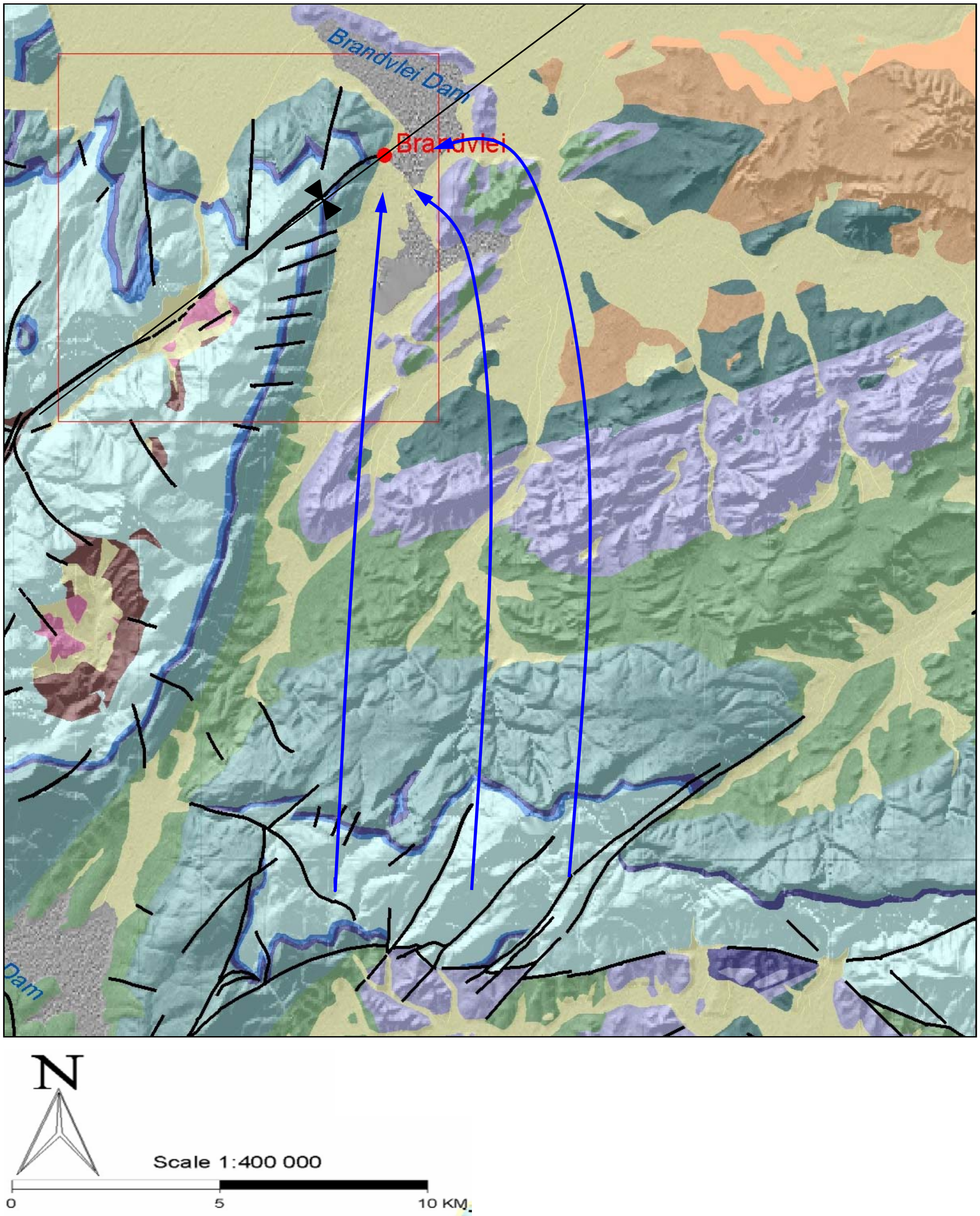


Figure 3-3 Suggested flow paths to the Brandvlei hot spring (Grant, 2007)

Based on these model results the conceptual model of the Breede Alluvium Aquifer was refined.

There are three major processes of groundwater discharge from the unconfined and confined TMG aquifers into the Breede River Alluvium, viz.

- discharge into mountain streams out of the unconfined TMG (short flow path),
- discharge of deep groundwater at hot springs out of the confined TMG (long flow path),
- direct lateral discharge subsurface into the Breede Alluvium Aquifer (unconfined).

3.3 CONCEPTUAL UNDERSTANDING OF GROUNDWATER FLOW SYSTEM IN ALLUVIUM

The BAA comprises a complex sedimentary sequence that varies vertically, laterally and downstream. In the Upper Breede the BAA is likely to have a coarsening upwards sequence. The Breede River starts to meander more below the Greater Brandvlei Dam, indicating an increase in variation of grain size of the fluvial sediments and most probably a decrease in hydraulic conductivity of the river bed sediments. It is assumed that there will be an increasing percentage of fine sediments as the river flows eastwards given the change in provenance of the bed load and that the river eroded through the Karoo Group valley infill over time. This would result in a more variable vertical sequence with more complex patterns of lateral hydraulic connectivity.

The flow pattern in the BAA is complex due to the varying geomorphological units present in the Breede River Alluvium (see **Figure 2-12**) and the lateral interactions with the surrounding fractured rock aquifers. The groundwater flow pattern can be divided into three distinct flux elements, described separately below:

- The lateral inflow mountain streams and underlying aquifers, situated at the edges of the alluvium, especially at the fans,
- The flow pattern within the alluvial fans from the fan head towards the fan bottom, and
- The discharge into the Breede River.

3.3.1 TMG Inflow

The Reserve Determination for the Breede River, undertaken as part of the Breede River Basin Study (DWAF, 2002), states that "baseflow from the TMG aquifers recharge the alluvial aquifer in the Breede River valley, from which the bulk of groundwater abstraction occurs." This statement refers to the TMG-fed perennial mountain streams flowing into and over the alluvial fans, mainly originating in the Haweqwas and Hex River mountain ranges, where part of the stream flow infiltrates the subsurface and recharges the aquifer.

The TMG also underlies the Breede River Alluvium in the areas between the western and south-western mountain ranges, i.e. the Slanghoek and Haweqwas mountains (see **Figure 2-15**). A direct contact of the two aquifers exists in these areas, allowing discharge from the TMG aquifers into the Alluvium along preferred flow paths. However, the actual area over which there is direct contact is considered to be minimal (as represented in **Figure 3-4**). Elsewhere the BAA is primarily underlain by impermeable Bokkeveld through which water from the confined TMG is not expected to reach the alluvium.

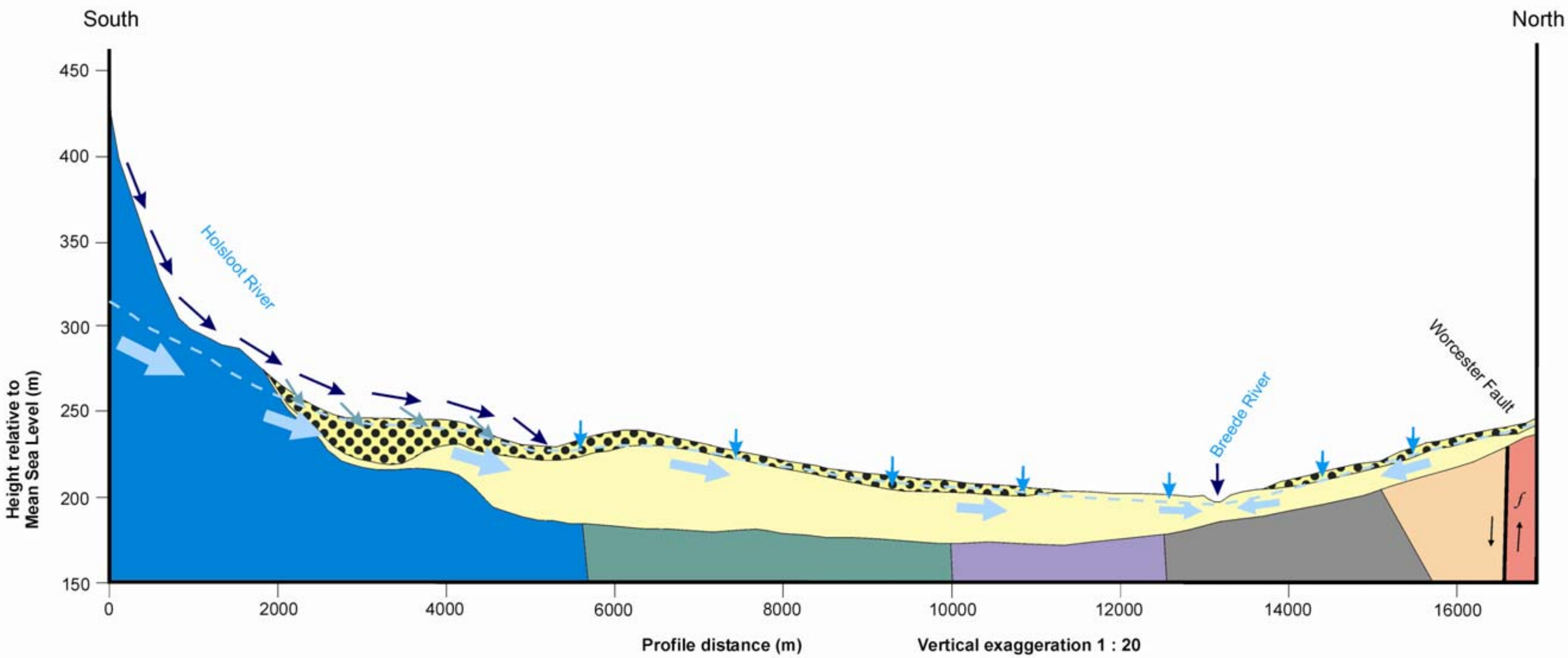
3.3.2 Flow within Alluvium and discharge to the Breede

Once the water from mountain streams or directly from the TMG aquifers along the valley walls enters the Alluvium, the groundwater table parallels the topographic gradient and follows the preferred flow paths in the alluvial fans to flow down gradient towards the Breede River (see **Figure 3-4**). The hydraulic gradient in the Breede River Alluvium is considerably flatter than in the TMG aquifers, with the break of slope most probably at the elevation of the alluvial fan head.

The tributaries to the Breede River are considered a source of water for the aquifer, and it is assumed they become influent close to their confluence with the Breede River where the topographic slope shallows and beyond the extent of the coarse boulder deposits. The Breede River itself is assumed to be an effluent river after the Michell's Pass, becoming influent again only at the confluence with the Wabooms River, especially in the middle and lower reaches of the model domain (**Figure 3-5**).

In summary, relevant fluxes of water to the alluvial groundwater system are TMG-fed springs entering the fan heads, flow from the TMG in direct contact with the alluvium in these positions, and recharge. Significant discharge processes include discharge along the Breede River and also to tributaries close to the Breede River.

In order to translate the complex surface and groundwater flow system described above over a large area into a robust numerical model that can be used for first order water resource planning purposes, it is necessary to make simplifying assumptions without losing physical reality. These are motivated and summarised in the next section.



LEGEND

- Direction of river flow
- Gravel bed recharged by surface river flow
- Alluvium recharged by rainfall (vertical recharge)
- Potentiometric surface
- Direction of groundwater flow

GEOLOGY

- Fault
- Boulder and gravel layer
- Alluvial sand
- Enon Formation
- Karoo Supergroup
- Witteberg Group
- Bokkeveld Group
- Table Mountain Group
- Malmesbury Group

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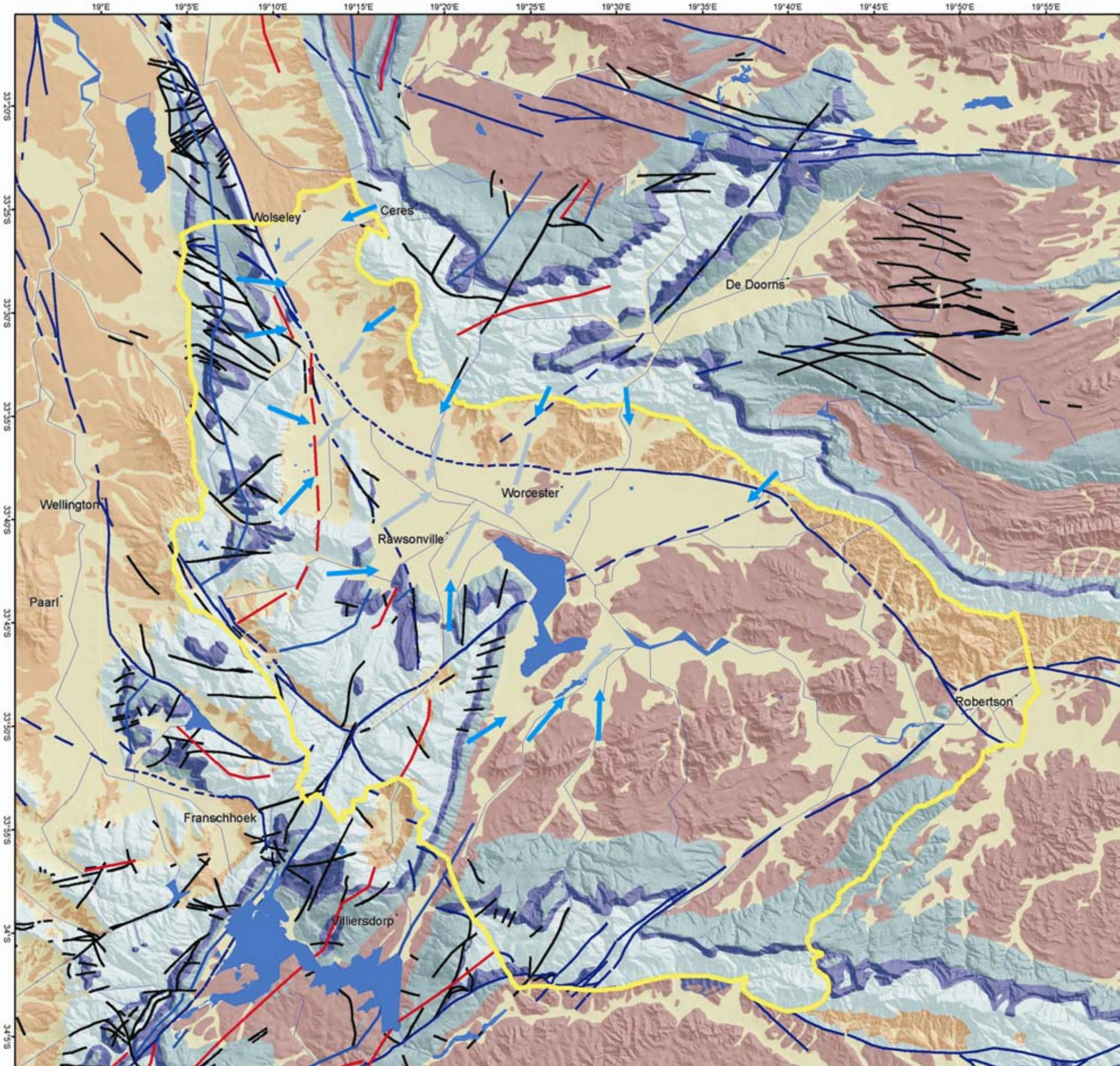
CONCEPTUAL CROSS SECTION MODEL OF GROUNDWATER FLOW IN ALLUVIAL FANS

FIGURE 3.4



Scale 1:400 000 (A3 Paper)

0 5 10 15 20 KM

N

UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E

LEGEND

- Towns
- Faults
- Hydrotects
- Anticline
- Syncline
- Dams
- Breede Alluvium Study Domain

AQUIFER TYPES

- Alluvium Aquifer
- Gydo Mega-aquitard
- Nardouw Aquifer
- Winterhoek Mega-aquitard
- Peninsula Aquifer
- Basement Aquiclude

- Recharge at alluvial fan heads
- Discharge into the Breede River

PROJECT NAME

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ALLUVIUM CONCEPTUAL FLOW MODEL

FIGURE 3.5

3.4 TRANSLATION INTO BREEDE RIVER ALLUVIUM NUMERICAL MODEL

Translation of a conceptual model into a numerical model involves mesh design as well as allocation of different parameters that mathematically determine groundwater direction and rate of movement and the rate and location of surface and groundwater flux exchange. The numerical model is described below with a focus on the model boundaries and representation of fluxes with boundary conditions. Other features of the modelling, for example the representation of the Breede River as a 'transfer boundary', and the input data for model layering, are described further in Section 4.

3.4.1 Model boundary: No-flow boundary condition

The model boundary on all sides is based on the 10 m alluvium thickness contour (**Figure 3-6**). The 10 m contour dictates that the model ends just south of the Greater Brandvlei Dam.

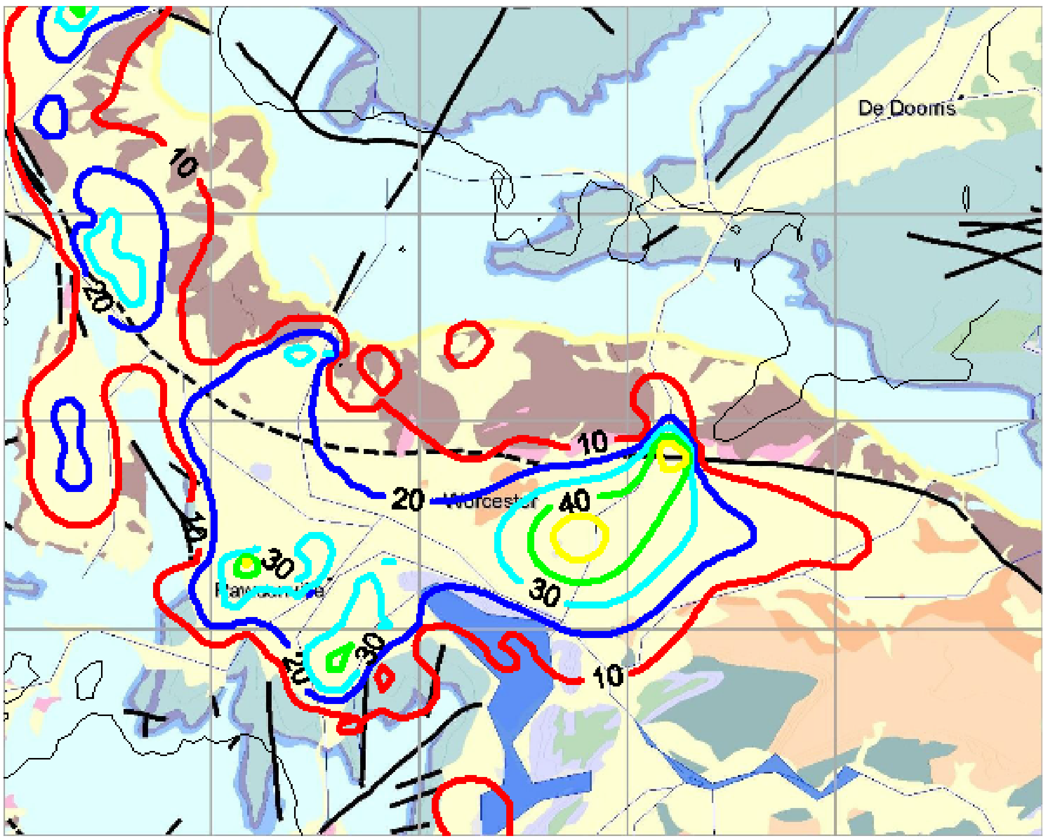

Figure 3-6 Thickness of the Breede River Alluvium Aquifer (after Van Zyl et al, 1981)

***Similar to Figure 2-14 this figure is shown again here so that other data referring to the model boundary (e.g section 6.2) has reference*.**

The assumptions are:

- groundwater flowing in alluvium thinner than 10 m is irrelevant to the regional flow regime;
- the 10 m contour is a no-flow boundary
- any water crossing the boundary is accommodated in the surface water boundary condition or is included in the surface flux, e.g. water entering the model from the north via the Slanghoek and Hartbees rivers are accommodated by defining constant head at the point

where these rivers transect the boundaries at the start of these rivers, and any groundwater exiting the model is considered surface water

The 10 m thickness contour, detailed by Van Zyl et al (1981) and arising from that geophysical investigation, is smoothed to generate the model boundary. The NGDB geology data is useful as point data information, but due to the heterogeneity inherent in any fluvial geology system, the geophysics is more relevant on a regional scale.

3.4.2 TMG-fed tributaries: Constant head boundary conditions

A 'constant head' boundary condition is a point at which the groundwater level is specified (in mamsl). It is set as a constant, and therefore can act as a source or a sink to the groundwater in the model, depending on the difference between the calculated model head and the specified 'constant head'. The difference then between a 'constant head' and a transfer or river boundary condition, is that there is a conductance term in a transfer boundary which represents the resistance for the discharge through bed sediments to a surface water system.

The point at which the TMG-fed springs enter the alluvial fan is replicated with a constant head. The assumption is that the springs recharge the aquifer before they recharge the tributary. i.e. if the water table in the fan is not at ground level, the river does not run. Representation with a constant head also assumes that the discharge from the TMG is a continual source to the alluvium, as suggested in the Brandvlei TMG model.

3.4.3 Internal rivers: River boundary conditions

The lateral tributaries draining into the Breede River Alluvium are modelled as rivers from the edge of the alluvial fans. This allows them to gain water from the aquifer, acting as a sink to the aquifer or to lose water to the aquifer if the groundwater table declines. The assumption is that the boulder layer defined by Van Zyl et al (1981) is the edge of the alluvial fan.

The Breede River itself is modeled as a river. It is replicated in the model at and downstream of the confluence with Wit River, that is where it flows in the centre of the valley. North of this the Breede River detours from the main river valley to flow over thin alluvium of negligible thickness to the west of the Kleinberg Mountains (**Figure 2-2**). A constant head source is used at the point at which the Breede River exits from this detour out of the main valley and it is assumed that this accounts for surface water flow to the north.

The piezometric map for the alluvium shows that flow in the narrow northern arm of the model is south-and southwestwards. The Breede River itself is modeled as a river from the point at which the flow changes towards the southeast. The pattern suggests that north of this point there are groundwater sinks along the western wall of the valley. Constant heads were defined along the western boundary instead of using the river package. This is consistent with the model boundary assumption that all groundwater flow and surface water flow is simultaneous and within the river itself at the boundaries, i.e. the groundwater elevation is the same the surface water elevation.

3.4.4 Long term hydraulic behaviour of the Breede River Alluvium Aquifer

It is assumed that the regional natural drawdown of the water table, through seasonal fluctuations, is not more than 35 m. The data available for the past 50 years, although not all time-series data, indicates that the minimum and maximum seasonal variability in the aquifer is up to ~5 m. The BAA is no thinner than 10 m in the model. To facilitate convergence, the model does not allow the water table to drop below half the thickness of the model. This was done by setting the second and third model layers as confined, without also introducing a confining layer of nominal hydraulic conductivity. This is a known model trick as FD models for confined behaviour are more stable. It also requires that in the confined aquifer parameters of specific storage is used in model calibration. Although alluvial aquifers are often considered simply unconfined, Rosewarne (1981) suggested that the Breede River Alluvium was semi-confined to confined (section 4.3.1).

4. MODEL INPUT DATA

The source and relevant metadata of all model input is either documented in Volume 2 of this report (DWAF, 2007a) or is obtained by geological or hydrogeological inference in which case it is detailed below or referenced to Volume 3 (DWAF, 2007b). Other data input is based on previous work or text book values and used as starter input data during calibration or to bracket a realistic range of values accepted as calibrated. It is critical that the data available as input or against which to calibrate the model is pertinent to the scale of the groundwater flow process being modelled.

4.1 REQUIRED INPUT DATA

A numerical groundwater model requires data for:

- Coordinates of the model boundaries;
- Top and bottom model surfaces;
- Internal aquifer geometry, defined by the hydrostratigraphy;
- Definition of all sources and sinks of water to the aquifer, including recharge and abstraction;
- Hydraulic properties and specific storage;
- River geometry and surface water elevation; and
- Calibration data are actual field water level measurements and or flow measurements but can also be inferred piezometric trends based on groundwater elevation, spring elevations and available empirical information.

Table 4-1 Summary of required input parameters

Model Input Parameter	Source	Type
Topography	20 m and 100 m DEM	Fixed
Bedrock topography	Literature and NGDB	Fixed
Layering	Based on geology and numerical requirements	Fixed
Hydraulic conductivity	1^{st} approx from typical literature values	Calibration in Alluvium model
Storage	1^{st} approx from typical literature values	Transient Calibration
Porosity	Typical literature values	Assumed from storage parameters
Recharge	BRBS method modified	Fixed for models, varied in scenario testing
Abstraction	WARMS	Fixed for steady state calibration, varied in scenario testing
River stages	Assumption based on data	Fixed
Conductance	Assumption based on data	Calibration

4.2 MODEL GEOMETRY

The model geometry is defined by the mesh and can have a significant impact on the model results. It is preferable to have the model geometry reflect the geological and hydrogeological realities, spatial relationships and volumes of different model layers as flow path lengths are implicit in modelling the scale of numerous processes. The issue of scale and dimension are resolved at the conceptual model stage but need to be rigorously considered during model configuration and are often an ongoing aspect of model upgrade.

4.2.1 Topography

A 100 x 100 m DEM was used to construct the model surface topography. In the GIS software TNT MIPS, a grid file containing point data for each cell of the DEM was created. The point data, because it is based on a 100 x 100 m grid, is denser than the model mesh. The data is automatically smoothed using the model software. This data was smoothed using the nearest neighbour inverse distance weighting method, which assigned an elevation value in mamsl to the centre of each model cell.

DEM data is available for the area at 20 x 20 m scale. This scale of information is used in converting measurements from depth below collar to mamsl (e.g. for NGDB water levels and for geology logs). However it cannot be used to assign elevations as the resultant files are too large to import into the model using XL. The 100 x 100 m is therefore used in the model for ease of data manipulation and because it is adequate for the modelling purposes.

4.2.2 Thickness of the alluvium

The thickness contours of Van Zyl et al, (1981) was used as alluvium thickness. The contours were digitised and based on the thickness and the topography, a surface generated for the base of the alluvium.

4.2.3 Internal Geometry

The aquifer is represented in the numerical model with 3 layers. The basal layer is 0.5 m thick simply in order to manage model software constraints. The remaining thickness of alluvium is split in half for the upper 2 layers.

4.3 AQUIFER HYDRAULIC PROPERTIES

4.3.1 Hydraulic conductivity

The Hex River alluvial system (Rosewarne, 1981) has transmissivity of from 20 – 280 m^2/day. The hydraulic conductivity is initially set at 10 m/d in all directions (isotropic) and varied in calibration.

4.3.2 Storage properties

The volume of water released through gravity drainage, per unit decline in head in an unconfined aquifer, is the specific yield (dimensionless). Water is also released elastically through this volume but is much less, and is known as the specific storativity (Ss) [L^{-1}]. The normal range of specific yield in an unconfined aquifer is from 0.01 – 0.30 (Hiscock, 2005). The Storage Coefficient (a common term in some texts) is the Ss multiplied by the aquifer thickness (dimensionless) for a confined aquifer and Sy for an unconfined aquifer.

A confined aquifer does not dewater, there is no gravity drainage and therefore the aquifer does not have a specific yield. Because of the lack of dewatering, the changes in pressure in the confined aquifer force more water to be released from elastic storage and therefore the specific storativity (elastic storage) is important.

Rosewarne (1981) reports that the alluvium in the Hex River has a storage coefficient of 1 E^{-1} to 1 E^{-3} (10% - 0.1%). He states that the alluvial aquifer in the Rawsonville – Goudini area has been defined as semi-confined with delayed yields but in upper parts of the catchment has confined conditions due to clay layers. The aquifer reportedly has a specific yield 1% – 5% and average transmissivity of 285 m^2/day.

In agreement with typical literature values the specific yield was assigned to 0.2 and the specific storage to 1 E^{-4} m^{-1} for all layers.

4.3.3 Porosity

Typical porosity for fluvial alluvium varies from 0.05 – 0.35 (Hiscock, 2005). The porosity affects only the speed of groundwater flow (important in particle tracking and contamination problems), and is required when calculating stored yield. The porosity can be assumed to be similar to the specific yield, if it is assumed that all stored water can be yielded.

4.4 SOURCES AND SINKS

4.4.1 Recharge

The recharge for the area calculated with the BRBS method (DWAF, 2002) is shown in **Figure 2-19**. This method is based on rainfall and geology and takes no account of the land use (the method is described in more detail in Volume 4 of this report, (DWAF 2007c). As with the other model reports the BRBS method is applied. For the alluvium model the recharge sums to 23 Mm^3/annum, equivalent to 47 mm. There are five defined ranges of recharge using constant intervals. The distribution of these zones is illustrated in Fig 4-1.

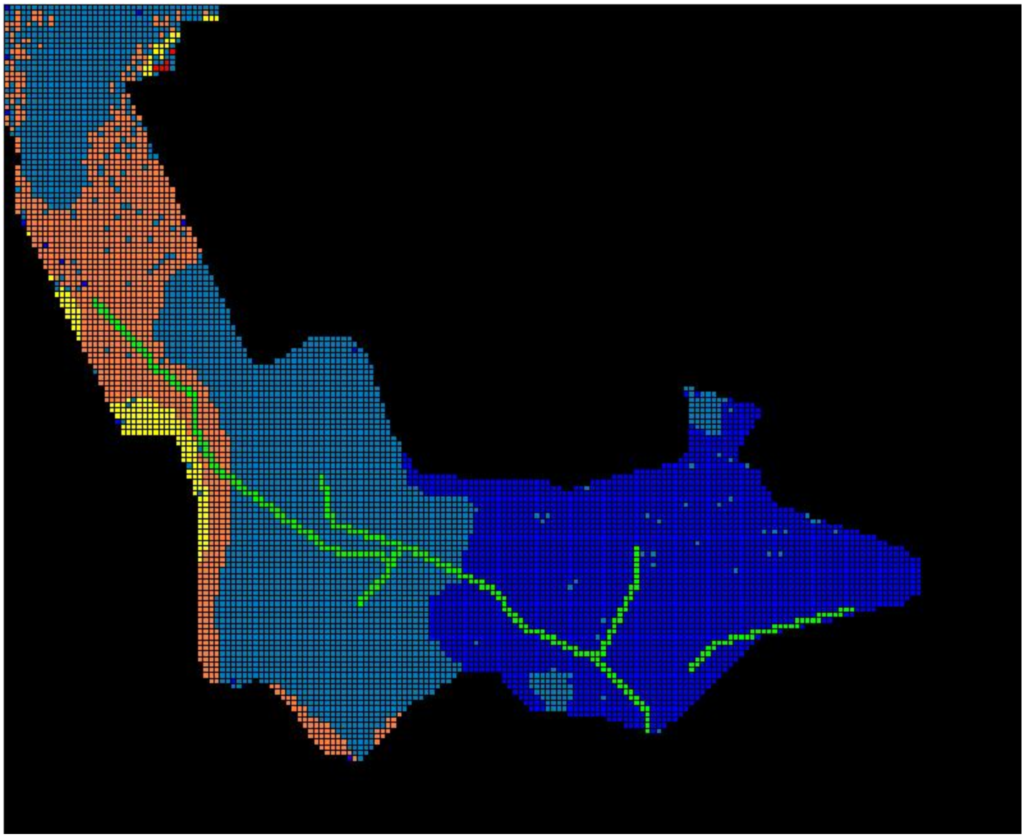

Figure 4-1 Recharge zones in the Breede River alluvium model

Zones are based on constant intervals, dark blue is the lowest, to light blue, orange, yellow and red the highest.

Monthly rainfall is entered per zone for the transient alluvium model. This variability is based on rain gauge data from within the model area – the Greater Brandvlei Dam and Worcester gauges as shown in **Figure 2-3** (the Rawsonville gauge is actually beyond the model domain). An average variability from mean was calculated and this applied to the value for each recharge zone.

4.4.2 Abstractions

The current abstraction in the area, as given by WARMS, is shown in **Figure 2-21**. In accordance with the other groundwater models in this project, the WARMS data is used as input to the model. Although it records registered use and not actual use, it is deemed the best available data source for groundwater use in this project (Volume 2 of this report, (DWAF 2007a). The registered abstraction for the alluvium model is 18 Mm^3/annum, which is ~80% of the recharge. This model is concerned with the effect of the current abstraction on the regional flow regime and water levels, not on predicting drawdowns at a specific position. For the best prediction of this, and because the WARMS data suggests such a large proportion is abstraction, the model was set up as a naturalised system, with zero abstraction. The effect of the abstraction is then investigated as a scenario (section 6.7.4). The model is a regional representation of the system and the abstraction was input in the scenario as net recharge. The model is not intended to be accurate at a local scale.

4.4.3 Rivers

The River Package enters a source or sink of water to the selected element based on a simple Darcy calculation between the head in the aquifer beneath the river (H_A) and the river stage (H_S), and the conductance (K/B), as follows:

$Q = K/B \times A \times (H_A - H_s)$

Where;

Q = flow [L^3T^{-1}],

K = hydraulic conductivity of bed sediments [LT^{-1}],

B = bed thickness [L]

A =cross sectional area of flow [L] (width x length river in cell)

HA =

H5 =

The following rivers are represented as internal boundary conditions; the Breede River downstream of the Wit River, lower reaches of the Hex, Jan du Toit, Molenaars, Nuy, Slanghoek, Holsloot, and Wabooms rivers. The positions of the river boundary conditions are based on the conceptual model of how spring flow-recharge the alluvial fans (see Section 3.4). The widths of the river lengths are taken from Google Earth (1:30m).

It is assumed that the Papenkuils Wetland between the Breede and Holsloot rivers convergence (northwest of the Greater Brandvlei Dam) is appropriately captured with a river line at 180 m width. This is the maximum measured width; it drops to 130 m in places. But using the maximum is assumed to account for the wetland areas. It is assumed that drainage towards the Molenaars and Holsloot rivers can be represented by one river line. In reality, in the downstream section where the river is assumed to be a sink to the groundwater, the two rivers are separated by 350 – 600 m distance, which is comparable to the width of 1 model cell. To avoid convergence problems, the two rivers were combined. As a result, the groundwater flow divide between these rivers is not represented in this mesh. A significantly finer mesh would be needed.

The model topography along river reaches was plotted. The lowest elevations in the relevant cells were assumed to be the base of the river and these were connected together to define a river profile. The data was checked against 1:50 000 topographic maps to ensure physical reality. The river stage was assumed to be 5m below the average smoothed topography.

4.4.4 Constant-head boundary conditions

The rivers fed by perennial TMG springs are replicated with constant heads at the points where they cross from the TMG to flow over the alluvium (i.e. where the river intersects the model boundary). The assigned head value was set as the topography at the point where the river crossed the model boundary and taken from the 100 m DEM and cross-checked with 1:50 000 topographic sheets. The following rivers are represented in the model with a constant head:

Table 4-2 Constant heads input to model

Constant Head ID	River constant head represents:
1	Breede at Michells Pass
2	Breede & Wit
3	Slanghoek
4	Molenaars
5	Holsloot
6	Nuy
7	Hex
8	Jan du Toits
9	Hartbees
10	Wabooms

5. NUMERICAL MODEL: BREEDE RIVER ALLUVIUM

5.1 MODEL DOMAIN AND MESH

Based on the boundary conditions as described in section 3.3.4 the modelled area covers 486 km^2. The Modflow software functions on a square grid. The problem is quasi 3-dimensional and contains 7,778 grid squares or cells in each layer, 23,334 in total. The length of the sides of cells are 250 m. The model functions by solving the groundwater flow equation at the centre of the cells only ('block-centred'). The solution for head is then averaged by linear interpolation between cells to produce a smooth appearance to the contours, and to generate a hydraulic head at every point in the model, including away from the centre of a cell. (All data in the model is handled in this way.) Therefore a solution could be accurate to the scale of ~250 m if data on all input parameters and calibration data was also available at this scale. The length scale of the problem is at least one order of magnitude greater than this scale of accuracy and therefore it is deemed sufficient.

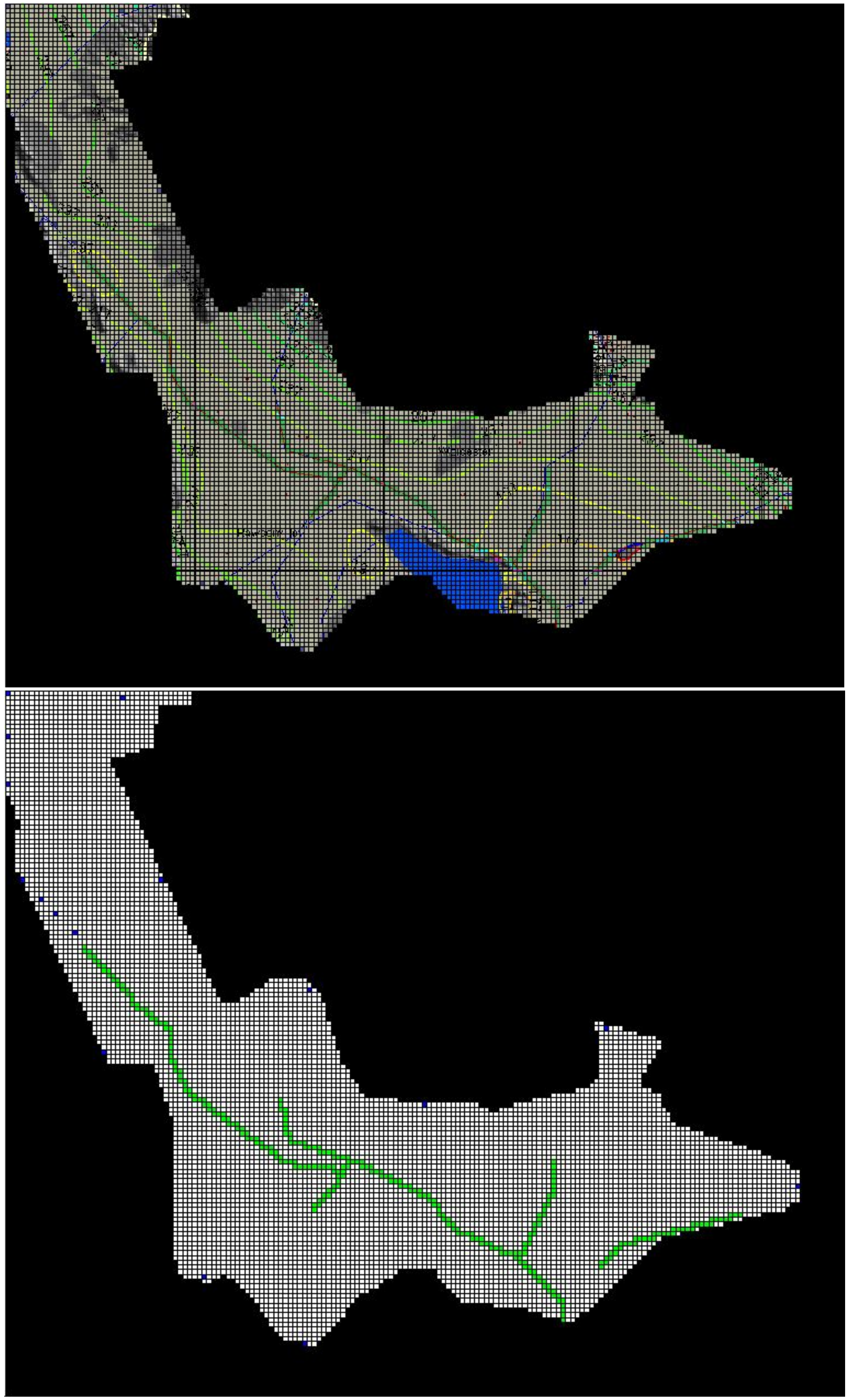

Figure 5-1 Model domain,

Shown with map background for orientation (compare to Figure 3-6), then shown without to highlight boundary conditions. Green cells are river boundary conditions, and blue are constant heads.

5.2 CALIBRATION PROCEDURE

The procedure is described in previous modelled reports (Volume 6 of this report, (DWAF, 2008)), and repeated here. The procedure adopted for calibration is standard to modelling investigations; the simulated steady-state heads and flows ("modelled" data) are compared against field-measured values ("real", or "observed" data). This is conducted first for steady-state simulations and subsequently for transient simulations. Aquifer parameters are varied until a reasonable fit is generated between modelled and real data selected as calibration data. The procedure and principles are consistent in all the model tasks undertaken on this project.

Parameter testing and evaluation of the model sensitivity to different parameters are established. A range of values for one or more parameters are input to the model in order to understand the model response to a particular variable, coupled variables or even a group of variables because it is preferable, but not always possible, to establish a unique model solution. However, the calibration is always assessed against what could be physically real. A unique model solution is unlikely for the model at this stage, given the inherent uncertainties in this model with respect to:

- bedrock topography;
- thickness and lateral extent of the alluvial fan coarse boulder beds;
- elevations of the various surface water tables in mamsl;
- rate of transfer between rivers and the aquifer;
- unknown vertical and lateral connectivity between
    - the Breede River and various units
    - the coarse alluvial fans and other deposits.

A unique model solution is also not necessary as a planning tool. This model aims to test various model scenarios and their effect on estimates of the long-term average flux to or from the Breede River and in so doing will provide insight to upgrade of the hydrological modelling of the Breede River using Pitman.

5.3 CALIBRATION DATA AND STANDARD

5.3.1 Steady-state water levels

There are no complete hydrogeological point records held in the NGDB for the Breede River valley, i.e. there are no boreholes that have geology data and water level data (**Table 5-1**). Also, the data that is available is sparse (see red data dots shown in **Figure 2-18**). It was not possible to select point data against which the model could be calibrated. A qualitative calibration is carried out instead. The modelled water levels are compared to the observed water levels based on a comparison of mapped data. This is considered an alternative and can be as robust a method as quantitative point data (Volume 6 of this report, (DWAF 2008)).

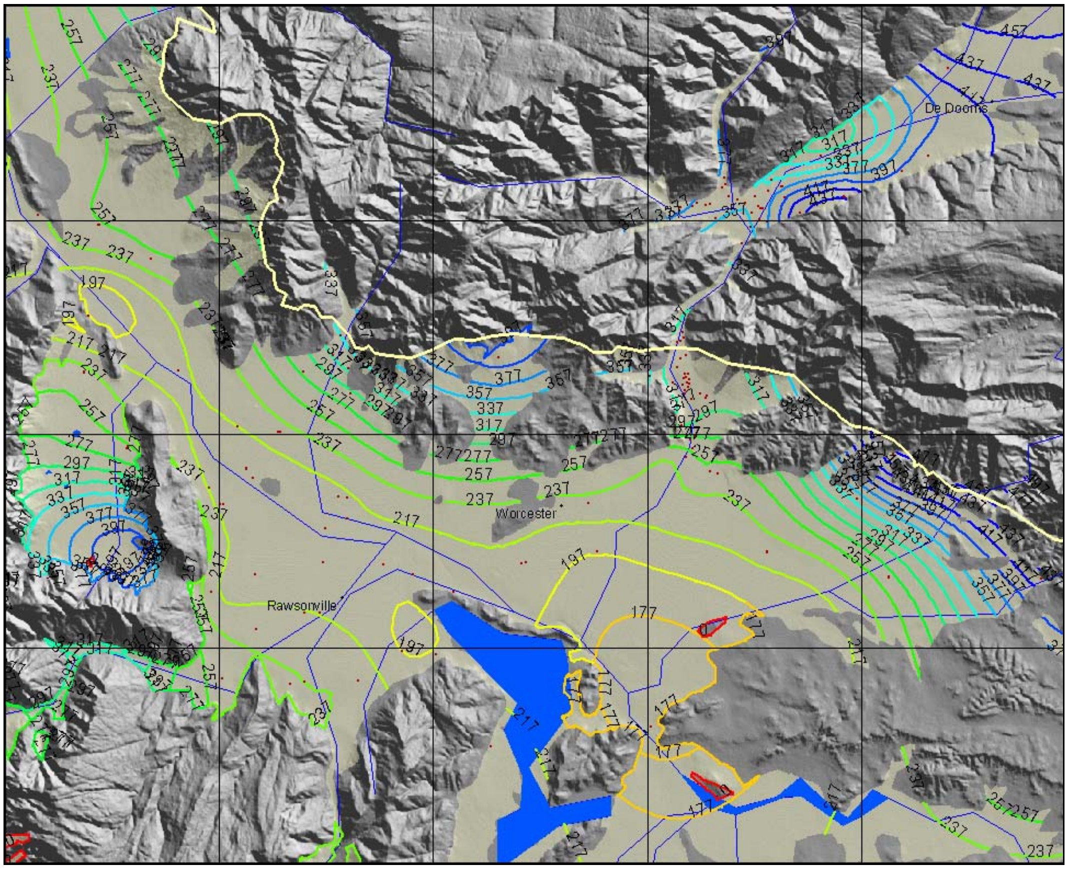

Figure 5-2 Static water-level map for the Breede River Alluvium Aquifer

*This is the same piezometric map as shown in **Figure 2-18**, shown again here focussed over the model area. This map is used as a background in the model to allow comparison of resulting modelled water levels.*

5.3.2 Water-level fluctuations

Table 5-1 below shows there is no long-term monitoring from boreholes whose depth or geology data is known. Of the 13 boreholes with useable monitoring data, 10 are situated in the central Breede Valley between Rawsonville and the Slanghoek-Breede confluence. The remaining 3 are south of Rawsonville close to the southern reach of the model domain (close to the TMG).

Table 5-1 NGDB statistics

Data Item (within mode domain)	Number
Boreholes	82
Boreholes with water level measurements (single and time series)	79
Boreholes with geology records	32
Boreholes with geology records and water level measurements	35
Boreholes with long-term (>2 year) monitoring data	19
Boreholes with geology records and long-term (>2 year) monitoring data	0
Boreholes with monitoring data not visibly affected by pumping, and in close proximity to other boreholes with geology records, and whose geology can be inferred and assumed representative of alluvium deposits.	**13**

The annual fluctuation in water levels in these 13 boreholes varies between 1.2 m and 4.8 m. The mean annual fluctuation is 2.5 m. The water levels respond to seasonal rainfall and groundwater peaks occur between July and October (**Figure 5-3)**. Example records are shown for typical minimum, mean and maximum annual variability. The boreholes are in the Rawsonville fan close to the Holsloot River, on the north side of the central Breede River Valley relatively close to the river, and on the south side of the central Breede at a greater distance from it for the example of minimum, mean and maximum respectively.

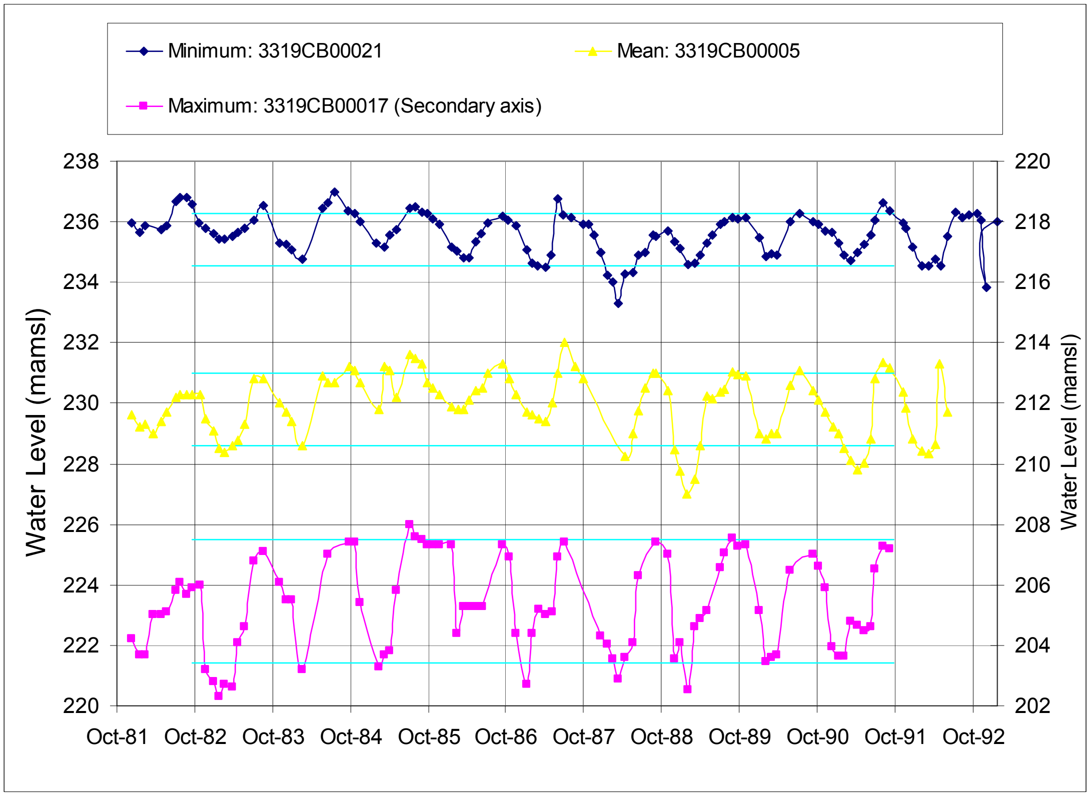

Figure 5-3 Typical seasonal water level fluctuation.

There are not enough time-series data records and the distribution within the model domain is not adequate to analyse the spatial variations of the seasonal changes in the groundwater table. It appears that the center of the valley and boreholes north of the Breede have lower seasonal variations (1.2-2 m) in groundwater elevation. The records showing ~4 m annual variability are south of the valley at a greater distance from the river. This possible pattern is not supported from records near the edge of the Rawsonville fan and further again from the central channel, where the records show 1.2 m variation. The magnitude of annual variability is likely to be controlled by local sedimentary character and land use e.g. grain size distribution and packing constrain storage while the percentage clay is a controlling variable for seasonal variation.

Over and above the sedimentary nature of the aquifer, groundwater level variation over time at any one site depends on the regional flow variability. Because of the local signatures affecting the variability of each individual point, the regional scale of the model, and the lack of data to support a possible spatial pattern in variability, it was decided to run various simulations investigating the storage parameters required to generate a 1m variability (the minimum observed), close to the mean variablility 2.5 m, and a 4 m variability (the maximum observed) rather than calibrate to an uncertain data set. Observed records are shown in **Figure 5-3** below.

5.3.3 River flow / River stage

The river stages from the steady-state situation are assumed to be the annual average of the stage in that position. Monthly river stages for gauging stations in the area were supplied by DWAF for the period 1980 – 2007. Monthly mean measurements over the time series of data recorded, and monthly mean of the daily peaks and minimum flows were supplied. Stations on tributaries to the Breede River close to the position where they cross from TMG into the alluvial fans were selected and analysed for use as model input for variability at the constant heads representing the springs entering the alluvium. Two stations in the central Breede valley were selected for analysis of the variability along the Breede River. One of these is on the Holsloot, but close to the confluence with the Breede River and so is assumed representative of the Breede (**Table 5-2**).

The river stage data supplied from DWAF are not convertible to mamsl and are given in metres above an unknown datum (pers comm. Frans Mouski, November 2007). Instead of using the data directly, an annual mean was calculated from the monthly mean and each month's level was converted to a variation from this annual mean.

The variability from the mean at each station was compared. Of the 4 flow gauges on tributaries to the Breede River, the two in the northwest of the domain (H1H006 & H1H018), which are west of the climatic divide, show identical variability. The two stations southwest of the climatic divide also show identical variability in terms of magnitude and timing (**Figure 5-4**) but the magnitude of the seasonal change is less than for those stations in the northwest. One average variability was applied to constant heads in the northwest of the model, and one to constant heads in the southwest.

Table 5-2 Flow gauge data for seasonal variability in surface waters (River stages and constant heads)

Flow Gauge	Position (see Figure 2-2)	Model Equivalent	Annual Variability (m)	Application in model
H1H006	Breede River at Michells Pass	Constant head	0.39	Average of H1H006 & H1H018 applied to constant heads northwest of and including the Molenaars and Jan Du Toits fan heads
H1H018	Molenaars River upstream of alluvial fan	Constant head	0.37	
H1H012	Holsloot River upstream of alluvial fan	Constant head	0.29	Average of H1H012 & H1H006 applied to constant heads southwest of and including the Holsloot fan head
H2H006	Hex River at transition TMG to alluvial fan	Constant head	0.25	
H1H009	Holsloot River, downstream near Greater Breede confluence	River boundary condition	0.41	Central Breede River boundary conditions upstream of Breede & Holsloot confluence
H1H015	Breede River near Greater Brandvlei Dam	River boundary condition	0.60	Central Breede River boundary conditions downstream of Breede & Holsloot confluence

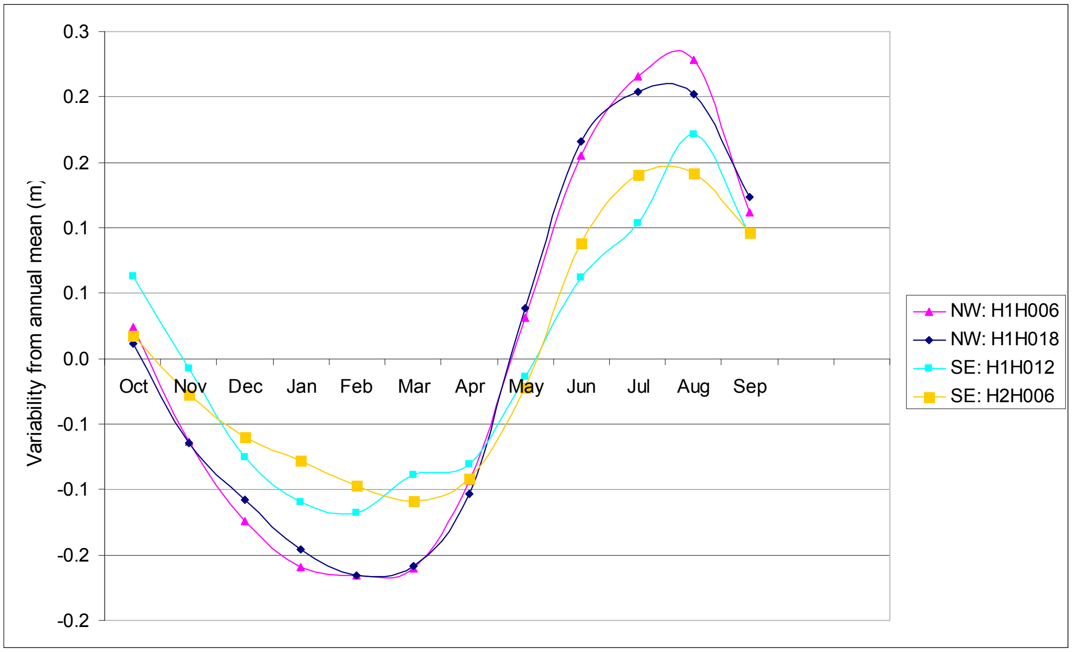

Figure 5-4 **Monthly variability in river stage, from annual mean, for various tributaries to the Breede River**

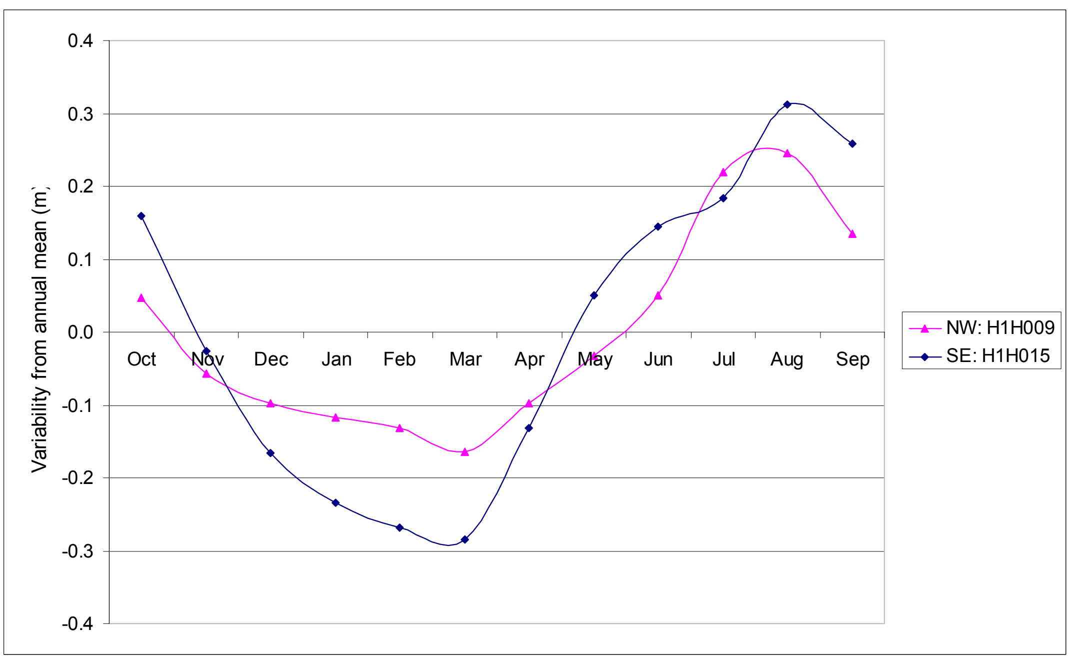

Figure 5-5 **Monthly variability in river stage, from annual mean, for the central Breede River**

5.4 PARAMETER CALIBRATION

5.4.1 Hydraulic conductivity

The model result is sensitive to variations in hydraulic conductivity. Model runs showed that the equivalent hydraulic conductivity in the valley must be in the range 10-100 m/d. Below 10 m/d the resulting water levels are significantly above topography. Above 100 m/d the valley sides are dry over large distances.

The hydraulic conductivity data set that gives best results, with respect to water levels within the steeply changing topography and basement (i.e. minimum flooded cells and minimum dry cells), and the one that also replicated the observed flow regime, is given in **Table 5-3** below. The best results were achieved with a hydraulic conductivity that is isotropic in the horizontal plane but reduced by an order of magnitude in the vertical plane. These directional variations are denoted with Kx and Ky representing hydraulic conductivity in the horizontal plane, and Kz representing hydraulic conductivity in the vertical plane. The distribution of hydraulic conductivity for Model Layer 1 is shown in **Figure 5-6**.

Table 5-3 Calibrated Hydraulic Conductivity Parameter

Layer	Kx, Ky, Kz (m/d)	Distribution
1	Kx 100, Ky 100, Kz 10 and Kx 10, Ky 10, Kz 1	Higher hydraulic conductivity (100) in northwest and in alluvial fans, lower in centre of the valley
2	Kx 10, Ky 10, Kz 1	Homogeneous distribution
3	Kx 0.1, Ky 0.1, Kz 0.01	Homogeneous distribution

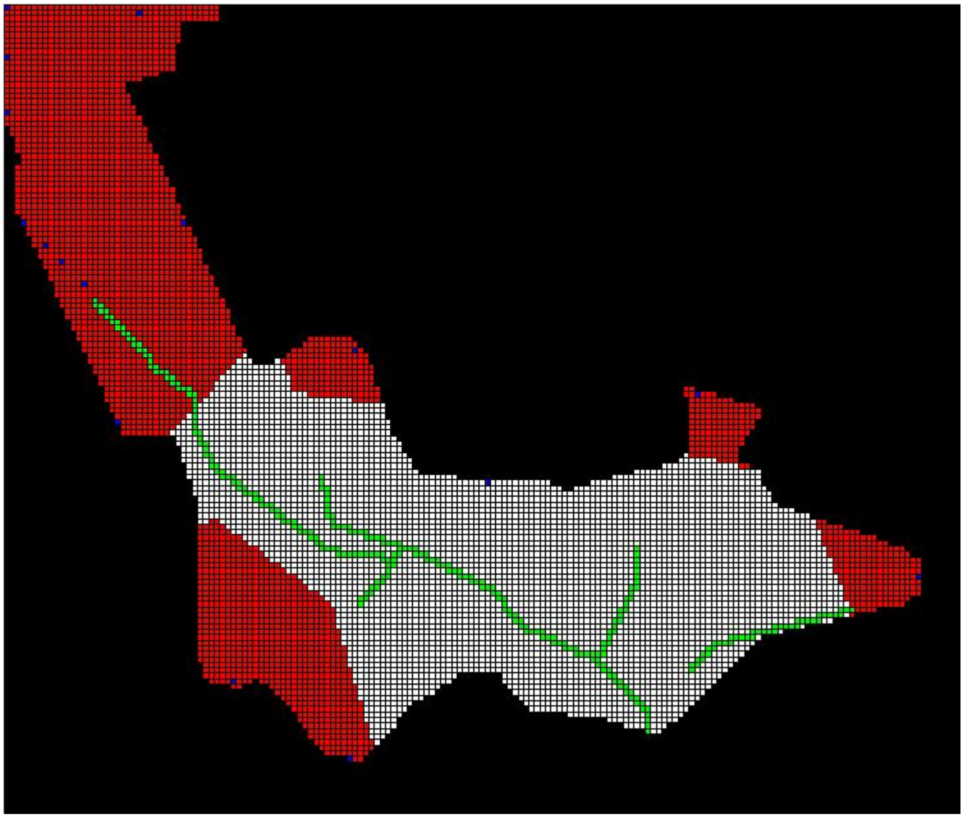

Figure 5-6 Hydraulic conductivity distribution in upper model layer

Cells with hydraulic conductivity as Kx 100, Ky 100, Kz 10 m/d, are shown as red, remaining white cells have hydraulic conductivity Kx 10, Ky 10, Kz 1 m/d.

5.4.2 Storage coefficient

The model was not sensitive to variations in specific yield, as only the upper layer is unconfined. Variations in specific storage affect changes in modelled seasonal variation. The effect of storage parameters on the seasonal variability (maximum water level- minimum water level) is shown in the table below. The result shown in bold (scenario 3) is closest to the average observed seasonal variability.

Table 5-4 Sensitivity to storage parameters

Scenario ID	Specific Yield Sy	Specific Storativity Ss	Average Model Variability (m)
1	0.1	1E-5	4.0
2	0.1	1E-4	3.3
3	**0.1**	**5E-4**	**1.5**
4	0.1	1E-3	0.9

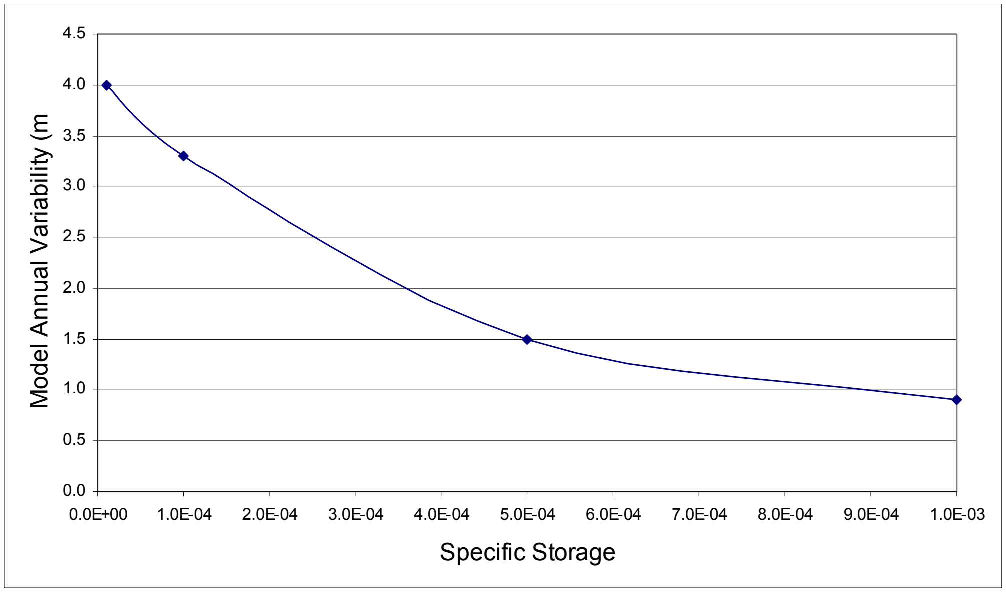

Figure 5-7 Variability for various storage settings

5.5 RESULTS

5.5.1 The flow regime

The major features of the flow regime are replicated in the model. Groundwater flows from the valley sides towards the Breede River, and also through the valley towards the southeast. The observed groundwater gradients are also broadly replicated – compare the contours in the valley sides in **Figure 5-8** (both observed and modelled are plotted at 20 m intervals- visible in the Hex valley for the base of the aquifer).

The model replicates the flow regime at a regional scale and gives expected mass balance numbers. However, with a regional model it is not possible to replicate rapidly changing water level gradients. The steepest parts of the valley remain dry. This is not considered to influence the centre of the model- i.e. flows around the surface water.

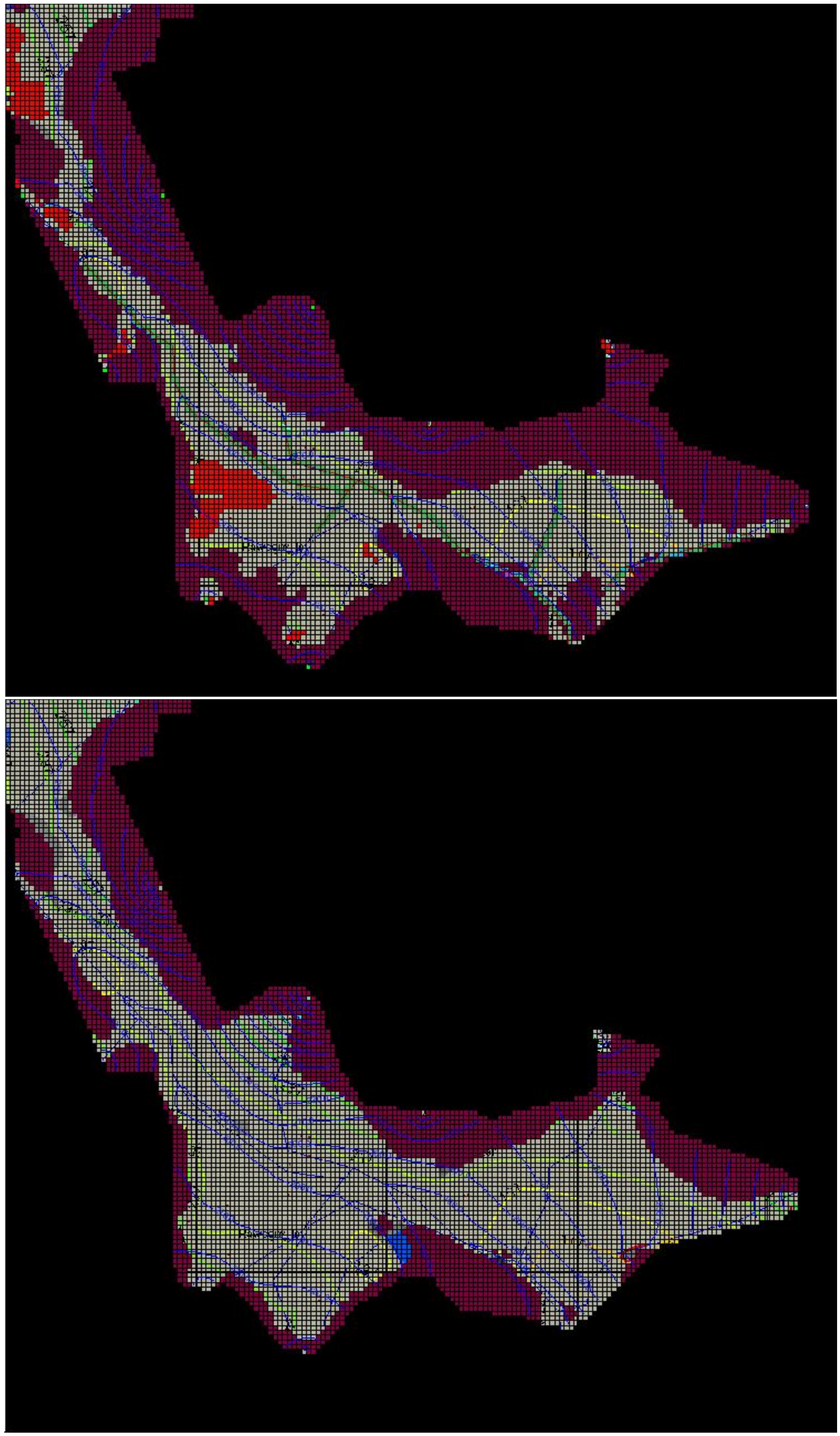

Figure 5-8 Flow regime in the alluvium aquifer, for the top of the alluvium (top) and base (bottom)

Red cells indicate water level greater than ground and purple indicates dry edges of the model

5.5.2 Seasonality

Modelled variability is higher on slopes and valley sides and lowest in the valley centre. It is forced to be ~0.4 in the centre of the valley based on the transient river boundary condition settings.

Figure 5-9 shows the annual variability at two points. One is in the Hex valley, one is closer to the Breede River perpendicular to the constant head representing the Hartbees River. These 2 points are both in proximity to the constant heads. They are both therefore influenced by the variability set at the constant heads and also to the recharge variability. The timing of these peaks is identical as the same things influence them. The plot shows how the variability is greater on valley sides (~4 m) than in the valley bottom (0.4 m).

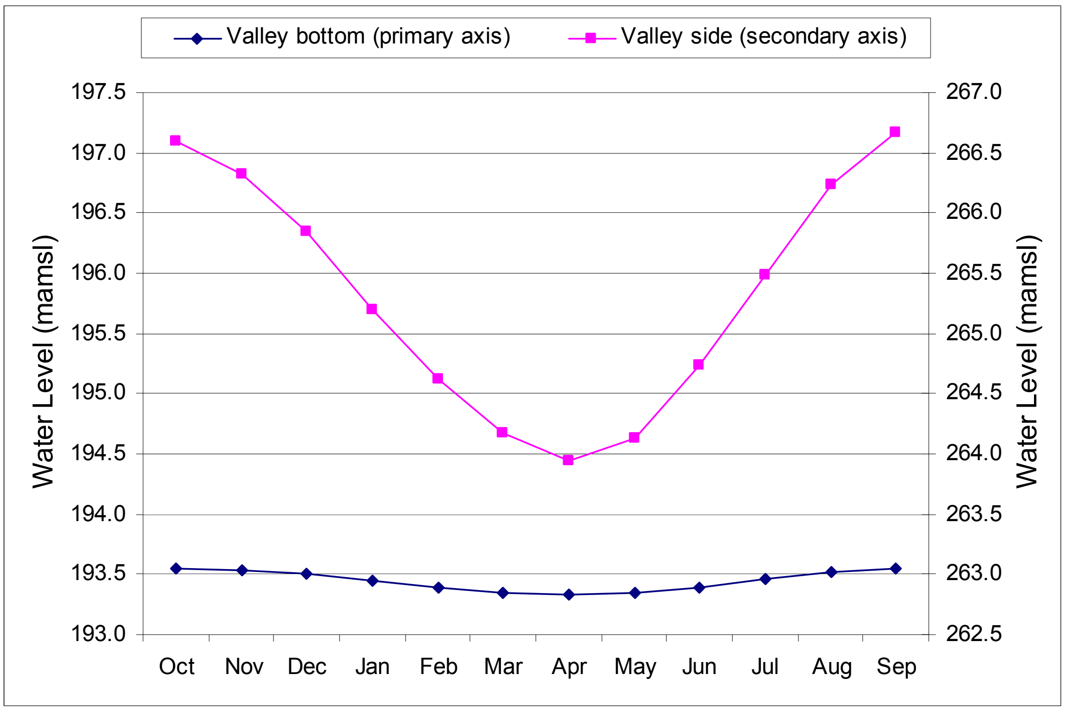

Figure 5-9 Modelled annual variability for points influenced by variability in spring flow (constant heads) and recharge

Figure 5-10 compares this variability to points which are not in the vicinity of constant heads or the river – such as valley sides away from sources, e.g. in between the Hex and Nuy rivers close to the model boundary. Here, the timing in the variability is influenced by recharge only, not the applied variability in modelled surface waters. The resulting modelled water level in these positions peaks and troughs before the points influenced by surface waters too; indicating that the behaviour of surface waters is delayed with respect to recharge. The relationship is of course also seen in the input data and therefore being reflected in the model results.

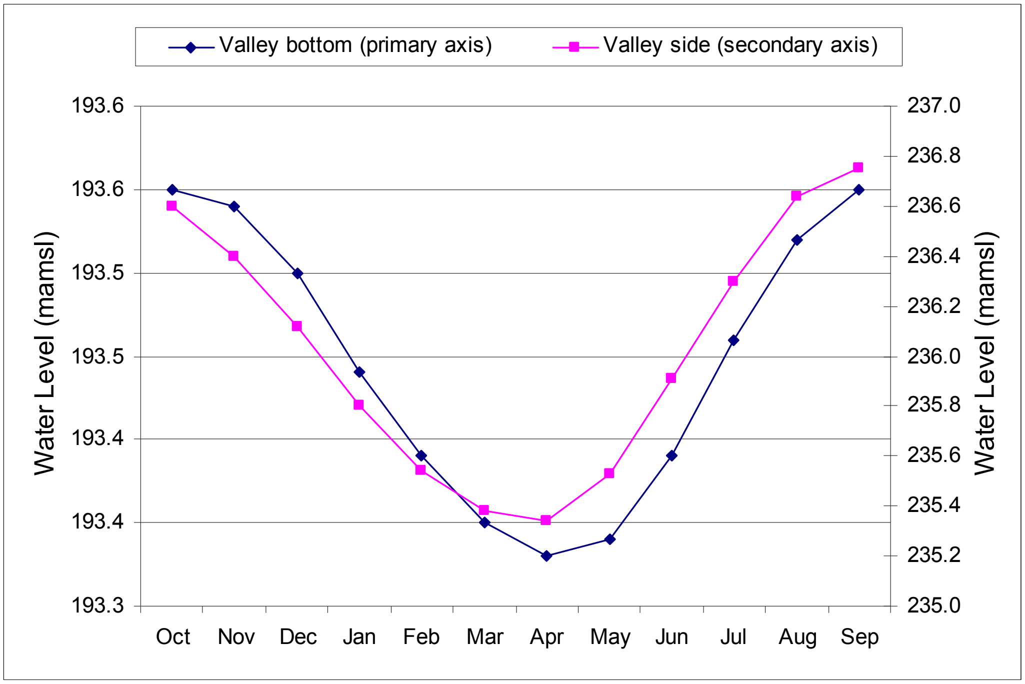

Figure 5-10 Modelled annual variability: comparison to points influenced by recharge only

5.5.3 Mass balance: Surface water – groundwater interactions

The mass balance for the steady state model is shown in **Table 5-5** below. Negative fluxes represent discharge from the aquifer. The mass balance shows that a much larger proportion of inflow to the alluvium occurs through vertical recharge than from the TMG-fed rivers.

Table 5-5 Steady-state model fluxes

	Influx		Discharge to	
	Recharge	Constant heads	Rivers	Balance
m^3/day	62 982	8 144	-71 062	64
Mm^3/anum	23	3	-25	0

The fluxes from the constant-head sources are shown below. The Waboomss and Jan Du Toits rivers are the most influent to the alluvium, followed by the constant head that is set to represent the Hartbees River. Each of these are on the northern side of the Breede Valley and it is possible that their effect is greater because the valley sides are steeper in the north (from observed topography sections). The model results in the Breede and Wit rivers being a sink to the groundwater. This is in agreement with the observed water level map confirming water flowing from the north west to the south down the valley, but also towards the south west, (in the northwest of the valley only).

Table 5-6 Model fluxes from TMG springs

Note: Negative fluxes represent discharge from the aquifer

Source	Flux m^3/day	Flux Mm^3/anum
Breede at Michells Pass	96	0.04
Breede & Wit rivers	-457	-0.17
Slanghoek	492	0.18
Meolnaars	1 949	0.71
Holsloot	1 442	0.53
Nuy	771	0.28
Hex	833	0.30
Jan du Toits	5 852	2.14
Hartbees	2 872	1.05
Wabooms	9 172	3.35

The seasonality of the mass balance is shown in **Figure 5-11** and **Table 5-7** below. The 'balance' reflects the storage capacity. In summer months the monthly balance is negative because more water is lost from the system than enters. This situation arises because the vertical recharge is low but discharge to the rivers continues. In winter this is reversed and the water table rises as recharge increases faster that it is discharged to the rivers. This pattern is key to the feasibility of ASR.

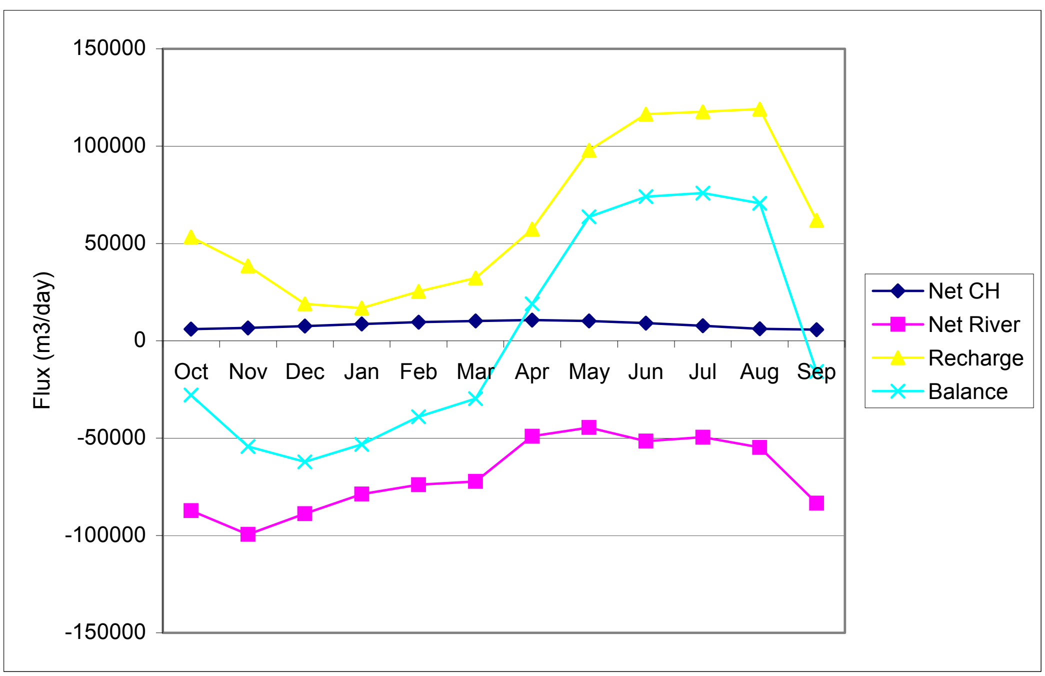

Figure 5-11 Transient mass balance plot

Table 5-7 Monthly mass balance (for storage parameter set 3)

Month	Influx m^3/a Recharge	Influx m^3/a Constant heads	Discharge to Rivers m^3/a	Balance m^3/a
October	53 313	6039	-87 184	-27 832
November	38 529	6637	-99 381	-54 215
December	18 991	7630	-88 787	-62 166
January	16 932	8706	-78 765	-53 127
February	25 377	9544	-73 945	-39 024
March	32 314	10214	-72 282	-29 754
April	57 332	10622	-48 955	18 999
May	97 902	10264	-44 528	63 638
June	116 463	9122	-51 476	74 109
July	117 687	7753	-49 438	76 002
August	119 098	6228	-54 727	70 599
September	61 842	5680	-83 319	-15 797
Annual (Mm^3/a)	22.7	3.0	-25.0	0.6
Total (Mm^3/a)				
	Influx		Discharge	
		25.6	-25.0	
Contribution to total influx / discharge, as percentage	88	12	100	3[1]

[1] Given as a % of the total discharge

5.5.4 Sensitivity of mass balance to storage parameters

The effect on the mass balance of the various storage parameter scenarios is minimal. The mass balances for the end-member storage parameter scenario are shown in **Table 5-8** and **Table 5-9**. Storage parameter scenario 3 is used in the remaining scenario testing.

Table 5-8 Alternative storage parameter scenario mass balance: scenario 1; minimum influx

Month	Influx m^3/a		Discharge to Rivers m^3/a	Balance m^3/a
	Recharge	Constant heads		
October	53 313	6 619	-86 518	-26 586
November	38 529	8 085	-96 093	-49 479
December	18 991	10 125	-85 765	-56 649
January	16 932	11 461	-75 724	-47 331
February	25 377	11 870	-71 231	-33 984
March	32 314	12 070	-69 839	-25 455
April	57 332	11 195	-48 586	19 941
May	97 902	8 666	-46 239	60 329
June	116 463	6 085	-54 631	67 917
July	117 687	4 267	-53 819	68 135
August	119 098	2 736	-59 363	62 471
September	61 842	5 089	-84 084	-17 153
Annual (Mm^3/a)	22.7	2.9	-25.0	0.7
Total (Mm^3/a)				
	Influx		Discharge	
		25.6	-25.0	
Contribution to total influx / discharge, as percentage	88	12	100	3

Table 5-9 Alternative storage parameter scenario mass balance: scenario 4; minimum outflux

Month	Influx m^3/a		Discharge to Rivers m^3/a	Balance m^3/a
	Recharge	Constant heads		
October	53 313	6 485	-87 147	-27 349
November	38 529	6 849	-99 300	-53 922
December	18 991	7 555	-89 872	-63 326
January	16 932	8 363	-79 905	-54 610
February	25 377	9 041	-64 164	-29 746
March	32 314	9 638	-73 554	-31 602
April	57 332	10 107	-49 010	18 429
May	97 902	10 021	-43 896	64 027
June	116 463	9 236	-50 497	75 202
July	117 687	8 194	-47 770	78 111
August	119 098	6 908	-52 757	73 249
September	61 842	6 331	-82 686	-14 513
Annual (Mm^3/a)	22.7	3.0	-24.6	1.0
Total (Mm^3/a)				
	Influx		Discharge	
		25.6	-24.6	
Contribution to total influx / discharge, as percentage	88	12	100	4

5.5.5 The impact of current abstraction

WARMS data suggests that abstraction within the model domain is 18 Mm^3. Recharge for the model area is 23 Mm^3 only. It is unlikely that the system is in steady state with this degree of abstraction, assuming these figures are correct. The model was calibrated in steady state and in transient to represent a naturalised system, i.e. with 23 Mm^3 recharge and with zero abstraction (the potential for abstraction to increase recharge is assumed negligible). To understand the effect of the abstraction on the natural system this level of abstraction was entered into the model as a transient scenario, and the effect on water levels and fluxes investigated. The abstraction was entered as a net recharge.

The mass balance presented below is shown for the 1st year of abstraction (**Table 5-10**). The following table compares the sum of the fluxes to the natural system (**Table 5-11**). The results show that the constant heads are faster to respond to the change in recharge than flow to rivers. Further work is needed to understand the implications of the time lag between surface and groundwater.

Table 5-10 Abstraction Scenario Mass Balance; year 1.

Month	Influx m^3/a		Discharge m^3/a	Balance m^3/a
	Recharge	Constant heads	Rivers	
October	6 949	6 755	-84 532	-70 828
November	5 022	8 198	-93 934	-80 714
December	2 475	9 460	-84 847	-72 912
January	2 207	10 572	-74 819	-62 040
February	3 308	11 579	-69 707	-54 820
March	4 211	12 582	-67 216	-50 423
April	7 473	13 667	-40 794	-19 654
May	12 761	14 657	-32 859	-5 441
June	15 180	15 247	-35 466	-5 039
July	15 340	15 530	-30 057	813
August	15 524	15 454	-32 495	-1 517
September	8 061	15 358	-61 948	-38 529
Annual (Mm^3/a)	3.0	4.5	-21.3	-13.8
Total (Mm^3/a)				
	Influx		Discharge	
		7.4	-21.3	
Contribution to total influx / discharge, as percentage	40	60	100	-65

Table 5-11 Effect of abstraction on mass balance

	Flux into Model (Mm^3/d)		Flux out of Model (Mm^3/d)	Balance error (Mm^3/d)
	Recharge	Constant heads	Rivers	
Natural System	23.0	3.0	-25.9	0.0
With Abstraction	3.0	4.5	-21.3	-13.8
Effect of Abstraction	Net recharge decrease to 13%	Increase of 50%	Decrease of 18%	System loses ~5x more water than it gains

With continued abstraction the system does stabilise to a new steady state with less outflow to the rivers, and reach a stable state where outflux is equal to influx. As time passes under the new recharge regime, the influx from the constant head sources increases, and the discharge to the rivers decreases (**Figure 5-12**). The largest changes in flux occurs in the first 5 years and by 10 years the system has almost re stabilised, with the imbalance coming close to zero.

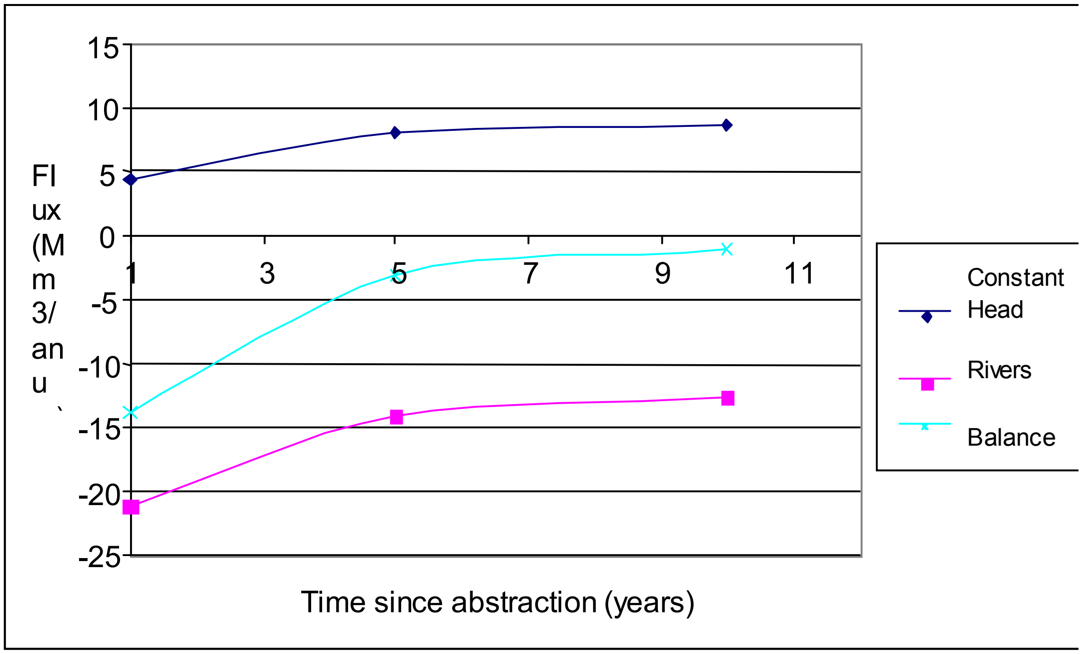

Figure 5-12 Modelled fluxes over time since abstraction: re stabilisation

6. SCENARIO SIMULATIONS

6.1 SCENARIO 1: LOW RIVER FLOW

Average minimum river stages and constant head values were entered into the model for 1 year. The recharge was unchanged. The assumption therefore is that recharge is less in the mountain catchments outside of the model domain and therefore the surface waters import less water to the BAA. The aim of the scenario is to determine whether groundwater can sustain the river flows. Minimum river stages were entered for all surface waters: the constant heads and the rivers.

The results are detailed in **Table 6-1** and **Table 6-2.** The flux in from the constant heads reduced by 3% as expected if the constant heads were to decrease. The flux out to rivers curiously is relatively unchanged. **Figure 6-1** does however show clearly that the monthly flux to the rivers is greater during the low flow. It is suggested that the expected trend is replicated, however that an error during month 13 affects the sum.

The system is fast to respond. The following year when surface waters return to the average conditions, the mass balance returns to the previous trend.

Table 6-1 Low-flow scenario mass balance

	Influx m^3/a		Discharge m^3/a	
Month	Recharge	Constant heads	Rivers	Balance m^3/a
October	53 313	6 041	-87 241	-27 887
November	38 529	6 636	-98 313	-53 148
December	18 991	7 629	-88 656	-62 036
January	16 932	8 706	-78 755	-53 117
February	25 377	9 542	-73 956	-39 037
March	32 314	10 215	-72 353	-29 824
April	57 332	10 505	-48 972	18 865
May	97 902	9 913	-54 974	52 841
June	116 463	8 728	-56 297	68 894
July	117 687	7 471	-60 774	64 384
August	119 098	6 221	-63 614	61 705
September	61 842	5 860	-74 314	-6 612
Annual (Mm^3/a)	22.7	2.9	-25.7	-0.1
Total (Mm^3/a)				
	Influx		Discharge	
		25.6	-25.7	
Contribution to total influx / discharge, as percentage	89	11	100	-1

Table 6-2 Effect of low flow on mass balance

	Flux into Model (Mm^3/d)		Flux out of Model (Mm^3/d)	Balance Error (Mm^3/d)
	Recharge	Constant heads	Rivers	
Natural System	23.0	3.0	-25.9	0.0
Low Flow	22.7	2.9	-25.7	-0.1
Effect of Low Flow	Decrease to 1.3%	Decrease of 3%	Decrease of 0.7%	System loses 0.4% more water than enters

6.2 SCENARIO 2: RIVER FLOOD

Monthly average (of daily) peak river stages and constant head values were entered into the model for 1 year. The recharge was unchanged. The assumption therefore is that recharge is higher in the mountain catchments outside of the model domain and therefore the surface waters import greater water to the BAA. The aim of the scenario is to determine whether groundwater can store the river flows – i.e. is the hydraulic gradient reversed and the rivers recharge the aquifer. Maximum river stages were entered for all surface waters: the constant heads and the rivers.

The model is set on monthly time steps as this is the scale of interest and there is not monitoring data to support finer detail. However, entering the monthly average peak values means that above average maximum peaks of duration much less than a month are not replicated. It is possible that these cause pulses of recharge into the aquifer. The monthly peaks entered are equivalent to a year of very high surface flows.

The results are detailed in **Table 6-3** and **Table 6-4.** The flux in from the constant heads increases by 3% as expected if the constant heads were to increase. The flux out to rivers is decreased by only 0.7% in total. **Figure 6-1** shows clearly that the monthly flux to the rivers is much reduced during the flood and even almost reversed during the peak surface flow. It is suggested that if a model was generated with sub-daily time steps, pulses where the surface water - groundwater interaction is clearly reversed would be traceable.

The system is fast to respond. The following year when surface waters return to the average conditions, the mass balance returns to the previous trend.

Table 6-3 Flood scenario mass balance

Month	Influx m^3/a		Discharge m^3/a	Balance m^3/a
	Recharge	Constant heads	Rivers	
October	53 313	6 041	-87 261	-27 907
November	38 529	6 636	-98 427	-53 262
December	18 991	7 629	-88 708	-62 088
January	16 932	8 706	-78 765	-53 127
February	25 377	9 544	-73 945	-39 024
March	32 314	10 214	-72 282	-29 754
April	57 332	11 734	-49 043	20 023
May	97 902	13 083	-1 212	109 773
June	116 463	12 233	-13 970	114 726
July	117 687	9 466	-42 229	84 924
August	119 098	5 761	-92 895	31 964
September	61 842	4 449	-96 700	-30 409
Annual (Mm^3/a)	22.7	3.2	-23.9	2.0
Total (Mm^3/a)				
	Influx		Discharge	
		25.8	-23.9	
Contribution to total influx / discharge, as percentage	88	12	100	8

Table 6-4 Effect of flood scenario on mass balance

	Flux into Model (Mm^3/d)		Flux out of Model (Mm^3/d)	Balance Error (Mm^3/d)
	Recharge	Constant heads	Rivers	
Natural System	23.0	3.0	-25.9	0.0
Flood Scenario	22.7	3.2	-23.9	2.0
Effect of Flood Scenario	Decrease to 1.3%	Increase of 3%	Decrease of 0.7%	System loses 0.4% more water than enters

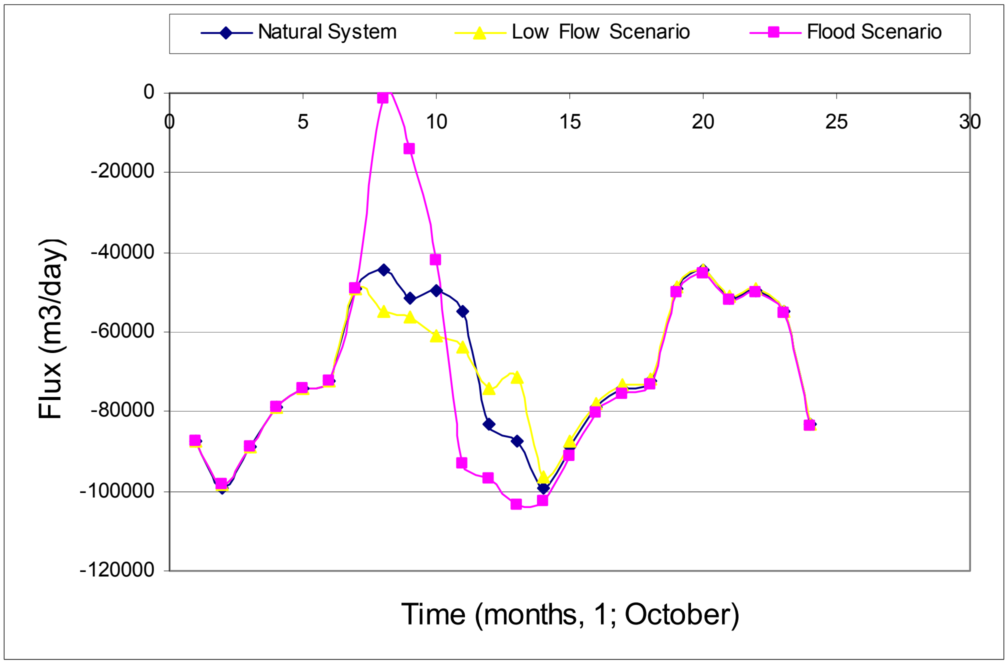

Figure 6-1 Surface water - groundwater fluxes under low-flow and flood scenarios

6.3 SCENARIO 3: AQUIFER STORAGE & RECOVERY

Available aquifer volume to store excess flood waters was calculated based from mapping the difference between the groundwater surface and the topographic surface (depth to water) (**Figure 6-2**). This illustrates that in the centre of the valley the flat lying areas have 0-10 m depth to water. The steepest edges of the model domain show >40 available space. This is considered an edge and scale effect as the model doesn't replicate the steep water level gradients.

Assuming a porosity of 0.1, and an available depth of 1 m, this volume translates to a minimum of 2 Mm^3 of available aquifer for storage of flood waters, and up to 40 Mm^3 based on 10 m available depth.

To further develop these scenarios sites where pump stations can be established must be identified, estimates of winter floods volumes that can be pumped ascertained, and these volumes reticulated to selected aquifer zones of optimum combination of thickness, porosity and storage parameters, hydraulic conductivity and proximity. From this first conceptual test, ASR appears feasible and warrants further investigation.

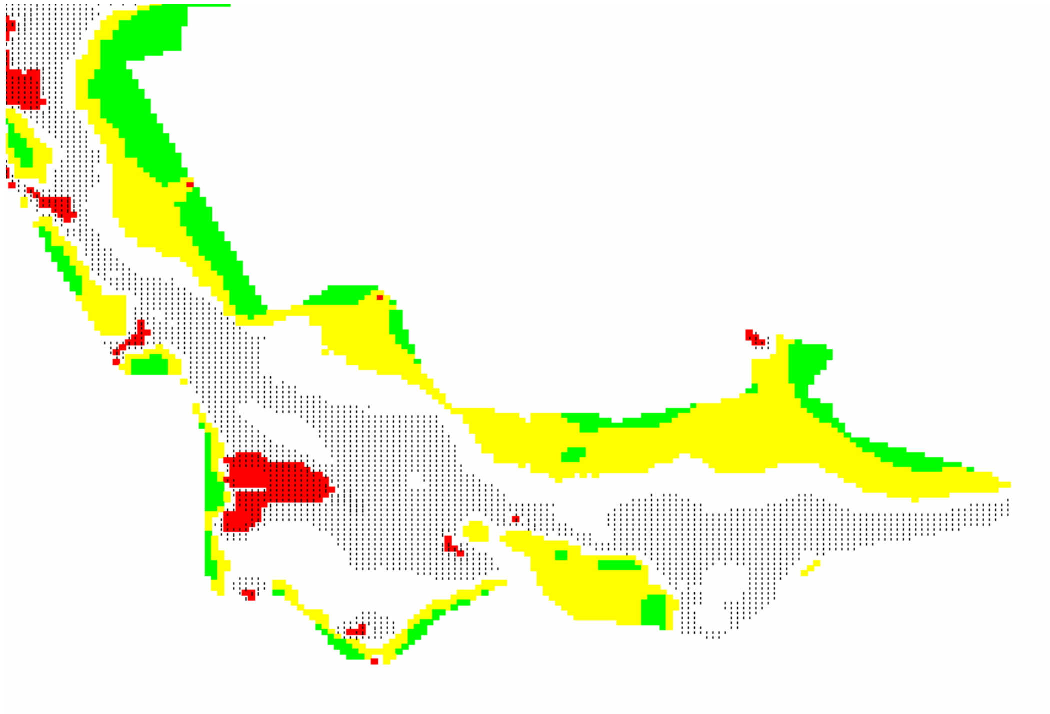

Figure 6-2 Map of modelled depth to groundwater, showing available storage.

Red cells are water levels at and above (up to 5 m) topography reflecting no additional storage, grey cells indicate 0-10 m depth to water, white cells indicate 10-12 m, yellow 20-40 m and green >40 m depth to water.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY OF INTERPRETATIONS

The conceptual model developed here details an aquifer where surface and groundwater are connected as one system, and with various exchanges between aquifer units operating at different scales. The TMG discharges to springs and perennial rivers, which flow from the steep mountainsides into alluvial fans within the Breede valley. The alluvial fans and the alluvium that underlies the central Breede River, together make up heterogeneous Breede River Alluvial Aquifer. The alluvial fans are coarsest at the fan heads and act as sponges to the perennial surface waters. The surface waters recharge the aquifer on entrance to the valley, and then these alluvial fans discharge to the Breede River in the centre of the valley. At the regional scale the groundwater movement is towards the centre of the valley, discharging at the Breede River, and also along the valley southwards. The alluvium overlies TMG aquifers and the aquitards of the Malmesbury and Cape Granite Suite. Lateral recharge from the TMG to the alluvium occurs where these units are juxtaposed. The third form of recharge to the alluvium is of course from rainfall.

The aquifer discharges to the Breede River along its length and groundwater also flows southwards through the valley, though ultimately discharging to the Breede as the alluvium reduces in volume and therefore capacity to carry the water south of Greater Brandvlei Dam and west of Robertson.

The conceptual model was translated to a numerical model and the finite difference groundwater software package Modlfow in Groundwater Vistas was used to numerically model the aquifer. Modelling the flow of the TMG to the Brandvlei hot spring showed that lateral discharge from the TMG to the alluvium was perennial and relatively constant with varying recharge. The TMG aquifer was therefore used as a fixed source in the Alluvium model. The borders of the alluvium model are no-flow boundaries, based on the 10 m thickness contour of the aquifer. The Breede River is set as an internal transfer boundary. The TMG-fed perennial rivers that act as tributaries to the Breede River and flow over the alluvial fans are set as constant sources of water at the model boundaries. The courses of these rivers internally in the model are also replicated as transfer boundaries where they are assumed to act as sinks to the aquifer

It was not possible to select point data against which the model could be calibrated. A qualitative calibration is carried out instead. The modeled water levels are compared to the observed water levels based on a comparison of mapped data. The major features of the flow regime are replicated in the model. Groundwater flows from the valley sides towards the Breede River, and also through the valley towards the southeast. The observed groundwater gradients are also broadly replicated. The model replicates the flow regime at a regional scale and gives expected mass balance numbers. However, with a regional model it is not possible to replicate rapidly changing water-level gradients. The steepest parts of the valley sides remain dry. This is not considered to influence the centre of the model- i.e. flows around the surface water. Model runs showed that the equivalent hydraulic conductivity in the valley must be in the range 10-100 m/d. The seasonal variation of the aquifer was simulated in transient modelling.

Scenario testing on the transient model suggests that the aquifer is relatively fast to respond to major changes in the influxes or outfluxes applied to the aquifer. The steady state model was run as a naturalised system. Inputting the assumed current abstraction to the transient model shows that the system re-adjusts the lower net recharge conditions and achieves stability after 10 years of this continued abstraction. The abstraction suggested by the WARMS database is a large proportion of the current recharge (almost 80%) and in order to determine the remaining safe yield of the aquifer (if any), this usage must be verified. The modelled system responds within 1 year to maximum and minimum surface water levels taken from flood and low flow records, suggesting a short time lag between groundwater storage and surface water. The relationship does suggest that the alluvium can readily take up excess surface water, and that this time lag could be optimised to store winter floodwater for use within the following summer dry period. The ASR scenario showed that there is a potential for significant storage within the aquifer, away from the centre of the valley. Local-scale mapping of water levels as depth to water is required to quantify such available storage.

The model has been based on robust assumptions, and relatively coarse calibration criteria were necessary due to the lack of complete groundwater point-source data sets. The model is seen as a first step to understand the temporal and spatial patterns of surface and groundwater in the Upper Breede. The aim was to generate a model which could established at least first order estimates of the rate and volume of exchange between the water in the alluvium and that in the river, and investigate the possibility for an ASR scheme to store surplus flood water. These aims have been achieved in this simple but robust model.

The model is also seen as the first steps to understand, numerically, the degree of connectivity in various aquifer interactions. The complex interactions between the TMG and alluvium were dealt with in 2 separate models, due to project constraints and available data that are applicable to this process (section 3.1). This means that their interdependence could not be explicitly tested. For example, this model cannot test the effect of increased abstraction on the inflow from the TMG into the alluvium, which is key to determining the total available groundwater (alluvium and TMG) abstractable in the Breede Valley. The need for a ‘natural laboratory’ where such aquifer, and surface- groundwater interactions can be monitored is apparent. The Breede Valley makes a good test case of an alluvial aquifer within a fractured rock basin, for such monitoring. These recommendations are addressed below.

7.2 RECOMMENDATIONS

7.2.1 General

The Breede Alluvium Aquifer model presents a challenge to reduce a complex interaction of different processes between 3 aquifers operating over a large area. The recommendations in this and other modelling volumes in this study series must presume, possibly prematurely:

- What is needed to upgrade input to the existing hydrological modelling;
- What is needed to upgrade the existing surface WRYM;
- What future applications there will be for the BAA model;
- What is needed to upgrade the BAA model;
- What is needed to support a systematic approach to improved aquifer modelling;
- What is needed to support a systematic approach to improved integrated surface and groundwater modelling;
- What is needed to initiate complete management of rainfall, aquifer and dam storage and thereby optimise the time lag between surface and groundwater.

It will be necessary to revisit the following recommendations once the final results of the Berg WAAS is complete and all findings and insights of both the surface and groundwater team are integrated along with those of the other WAAS teams. Based on this a series of focussed studies that plan and detail the way forward to realise improved integrated surface and groundwater modelling are anticipated.

Included in this could be review of the upgraded Sami model using the BAA model domain as a test case. It is noted that the input to the Sami model is in some respects the output of the BAA model. It is difficult to see how to use the Sami module in the WRYM in a systematic and quantitative manner such that there is planned upgrade and confidence in the WRYM results without prior groundwater flow modelling that is scale appropriate and aquifer specific. Improved groundwater modelling will result in improved and more reliable integration of groundwater data in the WRYM.

The difficulties in calibrating the hydrological model for the Breede is evidence of the importance of the time-series relationship in surface and groundwater data as well as the spatial dimensions of each identified flux exchange. The potential for management of the time lag between surface and groundwater is significant in the Upper and Middle Breede, and is motivated by

- juxtaposition of the aquifer storage, the river itself, the potential users;
- environmental issues associated with impact of usage on water quality and volume;
- competition for the resource;
- impact of proposed Michell's Pass Diversion on downstream Instream Flow Requirements (IFR) with respect to current allocations.

ASR is one of the ways in which the time lag between surface and groundwater is managed. Usage of groundwater storage to supplement the IFR that would otherwise reduce the yield of surface water schemes can be flexible insurance for environmental conservation, thus securing a quantitative and risk-management approach to the application of the National Environmental Management Act (NEMA). It will facilitate the overt inclusion of socio-economic factors in resource decisions rather than the often politicisation of the EIA process.

The following recommendations are made to support steady progress towards improved groundwater flow modelling and increasingly consistent and reliable hydrological and water resource yield modelling. The summary bullet recommendations have a short-term priority (1), a medium-term priority (2) and a long-term priority (3) with the numbers also indicating a necessary sequence of interventions. There are key groups of recommendations viz. Monitoring Data Acquisition; Model Uncertainty; Model Applications.

7.2.2 Monitoring Data Acquisition

Surface water data

- survey current surface water monitoring sites so as to reduce data to common datum, i.e. mamsl (1)
- review of sites identified in 2007 for flow gauges relevant to groundwater process mapping (1)

Hydrogeological data

- detailed mapping of all spring flow (seasonal and perennial) into the Breede Valley above Michell's Pass, between Wolseley and the Greater Brandvlei Dam (Upper Breede), the Greater Brandvlei Dam to Robertson (Middle Breede) and for completeness the Lower Breede (1)
- identification of key springs for installation of continuous flow metering (1)
- purpose-designed and drilled boreholes equipped for continuous water level monitoring (1 and phased thereafter)
- strategically sited boreholes for water quality monitoring if the above boreholes are not suitable (1 and responsive to land-use changes thereafter)
- hydrochemical and isotopic characterisation of the various aquifer units in the Breede, and thereafter regular monitoring to track and measure aquifer and surface-groundwater interactions (1)
- Hydraulic testing at selected sites (1 and as required thereafter for model upgrade, verification and validation and or for development of specific wellfield management models)

- Monitoring of groundwater use as an imperative data set for assessment of the available resource (1)

Hydroclimatic monitoring

- Select sites in key recharge areas (2)
- Install network of rainfall collectors (2)
- Install appropriate weather stations (2)

7.2.3 Reduce model uncertainties

Conceptual model testing

- Evaluate impact of selected model assumptions (element size, maximum of spatial average of 20 m decline in the water table) (1)
- Evaluate field evidence for lateral subsurface recharge from TMG along the southern Breede Valley walls (1)
- Confirm lack of lateral recharge from TMG aquifers north of the Worcester fault, i.e. the northern Breede Valley wall (1)

7.2.4 Model applications

Conceptual ASR schemes

- Select an alluvial fan at the base of a tributary on the southern and or northern side of the Breede Valley to evaluate the most suitable site for a pilot ASR scheme (2)

Develop wellfield management scenarios

- Design and optimise abstraction schemes (2)
- Select a conceptual wellfield for detailed evaluation of impact of abstractions (2)
- Physical process analysis to ensure maintaining the health of a selected ecosystem (2)
- Model impact of abstraction on fluxes to the selected ecosystems (2)

7.2.5 Suggested projects

The above recommendations can be summarised as discrete projects. These are:

6. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the Upper and Middle Breede to obtain time-series data on fluvial aquifer response to vertical and lateral recharge (1).
7. Map and understand the time lag between surface water and groundwater in the Breede to identify preferred sites for establishing a pilot ASR scheme as well as to upgrade the hydrological models that are input to the WRYM (2).
8. Hydraulic testing of the aquifer at selected sites to determine aquifer properties including storage potential and quantification of preliminary design of an ASR scheme (2/3).
9. Undertake model upgrade based on extensive testing and field confirmation of selected assumptions in the formal model test process, such that it can be used predictively and thereby realise medium to long-term upgrade of the hydrological data and WRYM (1 and ongoing)
10. Evaluate use of heat flow modelling of TMG aquifers (1).

7.3 APPLICABILITY OF THE MODEL

The model can be used for regional-scale resource planning and ongoing identification of critical process, knowledge and data gaps. It has merit as a scenario model in unwrapping the spatial and temporal dimension of surface-ground water interaction in a very complex environment. The model has shown itself to be very useful as a tool to explore likely aquifer responses, model dependency, model sensitivity to specific parameters, highlighting data collection needs, first-order partial tracking for contamination, and conceptual development of ASR schemes. This is a simple, robust model and can specifically test, therefore, for consequences of model assumptions and simplifications, and because it is simple, it is possible to understand the results. The advantage of this model is that it can build knowledge and insight into the patterns of surface and groundwater interaction, facilitate the improved calibration of the hydrological model, and be used to investigate different ways to integrate groundwater into the Water Resources Yield Model.

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Appendix 1

Numerical Model for the Brandvlei Hot Spring

NUMERICAL MODEL: BRANDVLEI HOT SPRING

INTRODUCTION

The numerical model for the Brandvlei hot spring was developed and calibrated by C Grant (2007) participating in the Umvoto Intern Programme. The model development and documentation formed part of her M.Sc. thesis at the University of Birmingham. The research was supervised by Dr Rae Mackay and Dr John Tellam of the University of Birmingham, and Dr CJH Hartnady of Umvoto Africa. The following sections summarise the results from the thesis.

Hydraulic parameters are not readily available for the various aquifers of the Breede catchment. The little data that exists is usually limited to boreholes drilled in the TMG and Bokkeveld rocks. For the TMG and Bokkeveld aquifers in the Hex River Valley, Rosewarne (1981) determined a transmissivity of from 23 to 110 m^2/day and storage coefficient of from 1 x 10^{-3} to 3.5 x 10^{-5} (0.1% - 0.004%); which is representative of semi-confined to confined aquifer conditions. In the Rawsonville–Goudini area the TMG aquifer is unconfined to semi-confined, with leakage in areas overlain by saturated alluvium.

MODEL ASSUMPTIONS

The numerical model is based on the following assumptions:

- Fracture flow can be approximated to flow in a porous medium at the scale of the model
- Groudwater temperature, density and viscosity remain constant
- Flow is isotropic in the horizontal plane
- System is in steady state.

It is clear that these assumptions are not fully representative of the system in question. The impact of faults, other than the Brandvlei fault zone, has been ignored. However, despite the limitations of the model, it provides a useful insight into the likely flow paths in the TMG aquifer system in the area around the Brandvlei hot spring.

MODEL DOMAIN AND MODEL MESH

The model was set-up using the Modflow code and Groundwater Vista as GUI. It consists of four layers representing the Peninsula Formation, the Winterhoek aquitard, the Nardouw Aquifer and the overlying confining sediments. The model occupies a 100 m x 100 m square grid of 500 m spacing, representing a 2 500 km^2 area, extending from the Riviersonderend Mountains in the south to the Worcester Fault in the north (see **Figure A-1**).

The shape of the Peninsula Aquifer was calculated using the dips of the arms of the anticlines and synclines. This results in the aquifer extending to unlikely depths in the northwestern corner of the model near the Worcester Fault, but is more reasonable for the area of interest. A cross-section taken from the model showing the two aquifers and aquitards is presented in **Figure A-2**.

Three different boundary conditions have been used in the model:

- The model domain is virtually a closed system, with the Worcester Fault and the Riviersonderend Mountain Fault bounding the northern and southern parts of the area respectively. These are normal faults, with large off-sets, juxtaposing low permeability rocks against the Table Mountain Group aquifers, and as such are included in the model as no-flow boundaries. An anticlinal structure extends along the eastern edge of the model towards the Worcester Fault forming a flow divide. This has been included in the model as a **no-flow boundary**. The western limit of the area has been delineated using the basement outcrops as a no flow boundary.

- In order to remove water from the system a series of **drains** have been used to represent the rivers and streams running off the mountainous TMG outcrop. Although the locations are approximately those of the largest rivers, the sizes are not representative, as they have been designed to incorporate the smaller flows that are not included in the model. The hot spring at Brandvlei is also represented by a drain, to ensure the correct discharge.

- Although the majority of the water in the Breede River comprises run-off from the surrounding mountain ranges, it is also fed by the underlying alluvium aquifer, which sits on top of the Bokkeveld and Witteberg Groups. The different formations have not been distinguished because the model is designed to investigate the deep flows within the TMG aquifers, rather than the complex interactions of the surface water and groundwater. The **river**, however, has been included as a boundary condition to remove water from these formations.

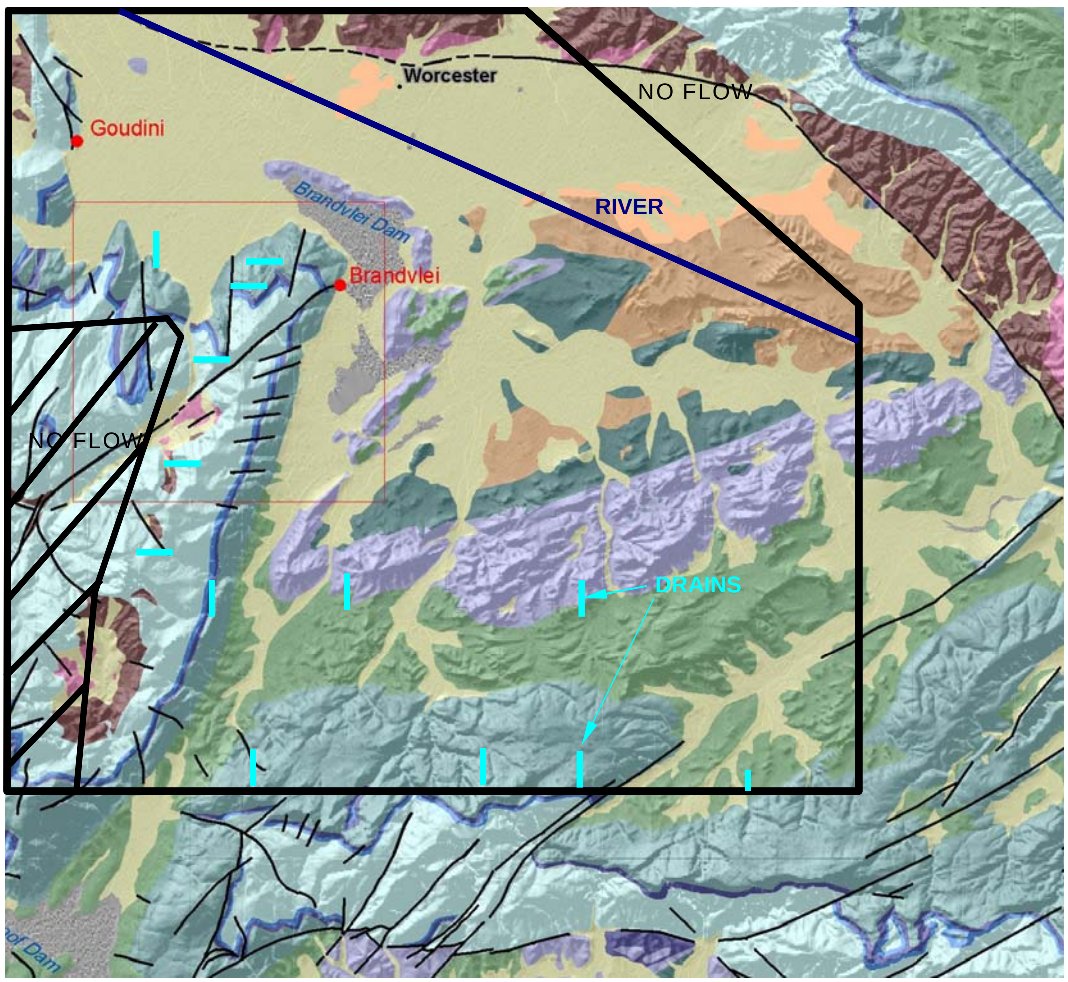

Figure A-1 Model Domain and Boundary conditions

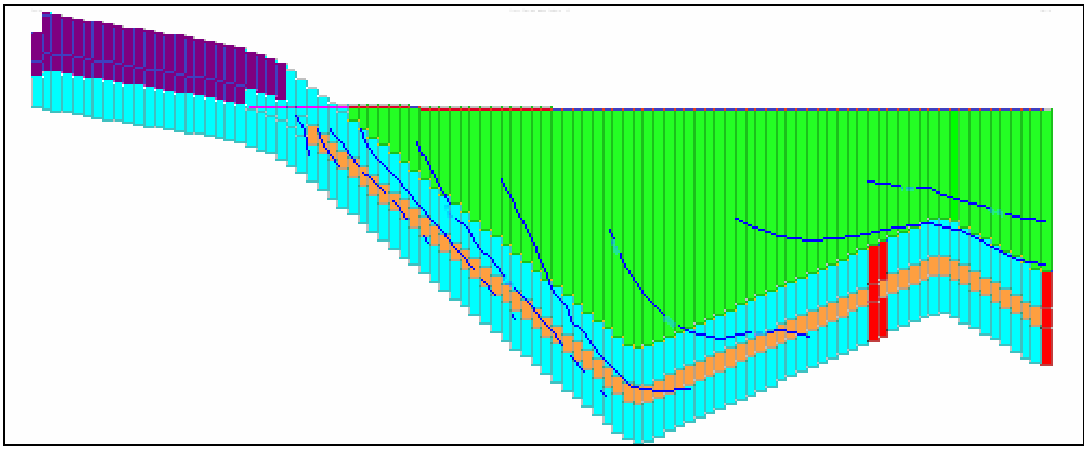

Figure A-2 Cross-section of flow model, showing the four different layers (Grant, 2007);

Light blue: Peninsula Aquifer and Skurweberg Aquifer (high permeability); orange: Cedarberg Shale Aquitard (very low permeability); light green: Bokkeveld Shale and overlaying formations (low permeability); red: fault zones (very high permeability); dark purple: dry cells

THERMAL MODELLING

The input parameters for the numerical model were estimated based on literature and applying thermal and silica mass balance calculations.

Input Parameters

Hartnady and Jones (2007) undertook an investigation into possible geothermal modelling on a basin wide scale within the TMG aquifers. They used the temperature gradients and laboratory and borehole estimates of the thermal conductivity, to calculate the heat flow in three boreholes representing different geological strata. The results of these analyses are summarized below.

Table A-1 Thermal conductivity data (Hartnady and Jones, 2007)

Geological Formation	Thermal conductivity (W/m.K)	Standard Deviation (W/m.K)	Heat Flow (mW/m^2)
Cape Granite	3.55	0.25	76
Peninsula Formation	7.35	0.34	105
Cedarberg Shale	1.6	-	57
Goudini Formation	3.9	-	90
Bokkeveld Shale	3.43	0.70	50-55

The following table summarises the other required input parameters for the thermal and silica mass balance model:

Table A-2 Input parameters for Mass Balance Model (Grant, 2007)

Parameter	Range	Value used	Source
Thickness (m)	500 – 1800	1000	De Beer, 2002
Porosity	0.0001 - 0.01	0.5	Rosewarne, 2002
Recharge (% MAP)	11 – 55	20	Parsons, 2002
Spring temperature (^oC)	57 – 61	60	Sampling and database
Spring SiO_2 concentration (mg/l)	12 - 19.5	18	Sampling and database
Spring discharge (l/s)	127	127	Kent ,1949

The model results suggest that a catchment area of at least 300 km^2, with the water descending to a depth of 4.2 km, is required to heat sufficient water to the correct temperature, but a recharge area of only 16 km^2 is needed to supply the volume of water discharged. The thermal gradient calculated is 10.3^{o}C/km. The mean residence time calculated indicates that the groundwater will take approximately 375 years to travel through the aquifer.

Thermal Modelling

The thermal gradient, as well as the thermal conductivity, has a strong impact upon the size of the likely catchment area of the aquifer. Whilst the mass balance calculations assume that this remains constant as groundwater circulates, it is an oversimplification of the system. As the cooler water from recharge descends to depth it will cause the thermal gradient to steepen, increasing heat flow, which will affect the area required to warm sufficient water to discharge at the Brandvlei hot spring. In order to assess the potential impacts of this a simplified version of the flow system was analysed using the Microsoft Excel-based heat transport code FAT3D_HEAT (Mackay, 2007) in order to gain a better understanding of the thermal controls and heat transport patterns within the system. A diagram of the system used is presented below. The recharge was fixed to equal the discharge at the spring. Thermal conductivities of the aquifer, basement and confining layer were taken from Hartnady and Jones (2007). The model assumes a fixed temperature at a depth of 6 km, well below the base of the Peninsula Aquifer in the area of interest, although the aquifer may extend to these depths nearer the Worcester Fault.

The mass balance calculations suggest that a catchment area of at least 300 km^2 is required. The Riviersonderend Mountain Fault marks the edge of the TMG Aquifer, 32.5 km south of the hot spring, so the model was initially run with L=30 km and W=10 km. This gave a temperature at the spring of 64^{o}C and a discharge of 127 l/s, which is very close to actual spring features. The results of this run suggested that the majority of horizontal flow occurs in the aquifer layer and that 99% of the water discharging at the spring comes from this layer.

The depth and area of the aquifer have a strong control on the temperature of the water discharging at the spring. If the aquifer were greater than 450 km^2 in area, then the water would only need to descend to 2000 m to heat up to 60^{o}C. However, given the synclinal nature of the aquifer in the area around the spring, it is considered more likely that the catchment of the Brandvlei hot spring extends to between 2000 m and 4000 m below sea level, and has an area of between 250 km^2 and 400 km^2.

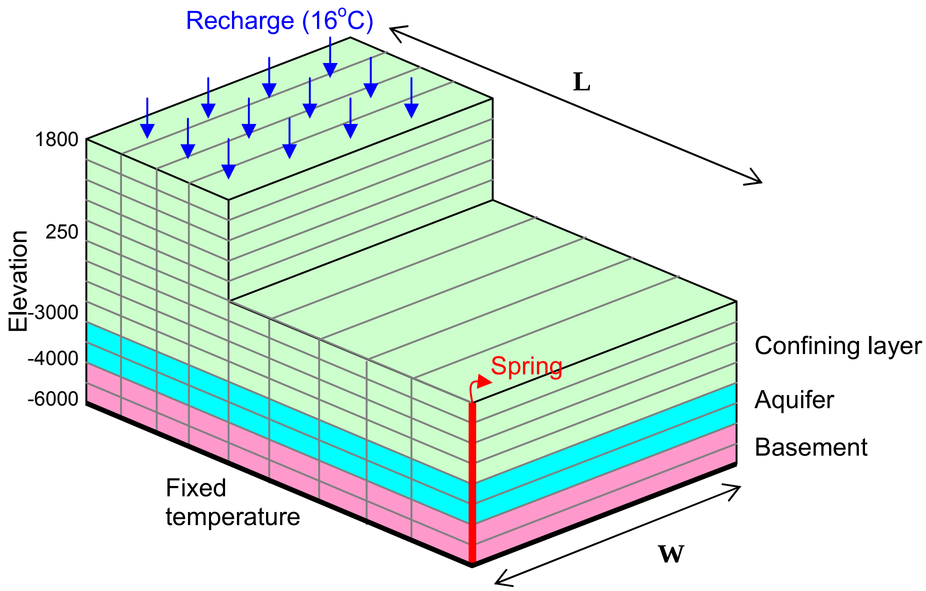

Figure A-3 Simplified thermal model of the Brandvlei Hot Spring (Grant, 2007)

PARAMETER CALIBRATION

The model was calibrated using regionally averaged values for horizontal and vertical hydraulic conductivity, porosity and recharge to reproduce the general flow pattern and water levels in the model domain area. No attempt has been made to reproduce water level fluctuations or local details of water levels within the alluvium aquifer.

The aquifer properties used in the calibrated model are summarized in **Table A-3** and graphic representations of the hydraulic conductivity and recharge distributions are presented in **Figure A-2** and **Figure A-4** respectively. The model has only been designed for steady-state calculations, so no storage parameters have been included.

Table A-3 Modelled aquifer properties

Unit	Hydraulic conductivity (m/d)			Porosity (%)
	K_x	K_y	K_z	
Bokkeveld Shales	0.1	0.1	0.01	10
TMG Aquifers	0.5	0.5	0.5	0.5
TMG Aquitard	0.005	0.005	0.0005	10
Fault zone	10	10	10	0.5

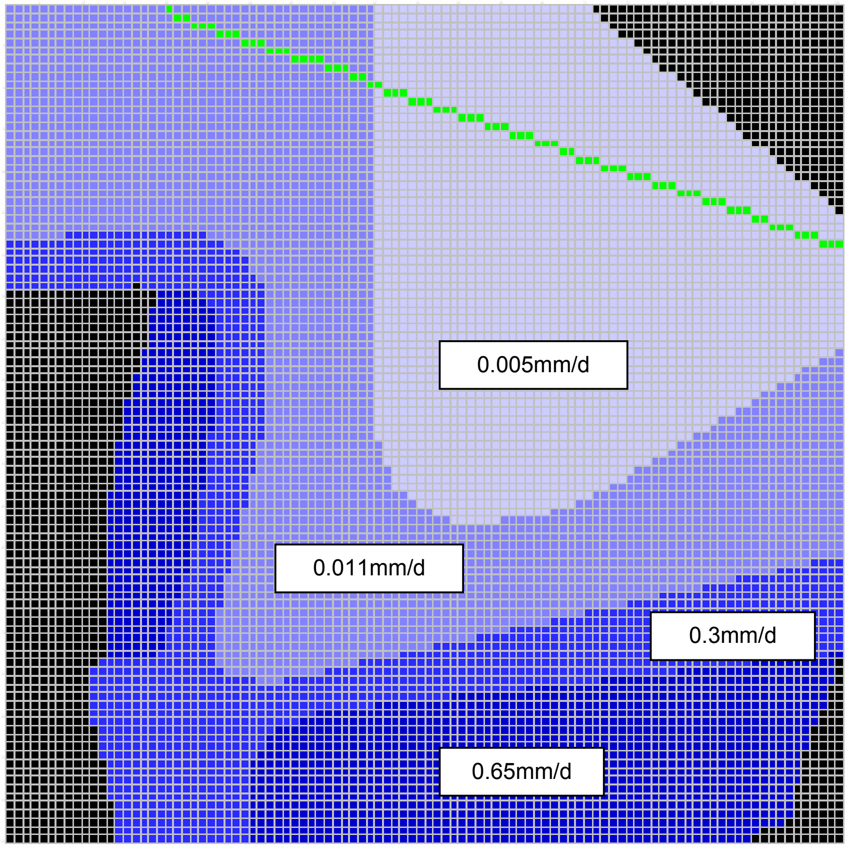

Figure A-4 Modelled recharge distribution (Grant, 2007)

RESULTS

The results of running this numerical model in Modflow and Modpath are presented in **Figure A-5**. The particle traces show that the water recharging over the Riviersonderend Mountains in the south flow in a northerly direction within the Peninsula Formation, until they encounter the Brandvlei Fault zone, which deflects the flows towards the hot spring. This suggests that the conceptual model is feasible.

The flow rate calculated by Modpath indicates that the water takes approximately 400 years to travel through the aquifer to the spring, which is similar to that estimated from the mass balance calculations (375 years). The catchment area for the spring is approximately 280 km^2, which is similar to the value obtained from the mass balance calculations and the thermal modelling (300 km^2).

MODEL CONFIDENCE

The sensitivity of the model to the estimated hydraulic properties and porosity was evaluated using a sensitivity analysis.

The porosity controls the speed with which the water flows through the aquifer. If it is lowered to 0.1% then the water takes less than 100 years to reach the hot spring, however if it is raised to 1% then it takes approximately 1000 years. In either case the water is likely to have reached silica saturation before it discharges at the spring.

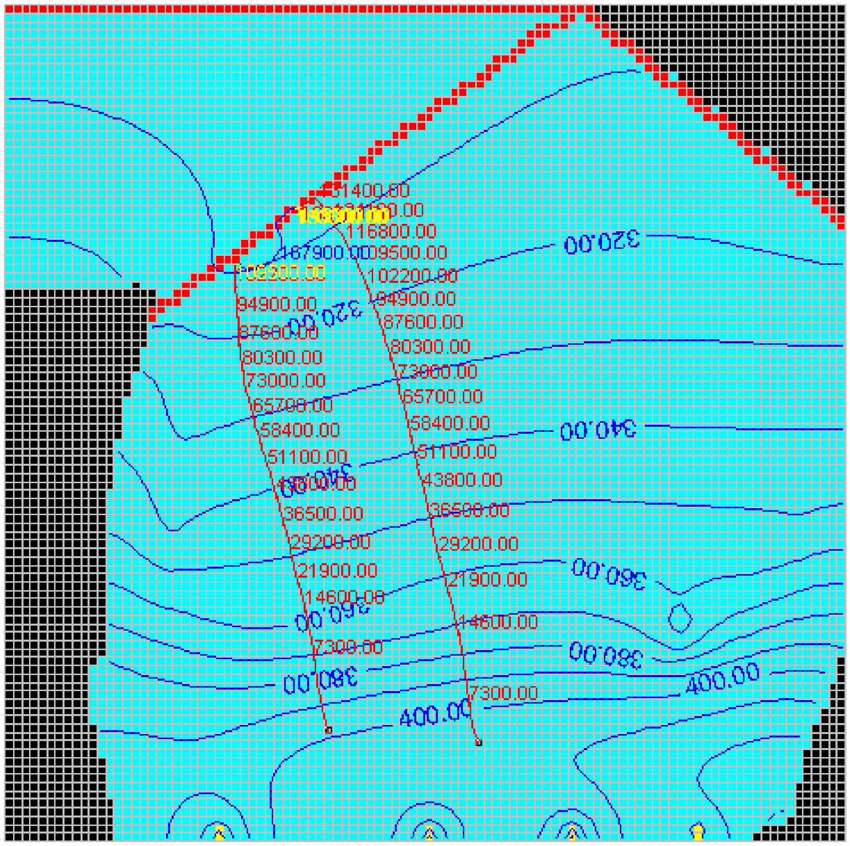

Figure A-5 Modelled flow within the Peninsula Aquifer (Grant, 2007)

Varying the hydraulic conductivity of the fault zone only alters the flow patterns if it is lower than the hydraulic conductivity of the aquifers. Although it is possible that there are sections of the fault zone that do have lower permeability, there is likely to be a fractured or brecciated zone adjacent to the fault plane that will have a higher conductivity than the surrounding aquifer.

Making the aquitards isotropic leads to more water migrating up towards the river and decreases the impact of the high permeability fault zone on the flow paths. However, this scenario is extremely unlikely, given the interbedded shales within the aquitards, which are of very low permeability, as demonstrated by the use of the Bokkeveld Shale as the liner of the Greater Brandvlei Dam.

Increasing the recharge leads to flooding of the model, suggesting that the drains need to be mapped with more accuracy to reflect the movements of the shallow groundwater more effectively. Lowering the recharge leads to a flattening of the piezometric surface in all the layers, with the waters flowing very slowly northwards towards the river. This does not reflect the current conditions in the area, but is an interesting example of one of the possible results of climate change.

Although the model was not fully calibrated against real data, the model results are feasible and resemble the expected flow pattern, water levels and balances. The applied input parameters are in a reasonable range.