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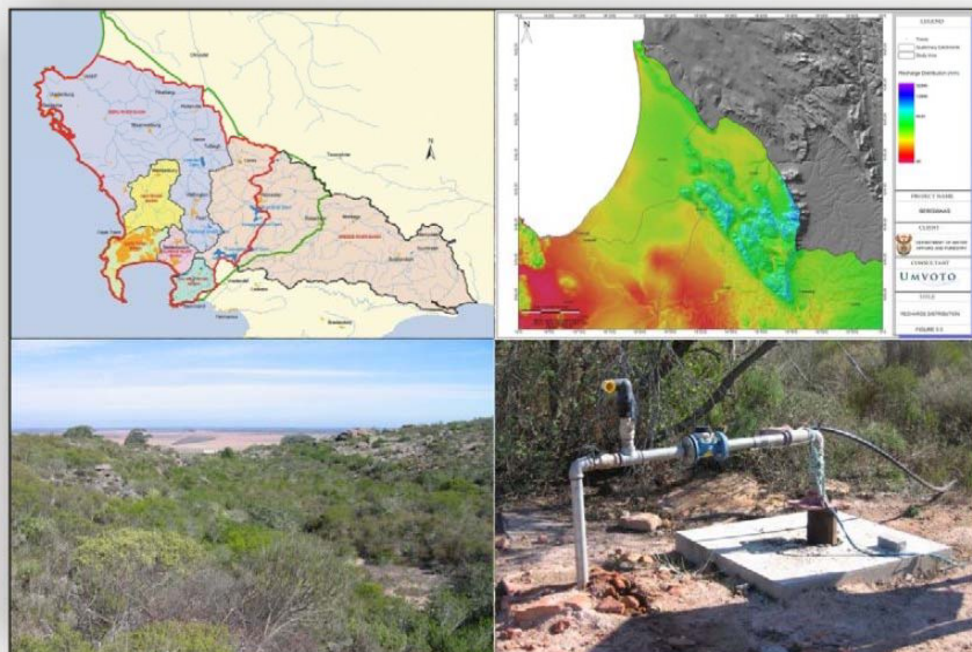
Department of Water Affairs and Forestry

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. 7
TMG AQUIFER, PIKETBERG MODEL



Final **August 2008**

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

FOUNDED IN 1932 NINHAM SHAND CONSULTING SERVICES

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DEPARTMENT OF
WATER AFFAIRS AND FORESTRY

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

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

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APPROVAL

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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 7 TMG AQUIFER, PIKETBERG MODEL

EXECUTIVE SUMMARY

INTRODUCTION

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

- 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: Summary Groundwater Availability Assessment (due at end of project)

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

Volume 6: Langebaan Road Aquifer

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium

This report is Volume 7 in the project series and contains the results of a water balance model for the Table Mountain Group aquifers in the Piketberg area. It should be read in conjunction with Volume 2, describing the data availability and Volume 3, describing the conceptual model, as the conceptual model has informed the delineation of Integrated Water Resources Management domains and the breakdown into aquifer types, as used in the water balance model.

STUDY DOMAIN

The Piketberg model domain extends from Elands Bay at the Atlantic coast along the Verloren Vlei valley towards the north eastern part of the Piketberg mountain range, from where it follows the Peninsula – Basement contact to the southern corner of the Piketberg mountain range, west of the town of Piketberg. The southern boundary follows the Peninsula – basement contact towards Aurora and extends westwards to the coast along the surface water divide.

The topography, drainage, hydroclimate, land-use and even the agricultural crops are largely determined by the underlying rock type and its structural character. This strong geological control also exerts an influence on the local climate and land-use potential, through orographic control over precipitation and the widely variable geochemical composition of the different formations. The model domain is host to predominantly rocks of the **Table Mountain Group** (TMG) and the overlying quaternary sediments of the **Sandveld Formation**.

The aquifers considered here include the Table Mountain Group (TMG) aquifers viz. the Piekenierskloof, the Skurweberg and the Peninsula aquifers ("Fractured rock aquifers"), as well as the primary aquifer between the Piketberg mountain range and the coast. The "fractured-and-weathered" or regolith zones are disregarded in this study.

PIKETBERG WATER BALANCE MODEL

It is imperative in this study to establish a groundwater balance that can be reasonably linked to the surface water balance. The main elements of the groundwater balance are recharge, storage and discharge, while the surface water balance comprises rainfall, run-off, evaporation and abstraction. The approach adopted in this study ensures that the input parameters for the estimation of the different components are the same as for the surface water modelling.

Storage

The storage capacity, viz. the total available storage of the different aquifers, is calculated with an in-house developed GIS model based on aquifer geometry calculated using first principles of structural geology and estimated values (based on text book and measured data) for effective porosity and storage coefficient.

The model of the aquifer storage intentionally makes use of low, geologically reasonable values for porosity and aquifer compressibility, so as to provide *minimum estimates of potential yields*. However, as new data accumulate from the TMG aquifers in the study area, these initial porosity and compressibility assumptions will probably be revised upwards.

The results indicate a storage capacity within the Peninsula Aquifer alone of 8 million m^3 (see **Table E-1**).

Table E-1 Rock Volume vs Pore Volume for Peninsula Aquifer, given a porosity of 0.05 (5%)

Peninsula Aquifer	Area (km^2)	Rock Volume (Mm^3)	Pore Volume (Mm^3)
Unconfined portion	236.66	93,974	4,699
Confined portion	53.64	67,202	3,360
Whole Peninsula Aquifer	**290.30**	**161,176**	**8,059**

Recharge

Aquifer specific recharge is estimated using a GIS-based Water Balance Model that takes rainfall, run-off and evapotranspiration into account. The results are compared with other GIS models. In addition, other recharge estimation methods, such as the Saturated Volume Fluctuation method, are applied to compare with the regional estimation.

From the comparison in **Table E-2** it is evident that the map-centric simulation results in reasonable estimates for the TMG aquifers, while the recharge for the intergranular-fractured and intergranular aquifers appears to be relatively high. On the other hand, the water balance method developed for the ISP studies results in higher recharge to the TMG aquifers and lower recharge to the intergranular and intergranular-fractured aquifers. The GRA II method yields the lowest estimates. The averaged recharge from all four methods is used for estimation of the groundwater potential.

Table E-2 Comparison of recharge estimations

Aquifer type	Recharge [million m^3/a]					
	BRBS	ISP	GRA II	Map-centric	Average	SVF conf
Peninsula	10.9	15.0	7.8	13.3	11.8	12.2
Nardouw	1.5	2.2	1.0	2.2	1.8	N/a
Fractured	3.0	2.9	2.4	3.9	3.1	N/a
Intergranular-fractured	2.8	1.7	2.6	4.2	2.8	N/a
Intergranular	18.5	12.0	13.2	26.5	17.6	N/a
Total aquifer specific	**36.8**	**33.9**	**27.1**	**50.1**	**37.0**	**N/a**

Discharge

Discharge from the aquifer systems is two-fold; i.e. natural discharge via springs or baseflow, and groundwater abstraction. For both parameters the currently available regional estimates are disaggregated into aquifer specific values, using assumptions and knowledge about distribution of discharge sites and boreholes. The groundwater contribution to baseflow is set to zero as the rivers in the model domain are classified as ephemeral. However, there are known perennial springs along the TMG outcrop on the southern and eastern side of the model domain.

A comparison between the GRA II data sets on groundwater use and the WARMS database shows significant differences in the total volume of abstraction. The data from the GRA II are considered conservative and will be used in determining the groundwater potential (see **Table E-3**).

Table E-3 Estimated groundwater use per aquifer (after GRA II)

Quaternary catchment	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*
G10K	0.45	0.10	0.06	0.06	0.02	0.69
G30A	0.06		0.11	0.02	1.86	2.05
G30D	0.19		0.21	0.37	1.80	2.57
Total	**0.69**	**0.10**	**0.38**	**0.44**	**3.69**	**5.30**

YIELD MODEL

The water balance and yield model suggests a total remaining long-term averaged groundwater potential of 33 million m^3/a within the study area, based on a comparison of the average recharge estimation, baseflow and current groundwater use (see **Table E-4**).

Table E-4 Summary results of groundwater potential per aquifer (all values in Mm^3/a)

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	11.8	0.4	11.4	0.69	10.69
Nardouw	1.7	0	1.7	0.10	1.65
Fractured	3.1	0	3.1	0.38	2.67
Intergranular-fractured	2.8	0	2.8	0.44	2.39
Intergranular	17.6	0	17.6	3.69	13.87
Total	**37.0**	**0.4**	**36.6**	**5.30**	**31.27**

However, the impact of abstraction and acceptable drawdown within the aquifer determine the groundwater yield on shorter time frames. By utilising the storage capacity of the confined portions alone, the Peninsula Aquifer can deliver a yield of between 2 and 8 million m^3, depending upon the acceptable average drawdown of between 5 m and 20 m respectively.

The results of the water balance and yield model will be used as input to the WRSM and WRYM.

CONCLUSIONS

A robust water balance and yield model was applied to estimate the groundwater potential from different aquifers within the study area as well as to produce reasonable values for input parameters to the groundwater modules of the WRYM and WSAM. The model is based on the following components:

- Aquifer-specific recharge, calculated with a variety of GIS-based methods and compared to / verified with results from previous studies;
- Modelled overland flow, based on slope distribution, as input to the recharge model;
- Modelled evapotranspiration, using the Turc (1954) approach, as input to the recharge model;
- Storage capacity in the Peninsula Aquifer, based on 3-d modelling of the geological structure;
- Aquifer-specific natural discharge, based on groundwater contribution to baseflow and recharge per quaternary catchment;
- Aquifer-specific groundwater use, based on registered use on the WARMS database;
- Storage yield for the confined portion of the Peninsula Aquifer, based on the modelled storativity and reasonable values for specific storage;
- Groundwater potential, based on recharge, baseflow and groundwater use.

RECOMMENDATIONS

The results of the Water Balance Model for the Piketberg Model Domain shows that the uncertainty of the data input as well as the applied method has a significant impact on the reliability of the output and any decision that would be based on these results. It is therefore strongly recommended to initiate a data collection and monitoring programme. The following activities are required for increasing the confidence in the model outputs of any model updates or refinements:

- Conducting a spring hydrocensus including diverse hydrochemical sampling to verify discharge rates;
- Continuous flow monitoring of selected springs, e.g. Aurora spring;
- Conducting a borehole hydrocensus to verify groundwater abstraction;
- Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg aquifers to improve the estimate for the specific storage;
- Hydrochemical sampling at specific river reaches to be used in mixing models for baseflow estimation.

In addition to these data collection activities long-term monitoring should be initiated for the following aspects:

- Rainfall sampling and chemical / isotope analysis in selected recharge areas for calibration of the recharge model with the Chloride Mass Balance and Isotopes;
- Seasonal and event response sampling of rainfall, spring flow and groundwater for calculation of residence time and interflow/rejected recharge;
- Monitoring of key abstraction points for aquifer response to abstraction for considering the impact of existing groundwater use with respect to refining unused potential estimates;
- Monitoring of ambient boreholes in different aquifers to establish seasonal fluctuation of water levels for calibration of recharge estimation.

It is recommended to use the results of the water balance model as input for the WRYM and WRSM. If further exploitation of the aquifers in the Piketberg area is considered, a feasibility study is recommended that comprises the development of a flow model on the wellfield scale, based on long-term monitoring data, as described above.

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 and recovery
ATL	Atlantis IWRM Domain
AWT	Agter-Witzenberg IWRM Domain
BRHS	Breede River Hydrological Study
BRV	Brandvlei IWRM Domain
CAGE	Citrusdal Artesian Groundwater Exploration
CFP	Cape Flats - Peninsula IWRM Domain
CMA	Catchment Management Agency
CRD	Cumulative Rainfall Departure
CSIR	Council for Scientific and Industrial Research
CVA	Change Vector Analysis
DEM	Digital Elevation Model
DISA	Daily Hydrosalinity Model
DWAF	Department of Water Affairs and Forestry
EC	electrical conductivity
ECA	Environmental Conservation Act
EFR	Ecological Flow Requirements
E-W	east-west
EWR	Ecological water requirement
EVT	Evapotranspiration
FE	Finite Element
FT	Pitman Model Parameter
GIS	Geographical Information System
GRA	Groundwater Resources Assessment
HEX	Hex River IWRM Domain
IFR	Instream Flow Requirements
ISP	Internal Strategic Perspective
IWR	Integrated Water Resources
IWRM	Integrated Water Resources Management
KGB	Kogelberg IWRM Domain
km	kilometre
LRA	Langebaan Road Aquifer
m	metre
MAP	Mean annual precipitation
MAR	Mean annual run-off
MOF	Modelled overland flow
N-S	north-south
NEMA	National Environmental Management Act
NEMP	National Eutrophication Monitoring Programme
NGDB	National Groundwater Database
NMMP	National Microbiological Monitoring Programme
NWRS	National Water Resources Strategy
NWA	National Water Act
NUY	Nuy River IWRM Domain
op.cit.	work previously cited
PhD	Doctor of Philosophy
PAJA	Promotion of Administrative Justice Act
PKT	Piketberg IWRM Domain
POW	Pitman Model Parameter

PUB	Paarl – Upper Berg IWRM Domain
RBT	Robertson IWRM Domain
RDM	Resource Directed Measures
RQO	Resource Quality Objectives
SAWS	South African Weather Service
SFRA	streamflow reduction activities
SL	Pitman Model Parameter
ST	Pitman Model Parameter
STCC	short term characteristic curve
SVF	Saturated Volume Fluctuations
TDS	Total dissolved solids
THK	Theewaterskloof IWRM Domain
TMG	Table Mountain Group
TMGA	Table Mountain Group Aquifer
TOR	Terms of Reference
TWR	Twenty-four River IWRM Domain
VAS	Voëlvlei Augmentation Scheme
VHIMS	Vaal Hydrological Information Management System
VVT	Voëlvlei – Tulbagh IWRM Domain
WAA	Water Availability Assessment
WAAS	Water Availability Assessment Study
WARMS	Water-use Authorisation and Management System
WBK	Warm Bokkeveld IWRM Domain
WCSA	Western Cape System Analysis
WCT	West Coast IWRM Domain
WCWSS	Western Cape Water Supply System
WECSA	Western Cape Situation Assessment
WfW	Working for Water
WMA	Water Management Area
WRC	Water Research Commission
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WR	Water Resources
XLS	Excel Spreadsheet
ZMAX	Pitman Model Parameter
ZMIN	Pitman Model Parameter

1. INTRODUCTION

1.1 THE BERG 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 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 stream flow 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.

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

- 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 Study with model-based assessment of water resource augmentation options.

Ninham Shand (Pty) Ltd is the Lead Consultant for the Berg WAAS 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 complete 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 complete Palmiet and Steenbras catchments in the south of the Study Area, which flow in a southwesterly 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.

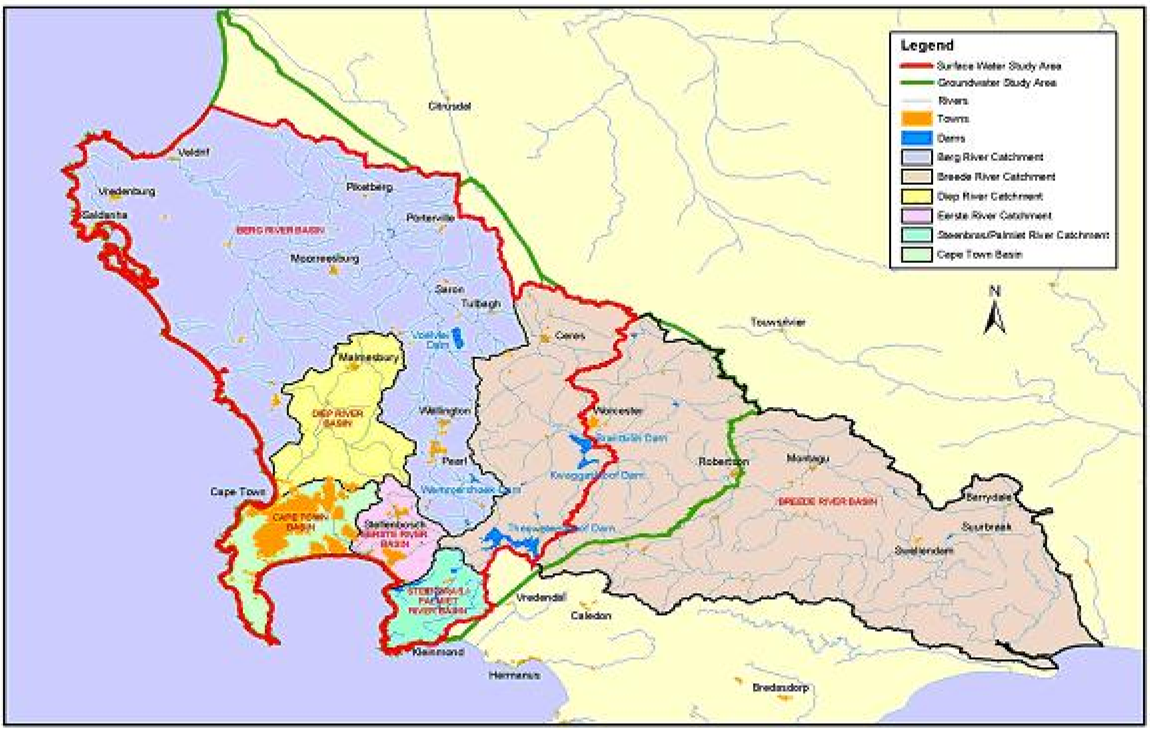


Figure 1-1: Study Area Locality

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 hydroelectric 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 N-S and E-W 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, 2004) 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.

Allocation of future surface water involves a 2D analysis of the hydrology and current use. Similarly 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. This is primarily a 3D problem in the study domain.

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

- total amount of water available within the catchment;
- temporal and spatial distribution of water availability;
- current and future water requirements;
- 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 aquifer development and management given the *status quo*.

The contrast between the 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 range of values for model input parameters. As improved data becomes available the range in value of model input variables or scenario testing is narrowed down.

The manner in which surface and groundwater model usage should 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 stream flows 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 bulk water supply to the City of Cape Town (in support of Western Cape Reconciliation Study)
    - Scenario for flood management (in support of Western Cape Reconciliation Study)
- Task 14: Review and update conceptual model for West Coast aquifers
    - Review of 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 Langebaan Road Aquifer
    - Refinement of surface water – groundwater interaction
    - Refinement of recharge and yield estimation
    - Scenario for artificial recharge schemes (in support of Western Cape Reconciliation Study)
- Task 15: Water balance and storage model for TMG Aquifer
    - Recharge estimation and water balance on 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 (in support of Western Cape Reconciliation Study)

- 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 Hex River Mountains
  - Quantification of surface water – groundwater interaction
  - Refinement of recharge and yield estimation
  - Scenario for Aquifer Storage Recovery (ASR) schemes (in support of Western Cape Reconciliation Study)
- 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 below are to be read in conjunction with each other 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 complete set of volumes are:

Volume 1: Summary Groundwater Availability Assessment (due at end of project)

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

Volume 6: Langebaan Road and Geelbek Aquifer Systems

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium

This report is Volume 7 of the groundwater model report and documents the model results of Task 15d. It should be read in conjunction with Volume 3 (DWAF, 2007b), which describes the study area and conceptual model, and Volume 4 (DWAF, 2007e), which describes the approach to and methodology of the water balance model. Details of the approach and methodology are not repeated in this volume.

1.2 TMG AQUIFER, PIKETBERG MODEL REPORT

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 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 Piketberg Model Domain is located in the north-western corner of the study area. It includes the area above the westerly extension of the Saron-Aurora Megafault Zone from the coast below Elands Bay as far as the Peninsula Formations contact with the Malmesbury shales east of Piketberg. The northern boundary of the Model Domain extends to the overall study boundary at the Verlorenvlei River.

The Piketberg area is predominantly rural with a very small population compared to the remainder of the Berg WAAS area. The ~800 to ~1400 m high Piketberg Mountains in the south-eastern corner give way to coastal dunes to the west before meeting the ocean in Elands Bay. The surface-water run-off is controlled by this surface topography, draining westward toward the coast by means of the Krom Antonies River and Verlorenvlei River. Surface-water flow also drains southward into the Lower Berg River by means of the Boesmans and Platkloof rivers.

The Piketberg Mountains are made up of the Lower TMG sequence including the Graafwater and Piekenierskloof formations forming the base overlain by the Peninsula and Nardouw Formations. Several outcrops of basement Malmesbury Formation occur in the north-eastern part of the Piketberg area, and this basement underlies the coastal dunes in the west. It is suspected that the Peninsula Aquifer that outcrops in the Piketberg Mountains also extends north-west along a strike below the Sandveld Aquifer although it is unknown to what extent.

In order to evaluate the conflicting interests of using this aquifer and its impact on the surface water resources of the lower Berg River, it will be necessary to use a 3D modelling tool to:

- Model different abstraction scenarios under different actual and predicted rainfall conditions,
- Model different scenarios under different hydrological conditions (e.g. flood, drought, surface water abstraction),
- Evaluate lateral and vertical inflow/recharge and discharge into open water bodies
- Evaluate impact of preferred abstraction scenario on existing wetlands, open water bodies, and areas of natural/indigenous/protected vegetation.

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 and ocean,
  - Yield estimation,
  - Rainfall dependency of gw-sw interaction, recharge and yield,
- Identification of areas and quantification of high impact of aquifer abstraction on stream flow,
- Identification of key data gaps and uncertainties in quaternary-scale resource evaluation.

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 Piketberg Integrated Water Resource Management Domain (Piketberg) is situated in the north-western part of the Berg WAAS area. It is a relatively small domain with a total area of 1 303.42 km^2. The Piketberg is bounded by the Atlantic Ocean on the West Coast and the West Coast to the south. The northern boundary follows the Berg WAAS study area boundary, a combination of both quaternary and quinternary boundaries. The eastern boundary follows the Table Mountain Group-Malmesbury contact that roughly parallels the northern segment of the quaternary catchment boundary separating the G10H and G10K. Surface-water flow occurs from the highlying Piketberg Mountains of the Table Mountain Group outcrop in the southeast by means of the Verlorenvlei River, through the coastal dunes to the Atlantic Ocean in the northwest.

The Piketberg comprises both Lower Table Mountain Group rocks inland and quaternary sediments of the Springfontein and Langebaan Formations with wind-blown dune sands bordering the coast. These sediments are underlain by Malmesbury basement in the northern half of the Piketberg and southwest of the Piketberg-Aurora Fault extension. It is highly likely that the Peninsula Formation extends along a strike below the quaternary sediments towards the coast. Groundwater flow occurs in the Peninsula Aquifer from the southeast toward the sea, recharging the Sandveld Aquifer that extends NE-SW along the Verlorenvlei palaeo channel.

The Piketberg is classified as a Fractured rock + Intergranular-Integrated Water Resources Management Domain, because future integrated ground and surface-water scheme development in this area will be based around the Table Mountain Group aquifers in the Piketberg range and the postulated palaeo channel linking the Velorenvlei drainage to the coastal plain south of Elands Bay.

The piezometric map developed in Volume 3 (DWAF, 2007b) illustrates that the water levels relative to the mean annual sea level are highest in the valleys opening out of the Piketberg Mountains in the southeast corner, decreasing towards the coast. It is noted here that the water levels also decrease toward the Berg River towards the south.

The main groundwater resource of interest in the Piketberg region is the Peninsula Aquifer, which straddles the divide between the Berg River drainage and the south-western part of the Olifants-Doorn WMA, i.e. the Verlorenvlei drainage system. Within the Piketberg, there are also zones where the Skurweberg Aquifer is locally significant. Along the western faulted margin of the Piketberg range, springs emerging from the Table Mountain Group aquifers in the Piketberg feed streams and groundwater in palaeo channels towards the lower Berg River, and together with boreholes are the sole supply to the small settlements along the south-western slopes of the mountain, e.g. the village of Aurora. The fractured rock groundwater is recharged in the mountains of Piketberg and discharged at sea beyond Elands Bay. Groundwater flow in the Peninsula Aquifer is from south-east to north-west.

Sub-surface discharge probably also recharges the Sandveld aquifers on the western and northwestern slopes of the Piketberg, north of the Berg Water Management Area boundary in the G30A catchment. From 1998 drilling results around the farm Bottelfontein, relatively good quality groundwater (electrical conductivity down to 61 mS/m) was discovered within one to four units of “quartzitic gravel” (TMG clasts?), interbedded with sands, clays and peats, within a dune-sand concealed palaeo channel overlying weathered Malmesbury bedrock at depths reaching ~49 m below sea level at a distance of ~3 km from the coastline. Groundwater flow in the intergranular aquifer drains from east to west. Water quality in this deeper aquifer is markedly better than in the overlying unconfined, fine sands, which indicates lateral recharge at depth.

1.2.3 Structure of this Volume of the Report

This volume of the report is structured into eight sections with several sub-sections each.

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

Section 2 provides a general description of the model domain in terms of topography, drainage, hydroclimatology, hydrogeology and water use.

Section 3 describes the general approach and methodology adopted in this study for the water balance model.

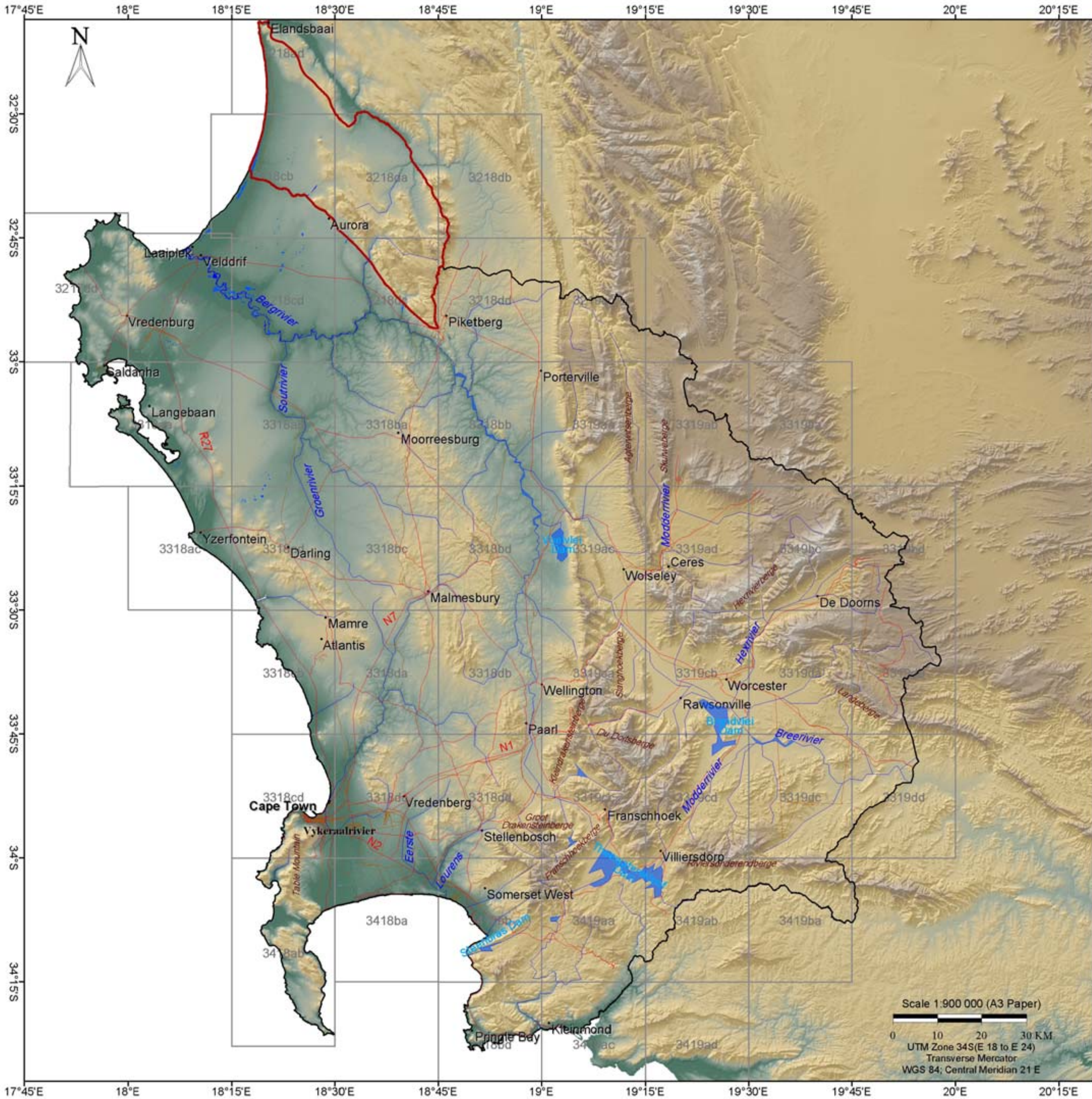
Section 4 describes the storage model methodology and results for the TMG aquifers

Section 5 describes the aquifer specific recharge models.

Section 6 describes the approach to and results of the discharge estimation, which includes both the natural discharge via springs and along rivers and the groundwater abstraction.

Section 7 uses the principles and results described in the previous chapters to give a first order estimate of aquifer yield and potential

Section 8 summaries the conclusions and recommendations.



LEGEND

- Towns
- Rivers
- Roads
- Dams
- Berg Boundary
- 1: 50 000 Toposheet
- Model Domain

Elevatiom (mamsl)

2101
1576
1313
1051
788
525
263
0

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

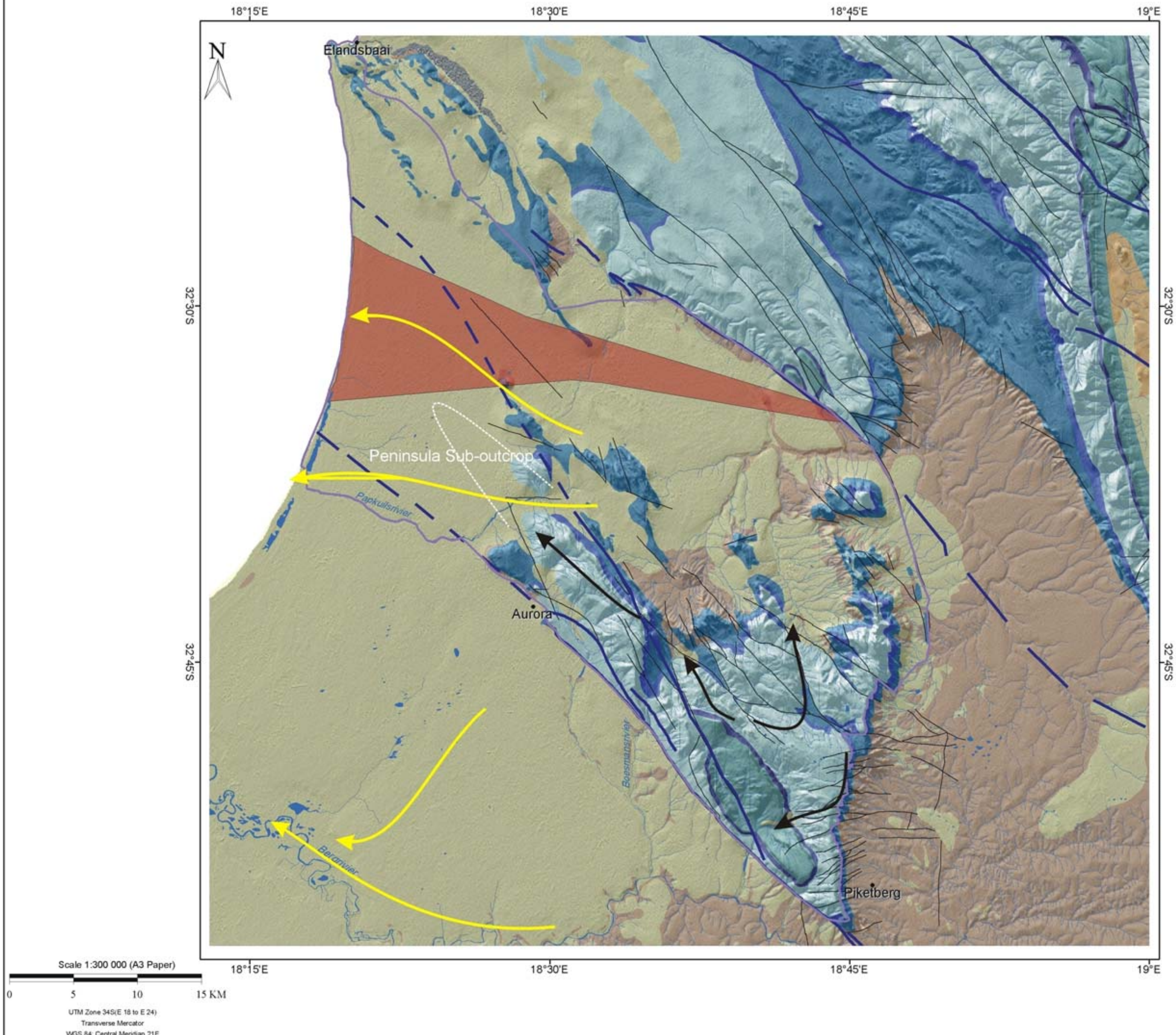
CONSULTANT

UMVOTO

TITLE

LOCALITY MAP

FIGURE 1.2



LEGEND

- Towns
- Rivers
- Faults
- Hydrotects
- Piketberg Model Domain
- De Duine Palaeochannel

(For geology legend refer Figure 5.1)

- Flow Paths (Peninsula)
- Flow Paths (Sandveld)

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

CONSULTANT

UMVOTO

TITLE

CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE PIKETBERG AREA

FIGURE 1.3

2. GENERAL DESCRIPTION OF THE STUDY AREA

A detailed description of the study domain, its physiography, hydrology, hydroclimatology and geology, is given in Volume 3 of this report (DWAF, 2007b). The following section gives a summary description as relevant to the purpose of this report. In addition further analysis is reported on.

The Model Domain for the Piketberg model is defined by the IWRM Domain boundaries, as defined in the Conceptual Model Report (Volume 3; DWAF, 2007b). The Piketberg Integrated Water Resource Management Domain (PKT) is situated in the north-western part of the Berg WAAS area. It is a relatively small domain with a total area of 1 303.42 km^2. The Piketberg is bounded by the Atlantic Ocean on the West Coast and the WCT to the south. The northern boundary follows the Berg WAAS study area boundary, a combination of both quaternary and quinternary boundaries. The eastern boundary follows the TMG-Malmesbury contact that roughly parallels the northern segment of the quaternary catchment boundary separating the G10H and G10K. Surface-water flow occurs from the highlying Piketberg Mountains of the TMG outcrop in the southeast by means of the Verlorenvlei River, through the coastal dunes to the Atlantic Ocean in the northwest (see **Figure 2-1).**

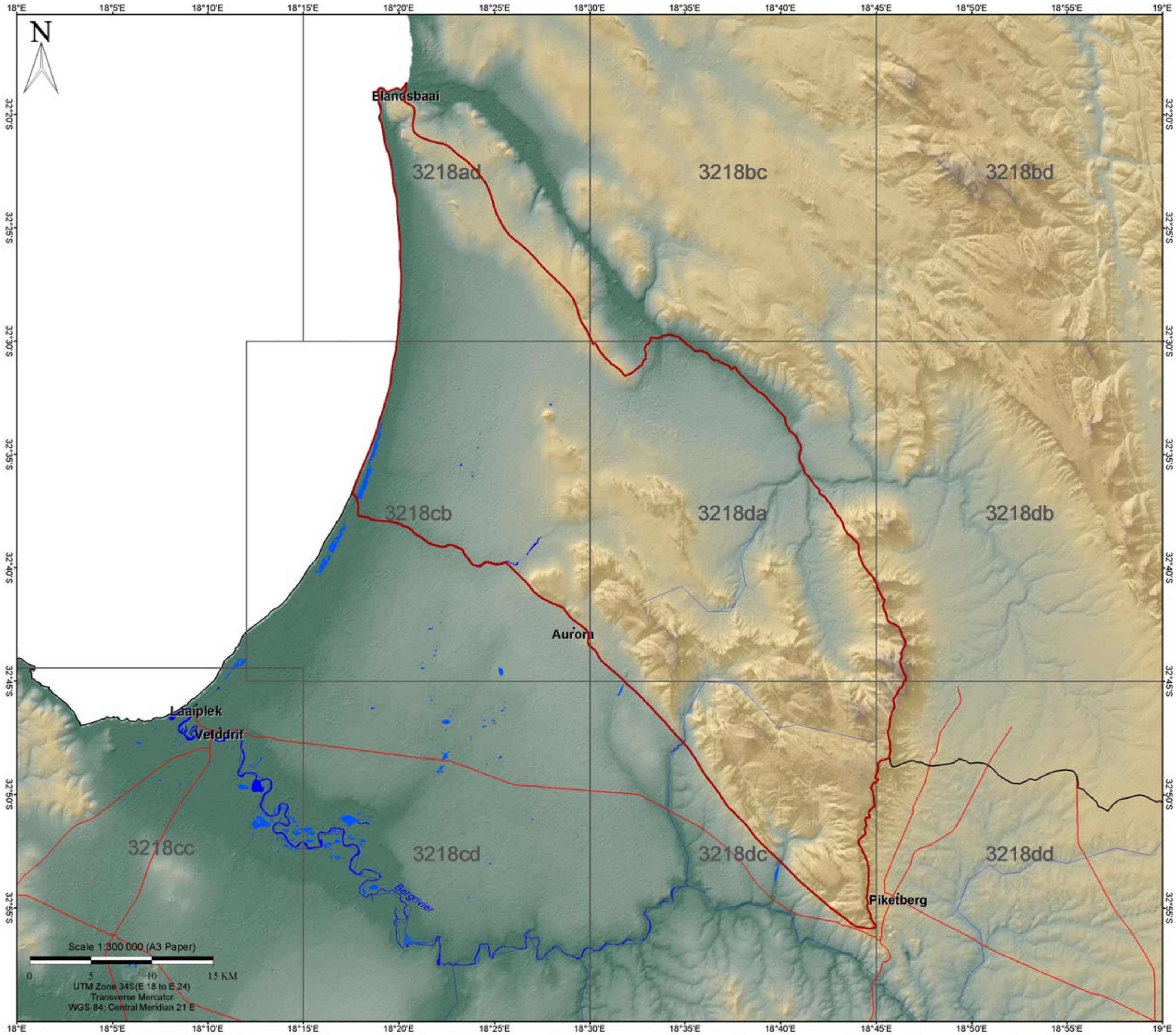
2.1 TOPOGRAPHY

The topography of the study area is dominated by an outlier of Table Mountain Group rocks that form an arcuate range of mountains, which extend in a N-S (Piketberge) and North West-South East (Skurweberge) direction from the town of Piketberg. The ranges have an average elevation of 300 m to 1000 m above MSL, with the highest point, Zebrakop, reaching an elevation of 1458.4 m above MSL (see **Figure 2-1)**. Numerous NW-SE orientated faults form deeply incised valleys within the ranges, e.g. Moutons and Voorste valleys, with the relatively large and distinct Piketberg Syncline forming the Wolfkloof Valley. A further outlying range of Piekenierskloof Formation sandstones at the edge of the Piketberg Model Domain form a NW-SE running ridge that runs parallel to the Verlorenvlei River and wetland system and ends at the coast, forming the Elands Bay peninsula (see **Figure 2-1)**. Between the Piketberg range and the Atlantic Ocean to the northwest, and Skurweberg range and Berg River to the southwest, is a flat coastal plain known as the Sandveld. The distinct linear elevation change between the Sandveld plains in the southwest and the Piketberg/Skurweberg range is due to the NW-SE orientated Piketberg-Aurora Fault Zone (see **Figure 2-1)**. The relatively flat Sandveld topography is characterized by extensive endorheic and ephemeral drainages due to the dominance of aeolian processes and parabolic dune formation in its recent (i.e. post-late Pliocene) geological history.

2.1.1 Slope Analysis

A model of slope gradients was produced (**Figure 2-2)** from the high-resolution (20 m pixel resolution) digital elevation model. At this scale, the areas of moderate (~30-50°) and high (>50°) slope angle are associated with TMG-dominated areas, in the ranges of the Cape Fold Belt, and also the Peninsula (G22A-B), Piketberg (G10K-G30D) and Riebeeck Kasteel (G10F-G21C) outliers.

As discussed in **Section 4.2.3** below, the slope angle θ is an important factor determining the run-off potential for individual slope elements in the digital slope model, and is used in the derivation of an overland-flow relationship within particular subcatchments and IWRM domains.



LEGEND

- Towns
- Rivers
- Roads
- 1: 50 000 Toposheet
- Model Domain

Elevatiom (mamsl)

1500
1200
900
600
300
0

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

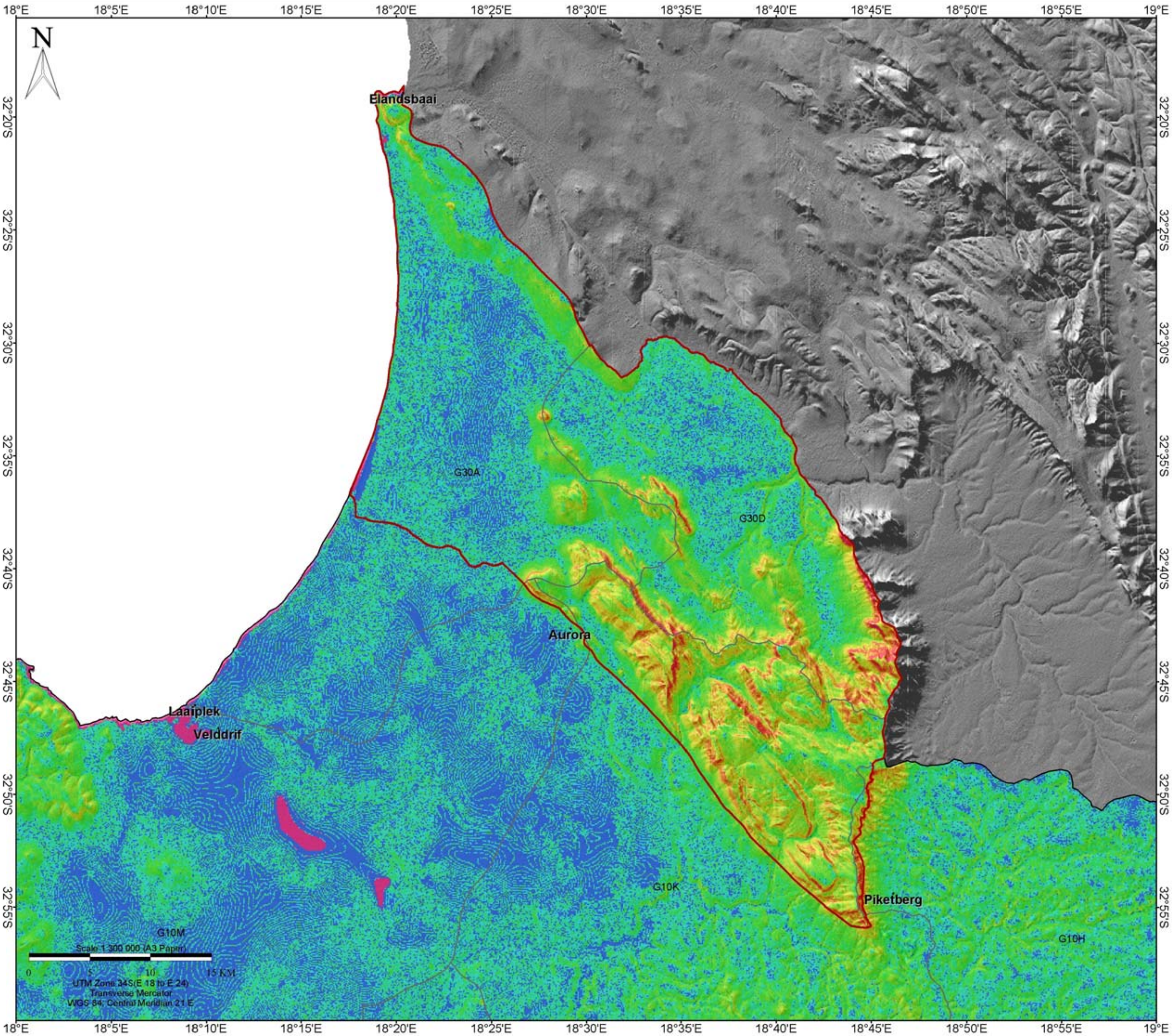
CONSULTANT

UMVOTO

TITLE

TOPOGRAPHY AND INFRASTRUCTURE

FIGURE 2.1



LEGEND

Towns

Quaternary Catchments

Model Domain

SLOPE (Degrees)

- 0 - 0
- 1 - 1
- 2 - 2
- 3 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 50
- 50 - 60
- 60 - 71

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

CONSULTANT

UMVOTO

TITLE

SLOPE MODEL

FIGURE 2.2

2.1.2 Slope Histograms

The spatial distribution of slope varies widely within the model domain. This is easily and visually evident from the topography (**Figure 2-1**) and the slope model (**Figure 2-2**). The statistical analysis of the slope distribution shows a lognormal distribution, while the cumulative histogram depicts a general exponential function indicating a high percentage of flat areas and fewer areas of steep slopes. The median slope is ~2.5 degrees and the maximum slope (based on the slope model) is 60 degrees.

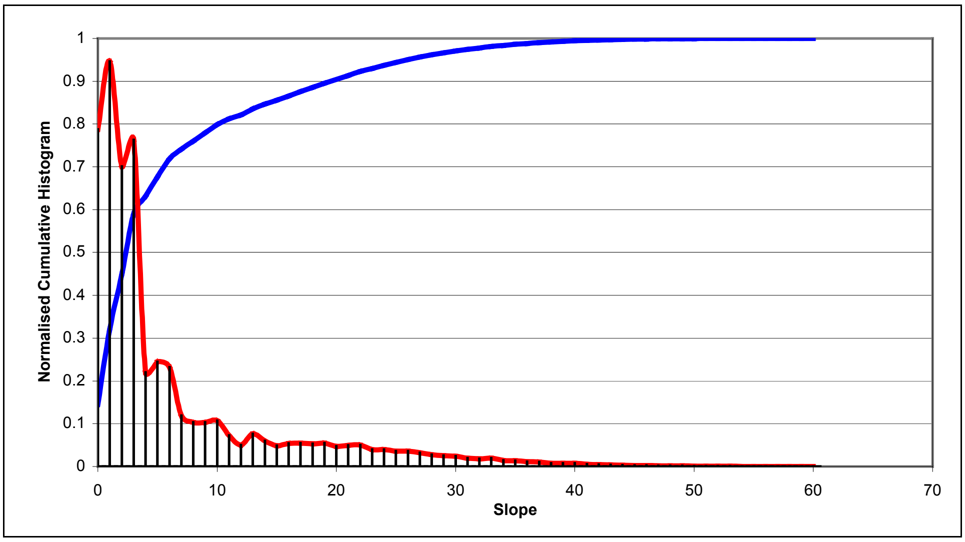


Figure 2-3 Slope distribution in Model Domain; Histogram (red curve) and Normalised Cumulative Histogram (blue curve)

The statistical analysis of the slope distribution and its relationship to geology, hydroclimatology as well as hydrology and hydrogeology is considered relevant, since slope is one of the main factors determining run-off. As demonstrated in the Regional Water Balance Model Report (DWAF, 2007e) the run-off efficiency of a catchment shows a general dependency on mean and maximum slope.

The shape of the cumulative histogram varies significantly between different catchments. Based on different slope distribution, the catchments in the Berg WAAS study domain were grouped into 10 distinctive groups, numbered from Group 1 for predominantly steep areas to Group 9 with predominantly flat areas; Group 7 and Group 0 comprise catchments with a bimodal distribution (see Volume 4; DWAF, 2007e).

The spatial distribution of these groups highlights the relationship between slope distribution and topography. However, it also illustrates that catchment boundaries do not necessarily align with geological and earth-process boundaries. This is especially obvious in the Piketberg area.

Group 7 comprises, *inter alia*, the catchments G10H, G10K and G30D of the Piketberg area, which are all characterised by large flat areas, but show a bimodal character in that they also comprise a component of very steep slopes, mainly along TMG outcrop.

Group 9 comprises, *inter alia*, the coastal catchments G30A, G10L and G10M that are characterised by very flat areas and few undulating hills due to bedrock outcrop (highest slope of 50°).

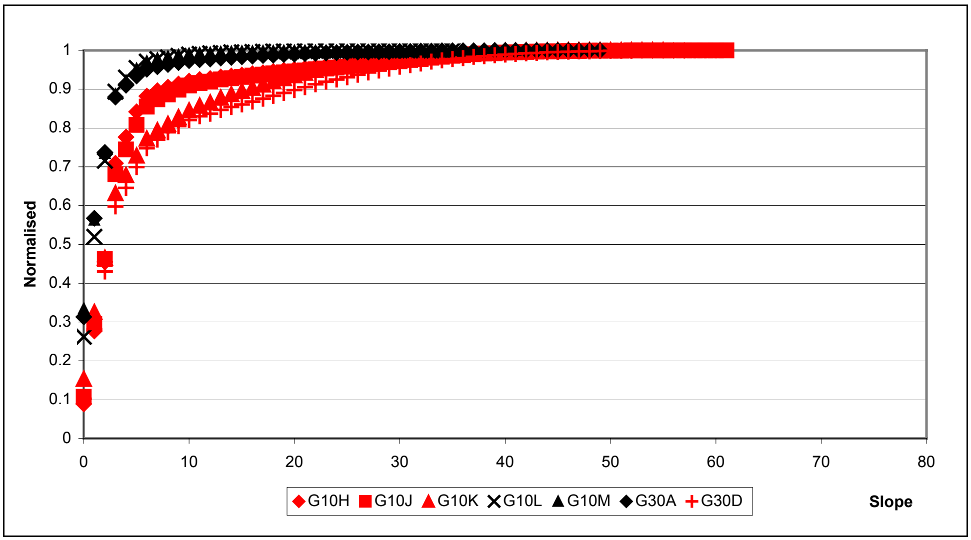


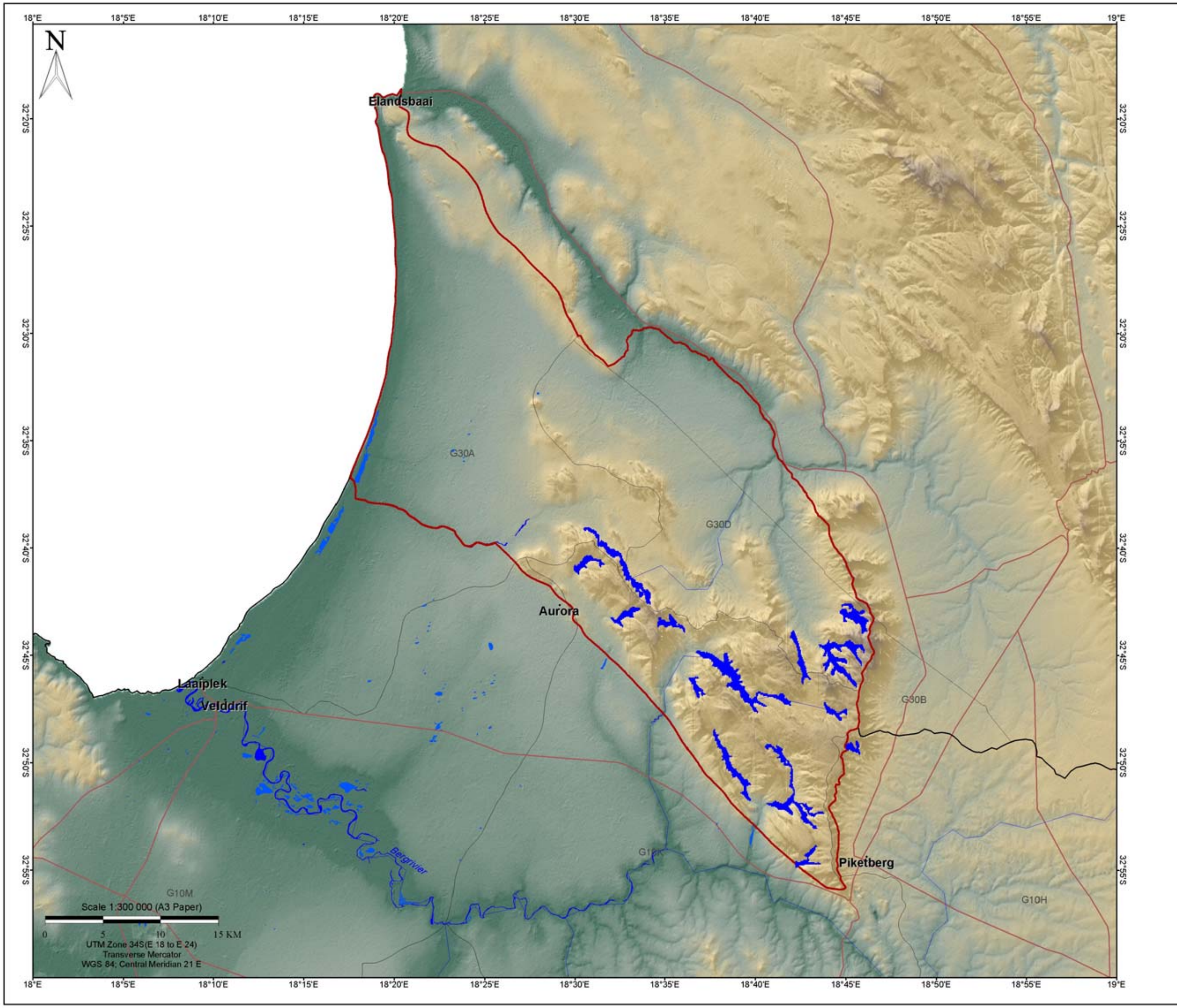
Figure 2-4 Slope distribution for catchments in model domain; red – Group 7; blue – Group 9

2.1.3 Terrain Roughness

A terrain roughness map was developed for the Regional Water Balance Model (DWAF, 2007e). As expected the map clearly shows that the roughest terrain is located in the Table Mountain Group-dominated, high-mountain areas, which are also the areas of higher orographic rainfall. In addition the relative relief was calculated from the Digital Elevation Model, to obtain a distinction between areas above and areas below the smoothed surface. The result is a map similar to the terrain roughness map showing positive values in the high mountain peaks and negative values in the valleys.

The relative relief clearly indicates areas within the valleys that can be considered discharge areas. For the application in the run-off and recharge model these areas are delineated with a threshold value of –40 (**Figure 2-5**), as this appears to be the best fit across the study domain. The recharge in these areas is then set to zero, as it is assumed that no recharge occurs in these clearly delineated discharge areas.

Similarly, areas outside of these discharge zones are considered recharge areas with the areas of positive relative relief, i.e. highlying and rough terrain, contributing most probably higher recharge, as these areas also coincide with the high rainfall areas.



LEGEND

Towns
Rivers
Roads
Model Domain
Quaternary Catchments
Study Area

Relative Relief

<40

Elevatiom (mamsl)

-7 - 45
46 -80
86 - 100
100 - 150
150 - 400
400 - 900
900 - 1100
1100 - 1500
> 1500

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

RELATIVE RELIEF

FIGURE 2.5

2.2 HYDROLOGY AND HYDROCLIMATOLOGY

2.2.1 Hydrology

The model domain comprises the southern part of the G30 tertiary catchment (G30A and G30D) of the Olifants Doorn WMA and straddles the lower parts of the G10 tertiary catchment (G10K) in the Berg WMA (see **Figure 2-6**).

The G10 tertiary catchment covers the Berg River catchment from its source in the Groot Drakenstein Mountains to the Berg River mouth at Laaiplek on the West Coast. Main storage reservoirs in the Berg River catchment include the Wemmershoek and off-channel Voëlvlei dams, while the construction of the Berg River Dam near Franschhoek was completed in 2007 (DWAF, 2005a).

2.2.2 Hydroclimatology

The study area experiences a typical Mediterranean climate with moderate temperatures and winter rainfall. Hydroclimatology data is further addressed in Volume 2 of this report (DWAF, 2007a). Key hydroclimatology data and patterns used in the water balance model are discussed and illustrated below.

Precipitation

As can be expected in an area where the rainfall is orographically controlled and the altitude range is from 0 mamsl in the west to a maximum of 1458 mamsl on the Zebrakop in the southeast, the Mean Annual Precipitation (MAP) varies significantly across the study area. It is highest in the high mountains in the east and south where the average rainfall is greater than 1000 mm/a, while it is less than 200 mm/a along the flat-lying coastal plain. The averaged MAP per catchment varies between 225 mm/a along the coast (G10M) and 400 mm/a inland (G30D and G10H).

As illustrated in Volume 2 (DWAF, 2007a), it was required to develop a revised spatial distribution of MAP, based on additional rainfall data and rainfall stations (DWAF, 2007c). The revised MAP distribution as shown in **Figure 2-7** is used in this study.

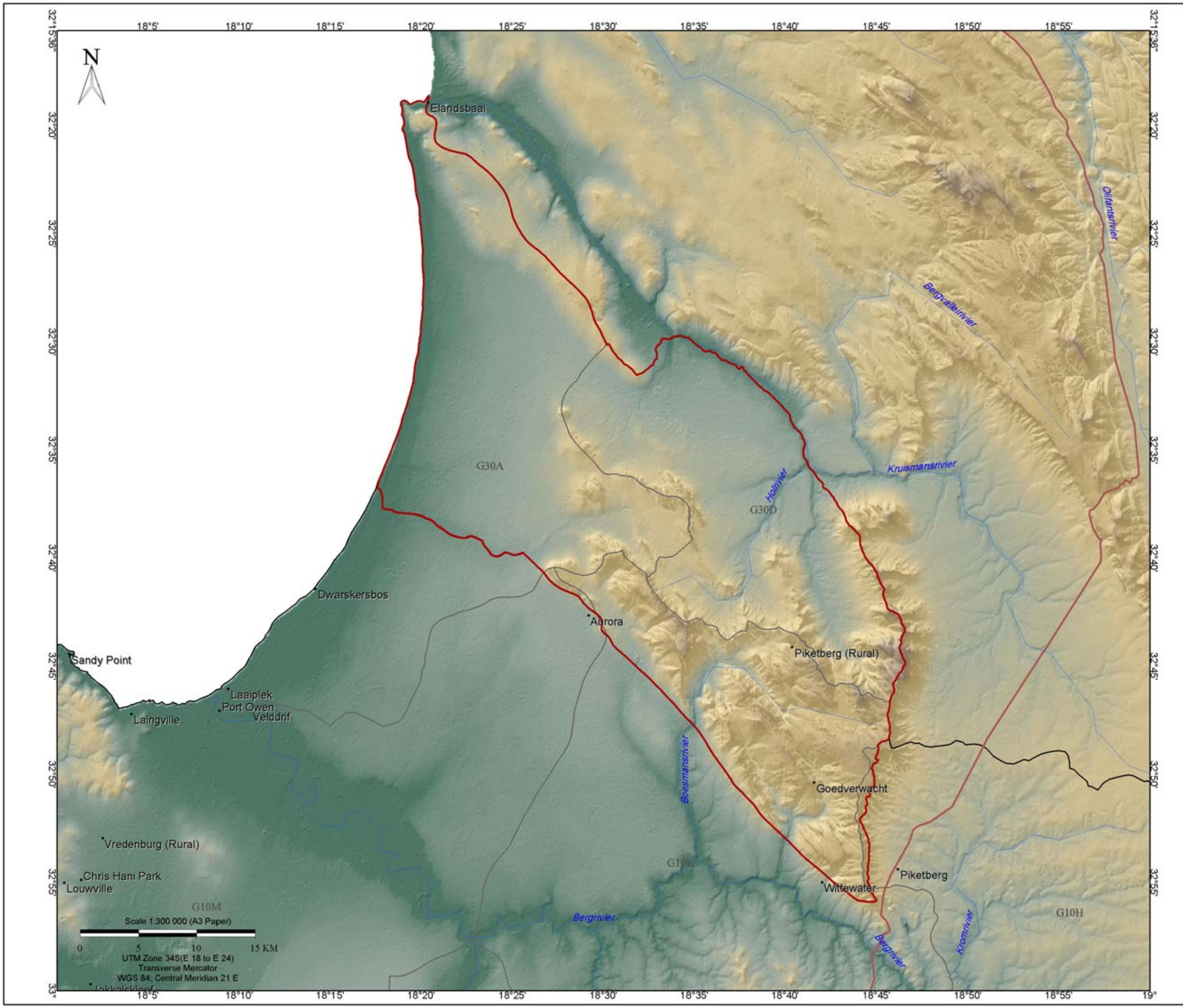
The seasonal pattern of rainfall is critical in the estimation of recharge since the aquifers are recharged in winter when the temperature and therefore evapotranspiration are also very low.

Run-off

The mean annual run-off (MAR) parallels the trend of mean annual rainfall with most river flow occurring in the high-lying mountains. Most recent estimates (WR2005) indicate that about 26 mm of water is discharged as run-off from the Piketberg mountains every year (G30D). This decreases toward the coast to about 13 mm of run-off per annum in G30A. The MAR values per quaternary catchment, as published in the WR90 report (Midgley et al., 1994a) and the WR2005 study are documented in Appendix A.

Evaporation

The mountain ranges and the ocean influence and moderate the Mean Annual Evaporation (MAE) resulting in increasing evaporation in the interior. The *potential* evaporation along the coast ranges between 1 300 and 1 400 mm/a, while the *potential* evaporation further inland ranges between 1 400 and 1 500 mm/a.



LEGEND

- Towns
- Rivers
- Roads
- Model Domain
- H40H Quaternary Catchments
- Study Area

Elevatiom (mamsl)

- 60 - 100
- 100 - 140
- 140 - 530
- 530 - 970
- 970 - 1500
- 1500 - 1900

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

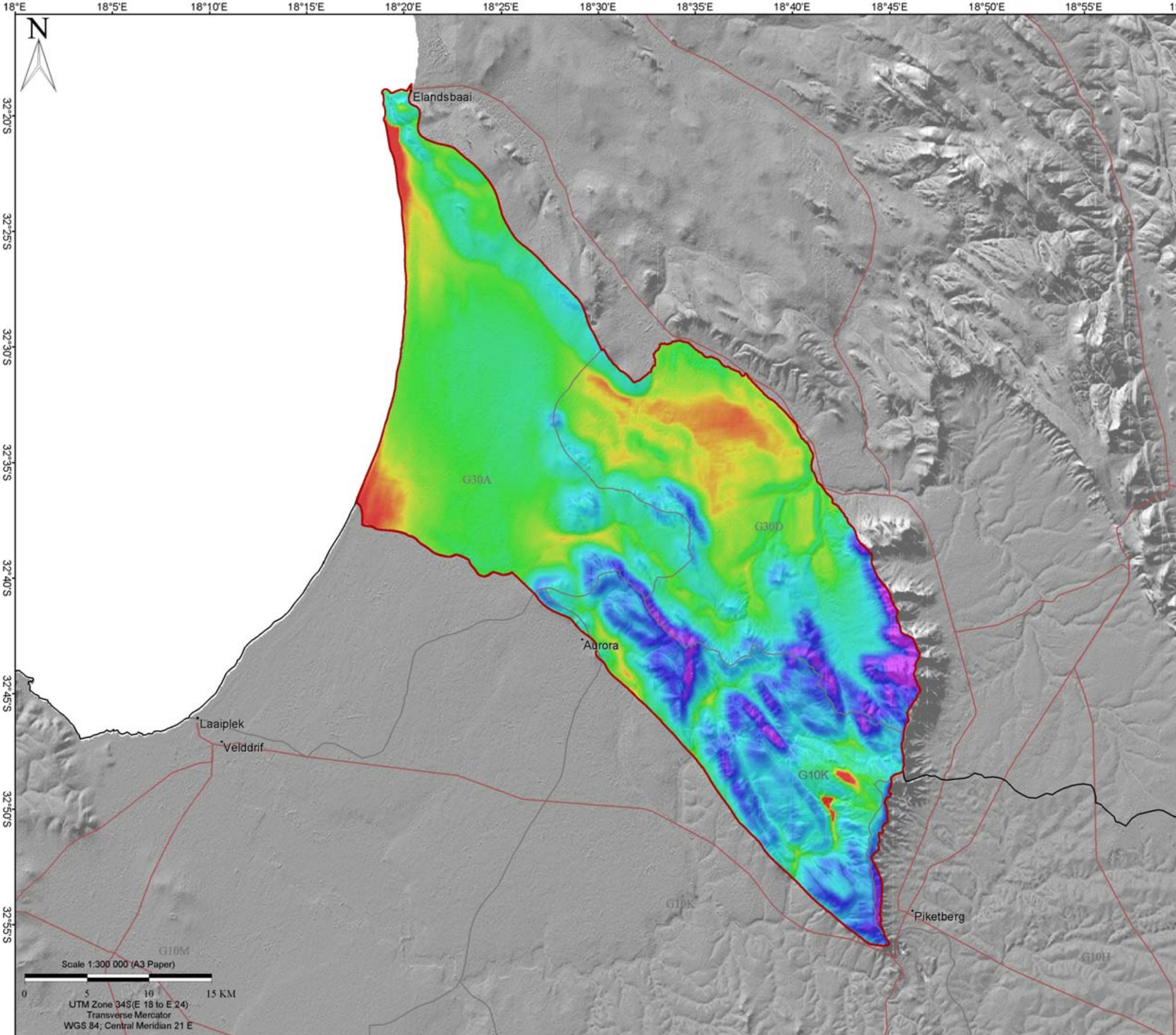
CONSULTANT

UMVOTO

TITLE

TOPOGRAPHY AND DRAINAGE

FIGURE 2.6



LEGEND

- Towns
- Roads
- Model Domain
- Quaternary Catchments
- Study Area

Rainfall (mm/a)

- 200 - 260
- 260 - 270
- 270 - 280
- 280 - 300
- 300 - 340
- 340 - 410
- 410 - 500
- 500 - 600
- 600 - 730
- 730 - 880
- 880 - 1120

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RAINFALL DISTRIBUTION (MAP)

FIGURE 2.7

2.3 STRATIGRAPHY AND AQUIFER CLASSIFICATION OF THE STUDY AREA

The Model Domain comprises both Lower TMG rocks inland and quaternary sediments of the **Springfontyn** and **Langebaan Formations**, with wind-blown dune sands bordering the coast. These sediments are underlain by **Malmesbury Group** basement in the northern half of the Model Domain and southwest of the Piketberg-Aurora Fault extension. It is highly likely that the **Peninsula Formation** extends along a strike below the quaternary sediments towards the coast. Groundwater flow occurs in the Peninsula Aquifer from the southeast toward the sea, recharging the Sandveld Aquifer that extends NW-SE along the Verlorenvleipalaeo channel.

2.3.1 Geology and Stratigraphy

Metamorphosed shales, schists and limestones form the **Moorreesburg** and **Piketberg Formations** of the **Malmesbury Group** (>555 Ma), and the basement to the overlying **Table Mountain Group** rocks and **Sandveld Group** sediments within the Piketberg Model Domain (see **Figure 2-8** and **Figure 2-9**). The **Cape Granite Suite** (555-510 Ma) does not outcrop within the Model Domain, although it occurs further southwest in the Langebaan region. Very minor outcrops of reddish coloured **Klipheuwel Formation** feldspathic sandstones, shales and conglomerates occur on the southwestern shores of Verlorenvlei (De Beer and Gresse, 1994), but are not observed in the rest of the Model Domain.

The highly faulted, mountainous Piketberg region is composed of an outlier of predominantly lower **Table Mountain Group** rocks, however rocks of the lower **Nardouw Subgroup** are exposed within the Piketberg Syncline, northwest of Piketberg town.

The basal **Piekenierskloof Formation** unconformably overlies the **Malmesbury Group**, and varies in thickness between 200 m and 350 m in the Model Domain (see **Figure 2-8** and **Figure 2-9**). The **Piekenierskloof Formation** is subdivided into a lower conglomeratic unit named the **Rest Member** and an upper, thickly bedded, coarse quartzitic sandstone unit termed the **De Hoek Sandstone Member**. De Beer and Gresse (1994) state that only the De Hoek Sandstone Member is present in the Piketberg area, where it resembles the Peninsula Formation. Outliers of the Piekernierskloof Formation extend northwestwards and outcrops can be observed up to Elands Bay, where they may also recharge the Sandveld Group aquifer which feeds the Verlorenvlei wetland system.

The red to purple shales and siltstones of the **Graafwater Formation** conformably overlie the **Piekenierskloof Formation** within the Model Domain, and reach a maximum thickness of approximately 150 – 200 m (see **Figure 2-8** and **Figure 2-9**). The **Peninsula Formation** conformably overlies the **Graafwater Formation**, and is composed of approximately 1200 m of thickly-bedded, fractured quartzitic units (see **Figure 2-8** and **Figure 2-9**). These poorly sorted units contain minor pebble horizons, preserved palaeo-channels, planar cross-beds and *skolithos* trace fossil horizons (De Beer and Gresse, 1994).

The **Cedarberg Formation** shales and siltstones are well developed in the Piketberg area and unconformably overlie the **Peninsula Formation**, as a result of the poorly understood absence of the **Pakhuis Formation** (Rust, 1967) (see **Figure 2-8** and **Figure 2-9**). The **Cedarberg Formation**, red siltstones and sandstones of the **Goudini Formation** and quartzites of the **Skurweberg Formation** are restricted to the NW-SE orientated Piketberg Syncline, and do not outcrop in the rest of the Piketberg Model Domain.

The semi to unconsolidated aeolian Langebaan and Springfontyn Formations of the **Sandveld Group** overlie the majority of the northwestern portion of the Model Domain. The **Langebaan Formation** is composed of bioclastic-siliciclastic to calcareous aeolianites and dune sands, which were deposited in interglacial dune systems during the Pliocene to Late Pleistocene (Roberts *et al*., 2006). Sediments of the **Langebaan Formation** are overlain by unconsolidated, quartzose aeolian sands of the Middle Pleistocene to Holocene **Springfontyn Formation** (Roberts *et al*., 2006).

2.3.2 Aquifer Classification in this Study

The hydrostratigraphic scheme adopted for the present study is based on **Table 2-1**, and focuses on the four main "coincident" or stratabound aquifer units within the Piketberg Model Domain, namely, the Piekenierskloof, Peninsula, Nardouw and Sandveld Aquifers. The non-coincident aquifer units, which correspond to the intervening "fractured-and-weathered" or regolith zones, are largely disregarded in this approach, except where they might interface laterally with, or grade into, TMG and/or Sandveld aquifer compartments. In these cases, the near-surface regolith zone may provide a diffuse or preferred flowpath between the different aquifers.

Of interest to this study are the "Fractured" Aquifer class, specifically the Peninsula Aquifers in theTable Mountain Group, and the Sandveld Group in the "Intergranular" Aquifer class. The Skurweberg Aquifer only forms a minor unconfined outcrop within the Model Domain, while the Piekenierskloof Aquifer thins southwards, and hence both are ignored in this study.

Table 2-1 Simplified hydrostratigraphic units of the study area and associated aquifer types

Superunits	Units	Aquifer Type
	Sandveld Aquifer	Intergranular
Aquicludes of the	[Malmesbury Group]	Fractured-and-weathered (regolith)
Table Mountain Superaquifer	Nardouw Aquifer	Fractured
	Peninsula Aquifer	Fractured
	Piekenierskloof Aquifer	Fractured
Aquicludes of the	[Malmesbury Group]	Fractured-and-weathered (regolith)

Intergranular aquifers

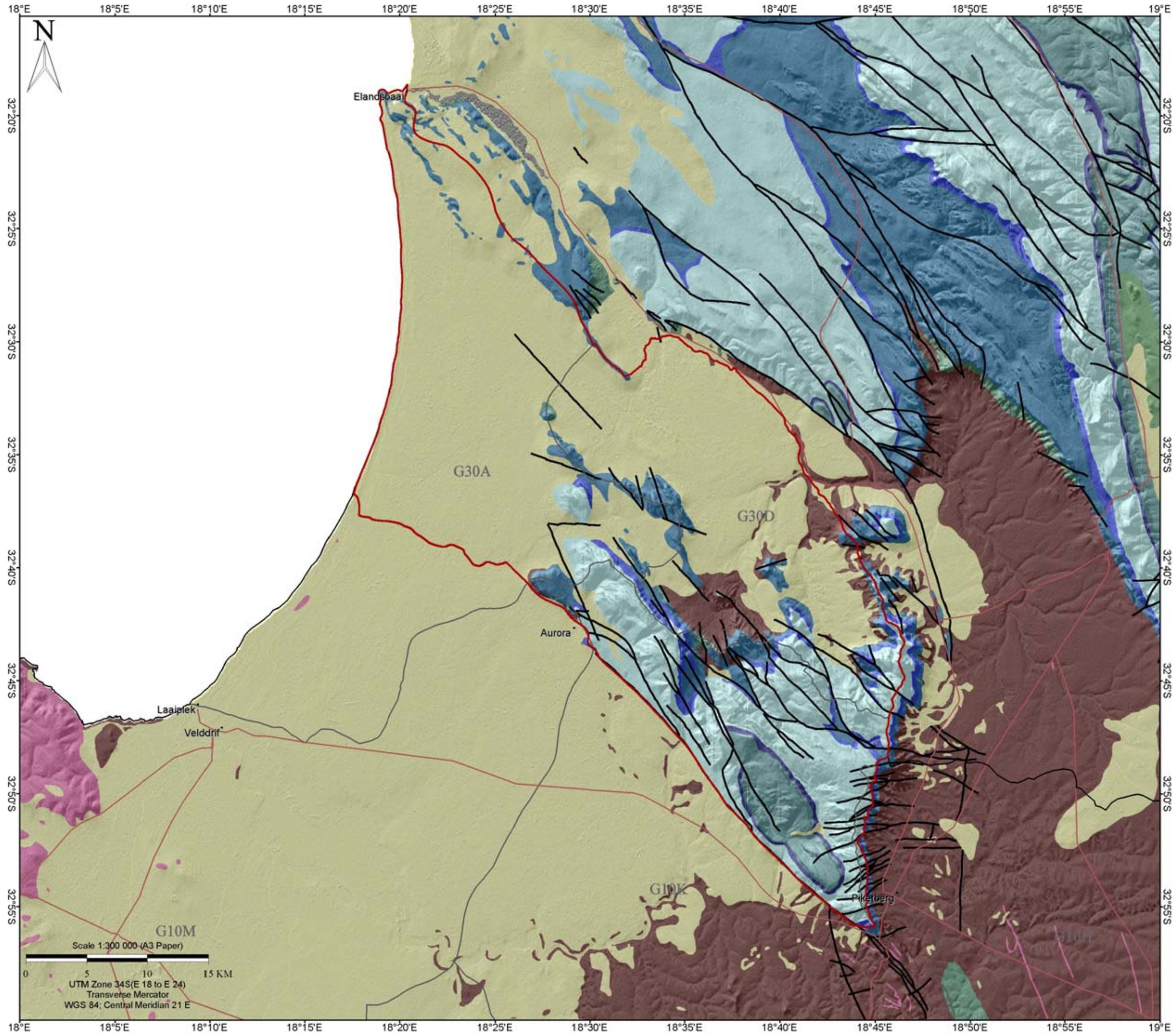
The intergranular aquifers are confined to the coastal Sandveld Aquifers, which includes the Langebaan and Springfontyn Formations of the Sandveld Group, and extend northwestwards from the base of the TMG and Malmesbury Group outcrops to the coastline.

Fractured-rock aquifers

The TMG quartzites are stratabound aquifers (i.e. having significant fracture porosity and a permeability greater than $10^{-16}\,m^2$), and therefore constitute "coincident" hydrostratigraphic units, as defined by Al-Aswad and Al-Bassam (1997), in that the hydrostratigraphic boundaries generally coincide with those of the lithostratigraphic units. The **Table Mountain Superaquifer**, which is composed of the larger **Peninsula Aquifer** (apparent thickness approximately 1600 m in this area) and is the principal focus of the present study.

Fractured-and-weathered (regolith) aquifers

The type d (or “intergranular and fractured”) aquifers as currently mapped (DWAF, 2000a) coincide with exposures of the **Malmesbury Group** in the Piketberg Model Domain.



LEGEND

- Towns
- Roads
- Faults
- Model Domain
- Quaternary Catchment
- Study Area

SIMPLIFIED LITHOLOGY

- Quaternary
- Uitenhage
- Ecca
- Dwyka
- Witteberg Group
- Nardouw Group
- Pakhuis Formation
- Peninsula Formation
- Graafwater Formation
- Piekenierskloof Formation
- Klipheuwel Group
- Malmesbury Group

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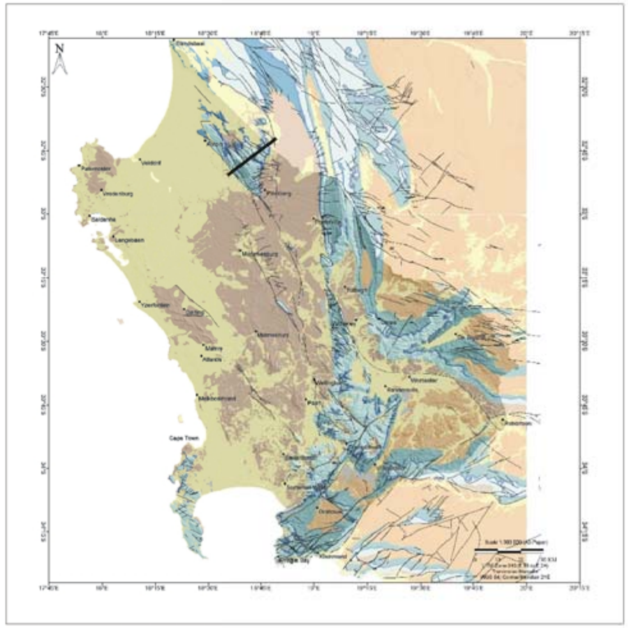
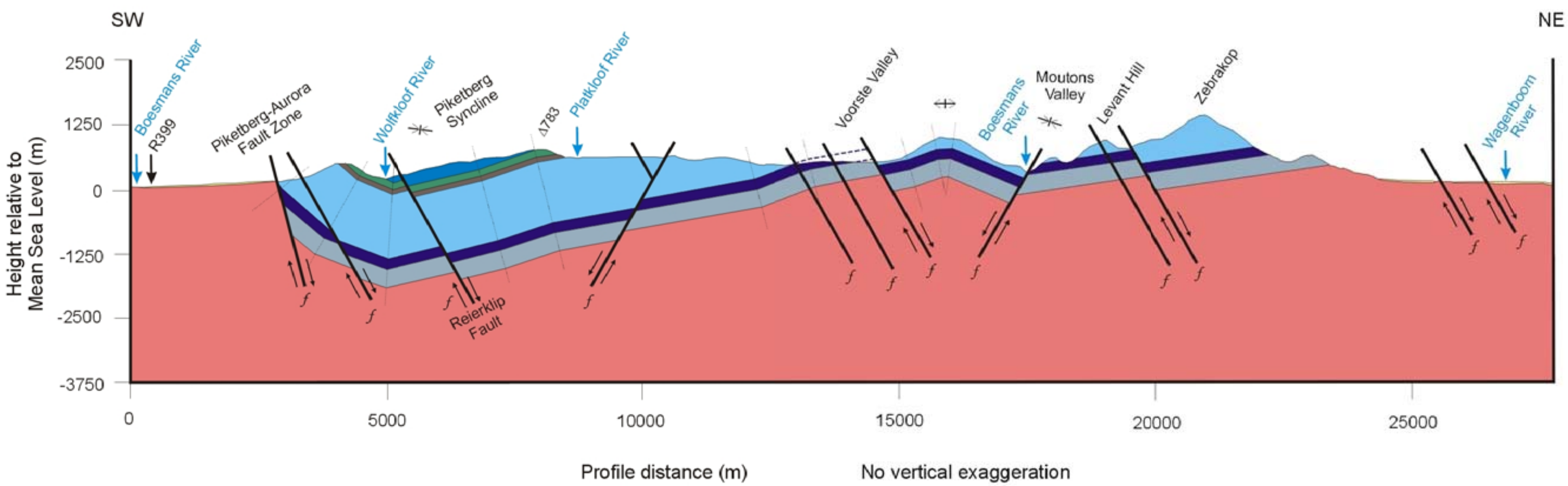
SIMPLIFIED GEOLOGY MAP OF THE STUDY AREA (1: 250 000)

FIGURE 2.8





LEGEND

Anticline
Syncline
Fault

GEOLOGY

- Sandveld Group
- Skurweberg Formation
- Goudini Formation
- Cedarberg Formation
- Peninsula Formation
- Graafwater Formation
- Piekenierskloof Formation
- Basement

Table Mountain Group

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TITLE

NE-SW BALANCED CROSS SECTION THROUGH THE PIKETBERG MOUNTAIN RANGE

FIGURE 2.9

2.3.3 Relationship between Aquifer Type and Topography

As mentioned in Section 2.1 above, it is assumed that a strong relationship exists between the topography, slope distribution and aquifer type. The statistical analysis of the slope distribution in the quaternary catchments and IWRM Domains indicate that the Peninsula Formation generally outcrops in higher terrain and generates steeper slopes than weathered, fractured-rock formations or intergranular formations. **Figure 2-10** shows the cumulative histograms of the slope distribution for the different aquifer types, which clearly supports the above statement.

- The intergranular aquifers predominantly form the flat areas, with slopes of less than 7° in more than 80% of the outcrop area. The histogram resembles the Group 8 and Group 9 character.
- The slope distribution for the ‘intergranular-fractured’ aquifer type shows a similar pattern, but with an increase in slope; viz. less than 20° in more than 80% of the area.
- The slope distribution for the Nardouw Aquifer shows a similar pattern as the ‘intergranular-fractured’ with less than 20° slope in 80% of the area.
- Normally, the histogram for the Peninsula Aquifer shows an S-curve type with very few flat areas and more than 20% with slopes above 30° or 40°. However, in the Piketberg Model Domain 80% of the area has a slope of less than 20°, indicating the flatter and not so steep Peninsula outcrops in the Piketberg area. The Peninsula Formation mainly forms the high lying, steep terrains.

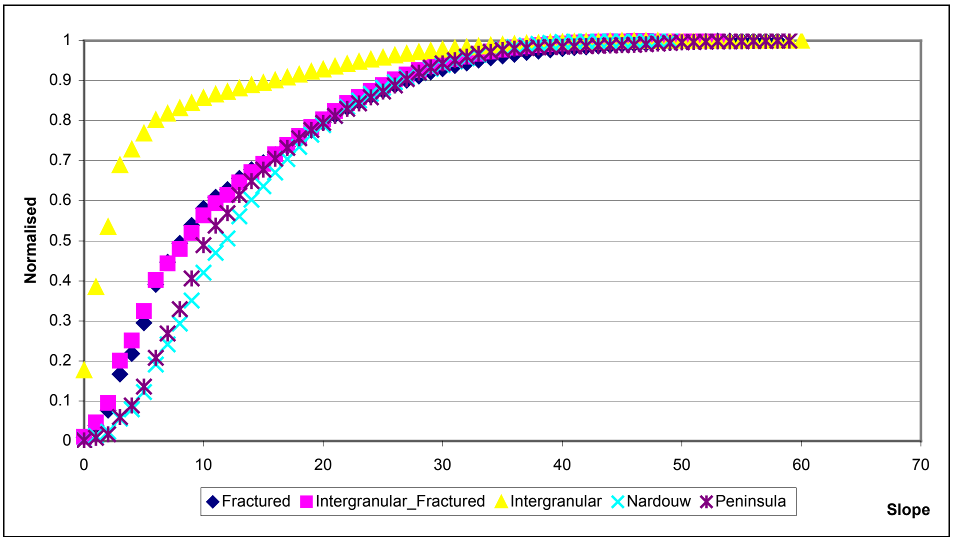


Figure 2-10 Slope Distribution per aquifer type in PKT IWRM domain

As the slope angle θ is an important factor determining the run-off potential and therefore the infiltration and recharge potential, a uniform rainfall – recharge relationship across the study domain is not sufficient. The aquifer-specific differences in slope frequency need to be taken into account in the recharge estimation (see Section 5.2.4).

The aquifer types summarise the underlying geology and rock formations and reflect to a certain degree the soil type. Since the soil conditions further determines the infiltration capacity and soil moisture retention, the correlation between aquifer type and soil type can be used in the run-off and recharge model (see Section 5.2.4).

3. APPROACH FOR WATER BALANCE MODEL

It is imperative in this study to establish a groundwater balance that can be reasonably linked to the surface water balance. The main elements of the groundwater balance are recharge, storage and discharge, while the surface water balance comprises rainfall, run-off, evaporation and abstraction. The approach adopted in this study ensures that the input parameters for the estimation of the different components are the same as for the surface water modelling. The approach for the water balance and yield model applied for in this report is discussed in detail in Volume 4 (DWAF, 2007e). The main elements of the model are:

- Storage capacity, as described in Section 4
- Recharge, as described in Section 5
- Natural discharge, as described in Section 6
- Abstraction, as described in Section 6
- Storage yield, as described in Section 7
- Groundwater Potential, as described in Section 7

The approach adopted in this study divides the rainfall into that part that directly runs off the surface, called overland flow, and that part that potentially infiltrates into the soil and unsaturated zone, called potential infiltration. Evaporation is then assigned to the overland flow only, while the potential infiltration is further reduced due to evapotranspiration. The remaining infiltration is then subdivided into the interflow and the recharge components. Depending upon the aquifer system, a part of the recharge discharges into rivers, contributing to base flow, while another part flows across catchment boundaries and discharges either in different catchments as springs or a component of baseflow or into the ocean.

The potential aquifer yield depends mainly on two factors, viz. the long-term replenishment and the impact of abstraction on the hydraulic head in the aquifer. Both parameters are taken into account in the yield estimation.

The long-term potential yield is calculated as recharge minus groundwater contribution to baseflow. These are compared to estimates for the TMG aquifers, applying the specific storage for the confined portion and different assumed acceptable drawdowns.

However, it must be noted that the actual yield of the aquifer depends on factors such as borehole siting, wellfield and aquifer management, acceptable impacts.

4. STORAGE MODEL

4.1 PRINCIPLES

The underlying principles and the detailed methodology for the storage modelling are described in Volume 4 (DWAF, 2007e).

The storage model aims to:

- develop an accurate 3D surface of the base and top of the Peninsula Aquifer.
- obtain the rock volume of the Peninsula Aquifer
- model the amount of water in storage in the Peninsula Aquifer
- model the amount of water available for sustainable abstraction from the Peninsula Aquifer.

The amount of water that can be released from the aquifer per unit area for a unit decline of head is termed storativity (S). In a confined aquifer, S is essentially the specific storage S_s multiplied by the aquifer thickness; in an unconfined aquifer, S is essentially equal to the specific yield S_y or the effective porosity (Sharp, 1999).

The above key definitions establish that, for the quantitative estimation of storage, data are required on the aquifer

- area,
- thickness,
- volume,
- effective porosity, and
- the particular hydrogeological setting (unconfined versus confined).

4.2 STORAGE MODELING

4.2.1 Methodology

Storage modelling was undertaken for the Peninsula Aquifer in the model domain using a combination of spreadsheet models developed by Dr. Chris Hartnady and GIS applications in TNTmips following the procedure used in the Clanwilliam Dam Raising Study (DWAF, 2006a).

The unconfined and confined portions of the aquifer are distinguished and delineated according to the surface expression of the overlying units. The total area, average apparent thickness and total rock volume are obtained for both the confined and unconfined portions of the aquifer and summed to obtain the totals. These parameters are then applied to hydrogeological principles to calculate the total pore volume and the impact of head decline as a result of abstraction.

The use of the above-described digital model has certain advantages over a pen-and-paper approach:

1. The model is physically correct in terms of obtaining the rock volume
2. It is possible to obtain a visually descriptive spatial overview of the aquifer geometry.
3. The apparent thickness of the aquifer can be more accurately determined than in earlier estimations where only broad / representative geology data could be applied.

The model does however have certain limitations

4. The model is only as accurate as the scale of the input data. A 20 m Digital Elevation Model and 1: 50 000 geological map were used, implying that the results are reliable for the scale of the model domain and with some revisions, for quaternary catchment scale.
5. Exact depth of contacts cannot be accurately determined at fault zones but can be reasonably estimated. Further detailed information can only be obtained from drilling.

The model is based on an assumption that in the Berg WAAS area, the aquifer units have undergone flexural slip (or bedding parallel) folding, implying that the orthogonal thickness of the units remains constant about the fold hinges and across the limbs of the folds. In light of this, particular attention was paid to the apparent thickness variations of the aquifer around major fold structures.

4.2.2 Model Input

The area where the aquifer outcrops or exists below surface is considered in the storage model. The lithostratigraphic / hydrostratigraphic contacts that were used during the modeling process include the base of the Peninsula Aquifer and the top of the Peninsula Aquifer.

The aquifer boundaries were delineated according to the bounding lithological contacts of the Peninsula Aquifer, namely the Graafwater – Peninsula and Peninsula – Cedarberg contacts, as present on the 1:250 000 3218 Clanwilliam Geological Maps. These boundaries enclose a total area for the Peninsula Formation storage basin of 298 km^2. A balanced cross section through the Piketberg and Skurweberg ranges was used as a control (see **Figure 2-9**).

4.2.3 Model scenario selection

Results of the spreadsheet-based numerical modelling tool using Microsoft Excel are used to illustrate various possible scenarios in the relationships between aquifer area, and apparent thickness, on the one hand, and assumed porosity-compressibility properties, on the other. In the absence of any measured data from the present study area, an extremely conservative range of porosity values is assumed, namely, 0.005 (or 0.5%) to 0.05 (or 5%) based on upper-crustal porosity values cited in a geophysical context (Talwani & Acree, 1985). The apparent thickness of the aquifers was obtained during modelling, having applied a true thickness for the Peninsula Aquifer of 1200m.

Porosity estimates for a 325-800 m deep section of the Peninsula Aquifer in the Blikhuis Experimental Deep Drilling (BEDD) Project borehole BH2, between Citrusdal and Clanwilliam, have been undertaken from downhole resistivity and density logging (Hartnady, in prep). Using the resistivity data combined with Archie's Law, and assuming normal TMG groundwater quality, the derived porosity values range from 0.06 (6%), for the "matrix" or relatively unfractured borehole sections, to 0.28 (28%) for highly fractured zones. Using the density logs and a reference value of 2 650 kg/m^3 for solid pure quartz, the matrix porosity is calculated at 0.048 (nearly 5%) and the fracture zone porosity at 0.163 (~16%).

These geophysically derived porosity values for the fractured zones are higher than those published in literature for fractured crystalline (0 – 10%; Freeze and Cherry, 1979) or metamorphic rock (2 – 5%; Freeze and Cherry, 1979). However, the values for relatively unfractured sections are in the same order as the published data. Although they still require future experimental confirmation from the present study area, they encourage the further expectation that, at the large scale of a borehole or wellfield, the *in-situ* compressibility values for the deep Peninsula Aquifer are also much higher than the values normally assumed for, or measured on small-scale laboratory samples of intact quartzite. A conservative approach is taken in this study and having taken into account the previously mentioned calculated porosity values, the storage modeling in this study applies a porosity of 0.05 (5%).

The range of pore-space compressibility (β_p) values used to calculate S_s according to the Jacob equation is between 3.3×10^{-10} Pa^{-1} and 6.9×10^{-10} Pa^{-1} (see **Table 4-1**), i.e., typical of “fissured” rock (Domenico and Schwartz, 1990, p. 111), which is close to the water compressibility cited earlier.

Table 4-1 Model Input Parameters for the Peninsula Storage Models

Model Input Parameters	Source	Detail
Contacts for aquifer base	1:250 000 and newly mapped	Goudini - Skurweberg Cedarberg - Goudini Peninsula - Cedarberg Peninsula - Quaternary Peninsula - Graafwater Graafwater - Piekenierskloof Piekenierskloof - Malmesbury/Quaternary
Controls	1:250 000	Faults
	Previous	Cross-sections (Figure 2-9)
Rock Compressibility (used to calculate S_s)	Domenico & Schwartz (1990)	$3.3\text{x}10^{-10}Pa^{-1}$ to $6.9\text{x}10^{-10}Pa^{-1}$
Porosity	Talwani & Acree (1985) & Blikhuis Borehole Data	0.005 - 0.163
Specific Storage (S_s; used for Storage Yield Model)	Calculated from Rock Compressibility and Porosity	3.0E-06 to 7.0E-06
True Thickness	Literature and remotely sensed observations	Goudini - 140 m Cedarberg - 90 m Peninsula - 1200 m Graafwater - 200 m Piekenierskloof - 350 m

4.3 STORAGE MODEL RESULTS

4.3.1 Peninsula Aquifer

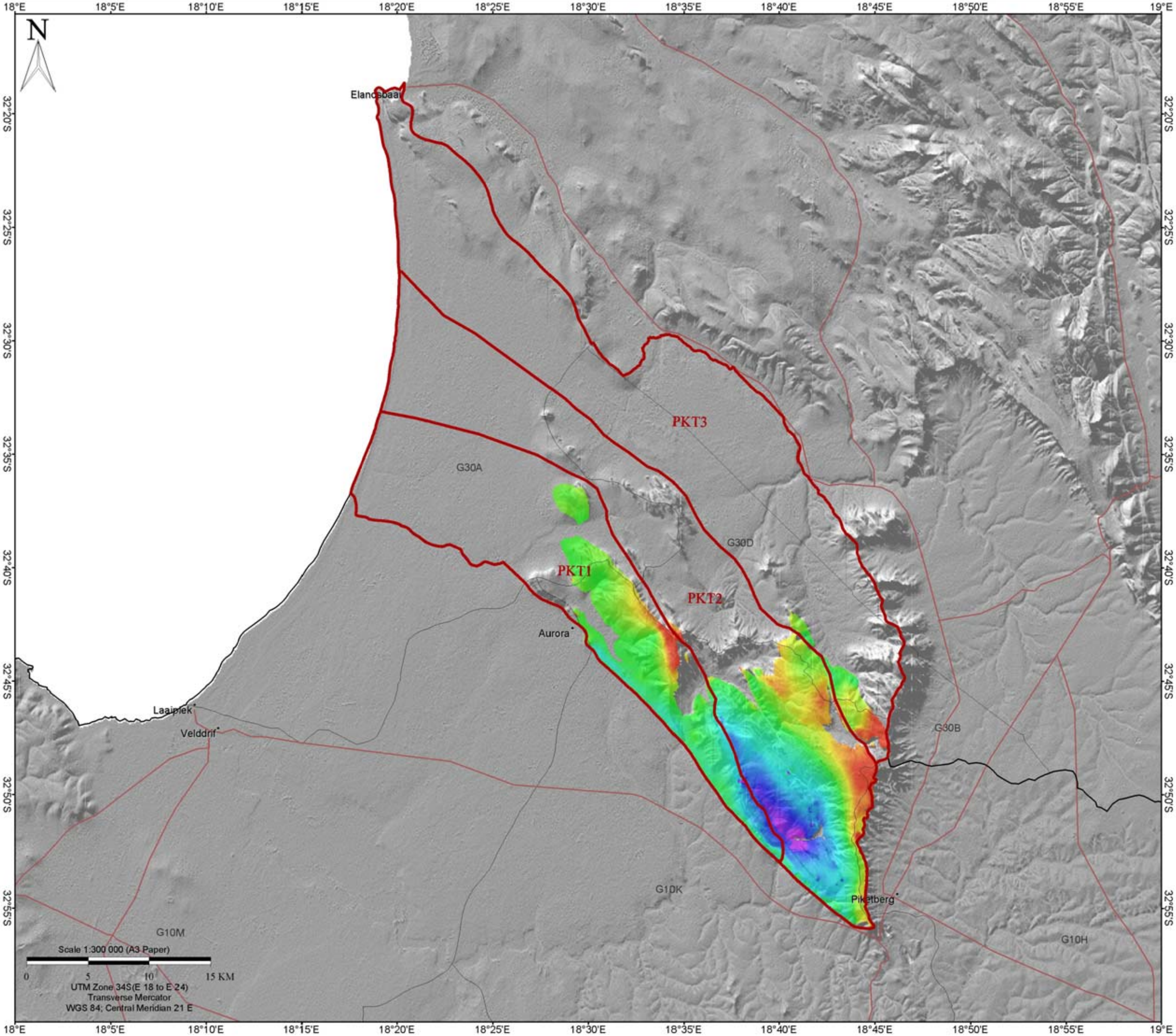
Figure 4-3 illustrates the storage modelling of the Peninsula Aquifer. The coloured sections of the study area cover the area where the Peninsula Aquifer exists either on or below surface. This is the area considered in the storage model. The colour palette illustrates the range in the aquifer rock volume per pixel over the storage area. i.e. for each pixel, the colour represents the vertical rock volume from surface to the aquifer in cubic meters. Blues and Purples thus indicate where the aquifers are at their deepest while reds indicate that they outcrop at surface.

The total solid material volume (rock volume) of the Peninsula Aquifer is 162 x 10^9 m^3. The total confined rock volume is 67 x 10^9 m^3. The total (and confined) modelled rock volume and the calculated pore volume, given an accepted porosity of 0.05, is summarized in **Table 4-2**. The total confined pore volume of the Peninsula Aquifer is approximately 3.3 x 10^9 m^3.

Table 4-2 Rock Volume vs Pore Volume for Peninsula Aquifer, given a porosity of 0.05 (5%)

Model Domains	Peninsula Aquifer	Area (km^2)	Rock Volume (Mm^3)	Pore Volume (Mm^3)
PKT 1	Unconfined portion	98.03	30 650	1 533
	Confined portion	6.75	8 378	419
PKT 2	Unconfined portion	117.20	5 681	2 849
	Confined portion	46.92	58 824	2 941
PKT 3	Unconfined portion	29.95	7 850	393
	Confined portion	0.00	0	0
Whole Peninsula Aquifer	Unconfined portion	245.18	95 482	4 774
	Confined portion	53.67	67 202	3 360
	Total	**298.85**	**162 684**	**8 134**

The model of the aquifer storage intentionally makes use of low, geologically reasonable values for porosity and aquifer compressibility, so as to provide *minimum estimates of the quantity of water in storage and subsequently the potential yield*. However, as new data accumulate from the TMG aquifers in the study area, these initial porosity and compressibility assumptions will probably be revised upwards.



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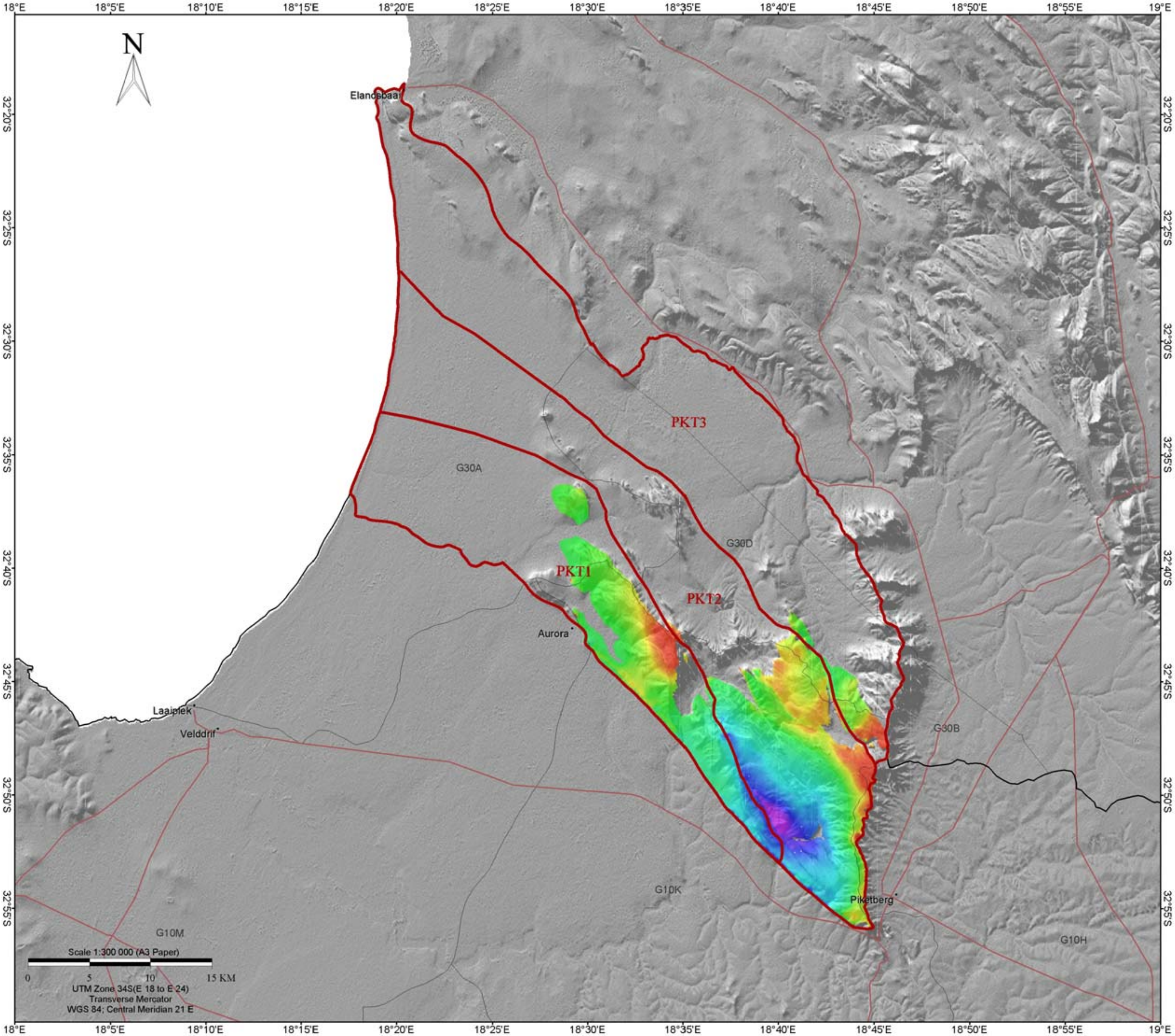
AQUIFER BOTTOM FOR PENINSULA AQUIFER

FIGURE 4.1



LEGEND

- Towns
- Roads
- Quaternary Catchments
- Study Area
- PKT3 Model Sub-Domain

Aquifer Top (m)

- -525 - -200
- -200 - -100
- -100 - 125
- 125 - 350
- 350 - 550
- 550 - 750
- 750 - 1000
- 1000 - 1200
- 1200 - 1500
- 1500 - 1700
- 1700 - 1800
- 1800 - 1900
- 1900 - 2200

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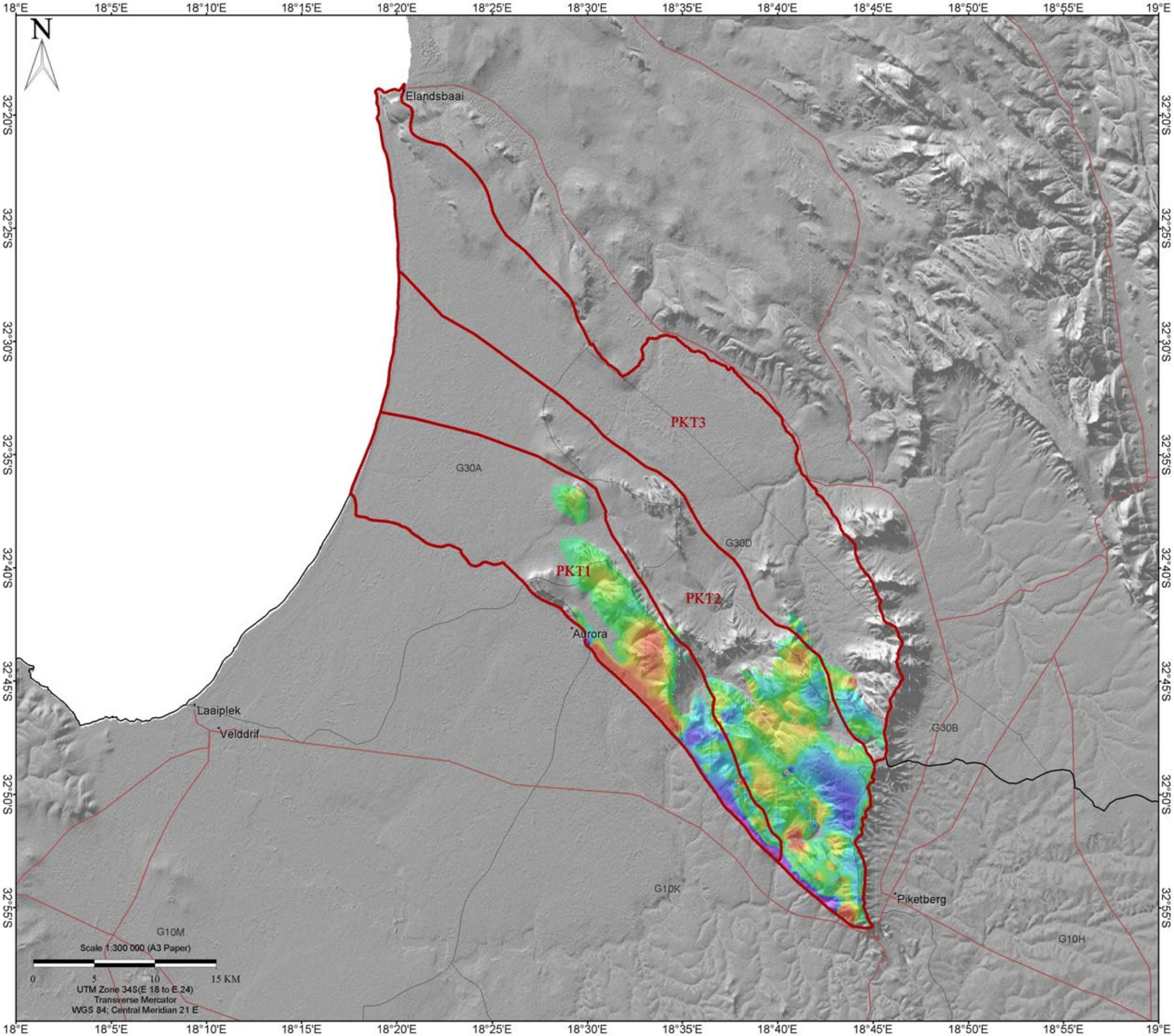
TITLE

AQUIFER TOP FOR PENINSULA AQUIFER

FIGURE 4.2



LEGEND

Towns

Roads

Quatemary Catchment

Study Area

PKT3 Model Sub-Domain

Aquifer Thickness (m)

100 - 500

500 - 700

700 - 1000

1000 - 1200

1200 - 1400

1400 - 1500

1500 - 1700

1700 - 2700

2700 - 3700

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ROCK VOLUME AND STORAGE MODEL OF PENINSULA AQUIFER

FIGURE 4.3

5. RECHARGE

5.1 PREVIOUS STUDIES

The quantification of recharge to the aquifers is critical to the development and improvement of the current water-balance analysis. Reliable estimates of average annual recharge and its interannual variability can only be obtained after several years of monitoring and reassessment.

In several previous studies in the Table Mountain Group terrain, recharge to the Peninsula Aquifer was estimated with different methods to vary spatially between 7% and 43% of Mean annual precipitation, depending upon the method used, the annual rainfall and the geographic location of the study area. In the Citrusdal Artesian Groundwater Exploration study (DWAF, 2000b) the spatially weighted average is 23% of Mean annual precipitation, where MAP varies from 200 mm – 2000 mm. If Mean annual precipitation is less than 200 mm per annum it was considered that there was no recharge.

Relatively recent estimates of groundwater recharge in the wider model area from the Groundwater Resource Assessment Phase II (GRA II) project (DWAF, 2006d) indicate a mean annual recharge of 73.5 million m^3/a. The GRDM software (DWAF, 2006f) contains recharge values per quaternary catchment, which are used as default values for the Reserve Determination on a quaternary catchment scale. Using the GRDM default values, the recharge in the study area is calculated as 78.5 million m^3/a (see **Table 5-1**)

Recharge estimations for the quaternary catchments south of the Model Domain are given in a recent study for the West Coast Municipality (SRK, 2004; see **Table 5-1** below). However, the estimates are neither aquifer specific nor spatially weighted. Because of the extreme topographic variation in an orographic rainfall area and the spatial distribution of the different aquifers with respect to altitude, temperature and rainfall character, these results are not suitable for the purpose of this study.

Table 5-1 Recharge estimations for the quaternary catchments of the Model Domain from previous studies (all values in million m^3/a)

Area	Quaternary Catchment	GRA II (2005) 1)	GRDM (2006) 1)	Local studies	
Piketberg and West Coast	G10K	15.3	17.0	16.9	SRK (2004)
	G10M	30.1	32.4	21.2	
	G30A	9.9	10.7		
	G30D	8.8	9.6		
	Subtotal	**73.5**	**78.5**		

5.2 GIS-BASED MODELS

5.2.1 Groundwater Resource Assessment Phase II (GRA II Method)

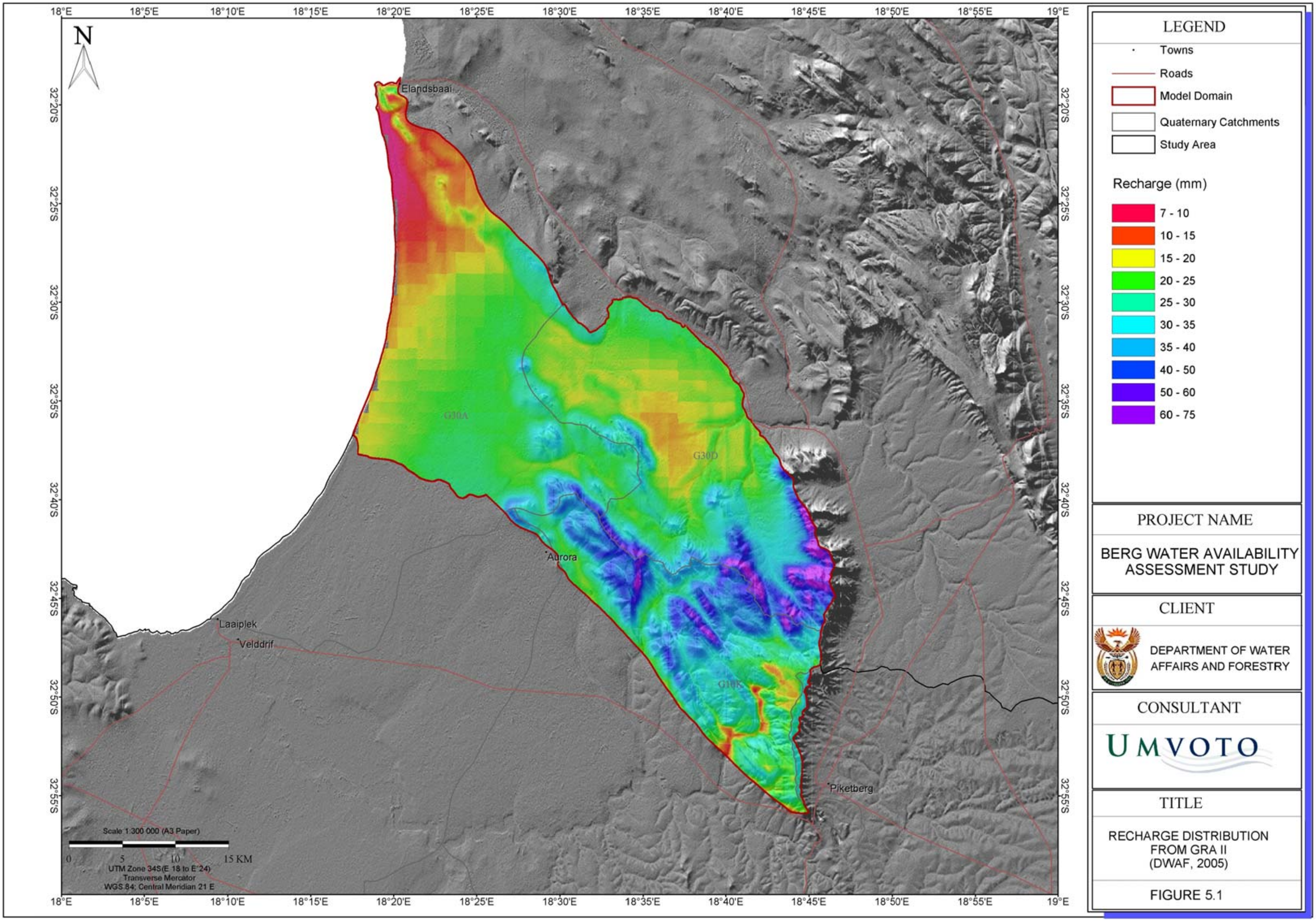
The Groundwater Resource Assessment Phase II (GRA II) project comprised five different tasks to develop a general methodology for groundwater resource evaluation and provide an estimate of groundwater potential on a national scale. The recharge estimation on a national scale was part of Task 3a (DWAF, 2006d).

The results are given as recharge percentage on a 1 kmx1 km grid and are based on the Chloride Mass Balance method, which requires that data on the chloride concentration in the rain and the groundwater are available. The input data sets were not available to check the distribution of input values.

Aquifer specific recharge is not directly available from the data set. However, recharge per grid was calculated applying the recharge percentage after GRA II and the revised MAP (DWAF, 2007c), and then overlain with the spatial distribution of the aquifer types to calculate recharge per aquifer type (**Table 5-2**). It appears from the distribution that there is a close correlation between recharge percentage and rainfall (**Figure 5-1**).

Table 5-2 Aquifer specific recharge estimation per catchment, using the recharge percentage from the GRA II, after DWAF (2006d)

Quaternary catchment	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Aquifer specific recharge**	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
G10K	5.79	1.03	0.67	0.73	0.21	8.43	28
G30A	0.46	0.00	0.59	0.16	7.38	8.58	15
G30D	1.59	0.00	1.16	1.72	5.66	10.13	23
Total	**7.84**	**1.03**	**2.43**	**2.60**	**13.24**	**27.15**	**21**


18°E
18°5'E
18°10'E
18°15'E
18°20'E
18°25'E
18°30'E
18°35'E
18°40'E
18°45'E
18°50'E
18°55'E
19°E
32°20'S
32°25'S
32°30'S
32°35'S
32°40'S
32°45'S
32°50'S
32°55'S
N
Elandsbaai
G30A
G30D
Aurora
Laaiplek
Velddrif
G10K
Piketberg
Scale 1:300 000 (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
Roads
Model Domain
Quaternary Catchments
Study Area
Recharge (mm)
7 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 50
50 - 60
60 - 75
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS AND FORESTRY
CONSULTANT
UMVOTO
TITLE
RECHARGE DISTRIBUTION FROM GRA II (DWAF, 2005)
FIGURE 5.1

5.2.2 Rainfall – Recharge relationship (BRBS Method)

In the Breede River Basin Study (DWAF, 2002) DWAF introduced a method for preliminary recharge estimation, which takes MAP per quaternary catchment into account. The rainfall - recharge ratios used are given in **Table 5-3**. Since rock types differ in their capacity to absorb infiltration, this method is combined with an aquifer specific factor, varying between 0.5 for low permeability aquifers and 1.5 for primary aquifers (see **Table 5-4**).

Table 5-3 Rainfall-dependent Recharge Factors (DWAF, 2002)

MAP Range [mm]		MAI
Min	Max	% of MAP
0	300	3
300	600	6
600	900	9
900	1200	12
1200	1500	15
1500	1800	18
1800	2100	21

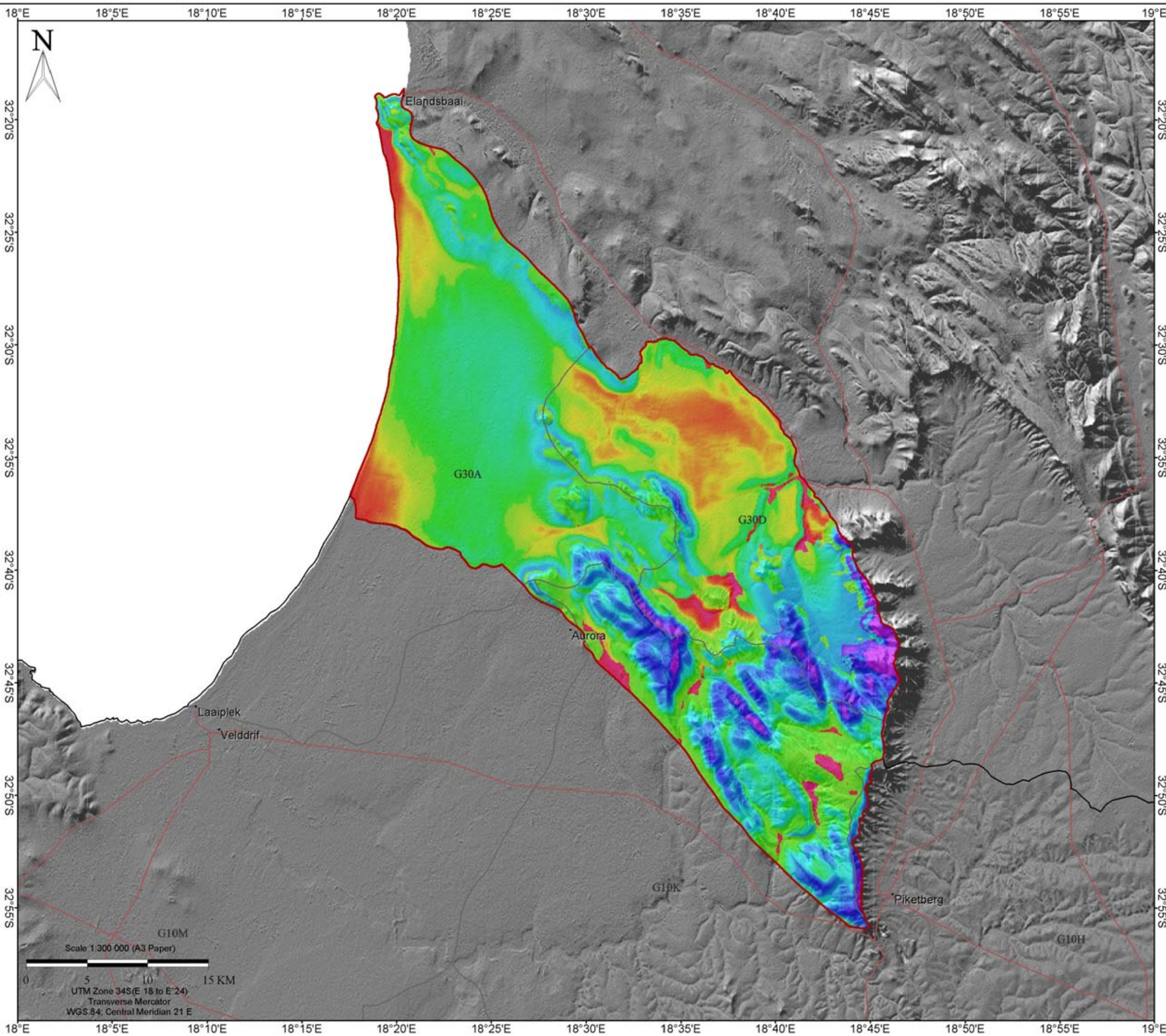
Table 5-4 Aquifer-specific Recharge factors (after DWAF, 2002)

Aquifer Type (DWAF, 2003)	Aquifer Type As per Table 5-2	Recharge factor
Primary Aquifer	Intergranular	1.5
Fractured Rock Aquifer	Fractured	0.8
Peninsula Aquifer	Peninsula	1.0
Skurweberg Aquifer	Nardouw	1.0
Witteberg Aquifer	Fractured	0.8
Weathered Fractured	Intergranular fractured	0.7

Applying the recharge factors and outcrop area for the Peninsula and Nardouw Aquifers, the recharge is estimated to 10.8 million m^3/a for the Peninsula Aquifer, and 1.5 million m^3/a for the Nardouw Aquifer, respectively. The primary aquifers along the coast receive recharge of 19.4 million m^3/a. The results per quaternary catchment are documented in **Table 5-5**.

Table 5-5 Aquifer-specific recharge estimation per catchment, using the variable rainfall % and aquifer-specific recharge factors, after DWAF (2002)

Quaternary catchment	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	Aquifer specific recharge	
	Mm^3	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*mm*
G10K	7.88	1.51	0.70	0.97	0.27	11.33	38
G30A	0.55	0.00	0.73	0.20	11.49	12.98	23
G30D	2.52	0.00	1.56	1.67	6.73	12.47	28
Total	**10.94**	**1.51**	**2.99**	**2.84**	**18.49**	**36.78**	**28**



LEGEND

- Towns
- Roads
- Model Domain
- Quaternary Catchments
- Study Area

Recharge (mm)

- 5 - 7
- 7 - 10
- 10 - 12
- 12 - 15
- 15 - 20
- 20 - 30
- 30 - 35
- 25 - 40
- 40 - 60
- 65 - 75
- 75 - 85
- 85 - 105
- 105 - 165
- 165 - 190

PROJECT NAME

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AQUIFER SPECIFIC RECHARGE VOLUME (Using BRBS Method)

FIGURE 5.2

5.2.3 Aquifer specific Water Balance Model (ISP Method)

DWAF refined the regional recharge estimations during the ISP process in the Olifants/Doorn WMA (DWAF, 2005d), using a GIS-based model, developed by Riemann et al. (2004), to calculate aquifer-specific recharge and groundwater potential at the scale of a quaternary catchment. The model is based on existing maps of rainfall and temperature distribution, aquifer yield, lithology and catchment boundaries. However, this information is captured at different scales.

For each quaternary catchment MAP and MAR are obtained from existing data sets (DWAF, 2007c; WR2005). Evapotranspiration is then calculated using a modification of the approach of Turc (1954), which was originally developed in the context of Mediterranean climatic areas, depending on MAP and mean annual temperature (see Section 5.2.4). Recharge is then calculated as:

Recharge = MAP – MAR – EVT **(1)**

To distinguish the recharge per aquifer unit, the exposed outcrop areas of the different formations were calculated from a common GIS overlay of the digital geological map and digital map of quaternary sub-catchments, with area polygons of different aquifer units differentiated for each sub-catchment.

Since Mean Annual Run-off values are only available as average per catchment, a spatial distribution of MAR is simulated, assuming that the run-off efficiency is uniform across the catchment. The relevant MAR for the aquifer outcrop areas is then calculated as

MAR aquifer = MAP aquifer * MAR / MAP

Applying the GIS-based model above with respect to the MAP distribution within the quaternary catchment and therefore related to aquifer outcrop areas, recharge in the Model Domain is calculated as 15 million m^3/a for the Peninsula Aquifer and 2.23 million m^3/a for the Nardouw Aquifers, respectively. The primary aquifer along the coast receives recharge of 12 million m^3/a. The results per quaternary catchment are documented in **Table 5-6**.

Table 5-6 Aquifer-specific recharge estimation per catchment from Water Balance Model (ISP Method)

Quaternary catchment	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Aquifer specific recharge**	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
G10K	10.19	2.23	0.85	0.17	0.12	13.57	45
G30A	0.79		0.47	0.11	7.32	8.69	15
G30D	4.07	0.00	1.54	1.40	4.60	11.61	26
Total	**15.05**	**2.23**	**2.87**	**1.68**	**12.04**	**33.86**	**26**

5.2.4 Map-centric Simulation of Recharge

The Citrusdal Artesian Groundwater Exploration map-centric simulation method (DWAF, 2000b) was adapted for the Berg WAAS with the emphasis on altitude and slope, these being the controlling variables on MAP, temperature and runoff as well as defining characteristics of aquifer type (Volume 4; DWAF, 2007e). The model takes into account:

- The MAP distribution was provided by the surface water team on a 100 m x 100 m grid;
- Mean monthly rainfall data from the Agrohydrology Atlas (Schulze et al., 1997) are re-calculated to be consistent with the revised MAP distribution;
- Model Overland Flow (MOF) calculated for each slope element in the terrain model (**Figure 2-2**) to account directly for a component of surface run-off that is not available for infiltration;
- Actual evapotranspiration estimated for each pixel element in the digital elevation model, based on effective infiltration (MAP-MOF) and monthly temperature distribution, obtained from the Agrohydrology Atlas (Schulze et al., 1997);
- Rainfall, overland flow and evapotranspiration are calculated per month.

The model approach and methodology is described in detail in Volume 4 (DWAF, 2007e). Aquifer specific correction factors were assigned for the model domain for calculating the modelled overland flow (see **Table 5-7**), based on the premises that

- the modelled overland flow should not be exceeding the reported MAR for a specific quaternary catchment;
- the aquifer specific factors are in a similar range across the study domain.

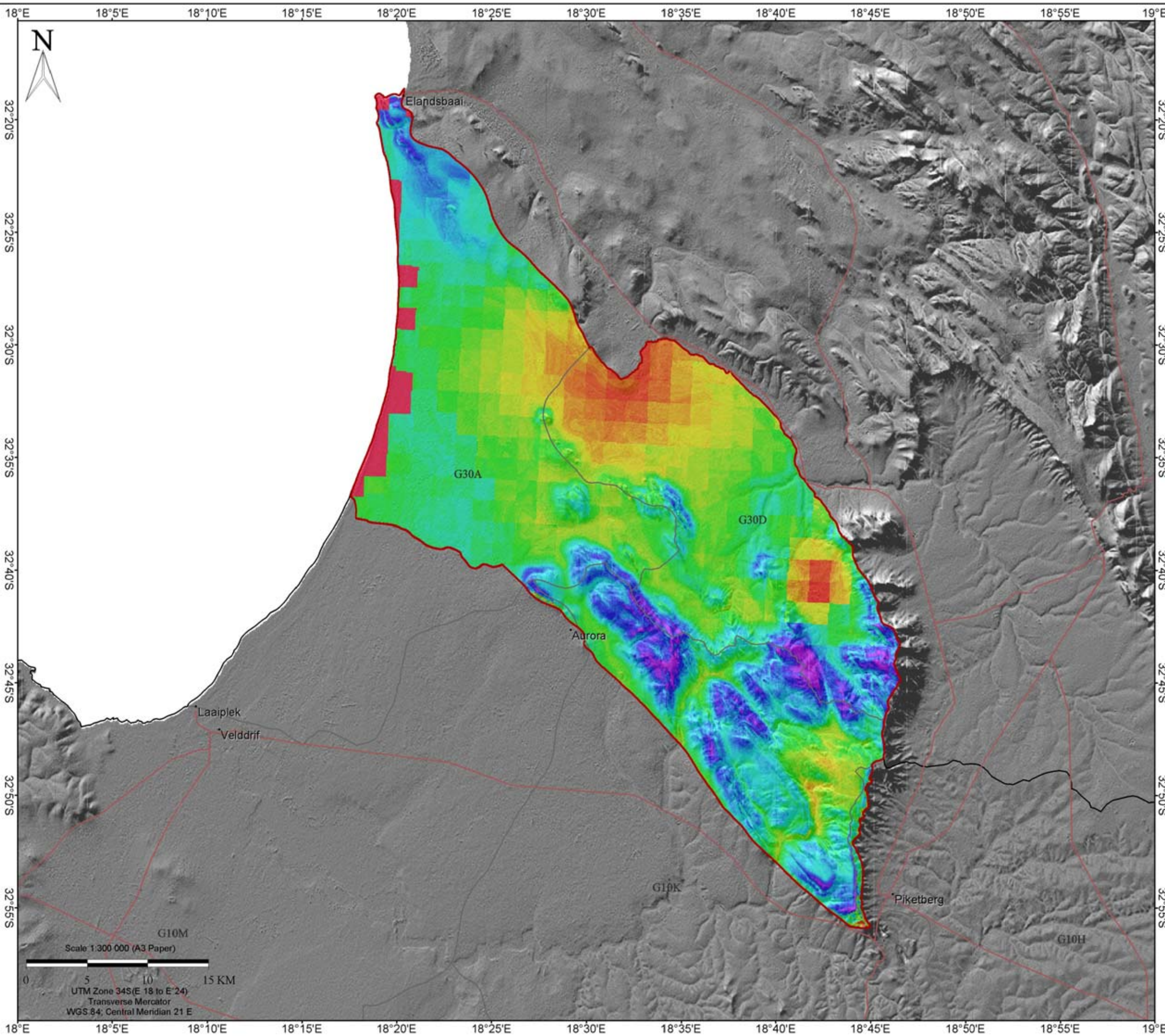
Table 5-7 Aquifer-specific correction factors per IWRM Domain for map-centric recharge estimation

IWRM Domain	Peninsula	Nardouw	Other Fractured	Intergranular fractured	Intergranular
PKT	0.5	0.4	0.6	0.6	0.8

The disadvantage of this approach is that it is not fully independent of the catchment run-off (MAR), which is measured as river flow and includes other components such as interflow and baseflow. The results are shown in **Table 5-8**.

Table 5-8 Aquifer-specific recharge estimation per catchment from map-centric Method

Quaternary catchment	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	Aquifer specific recharge	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
G10K	10.27	2.23	1.10	1.24	0.42	15.26	51
G30A	0.78	0.00	1.22	0.27	16.95	19.21	34
G30D	2.23	0.00	1.60	2.69	9.09	15.61	36
Total	**13.28**	**2.23**	**3.92**	**4.20**	**26.45**	**50.08**	**38**



LEGEND

Towns
Roads
Model Domain
Quaternary Catchments
Study Area

Recharge Distribution (mm)

0 - 15
15 - 25
25 - 35
35 - 45
45 - 55
55 - 65
65 - 75
75 - 85
85 - 124

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

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DEPARTMENT OF WATER AFFAIRS AND FORESTRY

CONSULTANT

UMVOTO

TITLE

RECHARGE DISTRIBUTION

FIGURE 5.3

5.3 WATER LEVEL FLUCTUATION METHODS

The seasonal groundwater level fluctuations can be used to calculate the recharge to the aquifer. However, the standard methods (i.e. Saturated Volume Fluctuation, SVF, and Cumulative Rainfall Departure, CRD) only apply to unconfined aquifers and require an estimate of the groundwater outflow or discharge.

An alternative method was developed for the confined Peninsula Aquifer, which is based on fluctuations in hydraulic head, measured in boreholes that are not influenced by pumping, and the storage coefficient, as derived in Section 6. The underlying assumptions are listed below (see Volume 4, DWAF, 2007e):

- Recharge enters the unconfined portion of the aquifer across the whole outcrop area;
- Recharge results in water-level rise in the unconfined portion at least up to the same amount than measured in the confined portion;
- Discharge from the confined portion of the aquifer continues during the recharge period;
- Storage coefficient is uniform over the confined portion of the aquifer;
- Specific yield is uniform over the unconfined portion of the aquifer.

Time series data of water level measurements in the confined Peninsula Aquifer are available from different sites within the wider study area. However, there are no data available for the Piketberg model domain itself. An analysis of these data indicated a range of seasonal water level fluctuations, depending upon physiographic setting and length of flow path from the recharge area (see **Table 5-9**).

Table 5-9 Seasonal water-level fluctuations in Peninsula Aquifer from different areas

Area	Source	Seasonal fluctuation	Physiographic setting
Hermanus	Umvoto (2007)	0.5 m	Coastal area, short flow path
Kogelberg	WRC (in prep.)	1.5 m	Faulted system, medium flow path
Purgatory	WRC (in prep.)	2.2 m	Faulted system, short flow path
Blikhuis	Hartnady (in prep.)	1.5 m	Within basin, long flow path

Based on these field data and local knowledge, an average annual water-level fluctuation of 0.5 m was assigned and the equation above applied to calculate the average annual recharge to the Peninsula Aquifer (see **Table 5-10**). The result is in the same order than the recharge estimates from the GIS methods.

Table 5-10 Recharge estimation for the Peninsula Aquifer, based on water-level fluctuations

Area [km^2]		Pore Volume	Seasonal Fluctuation	Recharge	Recharge Volume
Confined	Unconfined	[Mm^3]	[m]	[mm/a]	[Mm^3/a]
53.64	236.66	8 059	0.5	51.70	12.24

5.4 SUMMARY AND COMPARISON

The results of the GIS-based aquifer-specific recharge calculations are compared to other approaches and results from other studies (see **Table 5-11**).

A comparison of the different methods indicates significant differences in several quaternary catchments. While the GRA II method does not account for the varying infiltration capacity of different lithological units, the BRBS model from the Breede River Basin Study does not take into account different topographic settings as reflected in the rainfall – run-off responses. Neither methods take into account the winter recharge pattern in the study domain, i.e. the systems are recharged when evapotranspiration is at the lowest.

On the other hand the ISP method yields higher values of recharge to the Peninsula Aquifer than the other GIS-based methods. This is possibly due to the recharge in the high-lying areas that receive the most precipitation and have little evapotranspiration. Possible reasons for this discrepancy are the different approach and the different data sources as well as the different scale of the data sets.

The GRA II data set of recharge percentage is mainly based on the Chloride Mass Balance method, which requires the chloride concentration in the rain and the groundwater. The input data sets were not available to check the distribution of input values. However, several aspects are relevant and need to be considered:

- The chloride concentration in the rain varies significantly depending upon the proximity to the sea and will vary with proximity to industrial sources.
- The influence of a dry deposit of chloride is most relevant in close proximity to the sea, but also in generally dry areas.
- The spatial distribution of recharge and discharge areas is not taken into account.

The Piketberg Model Domain is situated at the coast, where a higher concentration of chloride in the rain and additional dry deposit of chloride can be expected, rendering the results of the Chloride Mass Balance unreliable.

Table 5-11 Comparison of recharge estimations

	Recharge [million m^3/a]					
Aquifer type	BRBS	ISP	GRA II	Map-centric	Average	SVF confined (section 5.3)
Peninsula	10.9	15.0	7.8	13.3	11.8	12.2
Nardouw	1.5	2.2	1.0	2.2	1.8	N/a
Fractured	3.0	2.9	2.4	3.9	3.1	N/a
Intergranular-fractured	2.8	1.7	2.6	4.2	2.8	N/a
Intergranular	18.5	12.0	13.2	26.5	17.6	N/a
Total aquifer specific	**36.8**	**33.9**	**27.1**	**50.1**	**37.0**	**N/a**

The map-centric simulation considers the different rainfall – run-off responses, the potential overland flow, as well as the actual evapotranspiration, which is dependent upon the effective rainfall and maximum temperature. Furthermore, the delineation of recharge and discharge zones and the seasonal pattern of winter rainfall are taken into account.

However, the results for the TMG aquifers are similar to the ISP method and higher than with the BRBS and GRA II methods (see **Table 5-11**). On the other hand, the results for the 'intergranular-fractured' aquifer type and the intergranular aquifer are significantly higher than compared to the other methods. This would require verification on a local scale prior to allocating the water for use.

Based on the comparison of the different approaches the average of the different methods (see **Table 5-12** will be used as average recharge in the discharge estimation and the water balance yield analysis (see Section 6.1 and 7.2).

Table 5-12 Average aquifer specific recharge estimation per catchment

Quaternary catchment	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Aquifer specific recharge**	
	Mm^3	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*mm*
G10K	8.53	1.75	0.83	0.78	0.25	12.15	41
G30A	0.64		0.75	0.18	10.78	12.36	22
G30D	2.60		1.47	1.87	6.52	12.46	28
Total	**11.78**	**1.75**	**3.05**	**2.83**	**17.56**	**36.97**	**28**

6. DISCHARGE

Discharge from the groundwater system occurs either naturally as discharge in springs and seepzones, into rivers or into the sea, or artificially as abstraction from boreholes.

6.1 NATURAL DISCHARGE

The most common way to estimate the natural discharge from aquifers into river reaches is the baseflow separation method. Historically, hydrologists separated river flow into floods and baseflow components based on flow characteristics, while geohydrologists tried to consider that component derived from groundwater, i.e. process hydrology. Depending upon the applied hydrograph separation method, baseflow comprises flow from different sources, i.e. interflow, delayed run-off and groundwater discharge. Groundwater contribution dominates only in prolonged dry periods.

In applying this method, it is therefore important to distinguish between the total baseflow and the groundwater contribution to baseflow. The published estimates for baseflow and groundwater contribution to baseflow in the different quaternary catchments are listed in **Appendix A**.

The differences in baseflow estimation indicate the inaccuracy and subjectivity of this method. It is beyond the scope of the regional water balance task to verify the baseflow estimation figures. It is recommended to use the GRDM data (DWAF, 2006f) as input for the water balance model and resource evaluation in section 7, as these are the most recent data and were prepared for the groundwater reserve determination and resource evaluation. Since the catchments within the Model Domain are considered ephemeral systems, the baseflow is set to zero.

However, there are known perennial springs emerging from the TMG in the Piketberg Mountain range, especially along the southern and eastern slopes, contributing to stream flow towards the Berg River. Some of these are used for water supply to towns (e.g. Aurora) and for irrigation.

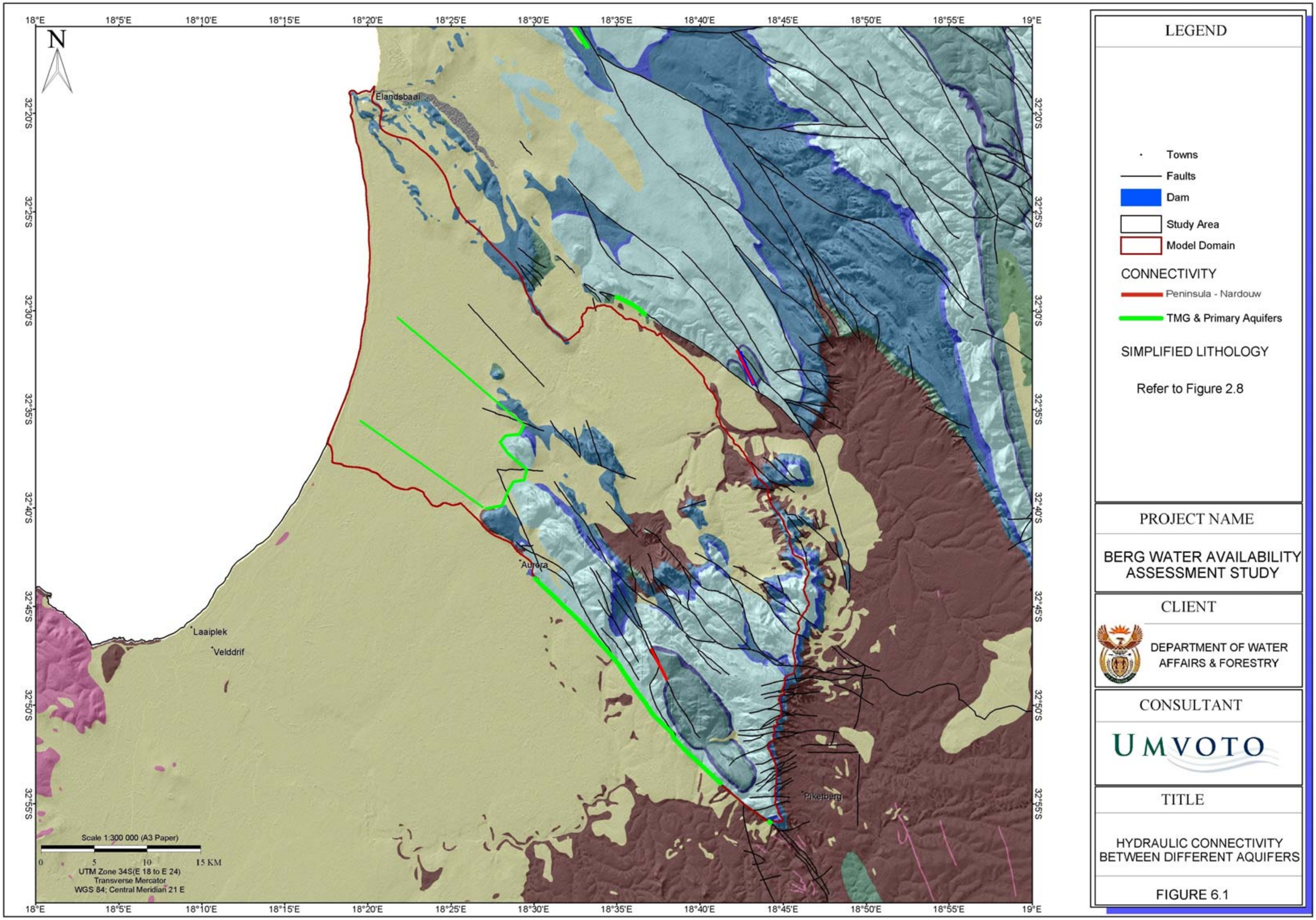
Flow rates given in the National Groundwater Database for the Aurora Spring indicate an average flow of 1.1 l/s, equalling 35 000 m^3/a. The NGDB and Water-use Authorisation and Management System databases list a total of 6 springs emanating from the Peninsula Formation in the Piketberg Mountains. Assuming a total number of perennial springs of up to 12, the total discharge from the Peninsula Aquifer is estimated at ~ 400 000 m^3/a.

6.2 LATERAL DISCHARGE – RECHARGE

The potential hydraulic connection between the Peninsula and the Skurweberg Aquifers was investigated by mapping where these two lithologies are contiguous due to faulting. There is only one such site in the model domain (see **Figure 6-1**) associated with normal down faulting. It is important to establish in the future whether these faults that separate the aquifers, are or are not, annealed. This is important for the appropriate design of a monitoring network for surface and groundwater, climate and the environment. Preliminary indications based on hydrocensus and piezometric levels as well as spring elevations suggest that the two aquifers behave as separate systems. This does not presume that under different head conditions resulting from large-scale abstraction this circumstance would not change. It does, however, indicate that the natural recharge and discharge process together with whatever abstraction is current (which implicitly take into account aquifer storage and hydraulic characteristics) have different time responses in both aquifers.

The Conceptual Model Report (DWAF, 2007b) showed distinctly different piezometric maps for the Nardouw and the Peninsula Aquifer, indicating that it can be reasonably assumed that the two aquifers respond independently. Therefore no account of lateral exchange between the two aquifers is made in the water balance results.

It is assumed in the conceptual model for the Piketberg Model Domain that the Peninsula Aquifer partially discharges into the alluvium in areas between the mountain range and the coast, where the Peninsula Formation is directly overlain by alluvium deposits. These areas can be mapped (see **Figure 6-1**), but the exchange between the aquifers cannot be quantified with the currently available data. However, this does not impact on the yield estimation, as the amount of water is available either from the Peninsula Aquifer or the primary aquifer. A reduction of lateral exchange between these aquifers would not negatively impact on the current water use from the primary aquifer, which is currently very limited (see Section 6.3).



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32°40'S
32°45'S
32°50'S
32°55'S
N
Elandsbaai
Aurora
Laaiplek
Velddrif
Piketberg
Scale 1:300 000 (A3 Paper)
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15 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E
LEGEND
Towns
Faults
Dam
Study Area
Model Domain
CONNECTIVITY
Peninsula - Nardouw
TMG & Primary Aquifers
SIMPLIFIED LITHOLOGY
Refer to Figure 2.8
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS & FORESTRY
CONSULTANT
UMVOTO
TITLE
HYDRAULIC CONNECTIVITY BETWEEN DIFFERENT AQUIFERS
FIGURE 6.1

6.3 GROUNDWATER ABSTRACTION

Relatively recent estimates of the groundwater use in the quaternary catchments surrounding the Model Domain from the Groundwater Resource Assessment Phase II (GRA II) project (DWAF, 2004) indicate an annual abstraction of 11.5 million m^3/a (see **Appendix A**). The highest demand is estimated for irrigation with 7.9 million m^3/a, mainly in the G10K, G30A and G30D catchments (above 2 million m^3/a each), followed by livestock with 1 million m^3/a.

According to the GRA II calculations urban domestic use accounts for 0.36 million m^3/a and is concentrated in the G10H catchment. Industrial demand accounts for 2.18 million m^3/a, mainly in the G10M catchment (Saldanha).

Since these estimations are not aquifer specific, it was decided to recalculate the groundwater use per aquifer per catchment, using two different approaches:

- disaggregating the GRA II values with respect to the outcrop area of the different aquifers, assuming an equal and *pro rata* spatial distribution of boreholes and abstraction points over the catchments;
- assigning the registered groundwater abstraction in the WARMS database to aquifers by linking WARMS registered use with boreholes in the NGDB and assigning volumes *pro rata* to the number of boreholes in different aquifers.

The disaggregating of the GRA II data (see **Table 6-1**) is purely based on the outcrop area of the different aquifers and therefore not physically correct. It is also not necessarily realistic since certain aquifers are very much more developed than others. It can be expected that the groundwater use from the primary aquifers as well as the ‘intergranular-fractured’ aquifers in certain areas is underestimated with this approach, as aspects such as accessibility and yield are not taken into account.

Table 6-1 Estimated groundwater use per aquifer per catchment, after GRA II

Quaternary catchment	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*
G10K	0.45	0.10	0.06	0.06	0.02	0.69
G30A	0.06		0.11	0.02	1.86	2.05
G30D	0.19		0.21	0.37	1.80	2.57
Total	**0.69**	**0.10**	**0.38**	**0.44**	**3.69**	**5.30**

As a comparison, it was decided to use the WARMS database and link the entries with borehole information from the NGDB to increase the confidence in groundwater use per aquifer. The cadastral data on farms and properties, as received from Department of Land Affairs, Chief Directorate: Survey and Mapping (CDSM), was used to link the registered groundwater use on the WARMS database to a farm or property.

The boreholes registered on the NGDB were also linked to the properties from the cadastral database and to the aquifers, based on the surface geology as described in Volume 2 of this report. Since a number of boreholes exist on most farms, often in different aquifers, the registered use from the WARMS was assigned proportionally to the aquifers with the most boreholes. In cases, where more than 90% of the boreholes were situated in a particular aquifer, the use volume was assigned to this aquifer only. The results of this calculation are documented in **Table 6-2.**

Table 6-2 Estimated groundwater use per aquifer per catchment, based on WARMS and NGDB

Quaternary catchment	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*
G10K	3.68	0.00	0.32	0.04	0.06	4.11
G30A	0.00		0.00	0.00	0.07	0.07
G30D	0.00		0.00	0.22	0.37	0.59
Total	**3.68**	**0.00**	**0.32**	**0.26**	**0.51**	**4.77**

Table 6-2 shows an unrealistically high groundwater abstraction from the Peninsula Aquifer in the G10K (Piketberg Mountain range), while the groundwater abstraction from the Nardouw Aquifers seems to be too low. The farmers in the Piketberg area abstract water mainly from the Nardouw. On the other hand, the abstraction from the intergranular aquifers, especially in the G30A and G30D catchments appears unrealistically low. These discrepancies could be due to

- the uncertainty of the registration in WARMS,
- the uncertainty of the borehole positions, as recorded in the NGDB,
- the uncertainty of whether the borehole is actually in use,
- the difference in borehole yield and
- the inclusion of dry boreholes in the calculation.

It is therefore suggested to verify the aquifer-specific groundwater use in these areas through detailed data analysis and field verification. Since the estimates from the GRA II are more conservative, these will be used in the estimation of the groundwater potential (Section 7).

7. YIELD MODEL

Resource evaluation is a transient rather than a steady state problem as it depends not only on standard mass balance of recharge and discharge, as discussed and documented in previous sections, but also on a more dynamic perspective of how recharge estimates and discharge rates are likely to change depending upon the time lag between recharge, discharge and abstraction, the available volume of water in storage and the aquifer development and management strategy.

The concept of "groundwater resource potential" (Vegter, 1995) embraces the following and these factors must be considered (*inter alia*) when evaluating a potential scheme:

- Accessibility - aquifer depth and drilling risk;
- Exploitability - yield and pumping depth;
- Availability - resource (i.e. storage) and recharge;
- Suitability - chemistry and risk of pollution; and
- Conservation - size and hydrodynamic situation.

This section addresses the yield analysis on the model domain level. At the level of this investigation (situation assessment) it would not be realistic to provide yield estimates per scheme or wellfield. To achieve this level of detail and confidence, a feasibility study would be required, comprising detailed geological fieldwork, exploration drilling, extensive testing, sample collection, analysis and modelling.

The approach taken for the yield estimation at the regional scale comprises two aspects:

- Sustainable yield estimation based on acceptable average drawdown
- Sustainable yield estimation based on long-term water balance (i.e. recharge – discharge).

Both methods will be discussed separately in the sections below and the results combined and compared in the summary section 7.3.

7.1 GROUNDWATER POTENTIAL

Aquifer specific recharge estimations are discussed in Section 5 for each quaternary catchment. Natural discharge and groundwater abstraction are discussed in Section 6 for each quaternary catchment. Using the relationship between recharge areas and potential discharge areas, as discussed in Volume 3 of this report, the available groundwater for abstraction for the model domain is estimated.

The unexploited potential is then estimated as recharge minus baseflow minus current use. This is considered conservative and realistic, as:

- the recharge estimation is aquifer specific and is calibrated with different methods;
- the possibility that some recharge does not reach the confined portion of the aquifer, but is discharged in other directions and or in floods, is taken into account;
- it is assumed that the baseflow volume is in a linear relationship to the recharge.

However, the method does not take into account the desired ecological status of the aquifer in terms of the Reserve Determination and RQOs, and does not consider the water quality.

In applying this method with the groundwater use data from WARMS, the groundwater potential for the Peninsula Aquifer and the Nardouw Aquifer was estimated to be 7.7 million m^3/a and 1.7 million m^3/a, respectively, applying the average recharge estimation (see **Table 7-1**). The total groundwater potential for the different aquifers varies between 23.1 million m^3/a (GRA II method) and 47 million m^3/a (map-centric method). Applying the groundwater use estimates from the GRA II project, the groundwater potential for the Peninsula Aquifer and the Intergranular aquifer was estimated to be 11 million m^3/a and 14 million m^3/a, respectively (see **Table 7-2**).

Table 7-1 Unexploited groundwater potential based on average recharge estimation and WARMS groundwater use (all values in Mm^3/a)

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	11.8	0.4	11.4	3.68	7.69
Nardouw	1.7	0	1.7	0.00	1.75
Fractured	3.1	0	3.1	0.32	2.73
Intergranular-fractured	2.8	0	2.8	0.26	2.57
Intergranular	17.6	0	17.6	0.51	17.05
Total	**37.0**	**0.4**	**36.6**	**4.77**	**31.79**

Table 7-2 Unexploited groundwater potential based on average recharge estimation and GRAII groundwater use (all values in Mm^3/a)

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	11.8	0.4	11.4	0.69	10.69
Nardouw	1.7	0	1.7	0.10	1.65
Fractured	3.1	0	3.1	0.38	2.67
Intergranular-fractured	2.8	0	2.8	0.44	2.39
Intergranular	17.6	0	17.6	3.69	13.87
Total	**37.0**	**0.4**	**36.6**	**5.30**	**31.27**

The detailed comparison of the estimated groundwater potential and the percentage of groundwater utilisation per quaternary catchment shows that all aquifers in the model domain are mostly un- or under-utilised. However, the high groundwater potential in the intergranular aquifer, especially in the G30A catchment does not take into account the poor water quality of the groundwater, originating in the catchment.

7.2 STORAGE YIELD MODEL

A storage yield model was developed to evaluate the potential yield of the aquifers with respect to hydraulic head decline and acceptable environmental impacts (Volume 4; DWAF, 2007e). The model uses the results from the storage model (see Section 4) to calculate the potential yield of the Peninsula Aquifer in the model domain. Since large-scale groundwater abstraction is proposed for the confined portion of the aquifer only, the regional hydraulic head decline due to abstraction depends upon the storativity of the aquifer.

The conservative estimate of porosity (i.e. 5%), as used in the storage model (see Section 4.2), coupled with the vertical compressibility of fractured rocks between $3.3 \times 10^{-10}\,Pa^{-1}$ and $6.9 \times 10^{-10}\,Pa^{-1}$ (Domenico and Schwartz, 1990) delineated a range of Specific Storage values between 3×10^{-6} and $7 \times 10^{-6}\ m^{-1}$ that were used to calculate the Effective Storativity. The accepted Specific Storage for further calculation for this study is taken as $6 \times 10^{-6}\,m^{-1}$, with a corresponding Effective Storativity of 7.5×10^{-3}.

The volume of water elastically released from confined storage in the Peninsula Aquifer, due to a unit (1 m) head or pressure decline causing mainly porosity reduction (aquifer compression), are just a small fraction, 0.01% of the total quantity of subsurface water, viz., 0.4 million m^3 only.

This comparison serves to put into quantitative perspective the common public perception that groundwater abstraction from the deep confined Peninsula aquifer will somehow significantly dewater the system, with (often unspecified) adverse ecological consequences. Even where the regionally averaged decline in hydraulic head approaches 50 m, the volume released by aquifer compression generally remains in the order of 0.6% of the total volume in slow circulation within the deep groundwater flow system. A vastly greater volume of groundwater is essentially *non-extractable* by any practical and/or economical means.

Provided an average drawdown of 20 m, averaged over the whole aerial extent of the suboutcrop, is considered possible and ecologically acceptable, the calculated yield from the deep confined storage in the 1 200 m thick Peninsula Aquifer is in the order of 8 million m^3. The results for the model scenario with Specific Storage of $6 \times 10^{-6}\,m^{-1}$ and porosity of 5% are summarized in **Table 7-3** below.

This approach is very conservative, as it does not take into account the annual replenishment of the aquifer. It therefore constitutes the yield potential during drought conditions from the confined portion of the aquifer only.

The total volume of water stored in the confined portions of the Peninsula Aquifer is tabled below (see **Table 7-3**) together with the yield (water available for abstraction) of these basins given a regional drawdown of the piezometric surface of 1, 5 and 20 m. How much water to actually abstract is an aquifer development design and management issue and would need to take into consideration

- impacts of abstraction
- social factors
- economic advantages
- advantages (environmental and yield) arising from conjunctive use
- water saving arising from conjunctive use.

Comparison of the yield or volume of water abstracted that would result in a 1, 5 or 20 m hydraulic head decline relative to the pore volume is never greater than 0.24% of the total pore volume.

Table 7-3 Potential Yield of the confined Peninsula Aquifer in the Model Domain, based on the storage yield model (Effective Storativity based on Specific Storage)

Model Sub-domain	Effective Storativity	Pore Volume Mm^3	Volume per head decline of:					
			1 m		5 m		20 m	
			Mm^3	%	Mm^3	%	Mm^3	%
PKT 1	7.45E-03	419	0.05	0.01	0.25	0.06	1.01	0.24
PKT 2	7.52E-03	2 941	0.35	0.01	1.76	0.06	7.06	0.24
PKT 3	No confined Peninsula Aquifer							
Total	**7.45E-03**	**3 360**	**0.40**	**0.01**	**2.01**	**0.06**	**8.06**	**0.24**

7.3 WATER BALANCE YIELD MODEL

The long-term averaged annual groundwater potential is calculated in Section 7.1 above, based on the aquifer specific estimations for recharge and discharge, both natural and abstraction. The yield from the confined portions of the Peninsula and the Skurweberg aquifers is calculated in Section 7.2 above, based on scenarios of acceptable averaged drawdown. The water balance yield model combines both the groundwater potential and the storage yield to establish an optimised strategy for short-term and long-term management of different aquifers.

The estimates, given in **Table 7-4**, constitute the potential groundwater yield for the Peninsula Aquifer and the Nardouw Aquifer, respectively. The actual yield that can be achieved depends upon aspects such as access, appropriate drilling technology, optimised borehole siting, economics of drilling, that need to be quantified as part of feasibility studies to refine the yield estimates.

Table 7-4 Groundwater yield for Peninsula and Nardouw aquifers based on average recharge and baseflow estimation, groundwater use per GRA II and storage yield (all values in Mm^3/a)

Aquifer	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)	Storage Yield	
				5 m drawdown	20 m drawdown
Peninsula	11.4	0.69	10.69	2.01	8.06
Nardouw	1.7	0.10	1.65	Not applicable	
Fractured	3.1	0.38	2.67	Not applicable	
Intergranular-fractured	2.8	0.44	2.39	Not applicable	
Intergranular	17.6	3.69	13.87	Not applicable	
Total	**36.6**	**5.30**	**31.27**	**Not applicable**	

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

A robust water balance and yield model was developed to estimate the groundwater potential from different aquifers within the study area as well as to produce reasonable values for input parameters to the groundwater modules of the WRYM and WSAM. The model is based on the following components:

- Aquifer-specific recharge, calculated with a variety of GIS-based methods and compared to results from previous studies;
- Modelled overland flow, based on slope distribution, as input to the recharge model;
- Modelled evapotranspiration, using the Turc (1954) approach, as input to the recharge model;
- Storage capacity in the Peninsula Aquifer, based on 3-D modelling of the geological structure;
- Aquifer-specific natural discharge, based on groundwater contribution to baseflow and recharge per quaternary catchment;
- Aquifer-specific groundwater use, based on registered use on the WARMS database;
- Storage yield for the confined portion of the Peninsula Aquifer, based on the modelled storativity and reasonable values for specific storage;
- Groundwater potential, based on recharge, baseflow and groundwater use.

The water balance and yield model suggests a total remaining groundwater potential of approximately 33 million m^3/a within the study area, applying the average recharge estimation (see **Table 8-1**). The recharge estimation for the Peninsula and Nardouw aquifers are considered conservative.

Table 8-1 Summary results of groundwater potential per aquifer (Mm^3/a)

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	11.8	0.4	11.4	0.69	10.69
Nardouw	1.7	0	1.7	0.10	1.65
Fractured	3.1	0	3.1	0.38	2.67
Intergranular-fractured	2.8	0	2.8	0.44	2.39
Intergranular	17.6	0	17.6	3.69	13.87
Total	**37.0**	**0.4**	**36.6**	**5.30**	**31.27**

Note: groundwater potential is based on recharge, baseflow and groundwater use. It represents the water that would otherwise discharge by various means, for example to the coast.

The very high groundwater potential for the intergranular and intergranular-fractured aquifers does not take into account the exploitability and the suitability for domestic or agricultural use. The groundwater quality in large areas of the Sandveld primary aquifer as well as the Malmesbury and Granite regolith aquifers does not comply with the drinking water standards and is not or only to a degree suitable for consumption.

8.2 RECOMMENDATIONS

The results of the Water Balance Model for the Piketberg Model Domain shows that the uncertainty of the data input as well as the applied method has a significant impact on the reliability of the output and any decision that would be based on these results. It is therefore strongly recommended to initiate a data collection and monitoring programme, as outlined below.

It is also evident that the groundwater – surface water interaction and the integration of groundwater potential and use into the water resource planning cannot be achieved reliably with the current groundwater modules in the WRSM and WRYM. Hence, the development of alternatives to these modules is strongly suggested.

8.2.1 Monitor

A monitoring programme and additional data collection is detailed in the recommendations of the Data Availability Report (DWAF, 2007a) and the Conceptual Model Report (DWAF, 2007b), of which the following activities are required for increasing the confidence in the model outputs:

- Conduct a spring hydrocensus including diverse hydrochemical sampling to verify discharge rates;
- Conduct a borehole hydrocensus to verify groundwater abstraction;
- Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg aquifers to improve the estimate for the specific storage;
- Hydrochemical sampling at specific river reaches to be used in mixing models for baseflow estimation.

In addition to these data collection activities long-term monitoring should be initiated for the following aspects:

- Rainfall sampling and chemical / isotope analysis in selected recharge areas for calibration of the recharge model with the Chloride Mass Balance and Isotopes;
- Seasonal and event response sampling of rainfall, spring flow and groundwater for calculation of residence time and interflow/rejected recharge;
- Monitoring of key abstraction points for aquifer response to abstraction for considering the impact of existing groundwater use with respect to refining unused potential estimates;
- Monitoring of ambient boreholes in different aquifers to establish seasonal fluctuation of water levels for calibration of recharge estimation;

It is therefore suggested to develop a comprehensive monitoring programme for the Berg WAAS area that comprises all the above aspects in an integrated and optimised manner.

8.2.2 Model

It is recommended to use the results of the water balance model as input for the WRYM and WRSM. If the further exploitation of the aquifers in the Piketberg area is considered, a feasibility study is recommended that comprises the development of a flow model on the wellfield scale, based on long-term monitoring data, a described above.

9. REFERENCES

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APPENDIX A

LIST OF HYDROLOGICAL PARAMETERS PER QUATERNARY CATCHMENT

APPENDIX A : LIST OF HYDROLOGICAL PARAMETERS PER QUATERNARY CATCHMENT

Table A-1: Catchment area and MAP

Quaternary catchment		MAP *WR90*	MAP *CCWR*	MAP *GRAII*	MAP *Berg WAAS*	MAP *WR2005*
		mm	*mm*	*mm*	*mm*	*mm*
G10K	1175.89	382	408	383	318	317
G10M	2004.68	300	271	298	225	225
G30A	761.28	260	261	262	309	309
G30D	438.59	384	345	384	398	399
Total	**4380**	**323**	**313**	**323**	**282**	**282**

Table A-2: Catchment area, MAR and Run-off efficiency

Quaternary catchment		MAR *WR90*	MAR *WR2005*	Difference	Run-off Effciency		
		mm	*mm*		*Berg WAAS / WR2005*	*WR2005*	*WR90*
G10K	1175.89	21	8	61.4%	0.03	0.03	0.05
G10M	2004.68	9	3	66.8%	0.01	0.01	0.03
G30A	761.28	6	13	115.5%	0.04	0.04	0.02
G30D	438.59	22	26	20.0%	0.07	0.07	0.06
Total	**4380**	**13**	**8**	**64.5%**	**0.03**	**0.03**	**0.04**

Table A-3: Baseflow, Groundwater Contribution to Baseflow and Recharge per catchment (after GRDM database)

Quaternary catchment	Base Flow *GRDM*	Base Flow *HUGHES*	Base Flow *PITMAN*	Base Flow *SCHULZE*	GW Contribution to Base Flow *GW_BFLOW*	Recharge *GRDM*
	mm	*mm*	*mm*	*mm*	*mm*	*mm*
G10K	0.0	2.14	0.00	0.00	0.00	14.47
G10M	0.0	0.56	0.00	0.00	0.00	16.18
G30A	0.0	0.07	0.00	0.00	0.00	14.04
G30D	0.0	1.72	0.00	0.00	0.00	21.97
Total	**0**	**0.88**	**0**	**0**	**0**	**13.80**

Table A-4: Groundwater use per catchment (after GRA II)

Quaternary Catchment	Groundwater Use [Million m^3/a]							
	Total	Rural	Municipal	Agric. Irrigation	Agric. Livestock	Mining	Industry	Aqua
G10H	1.4927	0.0050	0.2788	0.4034	0.1265	0.0000	0.6790	0.0000
G10K	2.6975	0.0240	0.0000	2.4656	0.2079	0.0000	0.0000	0.0000
G10M	1.9990	0.0070	0.0837	0.0000	0.4073	0.0000	1.5010	0.0000
G30A	2.7694	0.0040	0.0000	2.6167	0.1487	0.0000	0.0000	0.0000
G30D	2.5644	0.0000	0.0000	2.4580	0.1064	0.0000	0.0000	0.0000
Total	**11.523**	**0.0400**	**0.3625**	**7.9437**	**0.9968**	**0.0000**	**2.1800**	**0.0000**