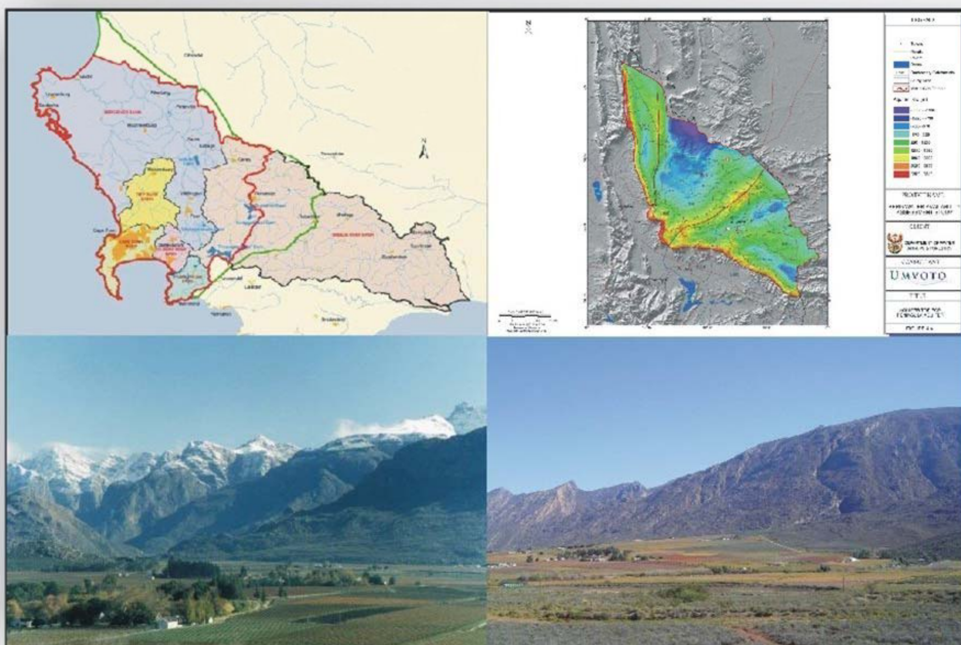
Ref No: P WMA19/000/00/0408

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. 8
TMG AQUIFER, WITZENBERG-NUY MODEL



Final **December 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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GROUNDWATER MODEL REPORT VOLUME 8
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APPROVAL

TITLE	:	The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models : Groundwater Model Report Volume 8 TMG Aquifer, Witzenberg-Nuy Model
DWAF REPORT NO.	:	P WMA 19/000/00/0408
CONSULTANTS	:	Umvoto Africa in association with Ninham Shand
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REPORT STATUS	:	Final
DATE	:	December 2008

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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		

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

GROUNDWATER MODEL REPORT VOLUME 8
TMG AQUIFER, WITZENBERG-NUY 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: Overview of Methodology and Results

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

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 8 in the project series and contains the results of a water balance model for the TMG aquifers in the Witzenberg-Nuy area. It should be read in conjunction with Volume 2, describing the data availability, Volume 3, describing the conceptual model that has informed the delineation of IWRM domains and the breakdown into aquifer types, and Volume 4, describing the regional water balance model.

STUDY DOMAIN

The Witzenberg-Nuy Domain is a combination of three subdomains, which include the Agter Witzenberg and the Tulbagh-Ceres Valley in the west, the Hex River area in the center and the Koo Valley east of De Doorns in the east. The Tulbagh-Ceres area and the Hex River area were previously considered separate model areas. However, conceptually, the groundwater flow in the various aquifers is not isolated to the originally defined domains and interbasin transfers are expected. For this reason it was decided to join the Tulbagh-Ceres and Hex River model domains as well as include the area east of De Doorns.

WITZENBERG-NUY 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.

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

Model Subdomains	Peninsula Aquifer	Area (km^2)	Rock Volume (Mm^3)	Pore Volume (Mm^3)
Witzenberg-Nuy 1	Unconfined portion	140.53	153 793	7 690
	Confined portion	365.54	510 177	25 509
Witzenberg-Nuy 2	Unconfined portion	175.77	192 331	9 617
	Confined portion	1 131.65	1 584 132	79 207
Witzenberg-Nuy 3	Unconfined portion	260.39	256 445	12 822
	Confined portion	935.24	1 300 645	65 032
Witzenberg-Nuy Model Domain	Total Unconfined portion	576.69	602 569	30 128
	Total Confined portion	2 432.43	3 394 954	169 748
	Total Aquifer	**3 009.12**	**3 997 523**	**199 876**

The results indicate a storage capacity within the Peninsula Aquifer of 200 x 10^9 m^3 (see **Table E-1**), and a storage capacity of 25 x 10^9 m^3 within the Skurweberg Aquifer (see **Table E-2**).

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

Model Subomains	Skurweberg Aquifer	Area	Rock Volume	Pore Volume
		(km^2)	(Mm^3)	(Mm^3)
Witzenberg-Nuy 1	Unconfined portion	177.97	36 207	1 810
	Confined portion	101.17	25 705	1 285
Witzenberg-Nuy 2	Unconfined portion	174.35	31 299	1 565
	Confined portion	877.49	218 061	10 903
Witzenberg-Nuy 3	Unconfined portion	201.81	47 581	2 379
	Confined portion	609.60	146 046	7 302
Witzenberg-Nuy Model Domain	Total Unconfined portion	554.13	115 087	5 754
	Total Confined portion	1 588.26	389 811	19 491
	Total Aquifer	**2 142.39**	**504 898**	**25 245**

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 conservative 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 ISP method results in higher recharge to the TMG aquifers and lower recharge to the intergranular and intergranular-fractured aquifers. 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	78	111	82	51	81	98
Nardouw	82	114	88	86	93	60
Fractured	1	2	2	1	1	N/a
Intergranular-fractured	39	36	57	67	50	N/a
Intergranular	12	10	11	14	12	N/a
Total aquifer specific	**212**	**272**	**241**	**220**	**236**	**N/a**

Discharge

Discharge from the aquifer systems is mainly 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. Other discharge pathways, e.g. discharge across catchment boundaries or along hydrotects towards the sea, are not estimated, as the available data are not sufficient to do so.

Table E-3 Aquifer-specific discharge estimation per subdomain, groundwater contribution to baseflow disaggregated according to average recharge

Model Subdomain	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Total GW contribution to baseflow**	
	Mm^3	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*mm*
Witzenberg-Nuy1	3.96	7.71	0.04	1.16	0.12	13.00	25
Witzenberg-Nuy2	4.12	5.98	0.20	5.03	1.10	16.42	13
Witzenbrg-Nuy3	3.67	2.43	0.00	0.48	0.29	6.87	6
Total	**11.7**	**16.1**	**0.2**	**6.7**	**1.5**	**36.3**	**12**

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 WARMS are considered reliable and will be used in determining the groundwater potential (see **Table E-4**).

Table E-4 Estimated groundwater use per aquifer (after WARMS and NGDB)

Model Subdomain	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*
Witzenberg-Nuy1	0.14	1.58	0.01	4.22	0.00	5.96
Witzenberg-Nuy2	0.49	5.63	0.00	14.64	2.86	23.62
Witzenberg-Nuy3	1.15	8.22	0.00	4.67	12.27	26.31
Total	**1.78**	**15.44**	**0.01**	**23.53**	**15.13**	**55.89**

YIELD MODEL

The water balance and yield model suggests a total remaining long-term averaged groundwater potential of 144 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-5**).

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 102 and 407 million m^3, depending upon the acceptable average drawdown of between 5 m and 20 m respectively.

Furthermore, the long-term averaged groundwater potential does not take into account the possibility of increasing recharge due to groundwater abstraction.

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

Table E-5 Summary results of groundwater potential per aquifer

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	80.6	11.7	68.9	1.8	67.2
Nardouw	92.5	16.1	76.4	15.4	61.0
Fractured	1.4	0.2	1.1	0.0	1.1
Intergranular-fractured	49.9	6.6	43.2	23.5	19.7
Intergranular	11.8	1.5	10.3	15.1	-4.8
Total	**236.2**	**36.2**	**200.0**	**55.9**	**144.1**

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 dimensional 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 Witzenberg-Nuy 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:

- Spring hydrocensus including diverse hydrochemical sampling to verify discharge rates;
- Continuous flow monitoring of selected springs;
- Borehole hydrocensus to verify targeted aquifer and groundwater abstraction;
- Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg Aquifer 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 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 regards 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.

Due to the over-utilisation of the aquifers in the Hex River Valley, compulsory licensing of groundwater use is strongly advised. This should be based on a detailed flow model for the valley, using the regional pattern as described and quantified in this report and on long-term monitoring data.

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
GVM	Gydo – Verlore Vlei Megafault
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	Voelvlei – 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 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, 2005):

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

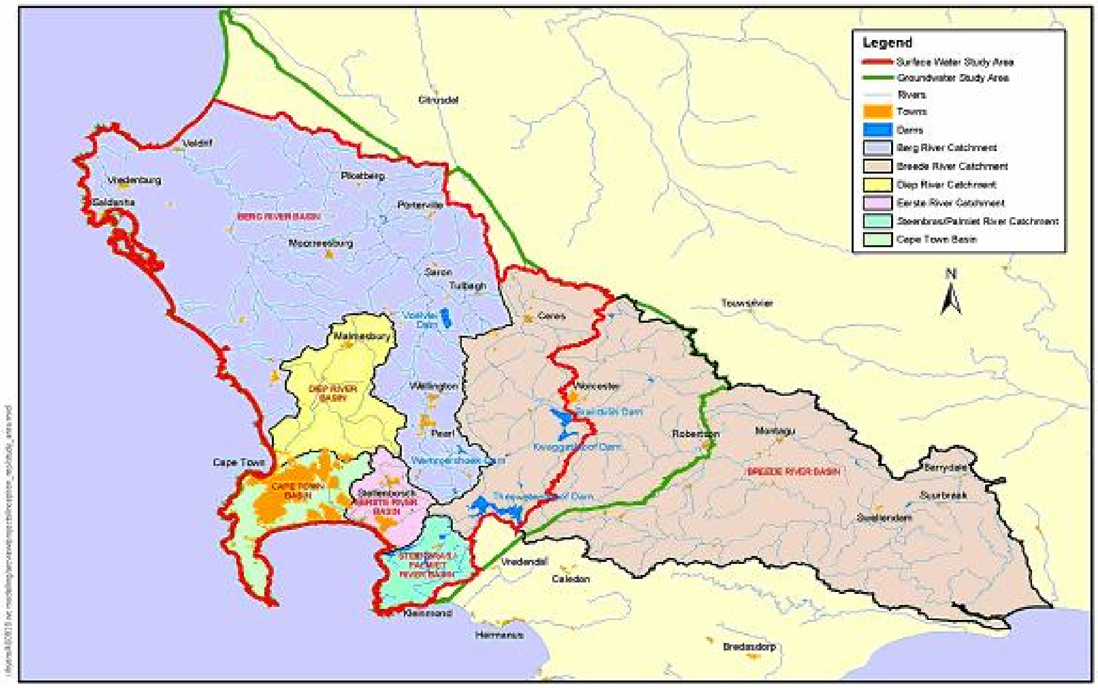


Figure 1-1: Study Area Locality

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, 2004a) if these aquifers are drawn down by 1 m 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 two-dimensional 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 three-dimensional problem in the study domain.

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

- total quantity of water available within the catchment;
- temporal and spatial distribution of water availability;
- current and future water 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 Resource directed (RDM) and a Water Quality (RQO) 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 the Western Cape Reconciliation Strategy Study)
    - Scenario for flood management (in support of the Western Cape Reconciliation Strategy 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 the TMG Aquifer
    - Recharge estimation and water balance on a regional scale
- Task 15a: Configuration of a numerical TMG groundwater model for Worcester
    - Quantification of surface water – groundwater interaction
    - Refinement of recharge and yield estimation
    - Scenario for Aquifer Storage Recovery (ASR) schemes (in support of the Western Cape Reconciliation Strategy 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: Overview of Methodology and Results

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

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 8 of the groundwater model report and documents the model results of Tasks 15b and 15c. 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, WITZENBERG-NUY 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 report). 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/knowledge gained from the smaller-scale modelling and, if available, on the basis of monitoring data and analysis.

The Witzenberg-Nuy Domain is a combination of three subdomains, which include the Agter Witzenberg and the Tulbagh-Ceres Valley in the west, the Hex River area in the center and the Koo Valley east of De Doorns in the east (see **Figure 1-2**).

The Tulbagh-Ceres area and the Hex River area were previously considered separate model areas belonging to the TMG Aquifer Conceptual and Water Balance Model requirement detailed in the Inception Report (DWAF, 2005). Preliminary investigations of the conceptual groundwater flow in the Peninsula and Skurweberg aquifers, as well as surface water flow are considerably different to one another. Conceptually, the groundwater flow in the various aquifers is not isolated to the originally defined domains of the Inception Report. Interbasin transfers translate to discharge of one subdomain being equivalent to recharge in the adjacent subdomain. From a modelling point of view, these subdomains cannot be considered individually. For this reason it was decided to join the Tulbagh-Ceres and Hex River model domains as well as include the area east of De Doorns.

The TMG Aquifer is already heavily utilised for irrigation within the Hex River valley. The increased groundwater abstraction can result in stream-flow reduction and therefore in reduced water availability to downstream users, especially in the flood plain of the Breede River around Worcester. Since it is anticipated that the water demand and groundwater abstraction from the TMG Aquifer in the vicinity of the Hex River Valley will increase further, it is important to understand and quantify the risk of stream flow reduction and the cascading effect on the possible future transfer scheme from the upper Breede River.

Similarly, the TMG Aquifer within the Tulbagh and Ceres areas (i.e. Agter Witzenberg, Ceres Valley) is also being utilized. It is envisaged to implement a transfer scheme from the Ceres Valley towards the Berg River, and it is therefore important to understand and quantify the interaction between the TMG Aquifer and the surface water system in this area. The impacts could be similar to the Worcester area.

The Inception Report states that the modelling of both the Tulbagh-Ceres and Hex River areas, which are combined in the Witzenberg-Nuy TMG Aquifer model, 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

Surface water flow is directed into the Klein Berg (Tulbagh-Ceres Valley), Olifants (northern Agter Witzenberg Valley), Hexrivier (Hex River Valley) and Breede River (Worcester Valley) basins. The Koekedou River and the Modder River in the Agter Witzenberg Valley flow southward to join the Breede River. These are fed by south-west flowing rivers in the Warm Bokkeveld including the Skaap River and the Titus River. The Hex River flows southwest through the Hex River Valley to join with the Breede River just south of Worcester. The Hex River Mountains form a large surface water divide shedding water into both the Warm Bokkeveld and the Hex River valley. The Kwadousberge sheds surface water into both the Hex River Valley and the Koo Valley. The Langeberge in the south-west shed surface water into the Koo Valley and the Breede River basin.

The main aquifers of interest are the TMG Peninsula and Nardouw (Skurweberg) aquifers. The Peninsula Formation dominates the high mountain areas, while the valleys and their flanks are layered with rocks of the overlying stratigraphy. This is due in part to the competency of the Peninsula Formation and to the folding in the Cape Fold Belt. As a result the Peninsula Aquifer is unconfined in the mountainous areas and confined in the valleys. The Skurweberg Aquifer has a smaller outcropping area that is unconfined in the Agter Witzenberg valley and along the flanks of the mountain ranges, and is confined in the valleys.

Water-level information was generated in the Witzenberg-Nuy area from all the points where the relevant aquifer's contact with an adjacent unit is crossed by a river. The assumption is that the topographic elevation of that point was equivalent to the water level relative to the mean annual sea level, with water levels being higher in elevated topographic areas.

For the Peninsula Aquifer (see **Figure 1-3**)

- The highest water levels occur in the northwestern flanks of the Hex River Mountains.
- The high water levels in the Hex River Mountains are characterized by steep piezometric gradients to the Hex River Valley floor.
- Water levels lower from the Skurweberge in the west across the Koue Bokkeveld to the Hex River Mountains in the east.
- The water levels decrease to the north and south of a latitudinal high in the Olifants River and Agter Witzenberg Synclines.
- The lowest water levels occur along the Nuy River near the confluence with the Breede River in the Worcester Valley.
- Water levels decrease eastward from the Kwadousberge.

For the Nardouw (Skurweberg) Aquifer (see **Figure 1-4**)

- The highest water levels occur on the northern flanks of the Hex River Mountains and along the Langeberge.
- The water levels in the Koue Bokkeveld decrease toward the centre and are at their lowest in the Mitchell's Pass.
- The piezometric lines parallel the Gydo – Verlore Vlei Megafault (GVM) hydrotect.
- The water levels decrease to the north and south of a latitudinal high in the Olifants River and Agter Witzenberg Synclines.
- The lowest water levels occur in the apex of the Hex River Valley.

High rainfall occurs in the high-lying mountainous areas onto the unconfined Peninsula Formation wherein the groundwater is recharged, which then flows to the discharge areas. Flow in the Agter Witzenberg valley is directed southward along the Agter Witzenberg Syncline and discharged in Mitchell's Pass. Flow in the Hex River Mountains is recharged by confined groundwater below the Warm Bokkeveld as well as high rainfall in the southern extension of the Hex River Mountains. This groundwater flow in the Peninsula Formation is discharged into the Hex River surface water flow. Rainfall in the Waaihoekberge and environs is discharged via surface water and groundwater flow directly into the Breede River. Groundwater flow in the Kwadousberge joins the Hex River Valley and is discharged into the Breede River.

Groundwater flow in the overlying Skurweberg Aquifer differs from that of the Peninsula Aquifer. While groundwater flow in the Peninsula Aquifer flows west to east into the Hex River, groundwater flow in the Skurweberg Aquifer flows east to west away from the Hex River into the Warm Bokkeveld.

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.

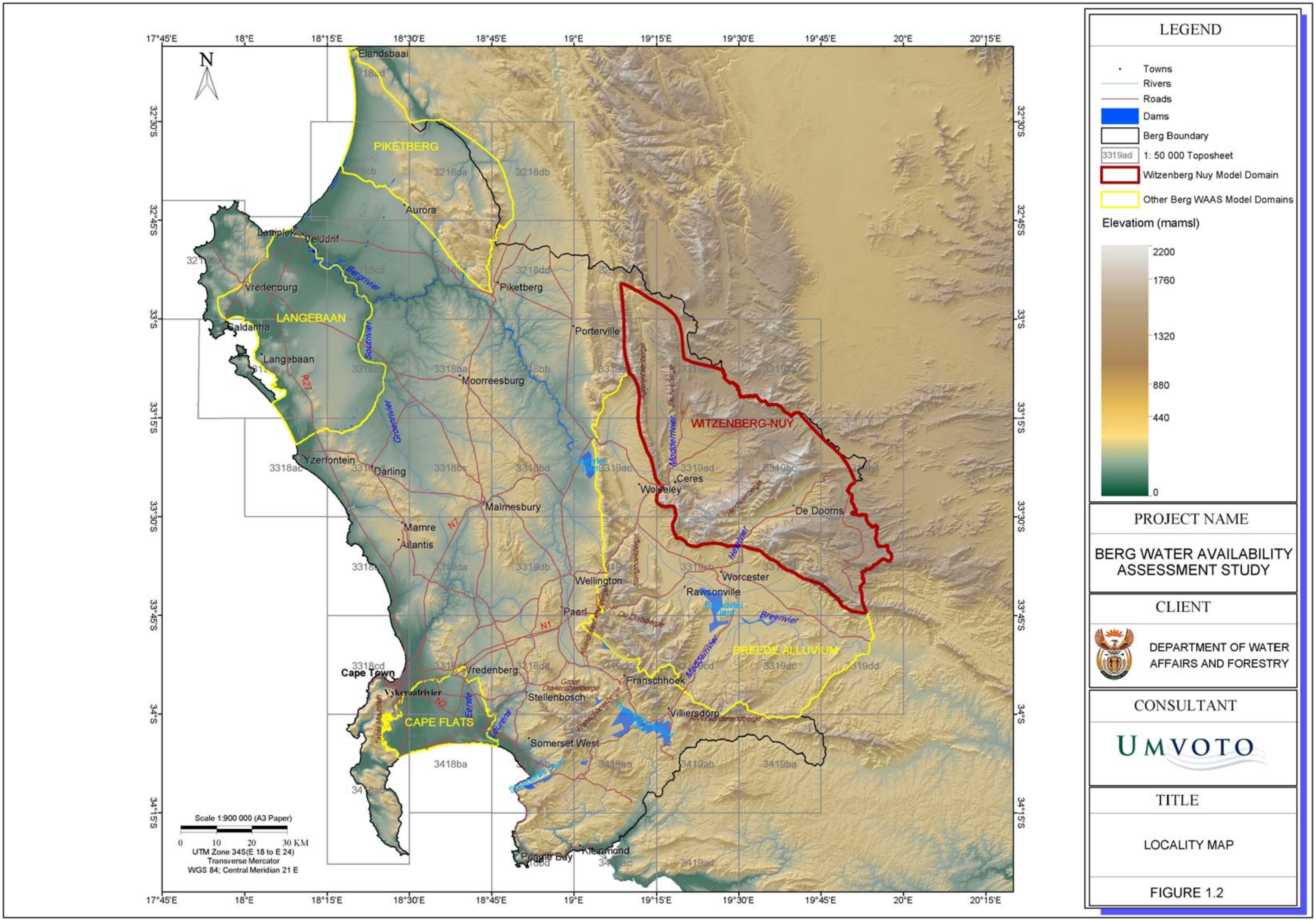
Section 4 describes the storage model methodology and results for the TMG aquifers.

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
3319ad 1: 50 000 Toposheet
Witzenberg Nuy Model Domain
Other Berg WAAS Model Domains
Elevatiom (mamsl)
2200
1760
1320
880
440
0
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS AND FORESTRY
CONSULTANT
UMVOTO
TITLE
LOCALITY MAP
FIGURE 1.2
Scale 1:900 000 (A3 Paper)
0 10 20 30 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E
PIKETBERG
LANGEBAAN
WITZENBERG-NUY
BREEDE ALLUVIUM
CAPE FLATS
Elandsbaai
Aurora
Laaiplek
Velddrif
Vredenburg
Piketberg
Saldanha
Langebaan
Porterville
Moorreesburg
Yzerfontein
Darling
Ceres
Wolseley
De Doorns
Malmesbury
Mamre
Atlantis
Wellington
Worcester
Rawsonville
Paarl
Cape Town
Franschhoek
Stellenbosch
Villiersdorp
Somerset West
Kleinmond
Bergrivier
Groenrivier
Modderrivier
Hexrivier
Breerivier
Eerste
Lourens
N1
N2
N7
R27
17°45'E
18°E
18°15'E
18°30'E
18°45'E
19°E
19°15'E
19°30'E
19°45'E
20°E
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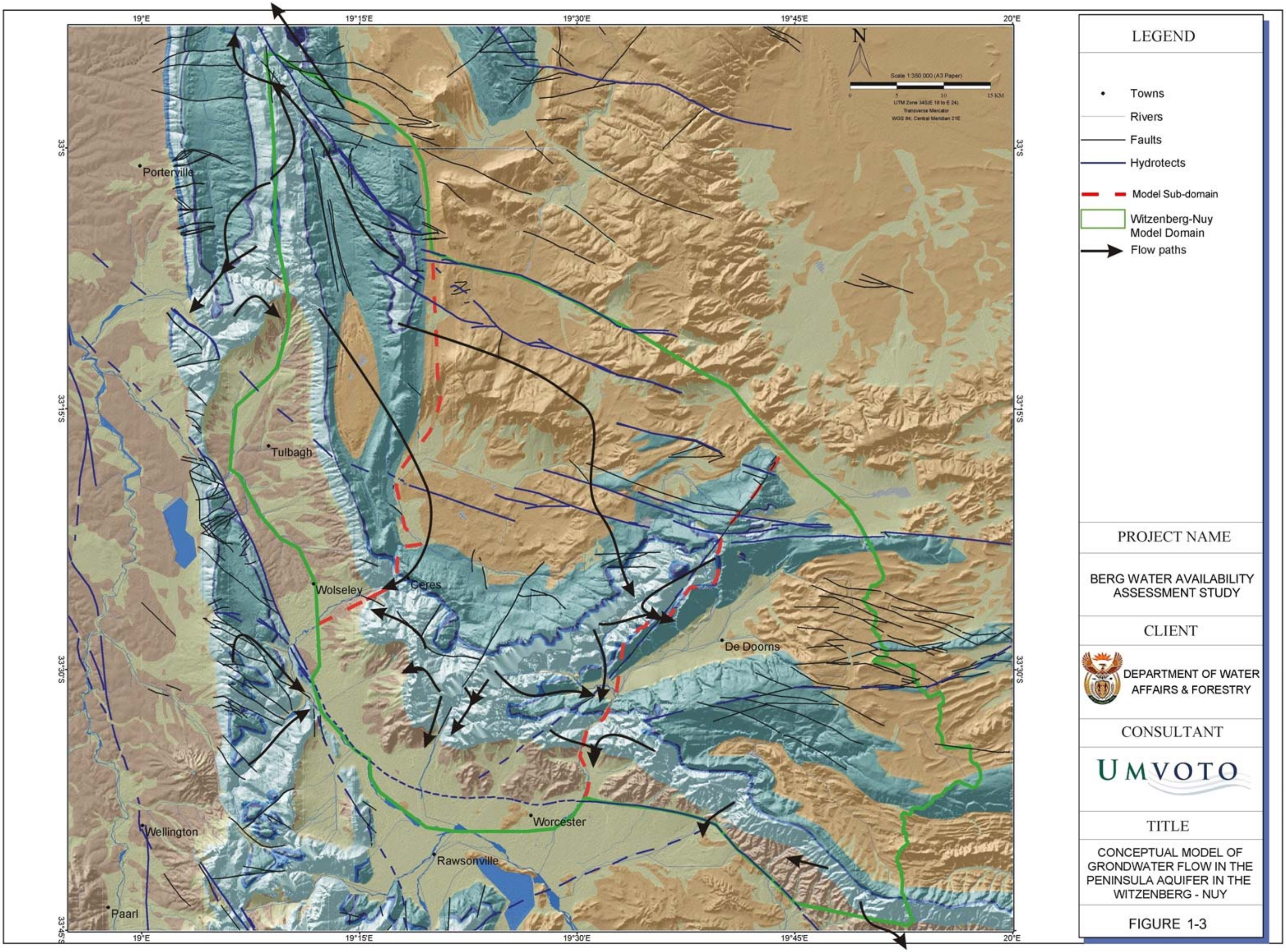
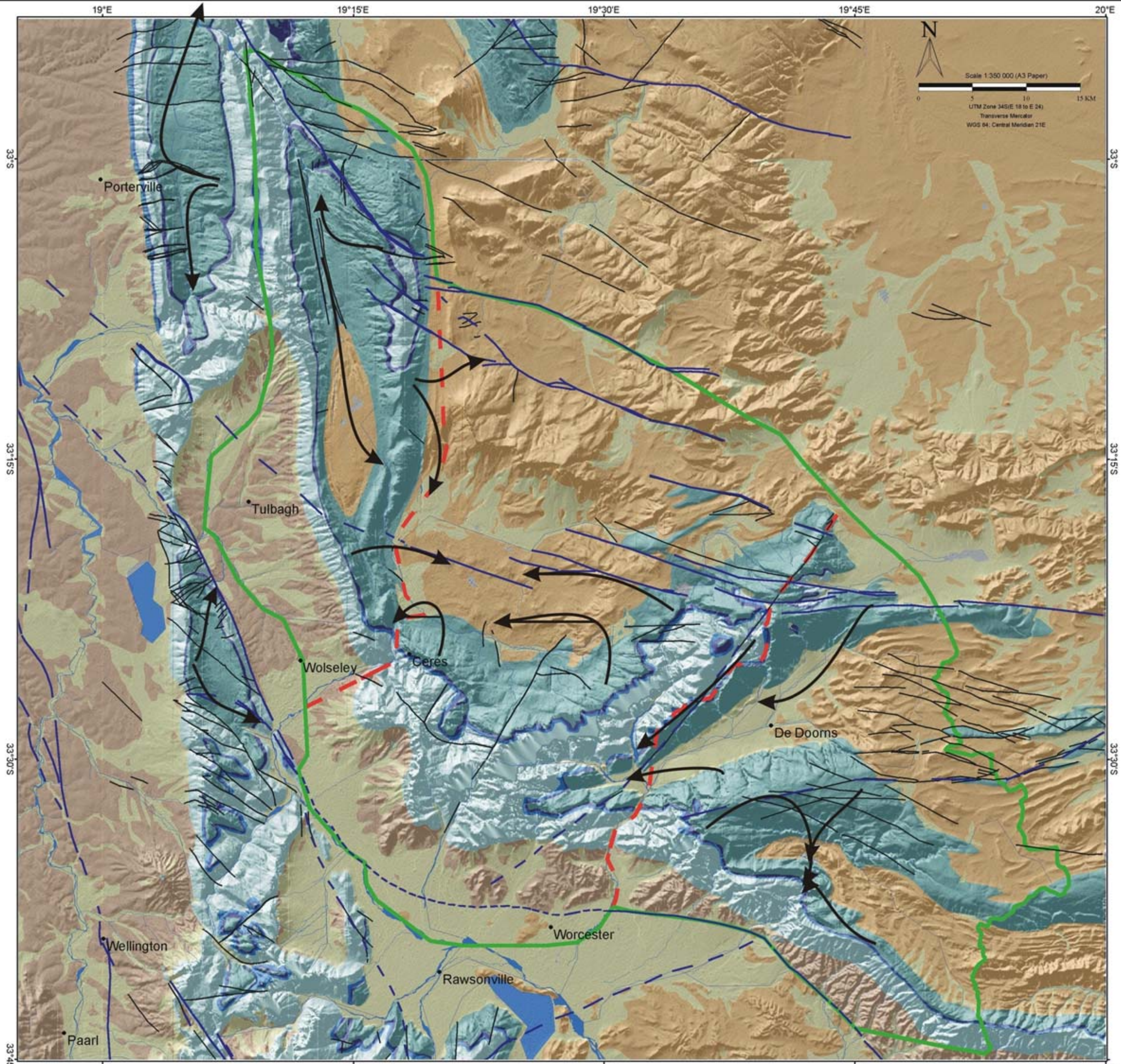
34°S
34°15'S



19°E
19°15'E
19°30'E
19°45'E
20°E
33°S
33°15'S
33°30'S
33°45'S
N
Porterville
Tulbagh
Wolseley
Ceres
De Doorns
Worcester
Rawsonville
Wellington
Paarl
LEGEND
Towns
Rivers
Faults
Hydrotects
Model Sub-domain
Witzenberg-Nuy Model Domain
Flow paths
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS & FORESTRY
CONSULTANT
UMVOTO
TITLE
CONCEPTUAL MODEL OF GRONDWATER FLOW IN THE PENINSULA AQUIFER IN THE WITZENBERG - NUY
FIGURE 1-3



LEGEND

- Towns
- Rivers
- Faults
- Hydrotects
- Model Sub-domain
- Witzenberg-Nuy Model Domain
- Flow paths

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

CONSULTANT

UMVOTO

TITLE

CONCEPTUAL MODEL OF GRONDWATER FLOW IN THE SKUWERBERG AQUIFER IN THE WITZENBERG - NUY

FIGURE 1-4

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 original Model Domain for the Witzenberg-Nuy model, as defined in the Conceptual Model Report (Volume 3; DWAF, 2007), is based on the IWRM Domain boundaries. The revised Model Domain is mainly defined by the contact between Peninsula Formation and Basement and does not include the Klein Berg River and Breede River valleys (see **Figure 2-1**).

The revised Witzenberg-Nuy Model Domain includes, in their entirety, the Agter Witzenberg (AWT), Warm Bokkeveld (WBK), Hex River (HEX), and Nuy (NUY) IWRM Domains, and straddles the Voëlvlei-Tulbagh (VVT) and Brandvlei (BRV) IWRM Domains. The AWT, WBK, HEX and NUY domains form the northeastern part to the Berg WAAS study area, deviating in the presence of large NW-SE orientated faults. The western and southern boundary of the Witzenberg-Nuy Model Domain is defined by the Hansiesberg Anticline in the northwest and the Peninsula – Basement contact towards the Klein Berg River and Breede River valleys. The Model Domain covers a total area of 3030 km^2.

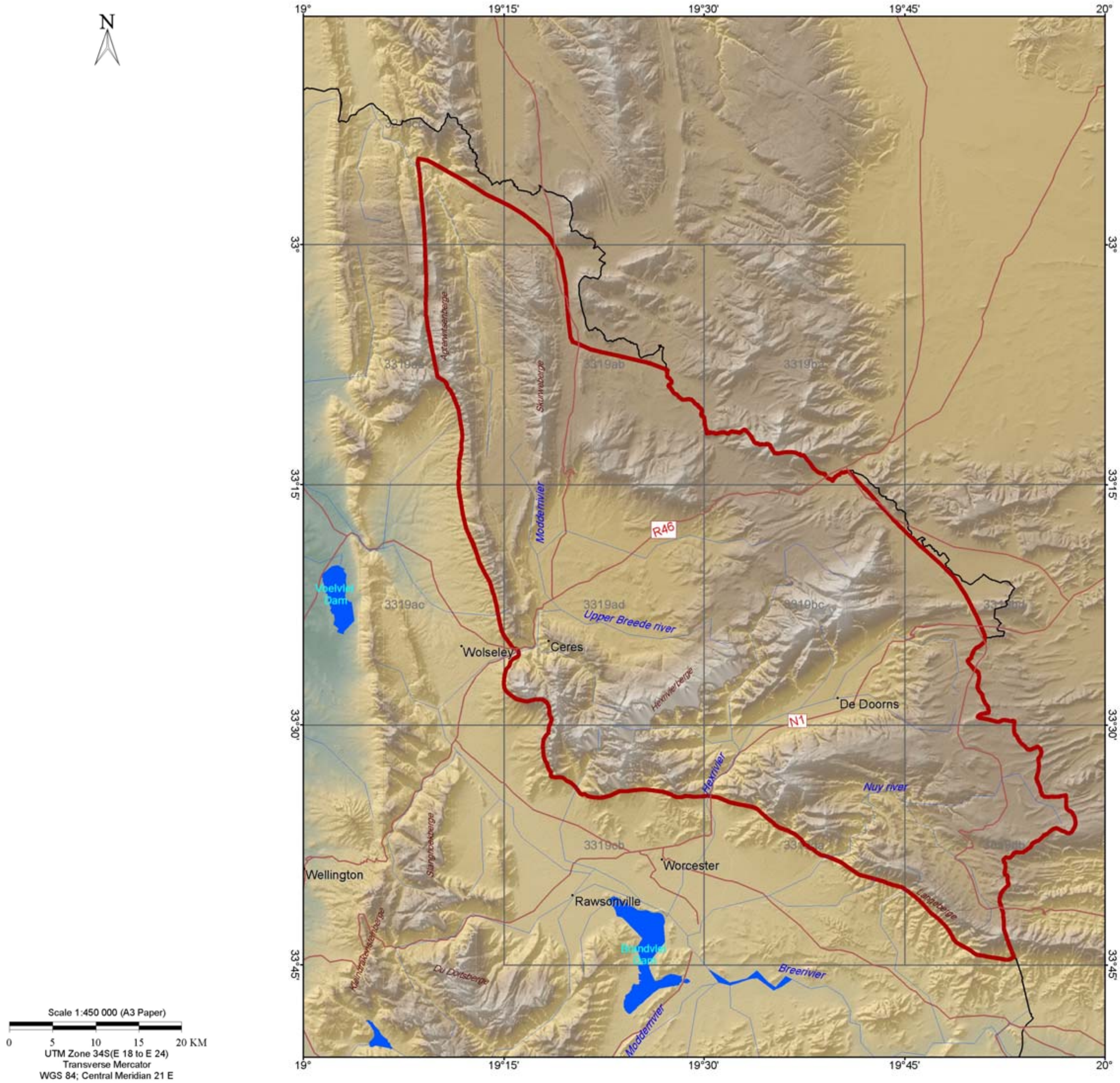
2.1 TOPOGRAPHY

The topography of the Witzenberg-Nuy Study Domain is dominated by Table Mountain Group mountain ranges. The northwestern (Groot Winterhoekberge, Agter-Witzenberge and Skurweberge) and southeastern (Kwadousberge and Langeberge) ranges generally strike N-S and E-W respectively, while the central Hex River Mountains strike NE-SW. This structural orientation within the Cape Fold Belt syntaxis results in the development of two adjacent, arcuate-shaped, high-relief mountainous zones, which enclose lower relief areas and form watersheds to various river valleys. In the west, the Agter Witzenberge and Skurweberge bound the Tulbagh-Ceres and Agter-Witzenberg Valleys. East of this lies the Koue Bokkeveld, bounded by the NE-SW arc of the Hex River Mountains in the south and east. Bordering the Hex River Valley is the Kwadousberge, adjacent to the Koo Valley. The Langeberge separate the Koo Valley from the Worcester Valley that traverses the full-length of the southern margin of the Witzenberg-Nuy area. Elevation in the mountainous areas ranges from 1400 m to 2000 m, reaching 2249 m at Matroosberg, 2073 m at Keeromsberg and 2078 m at Groot-Winterhoekpiek. The lower relief regions and valleys have elevations ranging from 200 m to 700 m.

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.

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
- Dams
- 3319ab 1: 50 000 Toposheet
- Model Domain
- Study Area

Elevatiom (mamsl)

- 60 - 100
- 100 - 140
- 140 - 530
- 530 - 970
- 970 - 1500
- 1500 - 1900
- 1900 - 2200

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

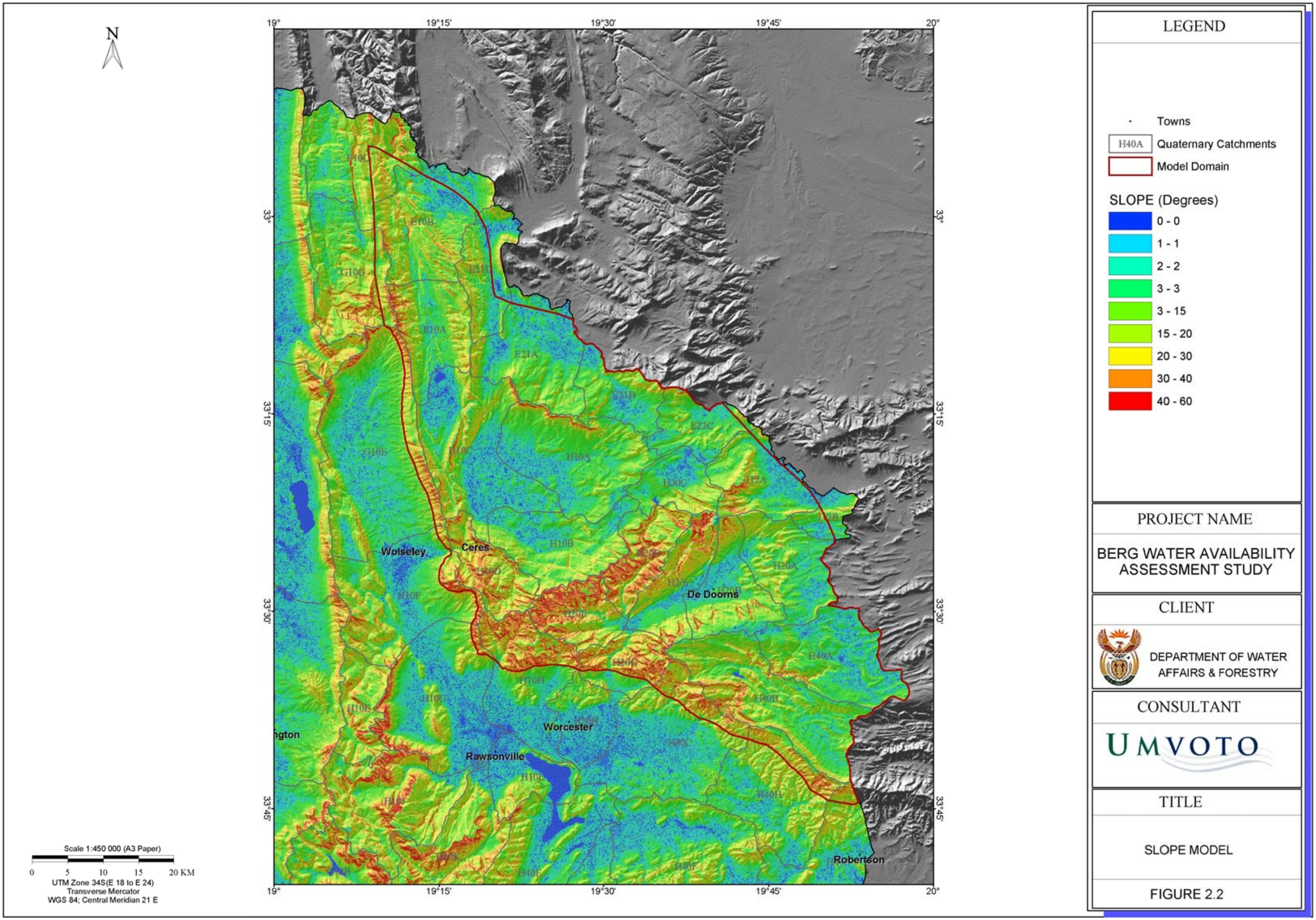
CONSULTANT

UMVOTO

TITLE

TOPOGRAPHY AND INFRASTRUCTURE

FIGURE 2.1


N
Scale 1:450 000 (A3 Paper)
0 5 10 15 20 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E
19°
19°15'
19°30'
19°45'
20°
33°
33°15'
33°30'
33°45'
Wolseley
Ceres
De Doorns
Worcester
Rawsonville
Robertson
LEGEND
Towns
H40A Quaternary Catchments
Model Domain
SLOPE (Degrees)
0 - 0
1 - 1
2 - 2
3 - 3
3 - 15
15 - 20
20 - 30
30 - 40
40 - 60
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 ~9.5 degrees and the maximum slope (based on the slope model) is 74 degrees.

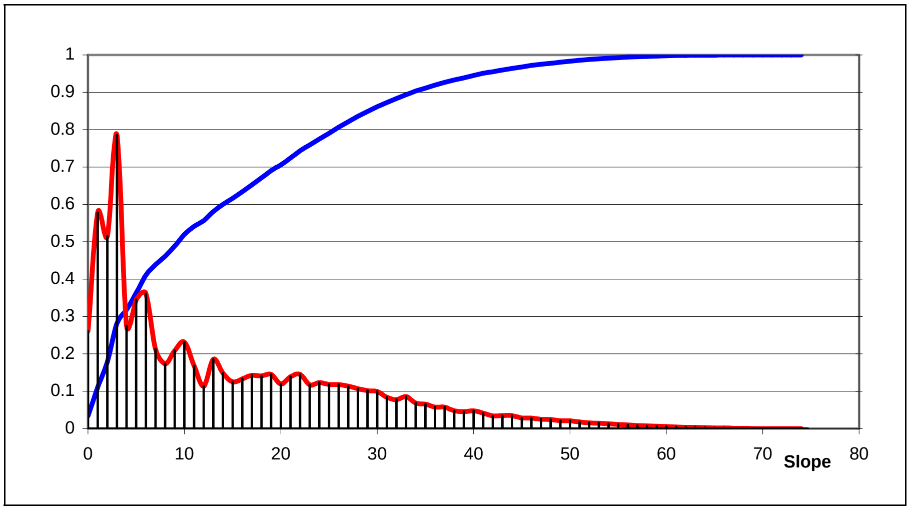


Figure 2-3 Slope distribution in Model Domain; Histogram (red curve) and Normalised Cumulative Histogram (blue curve). Y-axis is the proportion of distribution.

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 groups 2, 8 and 9 are not present within the Witzenberg-Nuy Model Domain.

Group 1 comprises small catchments in the Hex River Mountain chain (see **Figure 2-4**), including the headwaters of the Sand River (H20D, H20E). These catchments are characterised by steeply incised valleys (average slope of about 30°) within a high mountain range and contain very few flat areas.

Group 3 comprises two catchments, i.e. the Hex River Valley (H20F) and the Twenty-Four Rivers (G10G), which only partially belongs to the Witzenberg-Nuy Model Domain. These catchments are characterised by high mountains with larger flat areas, either in the valleys or as mountain plateaus.

Group 4 and **Group 5** comprise a variety of catchments with a mixed character (see **Figure 2-4**), mostly situated downstream of catchments of Group 1 to 3. These catchments consist of mountain ranges with lower slopes and larger flat areas.

Group 6 comprises catchments with low slopes along steeper mountain ranges, especially in the head waters of the Breede River (H10A) and the adjacent catchments in the Tankwa Karoo (E21A, E21B, E22C).

Group 7 comprises only the upper Nuy River (H40A), which is characterised by large flat areas, but shows a bimodal character in that it also comprises a component of very steep slopes, mainly along the TMG outcrops.

Group 0 comprises the catchments of the Breede River valley (H10G, H10H and H40C) that straddle the Witzenberg-Nuy Model Domain. They show a distinctly different slope distribution with a bimodal character (see **Figure 2-4**), indicating that at least two different physiographic settings, viz. large flat areas in the valley and steep mountain ranges at the catchment boundaries, are combined within each catchment.

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.

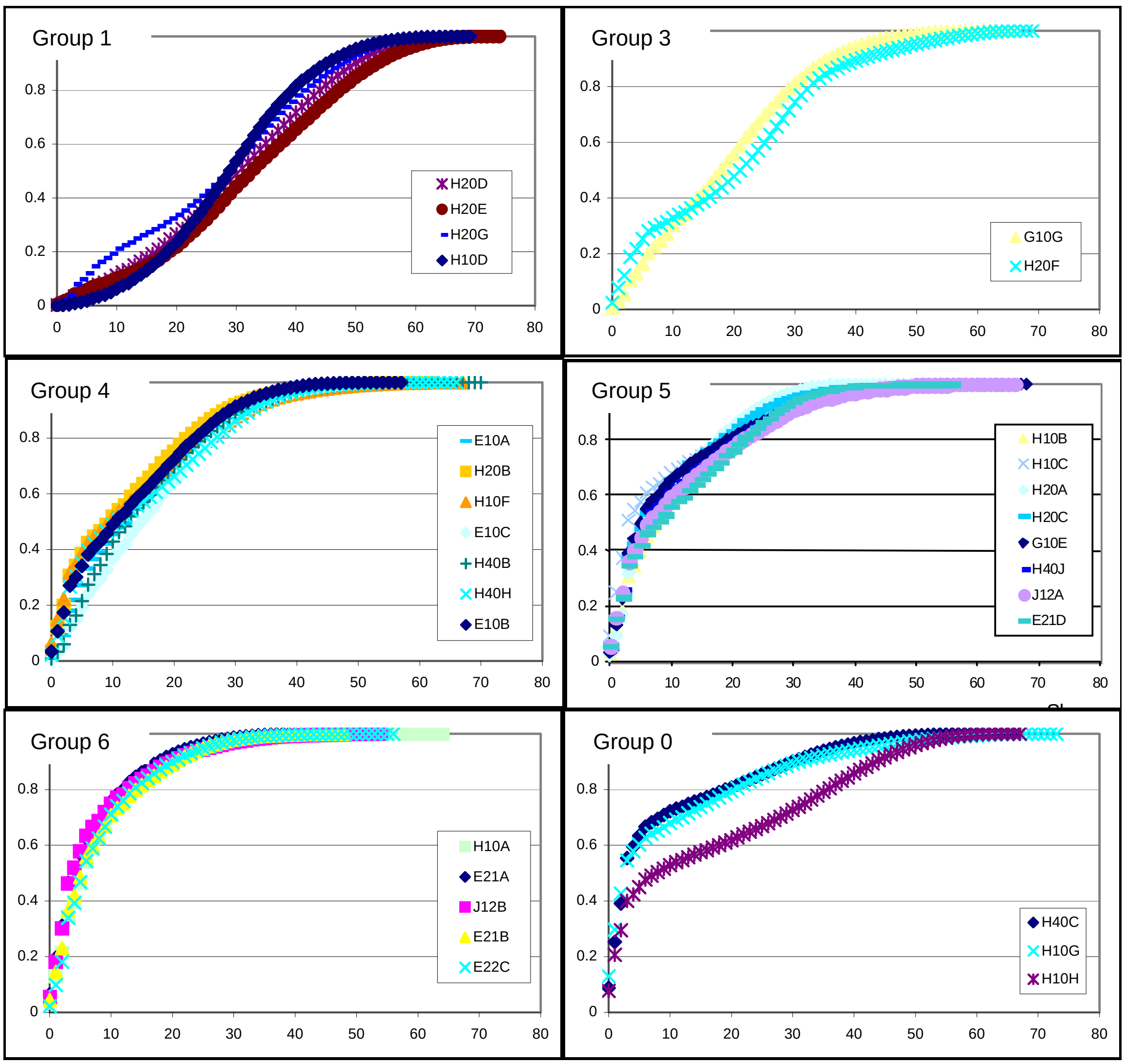


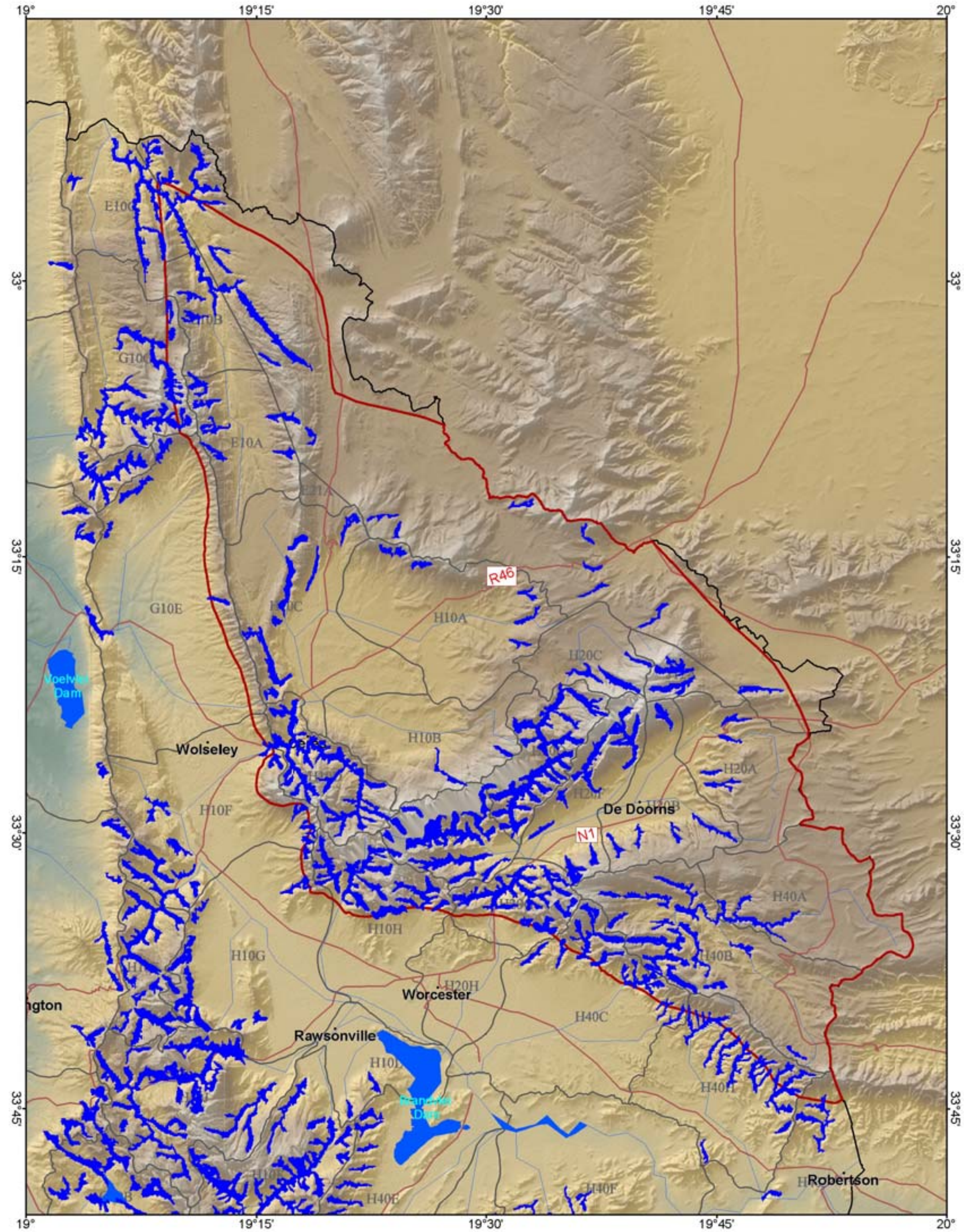
Figure 2-4 **Slope distribution for catchments in model domain; y-axis is proportion of distribution; x-axis is slope.**

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 TMG-dominated, high-mountain areas, which are also the areas of higher orographic rainfall. In addition the relative relief was calculated from the DEM, 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.



N

Scale 1:450 000 (A3 Paper)

0 5 10 15 20 KM

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

LEGEND

- Towns
- Rivers
- Roads
- H40A Quaternary Catchments
- Study Area
- Model Domain

Relative Relief

- <40

Elevatiom (mamsl)

- 60 -100
- 100 - 170
- 170 - 450
- 450 - 900
- 900 - 1350
- 1350 - 1800
- > 1800

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 major part of the H20 tertiary catchment (H20A to H20G), the northern part of the H10 tertiary catchment (northern boundaries of H10A to H10F, and H10G and H10H) and the eastern part of the H40 tertiary catchment (H40A to H40C, and H40H), of the Breede WMA (see **Figure 2-6**). The model domain also comprises the western part of the E10 tertiary catchment (E10A to E10C) and southernmost part of the E21 tertiary catchment (E21A) of the Olifants Doorn WMA. The Berg WMA, in the form of the western part of the G10 tertiary catchment (G10E and G10G), and the Gouritz WMA (quaternary catchment J12A) are also represented within the model domain.

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 a result of rainfall being orographically controlled and an altitude range from approximately 200 mamsl in the lower relief valleys to a maximum of 2249 mamsl at Matroosberg in the Hex River Mountains, the Mean Annual Precipitation (MAP) varies significantly across the study area. It is highest in the high mountain ranges in the east and central parts of the study domain, namely the Agter-Witzenberge, Skurweberge, Waaihoekberge, Gydoberge, Waboomberge and the Hex River Mountains, where the average rainfall ranges between 1000 mm/a and 1700 mm/a, while it decreases to approximately 500 mm/a and 200 mm/a within the Warm Bokkeveld and Hex River valleys respectively. 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.

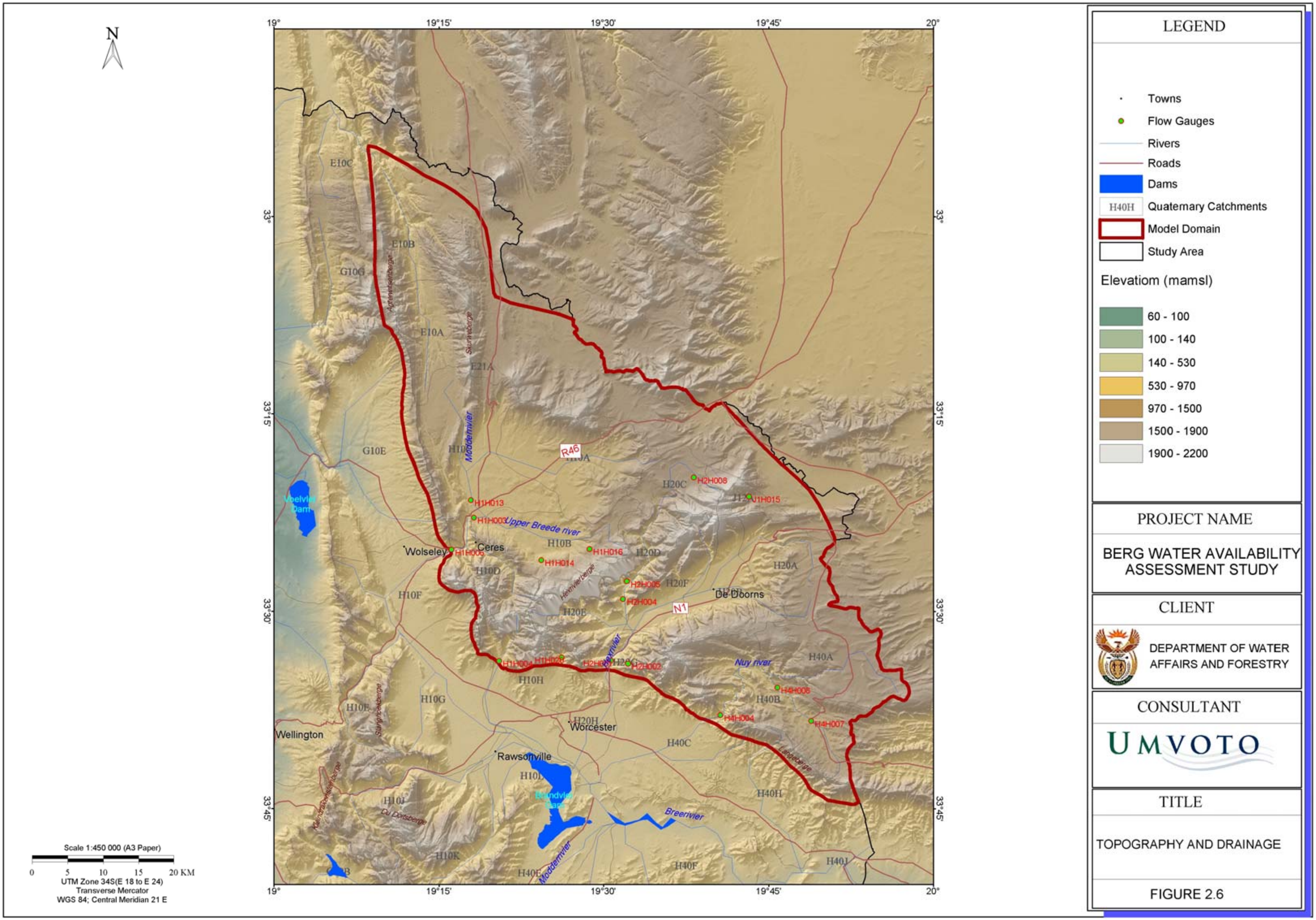
The seasonal pattern of rainfall is critical in the estimation of recharge since the aquifers are recharged in winter when the temperature and therefore evapotranspiration are also very low.

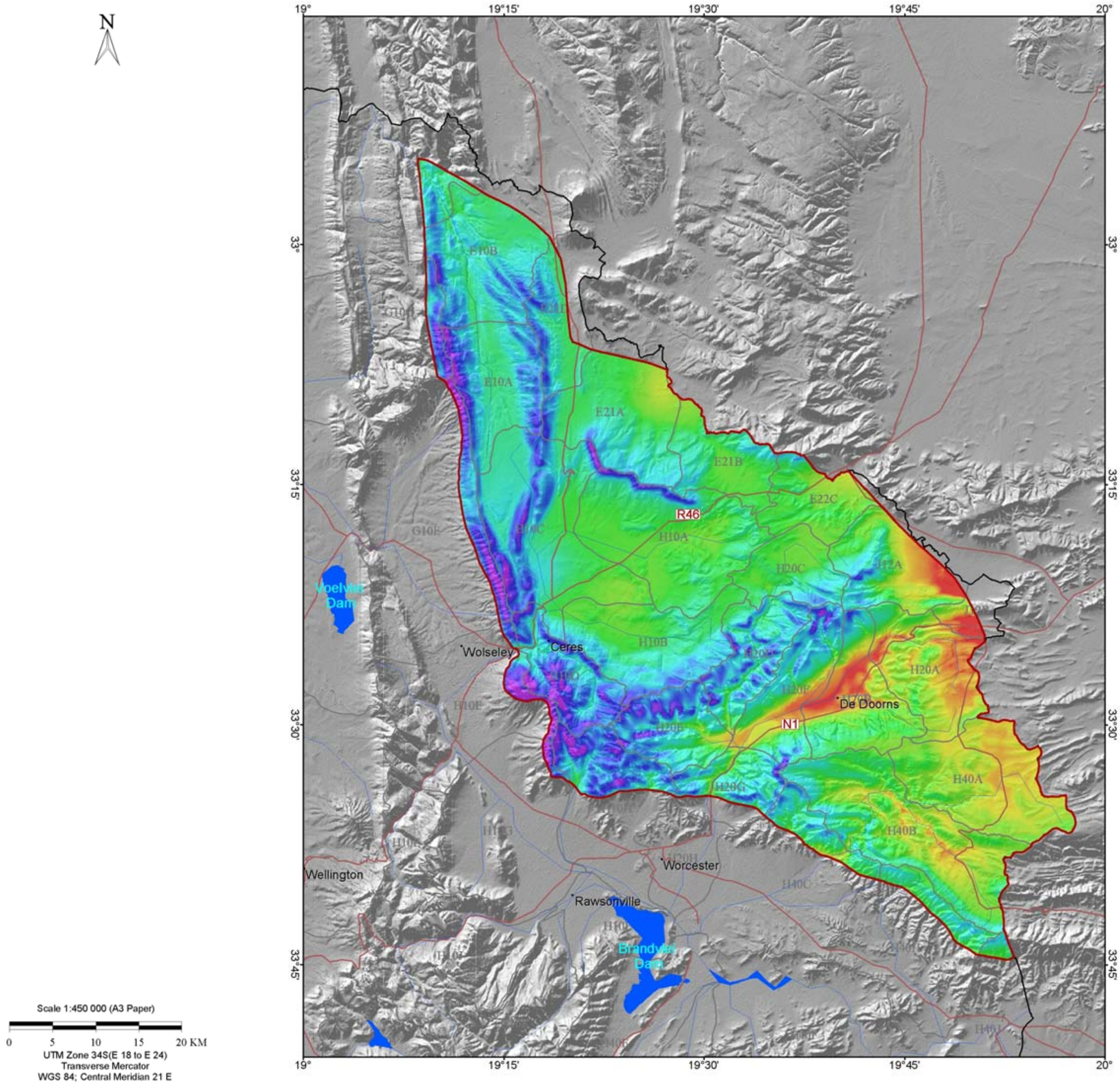
Run-off

The mean annual run-off (MAR) parallels the trend of mean annual rainfall with most river flows occurring in the high-lying mountains. MAR values range from 200 mm/a to greater than 500 mm/a for mountainous regions (e.g. H10D, H20D and H20E), to 10 – 50 mm/a for valley regions such as the Koo and Hex River valleys (e.g. H40B and H20B). 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 influence and moderate the Mean Annual Evaporation (MAE) resulting in increasing evaporation in the interior, with the *potential* evaporation ranging between 1600 – 1700 mm/a within the study domain.


N
19°
19°15'
19°30'
19°45'
20°
33°
33°15'
33°30'
33°45'
LEGEND
Towns
Flow Gauges
Rivers
Roads
Dams
H40H Quaternary Catchments
Model Domain
Study Area
Elevatiom (mamsl)
60 - 100
100 - 140
140 - 530
530 - 970
970 - 1500
1500 - 1900
1900 - 2200
PROJECT NAME
BERG WATER AVAILABILITY ASSESSMENT STUDY
CLIENT
DEPARTMENT OF WATER AFFAIRS AND FORESTRY
CONSULTANT
UMVOTO
TITLE
TOPOGRAPHY AND DRAINAGE
FIGURE 2.6
Scale 1:450 000 (A3 Paper)
0 5 10 15 20 KM
UTM Zone 34S(E 18 to E 24)
Transverse Mercator
WGS 84; Central Meridian 21 E
Wolseley
Ceres
De Doorns
Worcester
Rawsonville
Wellington
Upper Breede river
Nuy river
Breerivier
Moddernivier
R46
N1
E10C
E10B
E10A
E21A
G10G
G10E
H10F
H10B
H10D
H10H
H10G
H10E
H10J
H10K
H20C
H20D
H20F
H20E
H20A
H20H
H40A
H40B
H40C
H40H
H40F
H40J
H1H013
H1H003
H1H006
H1H016
H1H014
H2H008
J1H015
H2H005
H2H004
H2H002
H1H004
H4H006
H4H004
H4H007



LEGEND

- Towns
- Rivers
- Roads
- Dams
- H40A Quaternary Catchments
- Study Area
- Model Domain

Rainfall (mm/a)

- 160 - 240
- 240 - 260
- 260 - 300
- 300 - 360
- 360 - 540
- 540 - 620
- 620 - 750
- 750 - 980
- 980 - 1130
- 1130 - 1230
- 1230 - 1410
- 1410 - 1700

PROJECT NAME

BERG WATER AVAILABILITY ASSESSMENT STUDY

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TITLE

RAINFALL DISTRIBUTION (MAP)

FIGURE 2.7

2.3 STRATIGRAPHY AND AQUIFER CLASSIFICATION OF THE STUDY AREA

The Model Domain is dominated by rocks of the full Cape Supergroup sequence, along with outcrops of basement Malmesbury Group and minor Cape Granite Suite to the southwest, younger Karoo Supergroup sedimentary rocks to the northeast, and Quaternary sediments within major river catchments throughout the Domain (see **Figure 2-8**). Structurally, the Witzenberg-Nuy area is characterised by four major anticlinal ridges and their associated synclinal basins, which play an important role in groundwater flow in the region. Unconfined, mountainous Peninsula and Skurweberg Formation outcrops along the NW-SE orientated Koue Bokkeveld and Hansiesberg Anticlines and the NE-SW orientated Hex River and Kwadousberg Anticlines. These act as recharge areas to the confined Peninsula and Skurweberg Aquifers within the associated Agter-Witzenberg, Warm Bokkeveld, Hex River and Koo Valley Synclinal basins.

2.3.1 Geology and Stratigraphy

Metamorphosed shales, schists, feldspathic sandstones and limestones, north and northeast of the Worcester Fault in the vicinity of Worcester, form the **Brandwacht** and **Norree Formations** of the **Malmesbury Group** (>555 Ma). Minor outcrop of the **Worcester Pluton** (**Cape Granite Suite** (555-510 Ma)) also occurs in the same area. The **Malmesbury Group** is represented in the Tulbagh and Wolseley region by shales and feldspathic sandstones of the **Porterville Formation**. These rocks form the basement to the **Cape Supergroup** in the Witzenberg-Nuy Model Domain.

The **Table Mountain Group** dominates the topography of the Witzenberg-Nuy Model Domain, forming distinct high altitude mountain ranges. The basal **Piekenierskloof** and **Graafwater Formations** only outcrop in the far northwest of the Model Domain in the Groot Winterhoek range. The **Piekenierskloof Formation** is composed of medium to coarse-grained quartzite and conglomerate beds with thin, interbedded, purplish-coloured gritty shale beds (Gresse and Theron, 1992). The **Graafwater Formation** reaches a thickness of up to 100 m, and is composed of purplish to reddish coloured, thinly-bedded sandstone, siltstone and mudstone (Gresse and Theron, 1992).

The **Peninsula Formation** unconformably overlies the **Malmesbury Group** over most of the Model Domain, and is composed on average of approximately 1400 m of thickly-bedded, planar bedded, light-grey, fractured coarse-grained quartzitic units (Gresse and Theron, 1992). These units are often exposed in anticlinal ridges, which form the dominant mountain ranges within the Study Domain e.g. the Hex River Mountains. Minor vein-quartz pebble horizons (especially near the base and top of the formation), bioturbated zones, biogenic trails and rare arthropod traces are also present (Gresse and Theron, 1992).

The **Peninsula Formation** is conformably overlain by the glacial **Pakhuis Formation** throughout the study domain, separated by the gradational contact know as the “Fold Zone”, which represents syndepositional soft-sediment deformation. The **Cedarberg Formation** is subdivided into the basal, thinly laminated, micaceous **Soom Shale Member**, and the overlying, dominant **Disa Siltstone Member** (Gresse and Theron, 1992).

Conformably overlying the **Cedarberg Formation** are the formations of the **Nardouw Subgroup**, namely the reddish-weathering, micaceous siltstones and sandstones of the **Goudini Formation** (~ 160 m thick), the thick-bedded, coarse-grained, light-grey quartzites of the **Skurweberg Formation** (~ 250 m thick), and the light-grey felspathic sandstones and shales of the **Rietvlei Formation** (~ 200 m thick).

The **Bokkeveld Group**, which has an approximate total thickness of 1200 m, conformably overlies the **Table Mountain Group**, and is composed of thick formations comprised of shale, mudstone and siltstone units, with thinner alternating formations comprised of feldspathic sandstones and siltstones. Approximately 1000 m of alternating sandstones, shales and siltstones of the **Witteberg Group** conformably overlie the **Bokkeveld Group**. Outcrops of both groups occur within large synclinal basins within the Model Domain, and due to the erodable nature of the sedimentary units, often form large valleys between the anticlinal ridges of the Table Mountain Group, e.g. the Warm Bokkeveld, Hex River Valley and the Koo River Valley.

Dwyka Group tillites and **Ecca Group** siltstones and shales are present as down-faulted blocks within the Warm Bokkeveld Synclinal basin in the northern most central portion of the Witzenberg-Nuy Study Domain. Quaternary aged sediment, ranging from scree to alluvium, is found mainly in the vicinity of the Hex and Breede River valleys within the Study Domain, where sediment overlies the TMG/Bokkeveld Group and Malmesbury Group rocks respectively. Quaternary sediment is also present in the vicinity of the Skaap and Wabooms rivers within the Warm Bokkeveld region.

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 Witzenberg-Nuy Model Domain, namely, the Piekenierskloof, Peninsula, Nardouw and Quaternary 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 quaternary 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 and Skurweberg aquifers of the Table Mountain Group. The Piekenierskloof Aquifer is only represented by minor outcrop in the far northwest of the Study Domain and is ignored, along with the quaternary aquifers, which have been explained in detail in Volume 9 with respects to the Breede River alluvium.

Intergranular aquifers

The intergranular aquifers are confined to Quaternary sediment present within various river valleys, which includes the Hex, Breede, Skaap and Wabooms rivers.

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** and smaller **Skurweberg Subaquifer** (apparent thickness approximately 1400 m and 250 m respectively in this area), is the principal focus of the present study.

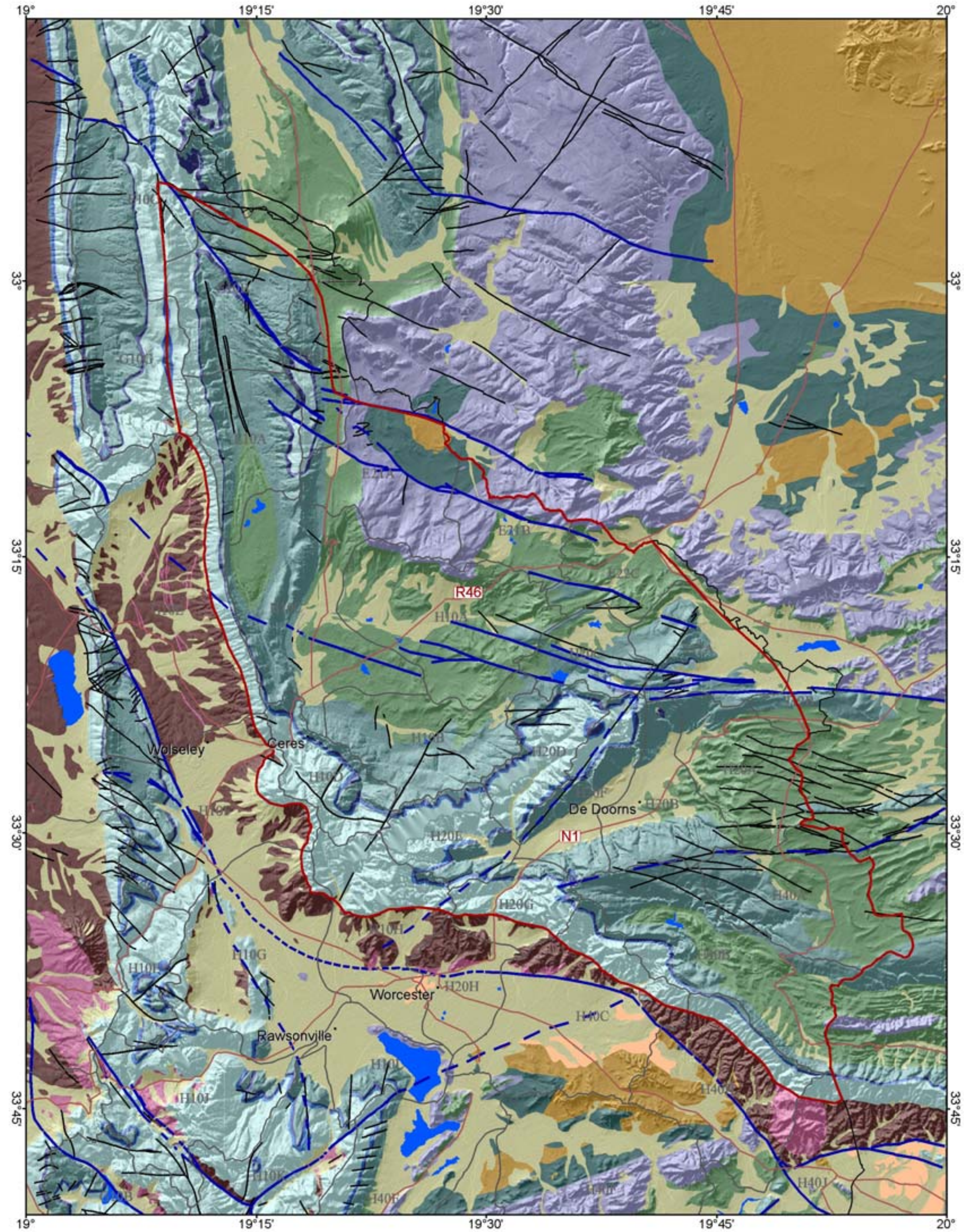
Fractured-and-weathered (regolith) aquifers

The type d (or “intergranular and fractured”) aquifers as currently mapped (DWAF, 2000a) coincide with exposures of the **Malmesbury**, **Bokkeveld**, **Witterberg**, **Dwyka** and **Ecca Groups** in the Witzenberg-Nuy Model Domain.

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

Superunits	Units	Subunits
	Quaternary Aquifer	Various discrete alluvial aquifers
	Locally underlain by the Malmesbury, Table Mountain, Bokkeveld and Witteberg Groups	
	Gydo Mega-aquitard	
Table Mountain Superaquifer	Nardouw Aquifer	Rietvlei Subaquifer
		Verlorenvalley Mini-aquitard
		Skurweberg Subaquifer
	Winterhoek Mega-aquitard	Goudini Meso-aquitard
		Cedarberg Meso-aquitard
		Pakhuis Mini-aquitard
	Peninsula Aquifer	Platteklip Subaquifer ? (not yet separately mapped throughout Berg WMA)
		Leeukop Subaquifer ? (not yet separately mapped throughout Berg WMA)
		Graafwater Meso-aquitard
		Piekenierskloof Subaquifer (localised)
	Aquicludes [Cape Granite Suite] [Malmesbury Group]	

N



Scale 1:450 000 (A3 Paper)

0 5 10 15 20 KM

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

LEGEND

- Towns
- Roads
- Faults
- Hydrotects
- H40A Quaternary Catchment
- Study Area
- Model Domain

SIMPLIFIED LITHOLOGY

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

PROJECT NAME

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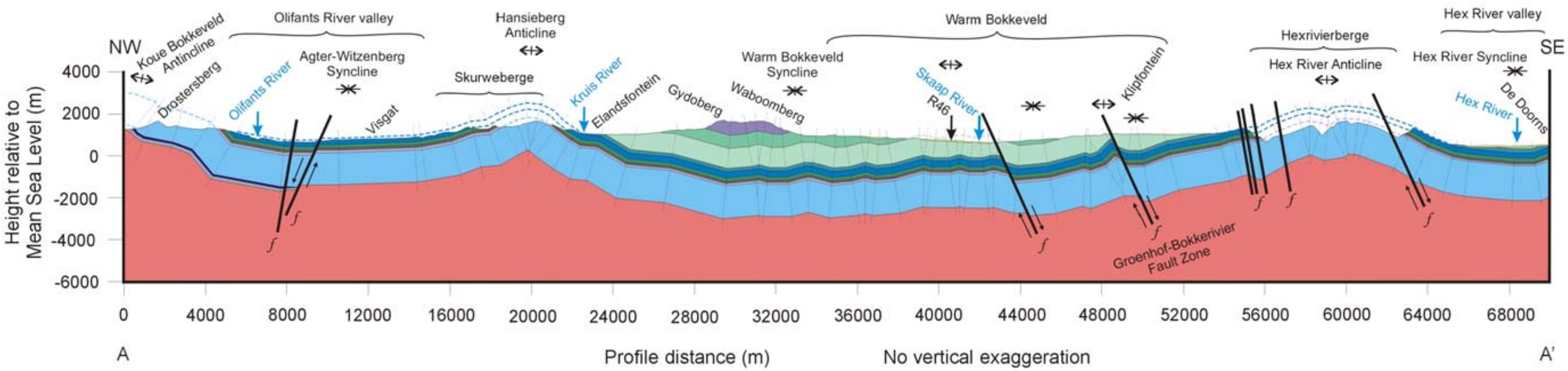
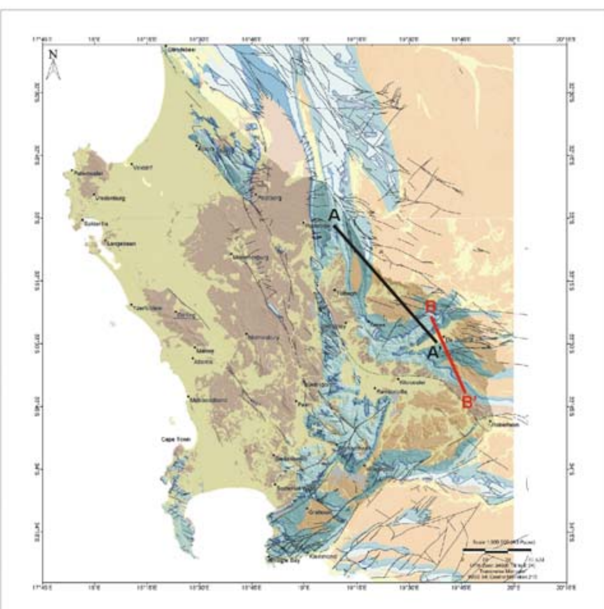
SIMPLIFIED GEOLOGY MAP OF THE STUDY AREA (1: 250 000)

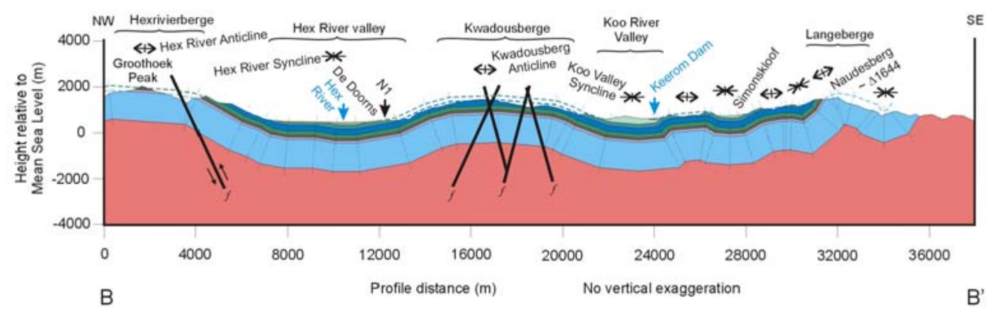
FIGURE 2.8

A) NW-SE AGTER-WITZENBERGBALANCED SECTION





B) NNW-SSE KOO VALLEY BALANCED SECTION



LEGEND

- Anticline
- Syncline
- Fault
- Surface water bodies

GEOLOGY

- Alluvium
- Witteberg Group
- Bidouw Subgroup (Bokkeveld Group)
- Ceres Subgroup (Bokkeveld Group)
- Rietvlei Formation (Table Mountain Group)
- Skurweberg Formation (Table Mountain Group)
- Goudini Formation (Table Mountain Group)
- Cedarberg Formation (Table Mountain Group)
- Pakhuis Formation (Table Mountain Group)
- Peninsula Formation (Table Mountain Group)
- Graafwater Formation (Table Mountain Group)
- Piekenierskloof Formation (Table Mountain Group)
- Basement

PROJECT NAME

BERG RIVER MODEL STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

CONSULTANT

UMVOTO

TITLE

BALANCED CROSS SECTIONS THROUGH THE WITZENBERG-NUY AREA

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 between the topography, slope distribution and aquifer type exists. 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, but with less than 20° slope in 60% 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°. The Peninsula Formation mainly forms the high lying, steep terrains.

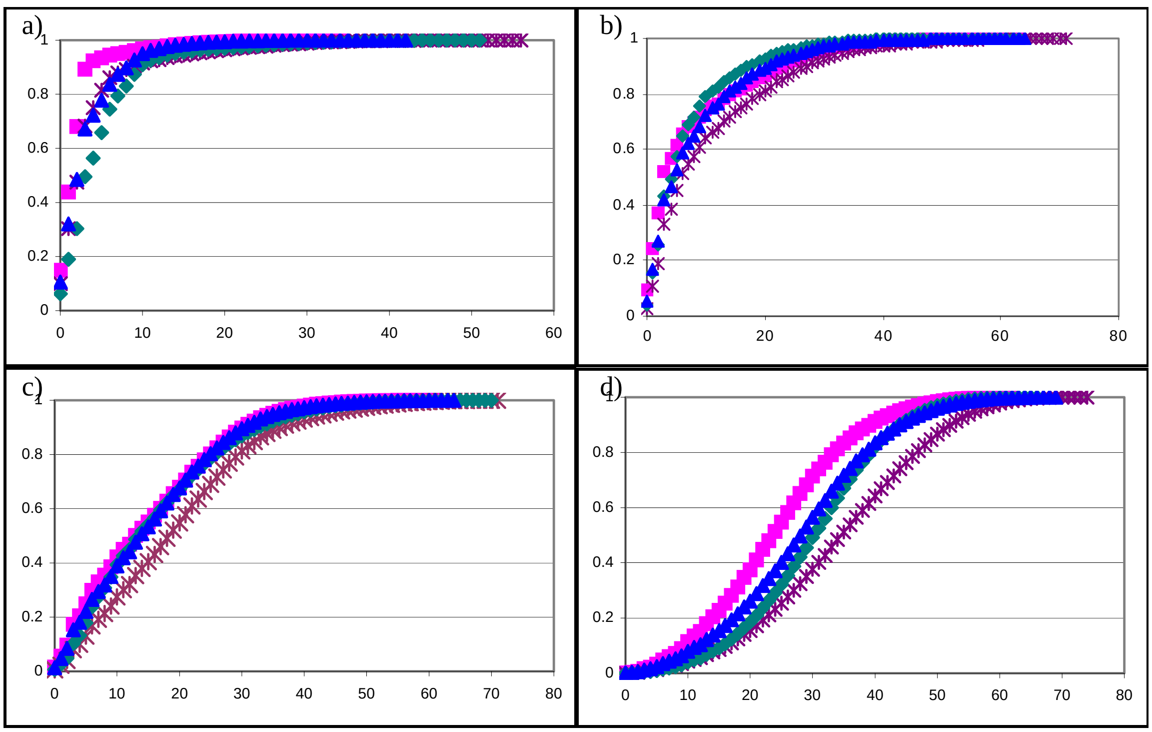


Figure 2-10 Slope Distribution per aquifer type in Witzenberg-Nuy Model Domain; a) Intergranular, b) Intergranular-fractured, c) Nardouw, d) Peninsula; y-axis is proportion of distribution; x-axis is the slope.

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 and Skurweberg aquifers.
- obtain the rock volume of the Peninsula and Skurweberg aquifers.
- model the quantity of water in storage in the Peninsula and Skurweberg aquifers.
- model the quantity of water available for sustainable abstraction from the Peninsula and Skurweberg aquifers.

The quantity 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, the following data elements are required for 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 and Skurweberg aquifers 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 previously applied spreadsheet model approach using broad / representative geology data:

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.

The model does however have certain limitations:

1. The model is only as accurate as the scale of the input data. 20 m DEM and 1: 50 000 geological maps were used, implying that the results are reliable for the scale of the model domain and with revisions, for quaternary catchment scale.
2. 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 and top of the Peninsula and Skurweberg Aquifers.

The aquifer boundaries were delineated according to the bounding lithological contacts of the Peninsula (namely the Graafwater/Basement – Peninsula and Peninsula – Pakhuis/Cedarberg contacts) and Skurweberg aquifers (namely the Goudini – Skurweberg and Skurweberg – Rietvlei contacts) as present on the 1:250 000 3218 Clanwilliam and 3319 Worcester Geological Maps. These boundaries enclose a total area for the Peninsula and Skurweberg Formation storage basins of 3009 km^2 and 2142 km^2 respectively. Balanced cross sections orientated NW-SE through the Witzenberg-Nuy area, passing through the Koue Bokkeveld, Olifants River valley, Warm Bokkeveld, Hex River Mountains, Hex River Valley, Kwadous Mountains and the Koo River Valley were 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 and Skurweberg Aquifers of 1400 m and 250 m respectively.

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 *et al.*, 2002). 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, 1:50 000 and newly mapped	Dwyka – Ecca Witteberg - Dwyka Bokkeveld – Witteberg Rietvlei – Bokkeveld Skurweberg – Rietvlei Goudini – Skurweberg Cedarberg – Goudini Pakhuis – Cedarberg Peninsula – Pakhuis Peninsula – selected others
Controls	1:50 000 Previous	Faults Cross-sections (**Figure 2-9**)
Rock Compressibility (used to calculate S_s)	Domenico & Schwartz (1990)	$3.3x10^{-10}Pa^{-1}$ to $6.9x10^{-10}Pa^{-1}$
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	Dwyka – 515 m Witteberg – 995 m Bokkeveld – 1200 m Rietvlei – 200 m Skurweberg – 250 m Goudini – 160 m Cedarberg – 90 m Pakhuis – 80 m Peninsula – 1400 m

4.3 STORAGE MODEL RESULTS

4.3.1 Model Sub-domains

The Witzenberg-Nuy storage model for both the Peninsula and Skurweberg aquifers was subdivided into three sub-domains or compartments, namely WN 1, WN 2 and WN 3, based on hydrogeological and structural boundaries (see **Figure 4-1** and **Figure 4-2**, which shows the unconfined and confined aquifer areas in relation to the model sub-domains).

The northern and southern boundaries of all three sub-domains are represented by the Berg WAAS Project IWRM boundaries and the Peninsula-Basement contact respectively (see **Figure 2-9**, **Figure 4-1** and **Figure 4-2**):

- **WN 1** is bounded in the west by the Koue Bokkeveld Anticline and in the east by the Hansiesberg Anticline, incorporating the Agter-Witzenberg Synclinal basin.
- **WN 2**, which incorporates the extensive Warm Bokkeveld Synclinal basin, is bounded in the west by the Hansiesberg Anticline and the east by the Hex River Anticline respectively.
- The Hex River Anticline forms the westward boundary of **WN 3**, which incorporates both the Hex River and Koo Valley Synclinal basins.

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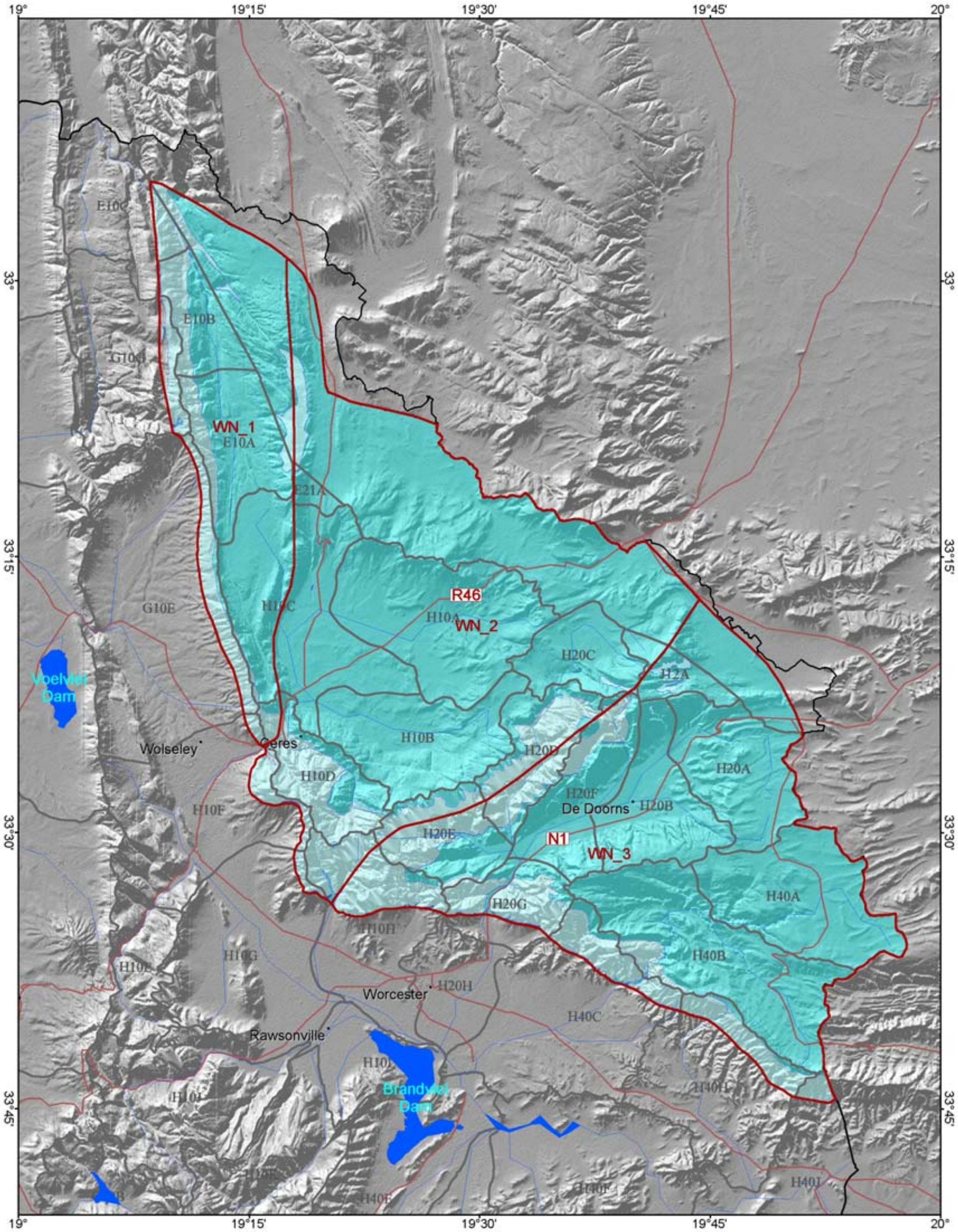

Scale 1:450 000 (A3 Paper)

0 5 10 15 20 KM

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

LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchments
- Study Area
- WN_3 Model Sub-Domain

AQUIFER CLASSES

- Unconfined Peninsula
- Confined Peninsula

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CONSULTANT

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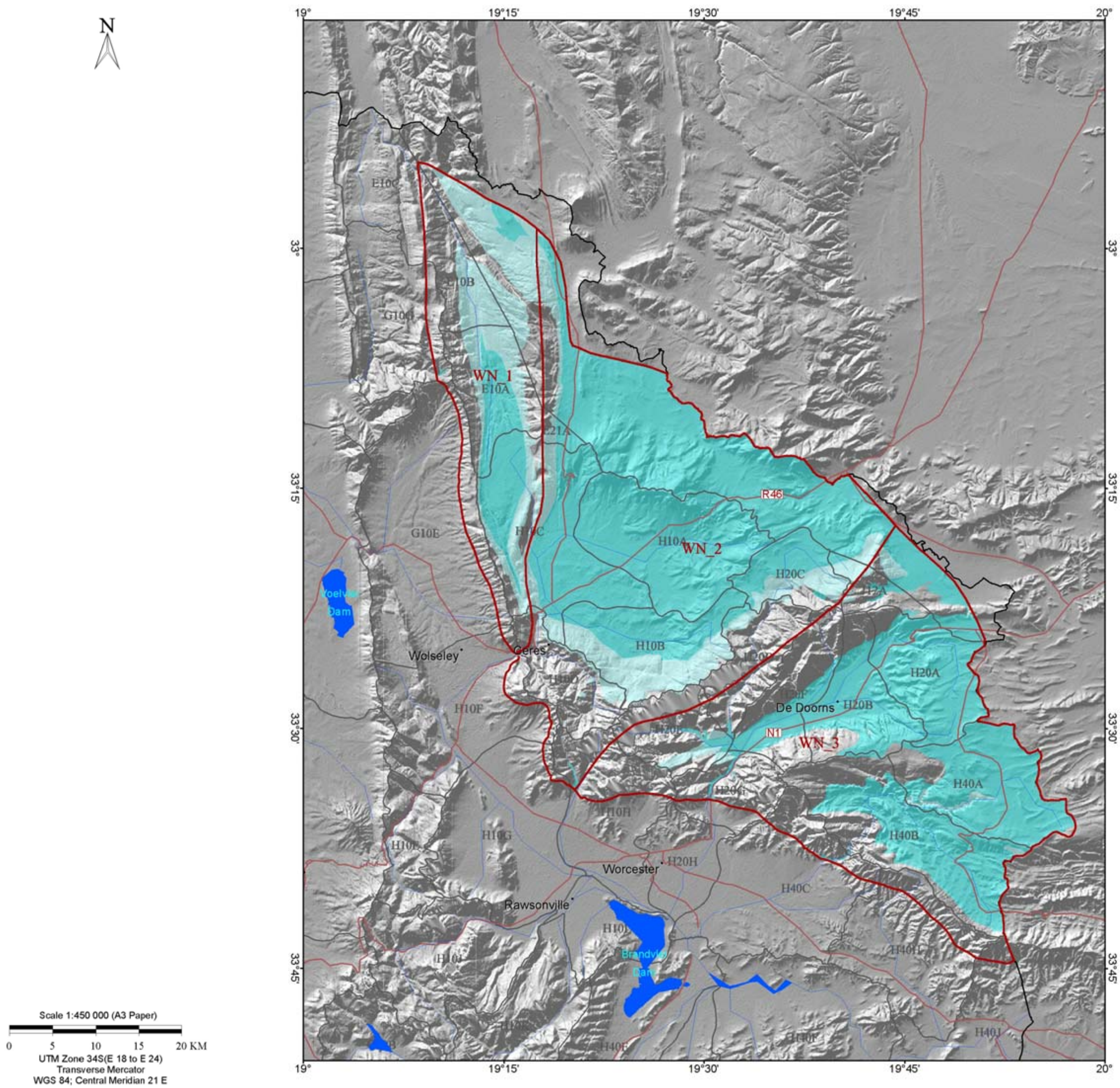
TITLE

CONFINED AND UNCONFINED PENINSULA

FIGURE 4.1



LEGEND

Towns
Roads
Rivers
Dams
H20C Quaternary Catchments
Study Area
WN_3 Model Sub-Domain

AQUIFER CLASSES

Unconfined Skurweberg
Confined Skurweberg

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CONSULTANT

UMVOTO

TITLE

CONFINED AND UNCONFINED SKURWEBERG

FIGURE 4.2

4.3.2 Peninsula Aquifer

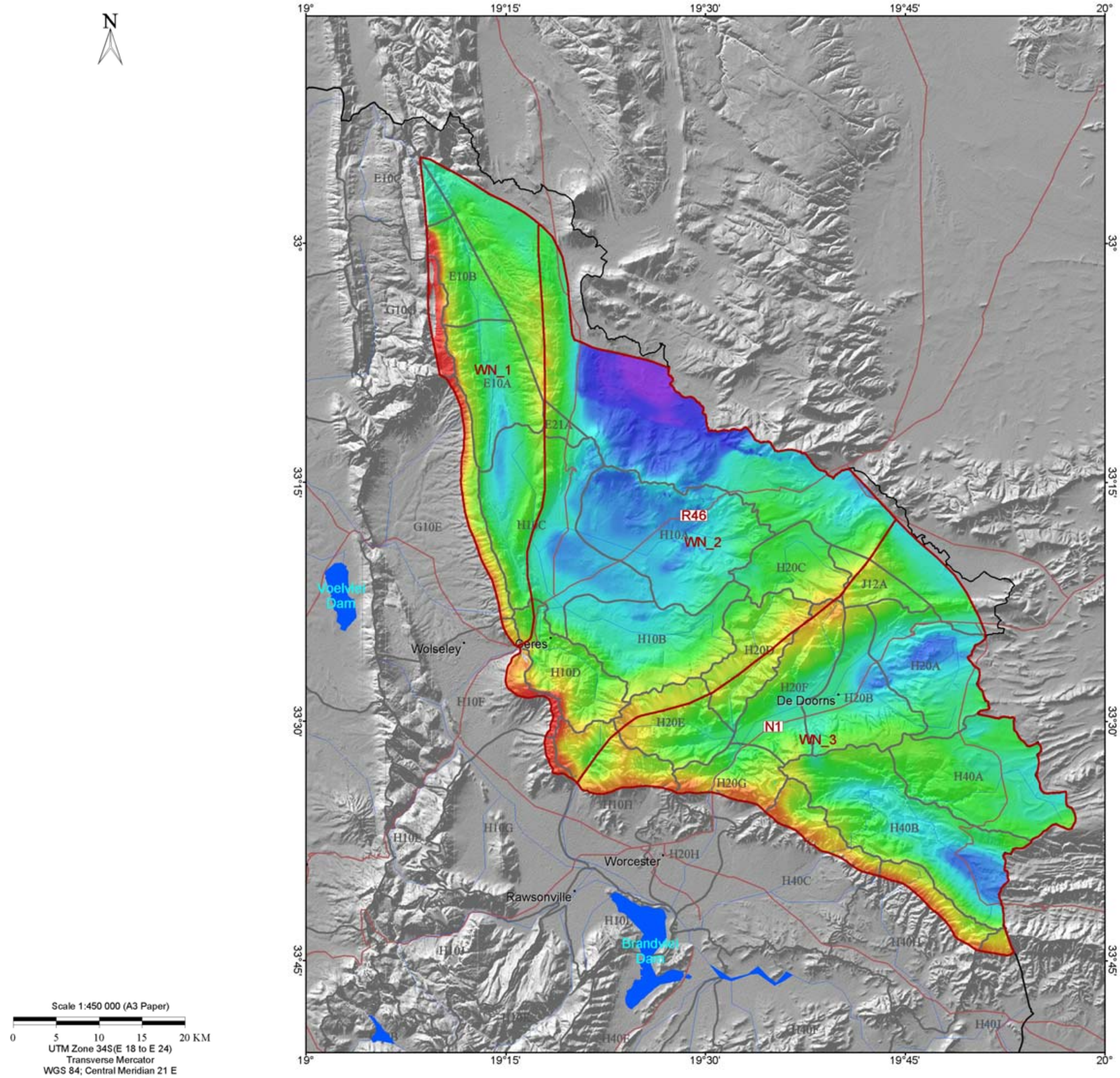
Figure 4-5 illustrates the storage modelling of the Peninsula Aquifer. The coloured sections of the study area cover the area where the Peninsula Aquifer exists either on or below surface. This is the area considered in the storage model. The colour palette illustrates the range in the aquifer rock volume 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 (see **Figure 4-3** and **Figure 4-4**).

The total solid material volume (rock volume) of the Peninsula Aquifer is 3997 billion m^3. The total confined rock volume is 2432 billion 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 169 billion m^3.

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

Model Subdomains	Peninsula Aquifer	Area (km^2)	Rock Volume (Mm^3)	Pore Volume (Mm^3)
Witzenberg-Nuy 1	Unconfined portion	140.53	153 793	7 690
	Confined portion	365.54	510 177	25 509
Witzenberg-Nuy 2	Unconfined portion	175.77	192 331	9 617
	Confined portion	1 131.65	1 584 132	79 207
Witzenberg-Nuy 3	Unconfined portion	260.39	256 445	12 822
	Confined portion	935.24	1 300 645	65 032
Witzenberg-Nuy Model Domain	Total unconfined portion	576.69	602 569	30 128
	Total confined portion	2 432.43	3 394 954	169 748
	Total aquifer	**3 009.12**	**3 997 523**	**199 876**

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 amount 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.



LEGEND

Towns
Roads
Rivers
Dams
H20C Quaternary Catchments
Study Area
WN_3 Model Sub-Domain

Aquifer Bottom (m)

-3600 - -3380
-3380 - -2170
-2170 - -2020
-2020 - -1490
-1490 - -450
-450 - -30
-30 - 20
20 - 560
560 - 950
950 - 1530

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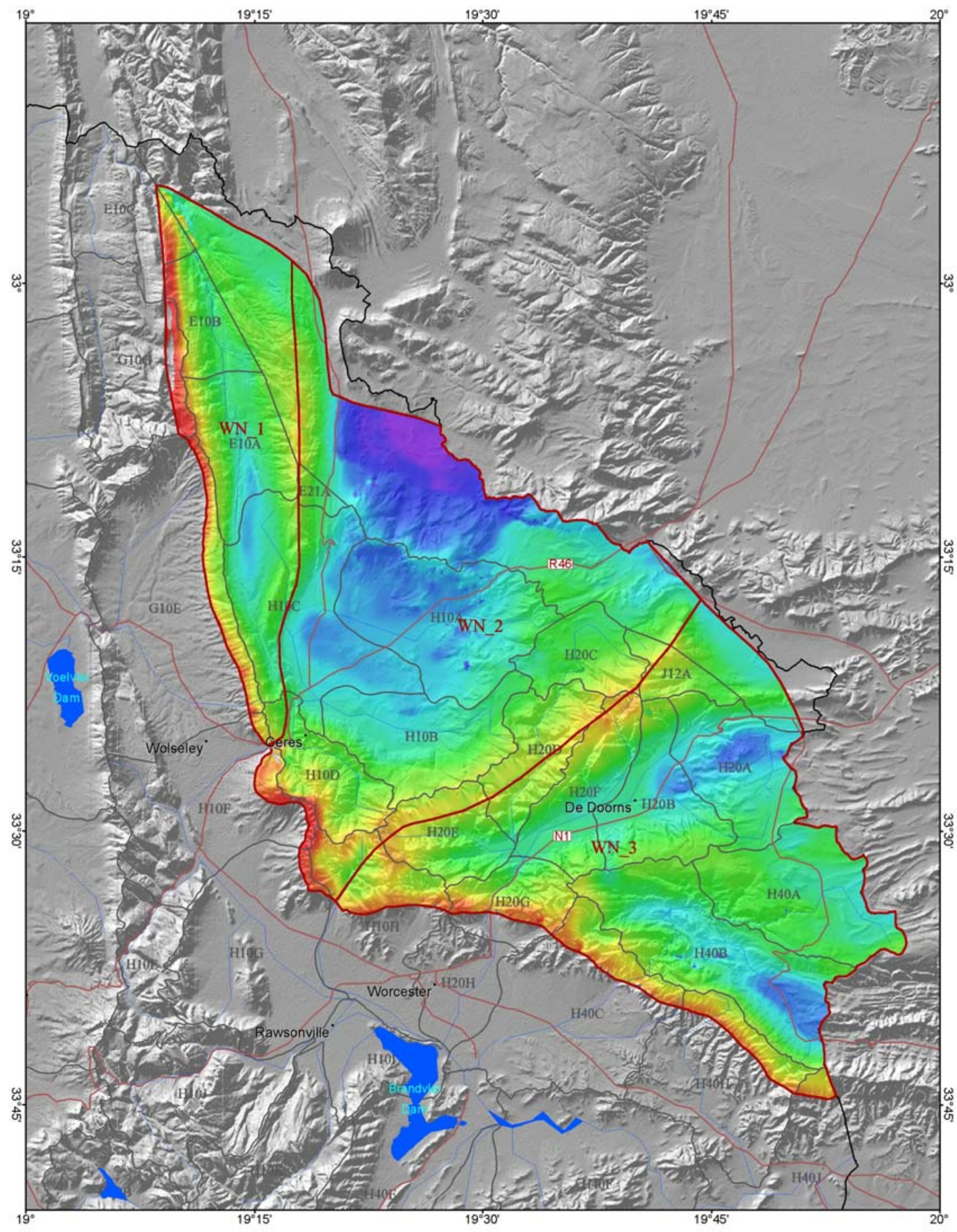
AQUIFER BOTTOM FOR PENINSULA AQUIFER

FIGURE 4.3



LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchments
- Study Area
- WN_3 Model Sub-Domain

Aquifer Top (m)

- -3036 - -1990
- -1990 - -730
- -730- -370
- -370 - 220
- 220 - 1250
- 1250 - 1690
- 1690 - 2020
- 2020 - 2800
- 2800 - 3510

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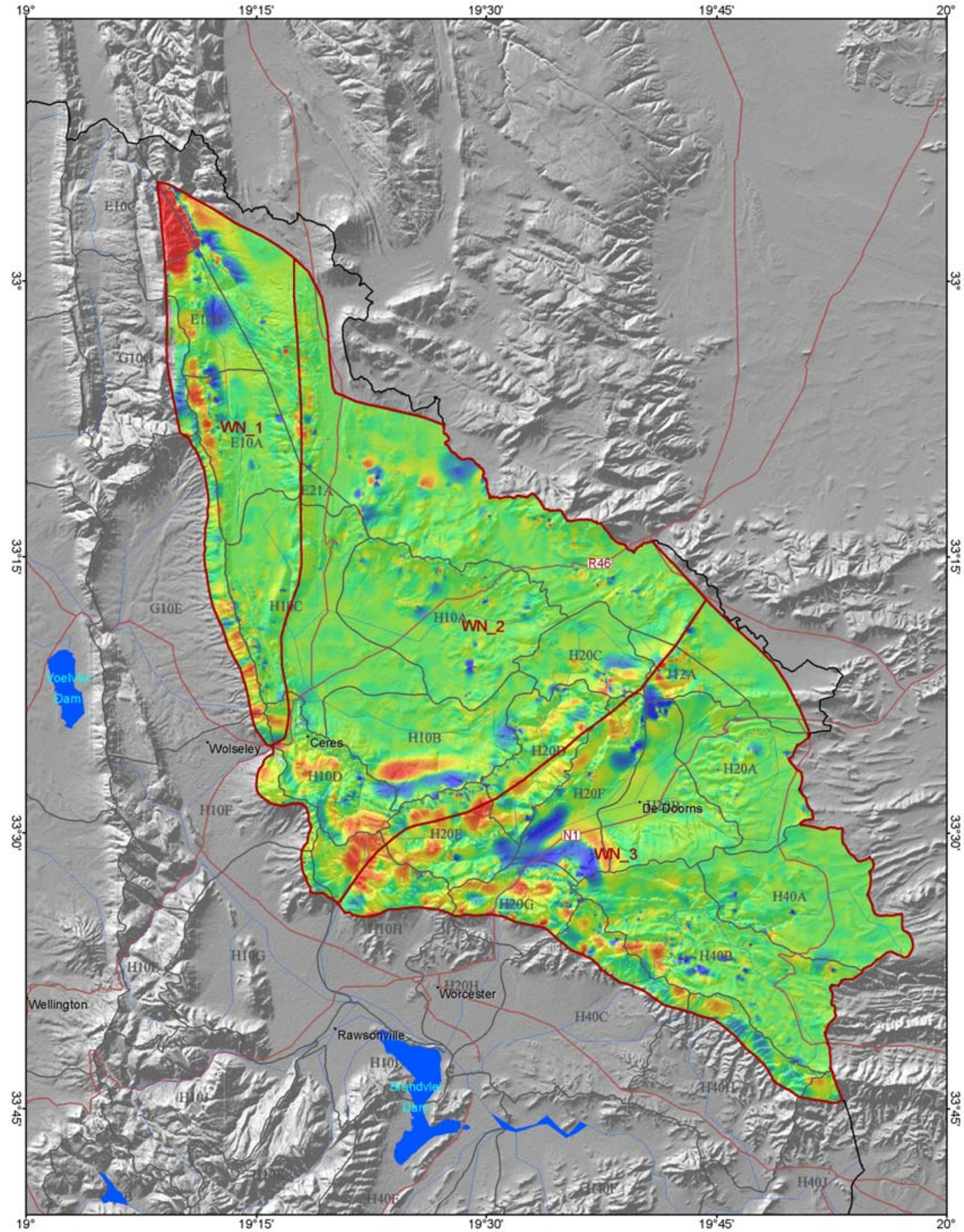
TITLE

AQUIFER TOP FOR PENINSULA AQUIFER

FIGURE 4.4

N



Scale 1:450 000 (A3 Paper)

0 5 10 15 20 KM

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

LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchment
- Study Area
- WN_3 Model Sub-Domain

Aquifer Thickness (m)

- 0 - 1381
- 1380 - 1460
- 1460 - 1570
- 1574 - 1600
- 1600 - 1700

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TITLE

ROCK VOLUME AND STORAGE MODEL OF PENINSULA AQUIFER

FIGURE 4.5

4.3.3 Skurweberg Aquifer

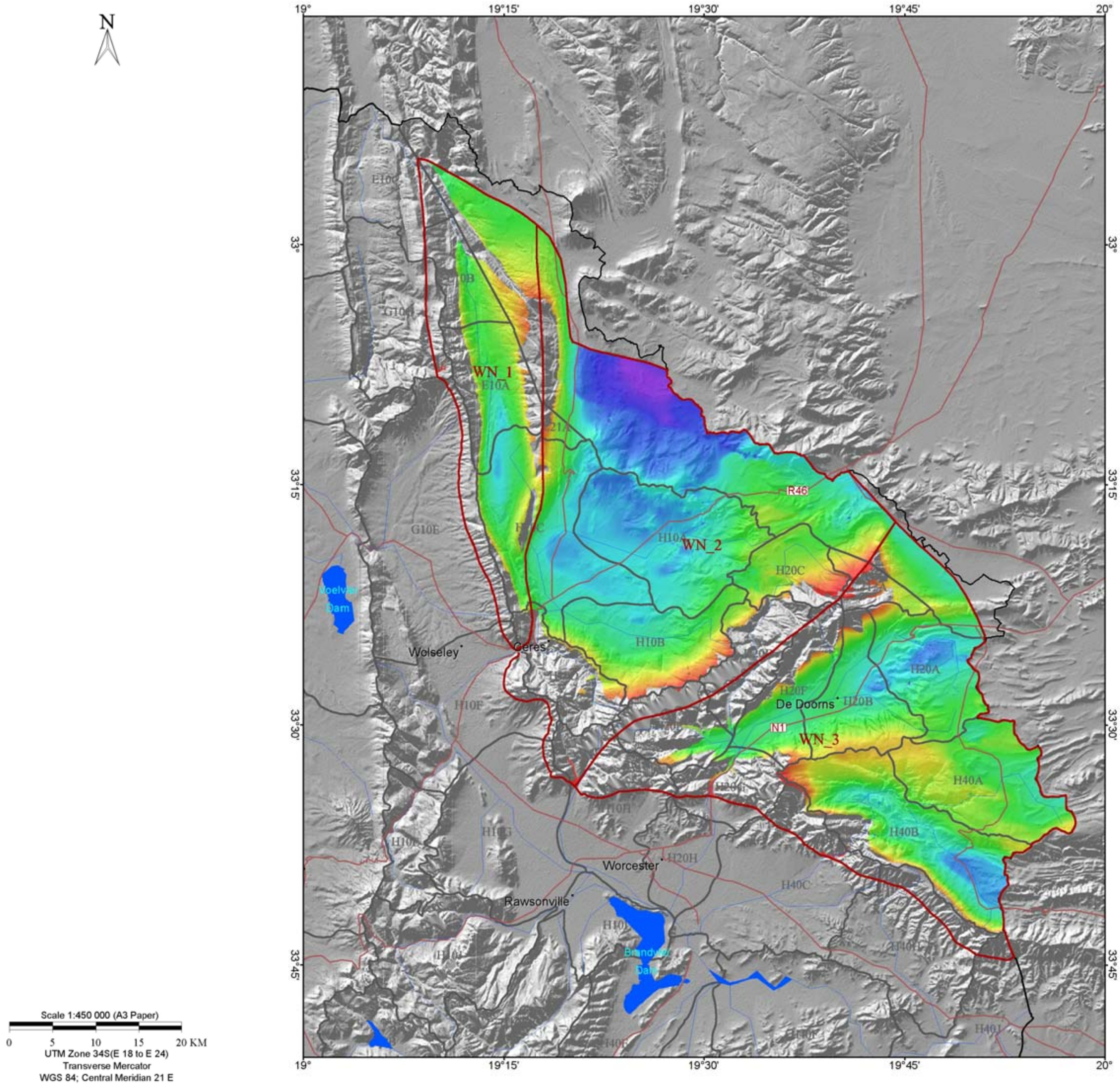
Figure 4-8 illustrates the storage modelling of the Skurweberg Aquifer. The coloured sections of the study area cover the area where the Skurweberg Aquifer exists either on or below surface. This is the area considered in the storage model. The colour palette illustrates the range in the aquifer rock 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 (see **Figure 4-6** and **Figure 4-7**).

The total solid material volume (rock volume) of the Skurweberg Aquifer is 504 billion m^3. The total confined rock volume is 389 billion 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 4-3**. The total confined pore volume of the Peninsula Aquifer is approximately 19 billion m^3.

Table 4-3 Rock Volume vs Pore Volume for Skurweberg Aquifer, given a porosity of 0.05 (5%)

Model Subdomains	Skurweberg Aquifer	Area (km^2)	Rock Volume (Mm^3)	Pore Volume (Mm^3)
WN 1	Unconfined portion	177.97	36 207	1 810
	Confined portion	101.17	25 705	1 285
WN 2	Unconfined portion	174.35	31 299	1 565
	Confined portion	877.49	218 061	10 903
WN 3	Unconfined portion	201.81	47 581	2 379
	Confined portion	609.60	146 046	7 302
Witzenberg-Nuy Model Domain	Unconfined portion	554.13	115 087	5 754
	Confined portion	1 588.26	389 811	19 491
	Total Aquifer	**2 142.39**	**504 898**	**25 245**

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 amount 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.



LEGEND

- · Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchments
- Study Area
- WN_3 Model Sub-Domain

Aquifer Bottom (m)

- -3687 - -1950
- -1950 - -940
- -940 - 70
- 70 - 800
- 800 - 1100
- 1100 - 1670
- 1670 - 3250

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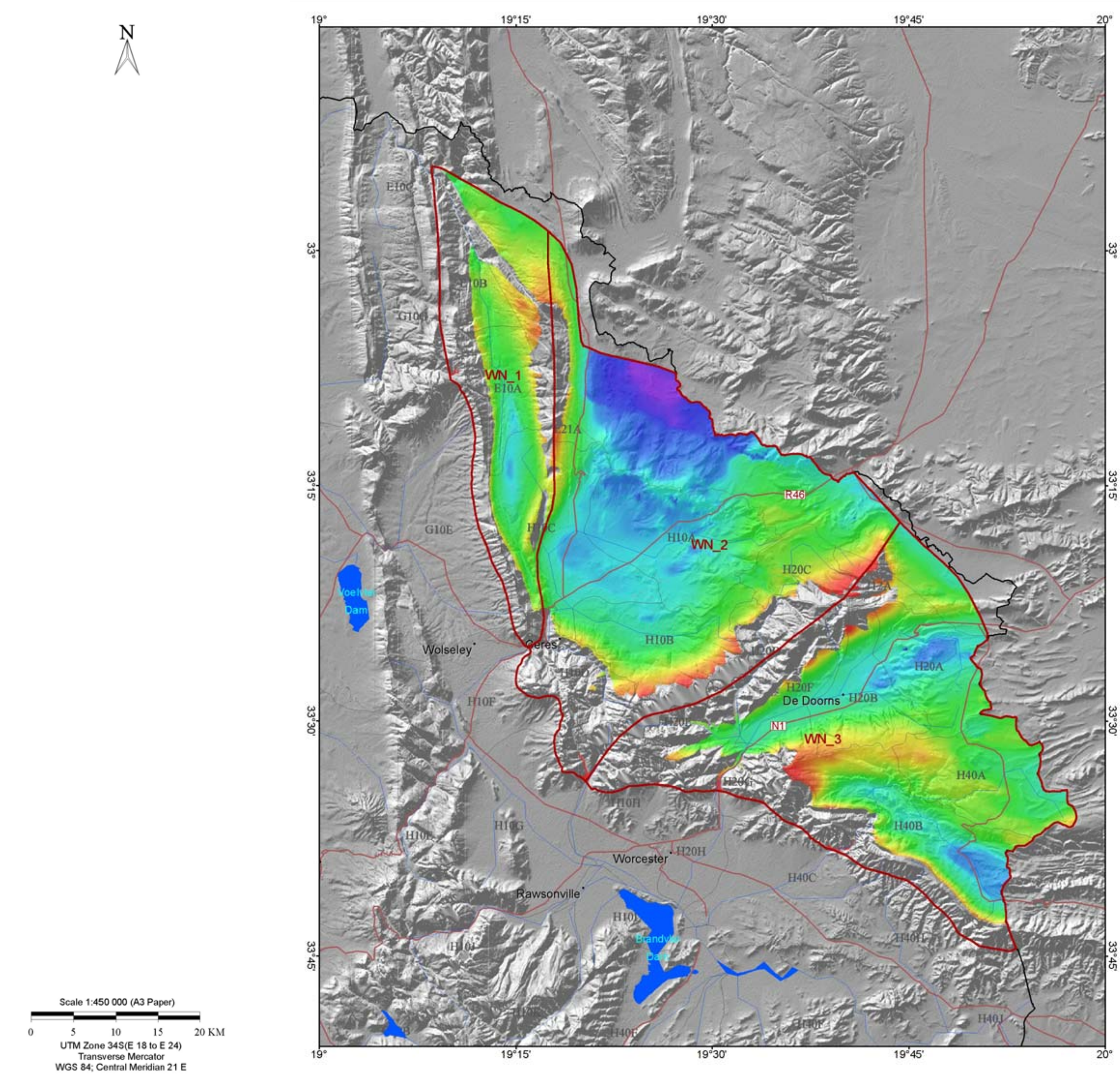
AQUIFER BOTTOM FOR SKURWEBERG AQUIFER

FIGURE 4.6



LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchments
- Study Area
- WN_3 Model Sub-Domain

Aquifer Top (m)

- -1900 - -1620
- -1620 - -130
- -130 - 170
- 170 - 900
- 900 - 1220
- 1220 - 1330
- 1330 - 1660
- 1660 - 2000
- 2000 - 2500

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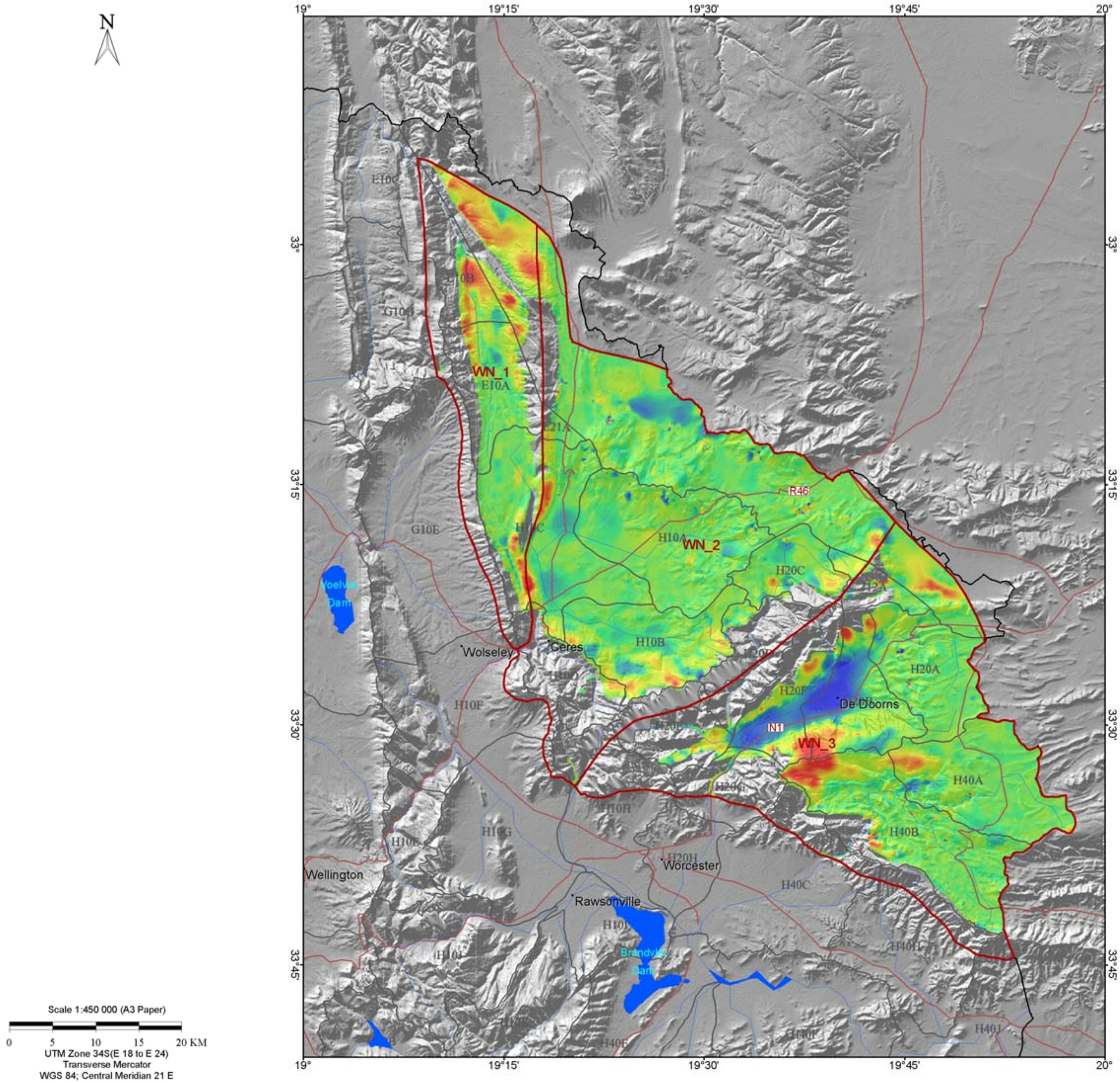
AQUIFER TOP FOR SKURWEBERG AQUIFER

FIGURE 4.7



LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchment
- Study Area
- WN_3 Model Sub-Domain

Aquifer Thickness (m)

- 0 - 90
- 90 - 240
- 240 - 320
- 320 -430
- 430 - 460
- 460 - 500

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TITLE

ROCK VOLUME AND STORAGE MODEL OF SKURWEBERG AQUIFER

FIGURE 4.8

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 TMG terrain, recharge to the Peninsula Aquifer was estimated with different methods to vary spatially between 7% and 43% of MAP, depending upon the method used, the annual rainfall and the geographic location of the study area. In the CAGE study (DWAF, 2000b) the spatially weighted average is 23% of MAP, where MAP varies from 200 mm – 2000 mm. If MAP 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 selected 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)]	BRBS (2002)
Upper Breede Valley	H10A	11.92	6.12	6.6
	H10B	12.83	9.53	11.1
	H10C	19.73	11.11	13.9
	H10D	14.34	10.02	12.6
	Subtotal	**58.82**	**36.78**	**44.2**
Hex River Valley	H20B	4.85	6.03	7.7
	H20D	7.85	6.10	6.8
	H20E	12.76	8.08	12.8
	H20F	7.69	8.94	10.7
	H20G	2.97	3.18 [*)]	7.0
	Subtotal	**36.12**	**32.33**	**45.0**

*) Estimated for the part of the catchment within Model Domain

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).

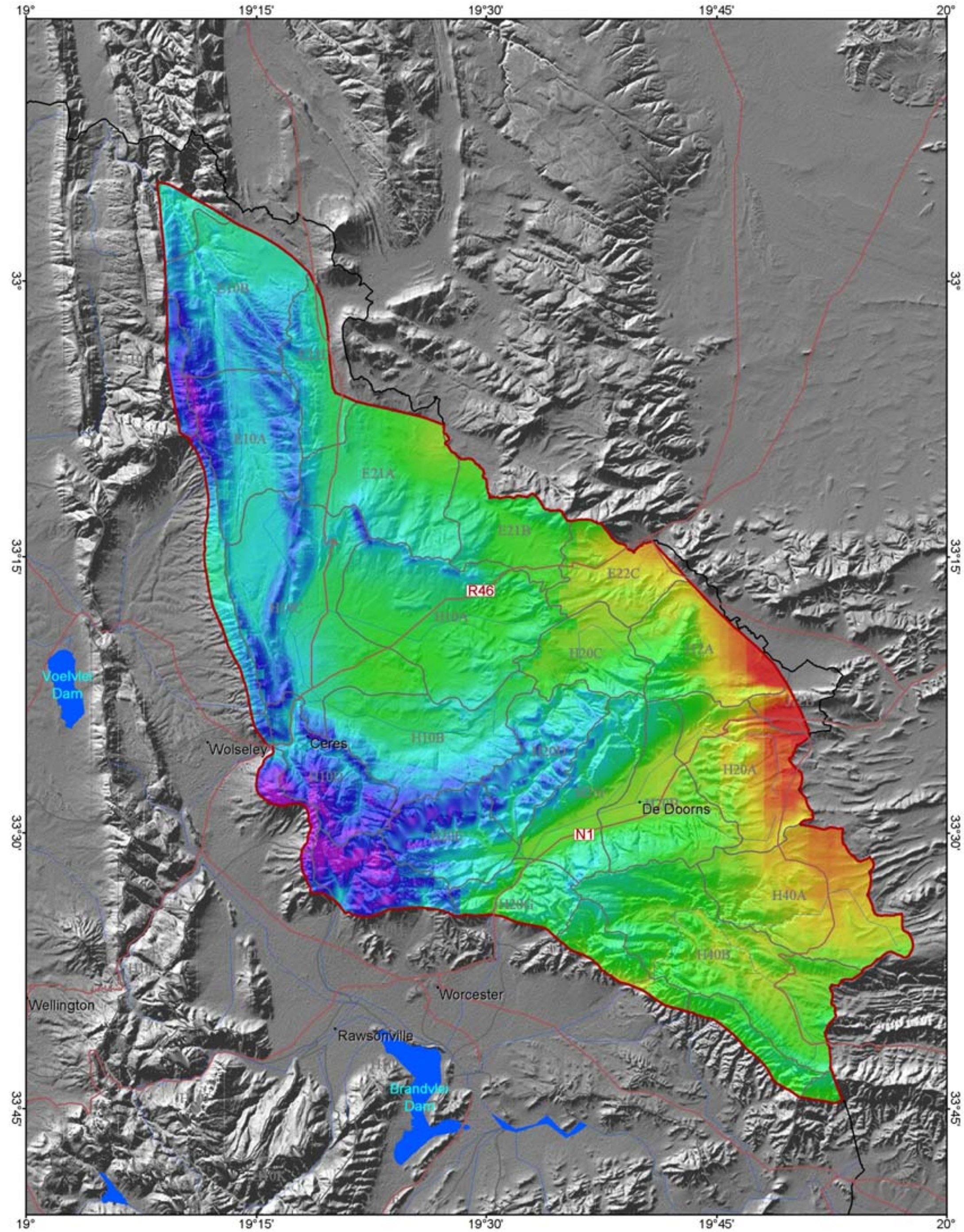
The results are given as recharge percentage on a 1 km x 1 km grid and are based on the Chloride Mass Balance method, which requires that data on the chloride concentration in the rain and the groundwater are available. The input data sets were not available to check the distribution of input values.

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. It appears from the distribution that there is a close correlation between recharge percentage and rainfall (**Figure 5-1**).

The recharge is estimated to be 82 million m^3/a for the Peninsula Aquifer, and 88 million m^3/a for the Nardouw Aquifer, respectively. The primary aquifers in the valleys receive recharge of 11.4 million m^3/a. The results per model subdomain are documented in **Table 5-2.**

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

Model Subdomain	Peninsula Aquifer	Nardouw Aquifer	Other fractured aquifers	Intergranular fractured aquifers	Intergranular aquifers	**Aquifer specific recharge**	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
WN1	21.82	36.55	0.68	8.77	0.53	68.34	133
WN2	32.45	30.49	0.98	40.28	7.46	111.67	85
WN3	27.86	21.09		8.31	3.40	60.66	50
Total	**82.12**	**88.13**	**1.66**	**57.35**	**11.40**	**240.66**	**79**



LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchments
- Study Area
- Model Domain

Recharge (mm/a)

- 3 - 6
- 6 - 10
- 10 - 13
- 13 - 25
- 25 - 80
- 80 - 120
- 120 - 140
- 140 - 160
- 160 - 205
- 205 - 220
- 220 - 330
- 330 - 335

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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, 2002c) 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, 2002c)

MAP Range [mm]		Mean Annual Infiltration
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

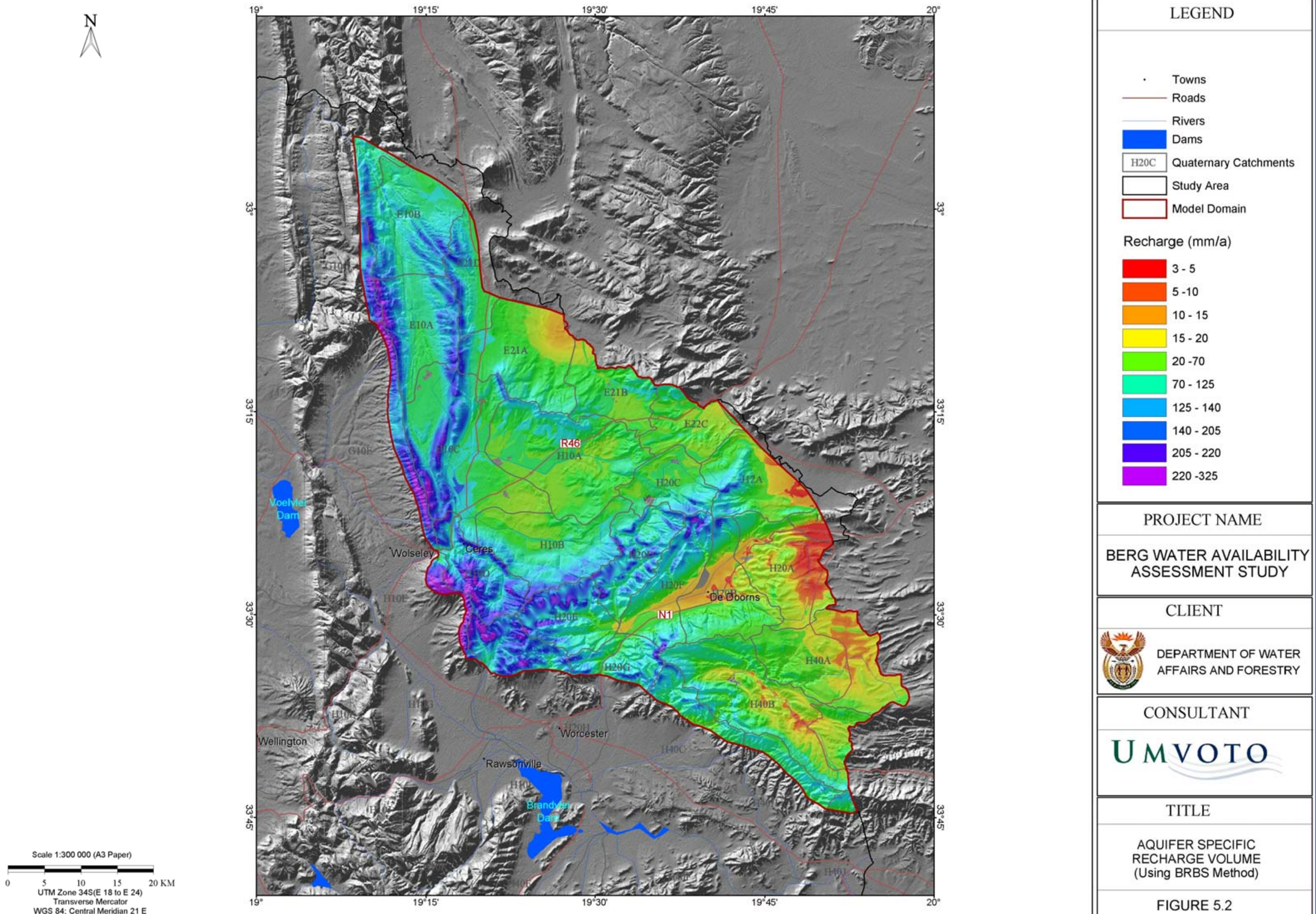
-Table 5-4 Aquifer-specific recharge factors (after DWAF, 2002c)

Aquifer Type		Recharge factor
(DWAF, 2003)	As per Table 5-2	
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 be 78 million m^3/a for the Peninsula Aquifer, and 82 million m^3/a for the Nardouw Aquifer, respectively. The primary aquifers in the valleys receive recharge of 11.8 million m^3/a. The results per model subdomain 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 (2002c)

Model Subdomain	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Aquifer specific recharge**	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
WN1	21.97	30.00	0.52	5.22	0.60	58.31	113
WN2	28.14	29.35	0.62	27.00	8.24	93.35	71
WN3	27.88	23.05		6.96	2.93	60.82	50
Total	**78.00**	**82.40**	**1.14**	**39.19**	**11.76**	**212.48**	**70**



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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). EVT 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 MAR 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 111 million m^3/a for the Peninsula Aquifer and 114 million m^3/a for the Nardouw Aquifer, respectively. The primary aquifer receives recharge of 9.8 million m^3/a. The results per model subdomain are documented in **Table 5-6**.

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

Model Subdomain	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Aquifer specific recharge**	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
WN1	34.04	34.85	0.61	3.27	0.26	73.03	142
WN2	34.33	41.72	1.12	27.74	7.42	112.34	86
WN3	42.63	37.14	0.00	4.64	2.17	86.58	72
Total	**111.00**	**113.71**	**1.74**	**35.65**	**9.85**	**271.95**	**90**

5.2.4 Map-centric Simulation of Recharge

The CAGE 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,
- 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.

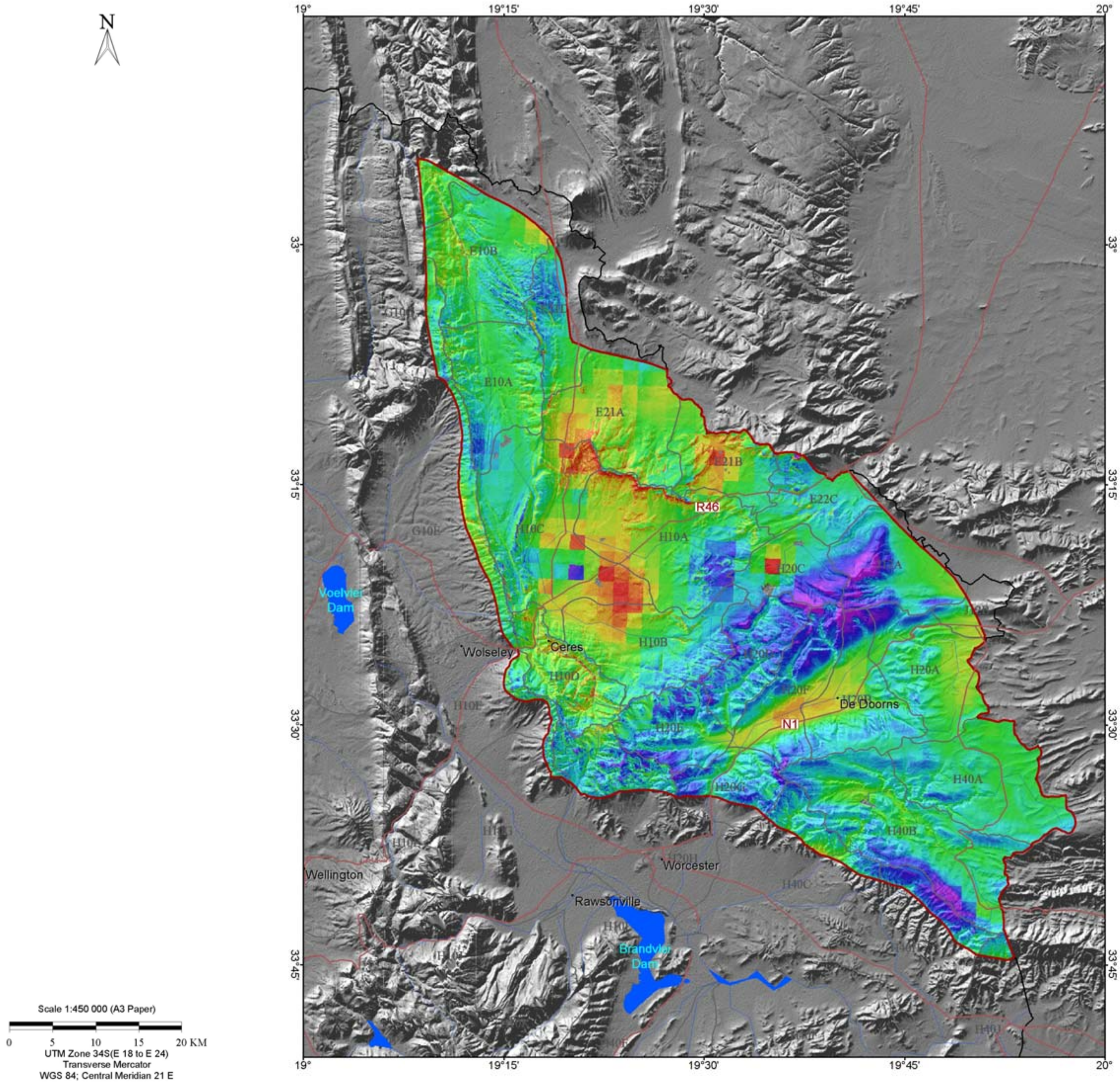
Table 5-7 Aquifer-specific correction factors per IWRM Domain for map-centric recharge estimation

IWRM Domain	Peninsula Aquifer	Nardouw Aquifer	Other fractured	Intergranular fractured	**Intergranular**
AWT	0.8	0.8	1.0	0.8	0.8
HEX	0.5	0.3		0.6	0.6
NUY	0.6	0.5		0.6	0.6
WBK	0.6	0.8	0.9	1.3	1.0

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

Model Subdomain	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Aquifer specific recharge**	
	Mm³	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*Mm³*	*mm*
WN1	9.67	19.24	0.28	5.81	0.32	35.32	68
WN2	14.98	25.87	0.73	36.45	6.87	84.91	65
WN3	26.75	40.72		25.06	7.00	99.54	82
Total	**51.41**	**85.83**	**1.02**	**67.33**	**14.19**	**219.77**	**72**



LEGEND

- Towns
- Roads
- Rivers
- Dams
- H20C Quaternary Catchments
- Study Area
- Model Domain

Recharge (mm/a)

- 0 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 70
- 70 - 90
- 90 - 100
- 100 -120
- 120 - 130
- 130 - 150
- 150 - 160
- 160 - 275

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RECHARGE DISTRIBUTION MAPCENTRIC METHOD

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 Witzenberg-Nuy 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 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 (2008)	1.5 m	Faulted system, medium flow path
Purgatory	WRC (2008)	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, a conservative average annual water level fluctuation of 1 m was applied to calculate the average annual recharge to the Peninsula Aquifer (see **Table 5-10**) and the Skurweberg Aquifer (see). The results are in the same order than the recharge estimates from the GIS methods. However, the conservative estimate of 1 m annual water level fluctuation across the different subdomains should be verified with continuous monitoring in the Peninsula Aquifer.

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

	Area [km²]		Pore Volume	Seasonal Fluctuation	Recharge	Recharge Volume
	Confined	Unconfined	[Mm³]	[m]	[mm/a]	[Mm³/a]
WN1	365.54	140.53	33 198	1	143.56	20.18
WN2	1 131.65	175.77	88 823	1	208.15	36.59
WN3	935.24	260.39	77 855	1	159.94	41.65
TOTAL	**2 066.89**	**436.16**	**199 876**	**1**	**170.64**	**98.41**

Table 5-11 Recharge estimation for the Skurweberg Aquifer, based on water level fluctuations

	Area [km²]		Pore Volume	Seasonal Fluctuation	Recharge	Recharge Volume
	Confined	Unconfined	[Mm³]	[m]	[mm/a]	[Mm³/a]
WN1	101.17	177.97	3 096	1	101.73	18.11
WN2	877.49	174.35	12 468	1	115.01	20.05
WN3	609.60	201.81	9 681	1	108.68	21.93
TOTAL	**1 487.09**	**376.16**	**25 245**	**1**	**108.44**	**60.09**

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 5-12**).

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 EVT 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 highest of precipitation and have little evapotranspiration. Possible reasons for this discrepancy are the different approaches and the different data sources as well as the different scales 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 dry deposits 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.

Table 5-12 Comparison of recharge estimations

Aquifer type	Recharge [million m^3/a]					
	BRBS	ISP	GRA II	Map-centric	Average	**SVF conf**
Peninsula	78	111	82	51	81	98
Nardouw	82	114	88	86	93	60 *)
Fractured	1	2	2	1	1	N/a
Intergranular-fractured	39	36	57	67	50	N/a
Intergranular	12	10	11	14	12	N/a
Total aquifer specific	**212**	**272**	**241**	**220**	**236**	**N/a**

*) Calculated for Skurweberg aquifer only

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 far less than with the other methods (see **Table 5-12**). 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.

The SVF method confirms the higher recharge values for the Peninsula Aquifer and the Nardouw Aquifer, as the method is only applied to the Skurweberg Aquifer.

Based on the comparison of the different approaches the average of the different methods (see **Table 5-13**) will be used as average recharge in the discharge estimation and the water balance yield analysis (see Section 6.1 and 7.2).

Table 5-13 Average aquifer specific recharge estimation per catchment

Model Subdomain	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*
WN1	22.00	29.59	0.52	4.88	0.31	57.30	111
WN2	26.92	32.16	0.86	33.24	7.41	100.60	77
WN3	31.71	30.77	0.00	11.36	3.90	77.74	64
Total	**80.63**	**92.52**	**1.39**	**50.00**	**11.91**	**236.44**	**78**

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.

Table 6-1 below shows the variations in the baseflow contribution for the aquifer types in the different subdomains, based on proportional recharge. A significant baseflow contribution is calculated from the Peninsula Aquifer (30% of total groundwater contribution to baseflow in the model domain). This increases to more than 50% in the TMG dominated subdomain WN3, which constitutes the Hex River Valley and the Nuy / Koo Valley. More than 50% of the groundwater contribution to baseflow in the subdomain WN1, i.e. Agter-Witzenberg, originates from the Nardouw Aquifer.

Table 6-1 Aquifer-specific discharge estimation per subdomain, groundwater contribution to baseflow disaggregated according to average recharge

Model Subdomain	Peninsula Aquifer	Nardouw Aquifer	Other Fractured Aquifers	Intergranular fractured Aquifers	Intergranular Aquifers	**Total GW Contribution to baseflow**	
	Mm^3	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*Mm^3*	*mm*
WN1	3.96	7.71	0.04	1.16	0.12	13.00	25
WN2	4.12	5.98	0.20	5.03	1.10	16.42	13
WN3	3.67	2.43	0.00	0.48	0.29	6.87	6
Total	**11.7**	**16.1**	**0.2**	**6.7**	**1.5**	**36.3**	**12**

6.2 LATERAL DISCHARGE – RECHARGE

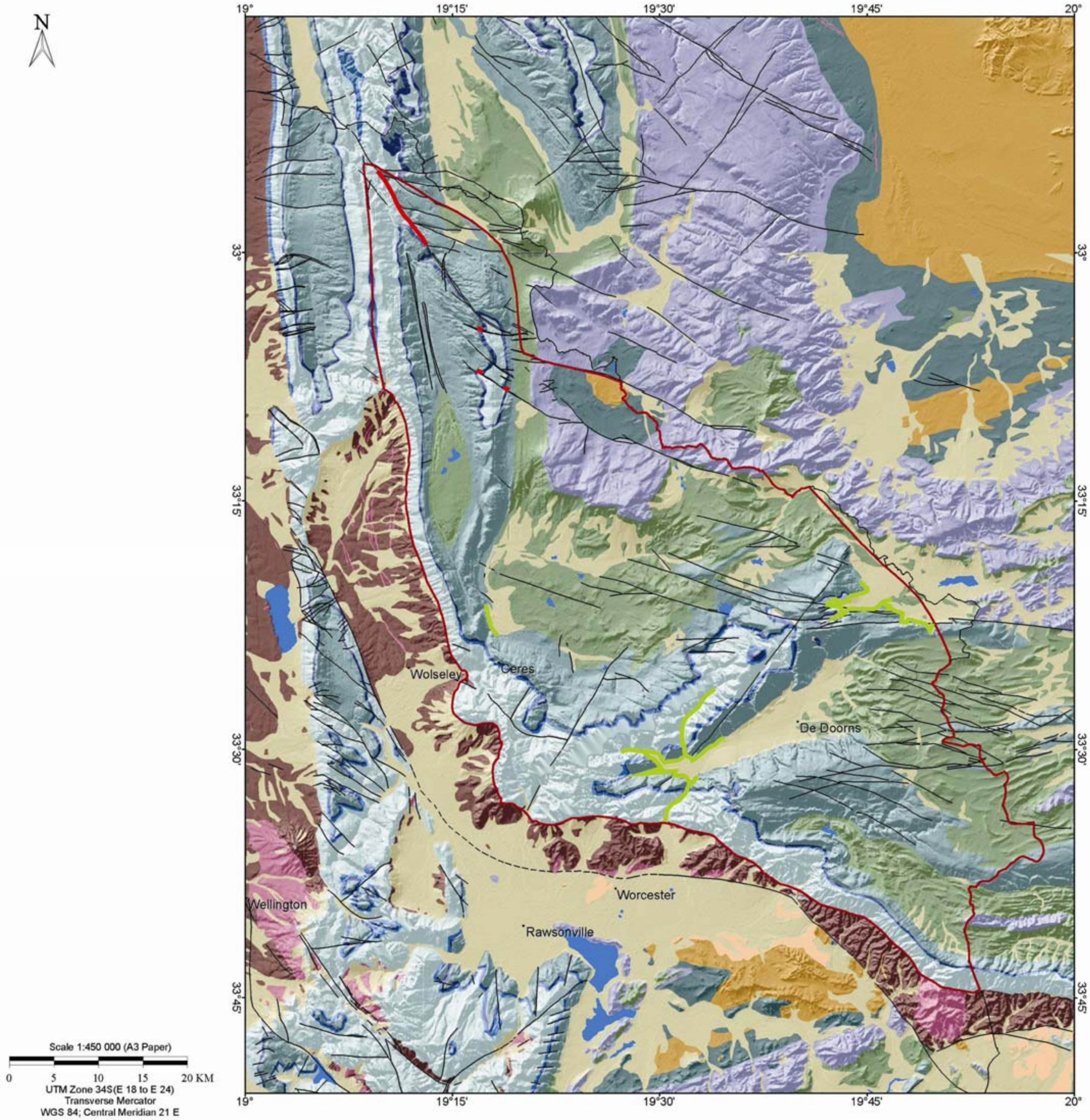
The potential hydraulic connection between the Peninsula and the Skurweberg Aquifers was investigated by mapping where these two lithologies are contiguous due to faulting. There is only one such site in the model domain (see **Figure 6-1**), associated with normal down faulting. It is important to establish 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.

There is only a few areas mapped in the Model Domain where the two aquifers might be in direct contact, allowing for hydraulic connection and lateral discharge / recharge (see **Figure 6-1**). These are:

- Contact between the Peninsula Aquifer and Nardouw Aquifer along the Gydo-Verloren Vlei Megafault across the northern end of the Agter-Witzenberg range;
- Contact between the Peninsula Aquifer and Nardouw Aquifer along smaller faults across the Hansiesberg anticline;
- Contact between the overlying primary aquifer and Nardouw Aquifer in Warmbokkeveld Valley north of Ceres,
- Contact between the overlying primary aquifer and the Peninsula and Nardouw Aquifer in the vicinity of the Bok River,
- Contact between the overlying primary aquifer and the Peninsula and Nardouw Aquifer in the Hex River Valley.

However, the exchange between the aquifers cannot be quantified with the currently available data. A reduction of lateral exchange between these aquifers would not impact on the yield estimation, as the quantity of water is available either from the overlying or the deeper aquifer.



LEGEND

Towns
Faults
Dam
Study Area
Model Domain

CONNECTIVITY

Peninsula Nardouw
TMG & Primary Aquifers

(Refer to Figure 2.8 for simplified lithology)

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 ~ 50 million m^3/a within the Model Domain (see **Appendix A**). The highest demand is estimated for irrigation with 48 million m^3/a, with the highest abstraction taking place in the H10C catchment (Agter-Witzenberg and Warmbokkeveld; 11.4 million m^3/a), followed by the E10A, E10B, E21A, E21D, H10A, H10B, H20B and H20F catchments (above 2 million m^3/a each).

According to the GRAII calculations urban domestic use accounts for 1.5 million m^3/a and is concentrated in the H10C catchment. Other groundwater use is insignificant.

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 6-2**) 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 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 6-2 Estimated groundwater use per aquifer per subdomain, after GRA II

Model Subdomain	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*
WN1	2.90	7.71	0.00	4.58	1.00	16.19
WN2	1.95	2.65	0.42	8.44	2.20	15.66
WN3	1.77	3.92	0.00	2.32	0.85	8.86
Total	**6.62**	**14.28**	**0.42**	**15.34**	**4.05**	**40.71**

Table 6-2 shows an unrealistically high groundwater abstraction from the Peninsula Aquifer in all three subdomains, while the groundwater abstraction from the Intergranular Aquifers seems to be far too low.

It was therefore 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 farm and properties, as received from CDMS, 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 on most farms a number of boreholes exist, 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 6-3.**

Table 6-3 Estimated groundwater use per aquifer per subdomain, based on WARMS and NGDB data

Model Subdomain	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*
WN1	0.14	1.58	0.01	4.22	0.00	5.96
WN2	0.49	5.63	0.00	14.64	2.86	23.62
WN3	1.15	8.22	0.00	4.67	12.27	26.31
Total	**1.78**	**15.44**	**0.01**	**23.53**	**15.13**	**55.89**

Table 6-3 shows a high groundwater abstraction from the intergranular-fractured aquifers in the WN2 subdomain, which is mainly due to the groundwater abstraction for Tulbagh and Ceres. Similarly, there is a high groundwater abstraction from the primary aquifer in subdomain WN3, which is mainly due to the agricultural use in the Hex River Valley. However, part of these high abstractions could come from the underlying aquifers, i.e. the Nardouw and or Peninsula.

It is therefore recommended that the aquifer-specific groundwater use in these areas be verified through detailed data analysis and field verification.

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, as well as for the different IWRM Domains. Natural discharge and groundwater abstraction are discussed in Section 6 for each quaternary catchment and IWRM Domain. Using the relationship between recharge areas and potential discharge areas, as discussed in Volume 3 of this report, the available groundwater for abstraction per IWRM Domain are 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 the groundwater potential for the Peninsula Aquifer and the Nardouw Aquifer was estimated to be 8 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).

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

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	80.6	11.7	68.9	1.8	67.2
Nardouw	92.5	16.1	76.4	15.4	61.0
Fractured	1.4	0.2	1.1	0.0	1.1
Intergranular-fractured	49.9	6.6	43.2	23.5	19.7
Intergranular	11.8	1.5	10.3	15.1	-4.8
Total	**236.2**	**36.2**	**200.0**	**55.9**	**144.1**

The detailed comparison of the estimated groundwater potential and the percentage of groundwater utilisation per quaternary catchment show that the Peninsula Aquifer is mostly un- or under-utilised, while the other aquifers are utilised in specific areas. Especially the intergranular-fractured and intergranular aquifers are over-utilised in the upper Breede Valley around Ceres (H10B and H10C), the Hex River Valley (H20B, H20E, H20F andH20G) and the Nuy Valley (H40B) (see **Table 7-2**).

It further appears from this calculation that the total available groundwater potential in the Hex River Valley is already over allocated.

Table 7-2 Groundwater Potential in selected stressed catchments

Quaternary Catchment	Peninsula	Nardouw	Intergranular-fractured	Interganular	Total Groundwater Potential
E21A	0.10	0.84	3.43	**-0.17**	4.19
H10B	0.00	3.72	**-1.23**	0.29	2.78
H10C	0.45	8.45	**-6.41**	**-0.50**	1.99
H20A	0.00	1.11	1.02	0.25	2.38
H20B	0.02	0.10	0.50	**-1.39**	**-0.76**
H20E	7.42	0.88	0.59	**-0.71**	8.18
H20F	2.71	2.05	0.58	**-6.75**	**-1.41**
H20G	3.08	0.74	0.27	**-0.69**	3.39
H40B	1.01	7.98	0.72	**-0.47**	9.25

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 3.3×10^{-10} Pa^{-1} and 6.9×10^{-10} Pa^{-1} (Domenico and Schwartz, 1990) delineated a range of Specific Storage values between 3 x 10^{-6} and 7 x 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 x 10^{-6} m^{-1}, with a corresponding Effective Storativity of 8.4 x 10^{-3} and 1.5 x 10^{-3} for the Peninsula Aquifer and Skurweberg Aquifer, respectively. These numbers correspond well with previously published estimates of storativity of 0.001 (Rosewarne, 2002).

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 amount of subsurface water, viz. 20.4 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 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 x 10^{-6} m^{-1} and porosity of 5% are summarized in **Table 7-3**.

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 in **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 Subdomain	Effective Storativity	Pore Volume Mm^3	Volume per head decline of: 1m		5m		20m	
			Mm^3	%	Mm^3	%	Mm^3	%
WN1	8.37E-03	25 509	3.06	0.01	15.31	0.06	61.22	0.24
WN2	8.40E-03	79 207	9.50	0.01	47.52	0.06	190.10	0.24
WN3	8.34E-03	65 032	7.80	0.01	39.02	0.06	156.08	0.24
Total	**8.37E-03**	**169 748**	**20.37**	**0.01**	**101.85**	**0.06**	**407.39**	**0.24**

Table 7-4 Potential yield of the confined Skurweberg Aquifer in the Model Domain, based on the storage yield model (Effective Storativity based on Specific Storage)

Model Subdomain	Effective Storativity	Pore Volume Mm^3	Volume per head decline of: 1m		5m		20m	
			Mm^3	%	Mm^3	%	Mm^3	%
WN1	1.52E-03	1 285	0.15	0.01	0.77	0.06	3.08	0.24
WN2	1.49E-03	10 903	1.31	0.01	6.54	0.06	26.17	0.24
WN3	1.44E-03	7 302	0.88	0.01	4.38	0.06	17.53	0.24
Total	**1.52E-03**	**19 491**	**2.42**	**0.01**	**12.11**	**0.06**	**48.42**	**0.25**

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 7-5**, 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 7-5 Groundwater yield for Peninsula and Nardouw Aquifer based on average recharge and baseflow estimation and storage yield (all values in Mm^3/a)

Aquifer	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)	Storage Yield	
				5m drawdown	20m drawdown
Peninsula	68.9	1.8	67.2	102	407
Nardouw	76.4	15.4	61.0	12	48
Fractured	1.1	0.0	1.1	Not applicable	
Intergranular-fractured	43.2	23.5	19.7	Not applicable	
Intergranular	10.3	15.1	-4.8	Not applicable	
Total	**200.0**	**55.9**	**144.1**	**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 recharge estimation for the Peninsula and Nardouw aquifers is considered conservative. The water balance and yield model suggests a total remaining groundwater potential of approximately 144 million m^3/a within the study area, applying the average recharge estimation (see **Table 8-1**). However, the intergranular aquifer appears to be over allocated. Several catchments are identified as stressed or over-utilised:

- Upper Breede valley / Ceres
- Hex River valley
- Nuy River valley.

Table 8-1 Summary results of groundwater potential per aquifer

Aquifer	Recharge	Baseflow	Recharge - Baseflow	Groundwater Use	Groundwater Potential (Re – BF - Use)
Peninsula	80.6	11.7	68.9	1.8	67.2
Nardouw	92.5	16.1	76.4	15.4	61.0
Fractured	1.4	0.2	1.1	0.0	1.1
Intergranular-fractured	49.9	6.6	43.2	23.5	19.7
Intergranular	11.8	1.5	10.3	15.1	-4.8
Total	**236.2**	**36.2**	**200.0**	**55.9**	**144.1**

8.2 RECOMMENDATIONS

The results of the Water Balance Model show 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 Monitoring

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:

- Spring hydrocensus including diverse hydrochemical sampling to verify discharge rates;
- Borehole hydrocensus to verify groundwater abstraction;
- Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg Aquifer 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 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 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 recommended that a comprehensive monitoring programme be developed for the Berg WAAS area that comprises all the above aspects in an integrated and optimised manner.

8.2.2 Modelling

It is recommended to use the results of the water balance model as input for the WRYM and WRSM.

Due to the over-utilisation of the aquifers in the Hex River valley, compulsory licensing of groundwater use is strongly advised. This should be based on a detailed flow model for the valley, using the regional pattern as described and quantified in this report and on long-term monitoring data.

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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 within Model Domain and MAP

Quaternary catchment	Area	MAP *WR90*	MAP *CCWR*	MAP *GRAII*	MAP *Berg WAAS*	MAP *WR2005*
	km^2	*mm*	*mm*	*mm*	*mm*	*mm*
E10A	133.73	899	743	907	966	899
E10B	162.71	736	648	724	869	736
E10C	26.58	587	552	581	840	587
E21A	169.04	620	475	582	718	620
E21B	92.76	497	336	540	666	497
E21D	69.33	627	620	771	851	627
E22C	86.34	324	394	426	551	324
G10E	41.58	640	656	660	767	764
G10G	20.91	912	672	935	995	997
H10A	233.67	512	473	550	652	734
H10B	162.46	708	424	653	778	734
H10C	259.60	674	722	668	862	1064
H10D	96.86	1019	586	977	1146	2000
H10F	20.12	784	627	799	883	784
H10G	4.69	788	703	804	816	788
H10H	77.23	886	381	864	753	749
H20A	140.31	357	281	356	374	357
H20B	124.39	590	312	539	488	590
H20C	80.57	643	503	627	673	643
H20D	100.67	696	383	697	945	967
H20E	95.20	906	301	957	967	906
H20F	116.57	797	322	757	714	797
H20G	63.26	680	347	684	765	680
H20H	0.00	300	276	294	365	300
H40A	184.15	426	293	435	382	426
H40B	240.42	577	357	649	542	578
H40C	46.91	375	269	356	380	375
H40H	37.16	461	342	417	415	461
H40J	7.47	417	307	358	372	424
J12A	117.28	437	326	469	531	437
J12B	16.36	268	258	274	282	268
Total	**3028.3**	**626.8**	**453.6**	**634.1**	**699.6**	**718.0**

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

Quaternary catchment	Area	MAR *WR90*	MAR *WR2005*	Difference	Run-off Effciency *Berg WAAS / WR2005*	Run-off Effciency *WR2005*	Run-off Effciency *WR90*
	km²	*mm*	*mm*				
459	459	458	459	0.3%	0.48	0.51	0.51
340	340	346	340	1.8%	0.39	0.46	0.47
248	248	259	248	4.3%	0.30	0.42	0.44
186	186	184	186	1.1%	0.26	0.30	0.30
121	121	121	121	0.3%	0.18	0.24	0.24
190	190	188	190	1.2%	0.22	0.30	0.30
25	25	27	25	7.7%	0.05	0.08	0.08
201	201	173	201	16.1%	0.26	0.26	0.27
314	314	668	314	53.0%	0.32	0.32	0.73
152	152	168	152	9.7%	0.23	0.21	0.33
152	152	288	152	47.4%	0.19	0.21	0.41
231	231	266	231	13.1%	0.27	0.22	0.39
1325	1325	520	1325	154.8%	1.16	0.66	0.51
235	235	349	235	32.7%	0.27	0.30	0.45
239	239	353	239	32.3%	0.29	0.30	0.45
216	216	423	216	49.1%	0.29	0.29	0.48
32	32	34	32	6.3%	0.09	0.09	0.10
91	91	33	91	176.1%	0.19	0.15	0.06
112	112	44	112	153.6%	0.17	0.17	0.07
247	247	277	247	10.9%	0.26	0.26	0.40
209	209	423	209	50.6%	0.22	0.23	0.47
117	117	97	117	20.5%	0.16	0.15	0.12
259	259	55	259	371.2%	0.34	0.38	0.08
1	1	29	1	95.7%	0.00	0.00	0.10
35	35	35	35	1.4%	0.09	0.08	0.08
12	12	15	12	21.2%	0.02	0.02	0.03
66	66	52	66	26.9%	0.17	0.18	0.14
46	46	88	46	47.8%	0.11	0.10	0.19
229	229	52	229	341.0%	0.62	0.54	0.12
32	32	38	32	17.0%	0.06	0.07	0.09
7	7	10	7	26.3%	0.03	0.03	0.04
193.6	**193.6**	**187.0**	**193.6**	**3.6%**	**0.27**	**0.28**	**0.30**

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*
E10A	49	133.9	14.95	56.6	29.1	75.67
E10B	33	100.13	3.64	42.7	28.71	60.18
E10C	24	74.22	3.14	31.5	23.22	42.28
E21A	20	56.91	5.07	24.4	11.76	35.19
E21B	13	36.71	3.37	16.4	11	23
E21D	21	58.53	5.06	24.9	11.77	39.99
E22C	0	1.73	0	0	0	7.89
G10E	20	55.21	5.78	23.9	13.62	39.7
G10G	71	207.4	16.44	84.9	14.75	117.96
H10A	17	50.43	3.58	20.7	3.23	26.19
H10B	30	87.98	6.65	36.7	20.66	58.66
H10C	28	81.97	5.98	33.6	20.5	42.78
H10D	55	162.69	11.69	65.3	21.15	103.44
H10F	37	109.06	7.75	43.8	21.06	61.77
H10G	37	110.68	7.95	44.2	21.14	66.38
H10H	45	133.11	9.5	53	21.14	64.3
H20A	0	0	0	0	0	15.11
H20B	3	9.54	0.97	3.8	4.51	48.48
H20C	6	12.68	3.6	4.8	7.82	36.01
H20D	31	86.52	9.83	35.5	22.16	60.61
H20E	49	136	15.47	54.8	22.82	84.87
H20F	9	28.74	2.06	8.3	11.91	76.65
H20G	5	15.61	1.41	5.6	9.5	50.29
H20H	0	0.27	0	0	0	11.59
H40A	0	2.49	0	0	0	18.13
H40B	3	6.28	1.74	3.6	4.37	41.64
H40C	0	4.65	0	0	0	12.34
H40H	0	9.8	0	0	0.63	21.04
H40J	2	9.13	0.44	0	0.9	16.13
J12A	0	4.08	0	0	0	15.28
J12B	0	0.38	0	0	0	6.03
Total	**19.0**	**55.3**	**4.6**	**22.6**	**11.9**	**44.3**

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
E10A	3.4516	0	0	**3.444**	0.0076	0	0	0
E10B	3.7288	0.007	0	**3.7143**	0.0075	0	0	0
E10C	0.3425	0	0	0.3346	0.0079	0	0	0
E21A	5.3593	0.013	0	**5.3397**	0.0066	0	0	0
E21B	1.3477	0.001	0	1.3389	0.0078	0	0	0
E21D	7.3865	0.007	0	**7.371**	0.0085	0	0	0
E22C	0.2093	0.017	0	0.1752	0.0171	0	0	0
G10E	11.1348	0	0	**10.98**	0.0578	0	0.097	0
G10G	0.0346	0	0	0	0.0346	0	0	0
H10A	3.2995	0	0	**3.2913**	0.0082	0	0	0
H10B	4.5534	0	0	**4.5477**	0.0057	0	0	0
H10C	13.3353	0	**1.4278**	**11.379**	0.0095	0	0.519	0
H10D	0.0034	0	0	0	0.0034	0	0	0
H10F	8.936	0	0	**8.794**	0.022	0	0.12	0
H10G	8.4146	0	0	**8.411**	0.0036	0	0	0
H10H	1.4186	0	0	1.05	0.0026	0	0.366	0
H20A	0.42	0.003	0	0.4082	0.0018	0	0.007	0
H20B	2.1175	0.019	0.0598	**2.034**	0.0017	0	0.003	0
H20C	1.8244	0	0	1.8216	0.0028	0	0	0
H20D	0.1357	0	0	0.1337	0.002	0	0	0
H20E	0.1768	0	0	0.1753	0.0015	0	0	0
H20F	2.1997	0.006	0	**2.192**	0.0017	0	0	0
H20G	0.4916	0.008	0	0.4825	0.0011	0	0	0
H20H	0.7075	0	0	0.4863	0.0012	0	0.22	0
H40A	0.0038	0	0	0	0.0038	0	0	0
H40B	0.799	0.013	0	0.7805	0.0055	0	0	0
H40C	4.2137	0.014	0	**4.196**	0.0037	0	0	0
H40H	0.0424	0.007	0	0	0.0104	0.024	0.001	0
H40J	0.0193	0	0	0	0.0113	0	0.008	0
J12A	0.4756	0	0	0.4707	0.0049	0	0	0
J12B	0.0022	0	0	0	0.0022	0	0	0
Total	**86.6**	**0.1**	**1.5**	**83.4**	**0.3**	**0.0**	**1.3**	**0.0**