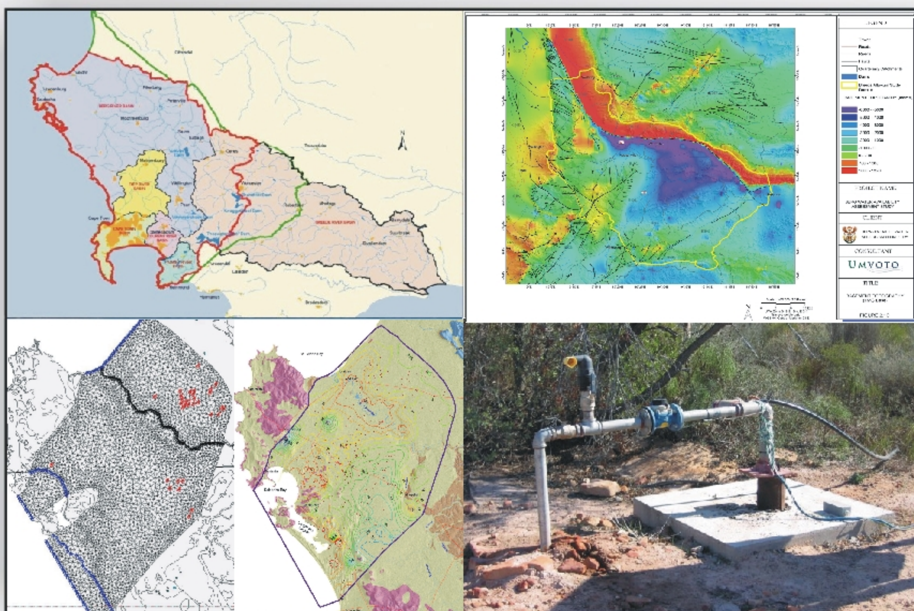
Ref No: P WMA19/000/00/0410

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. 1
## OVERVIEW OF METHODOLOGY AND RESULTS



**Final** **May 2010**

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

NINHAM SHAND CONSULTING SERVICES

UMVOTO

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

## GROUNDWATER MODEL REPORT VOLUME 1
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***Final***

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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 1
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# APPROVAL

| | | |
|---|---|---|
| **TITLE** | : | **The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models :**<br><br>**Groundwater Model Report Volume 1**<br>**Overview of Methodology and Results** |
| **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** | : | **May 2010** |

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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 Mhlatuze Assessment Studies (Refer to Report No.1) | | |
| 11 | Applicability of the Sami Groundwater Model to the Berg WAAS Area | | |

# REFERENCE

This report is to be referred to in bibliographies as :

Department of Water Affairs and Forestry, South Africa. 2010. *The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models: Groundwater Model Report Volume 1 – Overview of Methodology and Results*. Prepared by Umvoto Africa (Pty) Ltd in association with Ninham Shand (Pty) Ltd on behalf of the Directorate: National Water Resource Planning. DWAF Report No. P WMA 19/000/00/0410

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

# GROUNDWATER MODEL REPORT VOLUME 1
# OVERVIEW OF METHODOLOGY AND RESULTS

# 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 (DWA, 2005) of the Study are to:

- 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. The relationship between project tasks and report volumes are tabled below.

Each report documents model development and model scenarios, as well as recommendations for implementation and model upgrade. This report is Volume 1 in the project series, summarising the findings and recommendations from the different modelling tasks. It includes an overarching summary of the context and the context of Volumes 2 – 9 and presents key recommendations in order to ensure that results of further work will improve the model calibration and output. Furthermore it identifies strategic research, implementation and operational elements that warrant consideration by both DWAF and the WRC.

**Table E-1 Key Deliverables and Report Volumes**

| Task | Key Deliverable | Vol. | Title |
|---|---|---|---|
| **7** | **GIS database for groundwater component**<br>**Digitise Geological Maps** | **2** | **Data Availability and Evaluation** |
| **12** | **Regional model development** | | |
| | Conceptual model for study domain | **3** | **Regional Conceptual Model** |
| | GIS based water balance model for study domain | **4** | **Regional Water Balance Model** |
| **13** | **Configuration of a numerical model for Cape Flats Aquifer** | **5** | **Cape Flats Aquifer Model** |
| | Quantification of surface water – groundwater interaction | 5 | |
| | Calibration of recharge estimation and water balance | 5 | |
| | Scenario for augmentation to bulk water supply to Cape Town (as support of Western Cape Reconciliation Study) | 5 | |
| | Scenario for flood management (as support of Western Cape Reconciliation Study) | 5 | |
| **14** | **Review and update conceptual model for West Coast Aquifers and Configure a numerical groundwater model for Langebaan Road Aquifer** | **6** | **Langebaan Road Aquifer and Elandsfontein Aquifer Model** |
| | Review and revise recharge and yield estimation as well as water balance | 6 | |
| | Refine understanding and Quantify surface water – groundwater interaction | 6 | |
| | Scenario for artificial recharge schemes (support to Western Cape Reconciliation Study) | 6 | |
| **15** | **Water balance and storage model for TMG Aquifer(s)** | **4** | **Regional Water Balance Model** |
| | Configuration of a numerical TMG groundwater model for Worcester | **9** | **Breede River Alluvium Model** |
| | Configuration of a numerical TMG groundwater model for Hex River Mountains | **8** | **Table Mountain Group Aquifers – Witzenberg - Nuy area** |
| | Configuration of a numerical TMG groundwater model for Tulbagh - Ceres | 8 | |
| | Configuration of a numerical TMG groundwater model for Piketberg | **7** | **Table Mountain Group Aquifers – Piketberg area** |
| | Refinement of recharge and yield estimation as well as water balance on regional scale | 7 & 8 | |
| | Quantification of surface water groundwater interaction | 9 | |

## MAIN RESULTS

### Conceptual model – IWRM domains

An aquifer-specific conceptual model across the study area was developed with the aim to generate a 3D view of the aquifer geometry, hydraulic properties and preferred flow paths, and to identify zones of surface water / groundwater interaction and interaction between aquifers.

To meet one of the core requirement of the study, viz. to understand and map surface and groundwater interaction and to quantify it so far as possible, to be able to integrate groundwater into the Pitman and the WRYM models, the groundwater study boundaries were defined by areas called Integrated Water Resource Management Domains (IWRM Domains).

### Water availability

The water balance and yield model suggests a total remaining groundwater potential of 869 million $m^3$/a within the study area (see **Table E-2**). The recharge estimation for the Peninsula and Nardouw aquifers are considered very conservative and a higher groundwater potential from these aquifers can be expected, once the model is calibrated.

On the other hand, the recharge for the intergranular aquifer, and hence the groundwater potential, appears to be high, especially along the West Coast and the Cape Flats. These estimates need to be verified prior to further groundwater development, water allocation or licensing.

**Table E-2 Summary results of groundwater potential per aquifer for study area (in million $m^3$/a)**

| Aquifer | Recharge | Baseflow | Recharge - Baseflow | Groundwater Use | Groundwater Potential (Re – BF - Use) |
|---|---|---|---|---|---|
| Intergranular | 355 | 41.1 | 314 | 92.6 | 222 |
| Intergranular fractured | 267 | 39.2 | 228 | 58.4 | 170 |
| Fractured | 8.0 | 0.7 | 7.3 | 0.6 | 6.7 |
| Nardouw | 226 | 46.2 | 180 | 20.6 | 159 |
| Peninsula | 390 | 69.7 | 320 | 8.6 | 312 |
| Total | 1247 | 197 | 1050 | 181 | 869 |

### Over allocated catchments

The intergranular aquifer is the most developed and utilised across the study domain. There are the following areas of concern (see **Table E-3**):

- Over allocation of groundwater from the intergranular aquifer at least in the Hex River IWRM domains;
- Very high groundwater use (> 50% of Recharge – Base flow) in the Brandvlei, Nuy and Warm Bokkeveld IWRM domains;
- High groundwater allocation (> 20% of Recharge – Base flow) in the Atlantis, Kogelberg, Paarl-Upper Berg and West Coast IWRM domains;
- High groundwater use from the Nardouw Aquifer in the Brandvlei, Hex River and Warm Bokkeveld IWRM domains.

**Table E-3 Estimated groundwater potential and over allocation of groundwater in selected quaternary catchments (all values in million $m^3/a$)**

| Quaternary Catchment | Peninsula | Nardouw | Intergranular-fractured | Intergranular | Total Groundwater Potential |
|---|---|---|---|---|---|
| E21A | 0.04 | 0.20 | 3.24 | **-0.27** | 3.21 |
| G21B | 0.00 | 0.00 | 0.95 | **-1.65** | **-0.70** |
| H10B | 0.00 | 1.00 | **-1.31** | 0.29 | **-0.02** |
| H10C | 0.08 | 1.77 | **-8.29** | **-1.49** | **-7.93** |
| H10F | 4.52 | 1.52 | **-2.39** | 2.41 | 6.06 |
| H10G | 2.04 | **-0.60** | 2.07 | **-1.48** | 2.02 |
| H10J | 9.46 | **-0.83** | 1.15 | 1.58 | 11.36 |
| H10L | 0.52 | 0.47 | 0.49 | **-3.38** | **-1.90** |
| H20B | 0.00 | 1.51 | 1.28 | **-0.67** | 2.12 |
| H20E | 4.25 | 0.67 | 0.40 | **-0.83** | 4.48 |
| H20F | 2.35 | 2.22 | 0.57 | **-6.95** | **-1.80** |
| H20G | 3.45 | 0.94 | 0.75 | **-2.49** | 2.65 |
| H40B | 1.08 | 10.02 | 4.85 | **-0.23** | 15.71 |

**Yield not function of recharge**

Under natural conditions and on a time-scale of centuries, aquifers evolve towards a state of dynamic equilibrium in which wet years, when recharge exceeds discharge, are offset by dry years, when discharge exceeds recharge. Development of and abstraction from groundwater wells upsets this natural equilibrium by inducing a loss from aquifer storage and an approach to a new state of dynamic equilibrium when there is no further loss or minimal loss from storage. The new equilibrium is accomplished either by an increase in recharge, a decrease in natural discharge, or a combination of the two (Sophocleus, 2002); in other words, by capture.

**Dynamic storage**

A dynamic storage model was developed, which provides annual base flow sequences for each of the different abstraction scenarios in the WRYM. The spreadsheet model is based on the understanding of the TMG Aquifer behaviour and considers the potential impact of temporal variation in rainfall and abstractions in the TMG Aquifer system having time lags of a number of years on this base flow. The fluctuation in hydraulic head was calibrated against the available data and detailed groundwater model results.

**Integration with WRYM**

The second outcome of the dynamic storage model is an annual sequence of base flow that is used in the WRYM to refine the initial estimates of the contribution to the yield from groundwater. Pumping groundwater into dams might maximize the yield but could result in unnecessary spillage during wet periods, if conveyed via the existing dam infrastructure. Different operating rules for maximizing the yield and minimizing the pumping from the groundwater were investigated. For the scenario of intermittent groundwater abstraction during dryer periods, the yield increase is about twice the average abstraction from groundwater.

**MODEL APPROACH**

Based on the lessons learned, the recommended approach to modelling follows discrete steps to allow for an increasing level of confidence during the process, while the scale of investigation is refined from regional / basin scale to local wellfield and borehole scale. The main elements of this approach are:

- Good conceptual models are tested numerically to design and detail monitoring networks;
- Simple box and/or other storage models are constructed as being most cost-effective for aquifer-specific reconnaissance level assessments;
- 3D aquifer-specific flow models are established for preliminary resource evaluation and assessment of the impact of abstraction on the surface water regime and existing lawful use;
- Transient (4D space-time) wellfield models to evaluate wellfield design and management scenarios for all commercial or urban use.

As summarised in the following sections of this report, an iterative approach is proposed, as the models are updated with new and more detailed data and information while the scale of investigation gets more detailed.

The greatest error in groundwater resource evaluation and prediction of impacts on surface water and the environment is in unwarranted reduction of a 4D problem to 1D or 2D. To quantify a process in 2D it is necessary to have a 3D conceptual model and insight into the long term temporal patterns. To quantify in 3D (numerical models) it is necessary to have a physically real and verifiable insight into the likely variations in volumes, area and, at least the range in, expected seasonal variations and other factors that could influence this. A rule of thumb is that one can predict future behaviour of a system for double the amount of years that one has data provided one clearly understands (even conceptually) the spatial detail and temporal pattern that is mapped by that data.

The recommended approach relies on three critical aspects, viz.

- data collection at appropriate spatial position and frequency intervals relevant to the decisions to be taken;
- team interaction between surface water and groundwater specialists that have the necessary skills and knowledge of the earth and water processes, and good communication between the disciplines; and
- timely implementation of relevant monitoring infrastructure and model upgrade.

The applicability and outcome of these models are summarised in **Table E-4** with reference to the objectives of this study, i.e. water resource evaluation and compulsory licensing.

**Table E-4 Applicability and outcome of the various models**

| | **Conceptual Model** | **Water Balance Model** | **Numerical flow model** | **Wellfield model** |
|---|---|---|---|---|
| **General (applicable to all themes)** | | | | |
| Design of 2D & numerical models | X | | | |
| Design of monitoring networks | X | | Refinement | |
| Evaluation & Assessment of data | X | | | |
| Evaluation & Assessment of Model Results | X | | | |
| **Water Resource Evaluation** | | | | |
| First order ‘planning’ numbers | | X | | |
| First order impact assessment, | | X | | |
| First Order loss/gain to rivers to update WRYM | | | X | |
| Operational yield assessment | | | X | X |
| Rapid Reserve determination | | X | X | |
| **Compulsory Licensing (requires Water Resource Evaluation)** | | | | |
| Intermediate or comprehensive Reserve determination | | | X | X |
| Aquifer yield estimate for license (not of borehole) | | | X | |
| Estimate of impact of surface water usage on groundwater in storage | | | X | |
| Estimate of impact of groundwater abstraction on surface water flow | | | X | |
| Wellfield / Borehole licensing | | | | X |
| **Conjunctive Scheme Development (requires Water Resource Evaluation and Licensing)** | | | | |
| Scheme Concept & Design | X | | X | X |
| Scenario testing for (conjunctive) scheme options | | | X | |
| Wellfield management | | | | X |

In order to facilitate the upgrade of models and further studies, the recommendations are grouped into activity groups and structured according to priorities and logical sequence of activities:

- Data Acquisition and Database Compilation
- Design and Implementation of Monitoring Network
- Ongoing Monitoring
- Data Analysis and Interpretation
- Modelling
- Review and Revision

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

# GROUNDWATER MODEL REPORT VOLUME 1
# OVERVIEW OF METHODOLOGY AND RESULTS

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# ABBREVIATIONS

| | |
|---|---|
| ASR | Aquifer storage and recovery |
| BRBS | Breede River Basin Study |
| CAGE | Citrusdal Artesian Groundwater Exploration |
| CEDARE | Centre for Environment and Development for Arab Region and Europe |
| CGS | Council for Geoscience |
| 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 |
| EAS | Elandsfontein Aquifer System |
| EC | electrical conductivity |
| ECA | Environmental Conservation Act |
| EFR | Ecological Flow Requirements |
| E-W | east west |
| EWR | Ecological water requirement |
| FD | Finite Difference |
| FE | Finite Element |
| GIS | Geographical Information System |
| GRA | Groundwater Resources Assessment |
| IFR | Instream Flow Requirements |
| ISP | Internal Strategic Perspective |
| IWR | Integrated Water Resources |
| IWRM | Integrated Water Resources Management/Model |
| km | kilometre |
| LAU | Lower Aquifer Unit |
| LRAS | Langebaan Road Aquifer System |
| m | metre |
| $m^3$ | metre cubed |
| Ma | Million years |
| 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 |
| | |
| op.cit. | Work previously cited |
| | |
| PhD | Doctor of Philosophy |
| PAJA | Promotion of Administrative Justice Act |
| | |
| RDM | Resource Directed Measures |
| RQO | Resource Quality Objectives |
| | |
| SAWS | South African Weather Service |
| SFRA | stream flow reduction activities |
| STCC | short-term characteristic curve |
| SVF | Saturated Volume Fluctuations |
| | |
| TDS | Total dissolved solids |
| TMG | Table Mountain Group |
| TMGA | Table Mountain Group Aquifer |
| TOR | Terms of Reference |
| | |
| UAU | Upper Aquifer Unit |
| UNESCO | United Nations Educational, Scientific and Cultural Organisation |
| | |
| VAS | Voëlvlei Augmentation Scheme |
| VHIMS | Vaal Hydrological Information Management System |
| | |
| WAA | Water Availability Assessment |
| WAAS | WAA Study |
| WARMS | Water-use Authorisation and Management System |
| WCSA | Western Cape System Analysis |
| 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 |
| WSAM | Water Situation Assessment Model |
| | |
| XLS | Excel Spreadsheet |
| | |
| 1D | one-dimensional |
| 2D | two-dimensional |
| 3D | three-dimensional |

# 1. INTRODUCTION

## 1.1 THE WAAS PROJECT

### 1.1.1 Project Background

This Water Availability Assessment in the Berg River Catchment is central to the Western Cape Water Supply System (WCWSS), whose 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 plus 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 (DWA) has 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 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. It will ensure that the necessary infrastructure or other interventions are implemented in good time to reconcile supply with the future demands. This Strategy will be updated regularly.

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

- 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 DWA elsewhere, if these become available in time;
- Support the Reconciliation Study with model-based assessment of water resource augmentation options.

Ninham Shand (Pty) Ltd is the Lead Consultant 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.

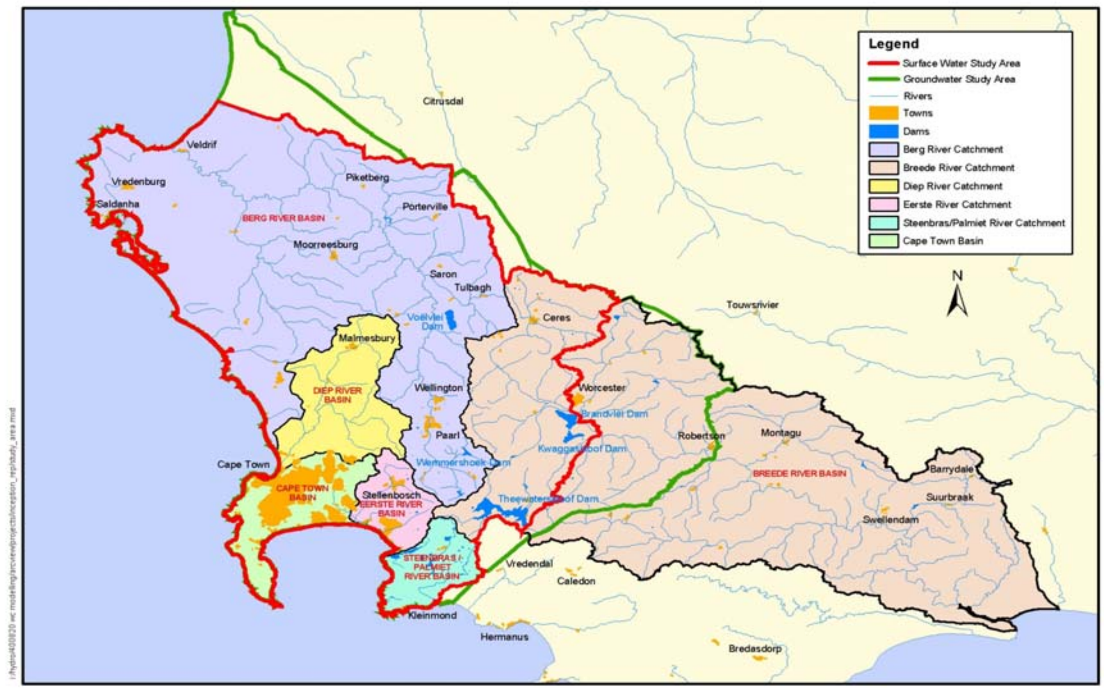


**Figure 1-1: Study Area Locality**

The Western Cape Water Supply System (WCWSS) is an integrated system of reservoirs, linked via a complex network of tunnels, pump stations and pipelines. It stores and reticulates the runoff from rivers for use in the greater Cape Town Metropolitan area. Inter-basin transfers of surface water 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 major fault zones (“hydrotects”) are the main structural elements forming natural components of the groundwater flow system. These elements therefore provide the conceptual basis of sound groundwater models in the TMG terrain of the Berg WMA.

### 1.1.3 Project Components

The Study is comprised of two phases: Phase 1 (Inception) and Phase 2 (Model configurations for assessment of current water availability and selected augmentation options). Phase 2 in turn consists of 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 million $m^3$/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 million $m^3$/a can be abstracted from the TMG depending upon the drawdown within the Breede River basin area of the WCWSS domain (City of Cape Town, 2004a).

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

Allocation of future surface water involves a two-dimensional (2D) analysis of the hydrology and current use. Similarly the impact of future groundwater use on current users, and therefore the sustainable utilisation of water in aquifer storage by both user groups, can only be assessed if the potential yield rather than the current yield is analysed with appropriate spatial and time series detail. This is a three-dimensional (3D) problem in the greater part of 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 demand;
- Impact of water abstraction at any point and time on the environment and other users;
- Scenario for optimal development of the aquifer and
- Scenario for best possible development and management of aquifer given the *status quo*.

The contrast between the latter two scenarios will indicate the extent to which *ad hoc* aquifer development and management impact on the resource from the perspectives of Source Directed Measures (SDMs) and Resource Quality Objectives (RQOs).

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 is 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 reconciling water supply and demand to best meet the Reserve and the RQOs in a given catchment (DWAF, 2003). Where limited data is available, it is good practice 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 can be integrated varies between catchments. Sound modelling outcomes depend not only on the impact of groundwater abstraction on base flow and on the ecology, but also on the temporal relationship/operating rules for groundwater storage and surface-water storage, and on the impacts of surface-water storage and reduced stream flows, both 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 models detailed in the task list below 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 Cape Town (in support of the Western Cape Reconciliation Study)
  - Scenario for flood management (in support of the Western Cape Reconciliation Study)
- Task 14: Review and update conceptual model for the 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 the Langebaan Road Aquifer
  - Refinement of surface water – groundwater interaction
  - Refinement of recharge and yield estimation
  - Scenario for artificial recharge schemes (in support of the Western Cape Reconciliation Study)
- Task 15: Water balance and storage model for the TMG Aquifer
  - Recharge estimation and water balance on regional scale
- Task 15a: Configuration of a numerical TMG groundwater model for Worcester

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

These volumes are:

Volume 1: Overview of Methodology and Results

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer Model

Volume 6: Langebaan Road and Elandsfonteyn Aquifer System Model

Volume 7: Table Mountain Group Aquifers – Witzenberg - Nuy Model

Volume 8: Table Mountain Group Aquifer – Piketberg Model

Volume 9: Breede River Alluvium Aquifer Model

### 1.1.5 External Review Process

The DWA appointed an external reviewer, Dr. Ingrid Dennis, in parallel to this study to ensure that the modelling approach and results are of acceptable standard. The comments received from the external reviewer and DWA officials from different directorates throughout the study were incorporated into the final reports of Volume 2 to 9 and utilised in this Summary Report.

A summary of the review comments and the team's replies is given in Appendix C.

## 1.2 SUMMARY REPORT

### 1.2.1 Purpose of this Report

A number of new approaches were developed in this study that have relevance to other areas in which a holistic approach to water resource evaluation and planning is or will soon be underway.

The Western Cape hydrology and hydrogeology presents some particularly unique features that required especial consideration by both the surface water and the groundwater fraternity. Both are dominated by the TMG topography and the controls that this topography exerts on the climatic patterns. The surface flow patterns, and the vegetation (Cape Floral Kingdom) are controlled by the lithology, the aspect and slope of the mountains, and at different scales, the structural fabric of the rock. All perennial rivers in the area depend on year-round springs originating primarily from the shallow unconfined and deep confined Peninsula Aquifer of the TMG. Some of these rivers drain from the mountains through relatively narrow synclinal valleys before emerging onto a flat coastal plain that is wider along the West Coast than along the south-east coast, where the TMG is either close to the surface or outcrops at the coast. Along the West Coast, both the TMG and the older shales and greywackes of the Malmesbury Group (basement) underlie the Quaternary and Tertiary sands that dominate the coastal plain. These geological differences along with the history of sea-level changes and the related sedimentary processes and products determine the drainage and recharge patterns along the coast and are a determining factor in water quality.

Combined, this geological and climatic setting, a distinctly seasonal water demand, a high agricultural demand for water, and environmental considerations related to natural biodiversity, make for a unique natural laboratory. It therefore is critical to map, quantify and understand the spatial and temporal patterns of the full hydrological cycle in order to reasonably evaluate available surface water or groundwater supplies.

The purpose of this report is to present a non-technical overview of the approach adopted for this study, the lessons learned and preliminary guidelines and recommendations for upgrading the current modelling approach and data input.

### 1.2.2 Structure of this Report

The report is structured into six (6) main sections with a number of sub-sections each.

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

Section 2 summarises the reasons for the proposed scope of work, the principles of the modelling approach and methodology used in this study, and why and how it differs from previous approaches. It summarises the key data sets available and motivates the input parameters chosen for the various models that were configured in this study.

Section 3 presents the key results of the modelling study. It uses examples from particular models to illustrate or motivate the conceptual model, summarises the relevant model input and output for different aquifers as per the terms of reference; viz. recharge and yield estimates, revised mass balance, quantification of surface and groundwater interaction and selected Aquifer Storage and Supply Scenarios.

Section 4 describes the proposed methodology for applying groundwater modelling for water resource evaluation and groundwater development and management.

Section 5 details and motivates in non technical terms the most important recommendations arising from this study that are considered imperative to make progress to improved surface and aquifer specific water resource evaluation and the quantification thereof;

Section 6 lists all references used in preparation of this document

The executive summaries of Volumes 2 – 9 are included in Appendix A1 to A8 at the end of the document. A glossary of terms used is provided in Appendix B.

A summary of the comments from the external reviewer and the team's reply to these comments is presented in Appendix C.

A suggested Scope of Work that would implement the recommendations made throughout this study and summarised in this report are presented in Appendix D.

# 2. SCOPE OF PROJECT WORK

## 2.1 OVERVIEW

The overarching purpose of the Berg Water Availability Assessment Study (WAAS) from the groundwater perspective is to develop and configure the necessary aquifer - specific numerical (3D) and GIS - based (2D) groundwater models, in order to contribute meaningfully to:

- Reconfigure the existing Water Resources Yield Model (WRYM) at a spatial resolution suitable for quantification of allocable water to support compulsory licensing;
- Use, where applicable, the reconfigured existing models or newly configured models for quantification of allocable water for both surface water and groundwater;
- Incorporate changes in concepts, models and approaches, as derived from pilot studies initiated by DWA elsewhere, if these become available in time;
- Support the Reconciliation Strategy Study with model-based assessment of water resource augmentation options, including the potential of Aquifer Storage Recovery (ASR) to increase yield in selected coastal aquifers and identify critical issues that could inhibit the use of the TMG as a medium to long - term augmentation option integrated into the WCWSS;
- Identify and advise DWA in which catchments it is necessary to consider compulsory licensing.

The study area for the groundwater component of the above key deliverables differed from that of the surface water team because of the aerial distribution and extent of the TMG. This difference is important because groundwater can be recharged in one catchment or basin and discharged in another, following deep flow paths that transect surface-water divides. Further, the regional direction of groundwater flow is not determined by topography, but by the orientation of large-scale planar features (“mega-faults”) and associated microfracture systems that are open at the surface and to significant depths within the two main aquifers. The TMG aquifers, Peninsula and Skurweberg, can be visualised as containing a complexity of interconnected planar features, variably orientated in space therefore intersecting at various depths within each aquifer, and variably transecting or striking parallel to the surface water drainage systems. Flow is therefore complex but predictable once the anisotropic structural fabric, and the patterns it imposes at different scales on the rock mass, is understood.

To meet one of the core requirements of the study, viz., to understand, map and quantify surface and groundwater interaction and, so far as possible, integrate groundwater into the Pitman and the WRYM models, the groundwater study boundaries were defined by areas called Integrated Water Resource Management Domains (IWRM Domain) (see Section 3.1)

## 2.2 DELIVERABLES

### 2.2.1 List of deliverables

The key deliverables, as defined in the Inception Report (DWA, 2005) and how they relate to the definition of tasks, are summarised in **Table 2-1** below.

**Table 2-1 Key Deliverables and Report Volumes**

| Task | Key Deliverable | Vol. | Title |
|---|---|---|---|
| | **Layman's summary of Methodology, Lessons Learned and Recommendations** | **1** | **Overview of Methodology and Results** |
| **7** | **GIS database for groundwater component**<br>**Digitise Geological Maps** | **2** | **Data Availability and Evaluation** |
| **12** | **Regional model development** | | |
| | Conceptual model for study domain | **3** | **Regional Conceptual Model** |
| | GIS based water balance model for study domain | **4** | **Regional Water Balance Model** |
| **13** | **Configuration of a numerical model for Cape Flats Aquifer** | **5** | **Cape Flats Aquifer Model** |
| | Quantification of surface water – groundwater interaction | 5 | |
| | Calibration of recharge estimation and water balance | 5 | |
| | Scenario for augmentation to bulk water supply to Cape Town (as support of Western Cape Reconciliation Study) | 5 | |
| | Scenario for flood management (as support of Western Cape Reconciliation Study) | 5 | |
| **14** | **Review and update conceptual model for West Coast Aquifers and Configure a numerical groundwater model for Langebaan Road Aquifer** | **6** | **Langebaan Road Aquifer and Elandsfontein Aquifer Model** |
| | Review and revise recharge and yield estimation as well as water balance | 6 | |
| | Refine understanding and Quantify surface water – groundwater interaction | 6 | |
| | Scenario for artificial recharge schemes (support to Western Cape Reconciliation Study) | 6 | |
| **15** | **Water balance and storage model for TMG Aquifer(s)** | **4** | **Regional Water Balance Model** |
| | Configuration of a numerical TMG groundwater model for Worcester | **9** | **Breede River Alluvium Model** |
| | Configuration of a numerical TMG groundwater model for Hex River Mountains | **8** | **Table Mountain Group Aquifers – Witzenberg - Nuy area** |
| | Configuration of a numerical TMG groundwater model for Tulbagh - Ceres | 8 | |
| | Configuration of a numerical TMG groundwater model for Piketberg | **7** | **Table Mountain Group Aquifers – Piketberg area** |
| | Refinement of recharge and yield estimation as well as water balance on regional scale | 7 & 8 | |
| | Quantification of surface water groundwater interaction | 9 | |

### 2.2.2 Iterative Approach to Deliverables

Physical insight into the aquifer geometry and preferred pathways between surface and groundwater regimes is necessary in order to have confidence in extrapolating data and assessing the degree of realism of model results. With this in hand, it is not necessary to rely only on published/available data or to use the data without appropriate critical evaluation of the design of the monitoring network and the protocols used for that data collection/validation. In earth and hydrological science it is necessary to understand (or have a hypothesis to test regarding) the spatial and temporal scales of the processes one wishes to measure before designing and implementing a monitoring network or protocol. It is important to know what is actually being measured where and at what time, and how to interpret the data. Thus Volumes 2 (Data Availability and Evaluation) and Volume 3 (Regional Conceptual Model) of this series were prepared in iterative and parallel fashion.

On completion of these reports the model domains and approach to both the coastal and fractured rock TMG aquifers were revised (see

**Figure** 2-1). It was agreed in a series of discussions between the client (DWA Head Office and Regional Office), the surface water and the groundwater team, documented in the relevant project meeting minutes and correspondence, that:

- Fully 3D numerical models would be developed for the coastal aquifers (Volume 5: Cape Flats Aquifer Model; Volume 6 Langebaan Road and Elandsfontein Aquifer System Model) using Finite Element (FE) software (FeFlow; Version 5.3)
- 2D and quasi 3D (in-house Storage Model) GIS-based models would be developed for the TMG aquifers (Volume 7: TMG Aquifer – Piketberg Model and Volume 8 – TMG Aquifer, Witzenberg-Nuy Model) using the same approach taken to develop an aquifer specific regional mass balance (Volume 4: Regional Water Balance Model) presenting results at a quaternary scale, but the geological and hydrogeological mapping and storage modelling would be done at a finer scale, thus increasing confidence in the output.
- ModFlow, a Finite Difference (FD) quasi-3D software would be used to model various scenarios to better understand the spatial and temporal patterns of surface and TMG groundwater interaction in the middle to upper Breede basin where there is limited hydrological data with which to calibrate surface water models (Volume 9: Breede River Alluvium Aquifer Model).

Hitherto efforts to more easily integrate and contrast groundwater with surface water information have focussed on developing spatially averaged numerical information that is added or patched at quaternary scale into composite aquifer units. In general, this approach reduces a fully 3 D problem to 1D with a significant loss of physical meaningfulness in the resultant data. It does not facilitate the identification of groundwater schemes or opportunities to manage surface and groundwater storage differently and thereby increase the actual yield of both dams and aquifers.

For these reasons the groundwater component of deliverables in the present study was designed to:

1. Build, step by step, a rigorous physical understanding and basis for groundwater modelling using first principles of earth and hydrogeological science;
2. Test and so far as possible establish initial approaches for 2D and 3D modelling to deliver aquifer specific water resource planning information where the scale and detail of the information was relevant and appropriate to the decisions to be taken (e.g. suitable for reconnaissance, pre-feasibility, feasibility studies at an IWRM / aquifer scale or to design, licence and develop management protocols for well fields).

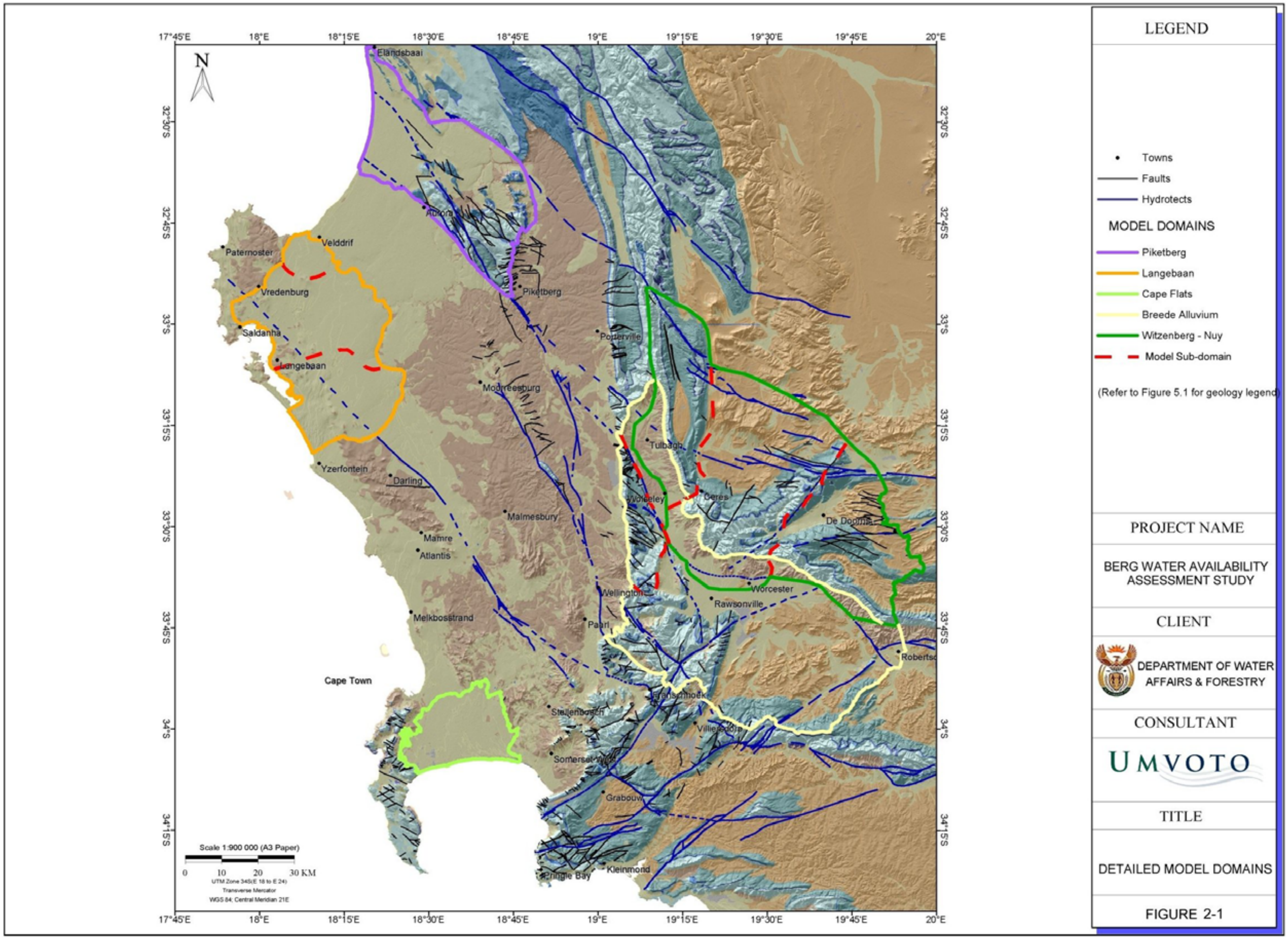


**Figure 2-1** **Detailed Model Domains**

## 2.3 MODELLING PROCESS

### 2.3.1 General Model methodology

A structured and systematic approach was taken to support three purposes of this study:

A. Water Resource Quantification, to evaluate how much groundwater is available in the Berg WMA, while documenting the methodology, uncertainties, shortcomings and or confidence in the results, as well as possibly identifying potential groundwater supply schemes;

B. Compulsory Licensing, to ensure that the results support the roll out of compulsory licensing in those catchments under stress through over allocation or over abstraction;

C. Options Identification, to enable conjunctive use through improved insight and quantitative understanding of surface and groundwater interaction patterns, rates, volumes, seasonal variations, impact of surface and groundwater usage on each other and potential for enhanced yield of both through optimal use of natural storage (aquifers) and dams.

The methodology is informed by the requirements of the study, the available data, the particular characteristics of the Western Cape environment and the need to make progress in developing an approach to aquifer-specific groundwater resource evaluation optimising the available data rather than being limited by it.

The focus of this section is on a modelling approach to meet the first two purposes of this study. There are distinct elements in that approach, which pertain to the steps taken to translate the understanding of the real world into a reliable computer-based version of it, called the model world. In this model world one can explore different scenarios, test the impact of aquifer parameters that diverge from the original estimates, and test the impact of different courses of action. A range of various models can be established that represent a variety of conceptual, monitoring or exploration/development hypotheses, in order to test the insight and understanding of the physical processes. One can furthermore test the uncertainties in the interpretation of 2D information (geological and hydrogeological) within a fully 3 D model, which improves confidence in the final, selected model that has implicitly been calibrated against different (geological, physical- and chemical - hydrogeological) data sets and observed natural patterns.

The coupling of all processes in the hydrologic cycle (see **Figure 2-2**) becomes essential to achieve an understanding of the water resource required for quantification of the water availability and to determine likely impacts of use.

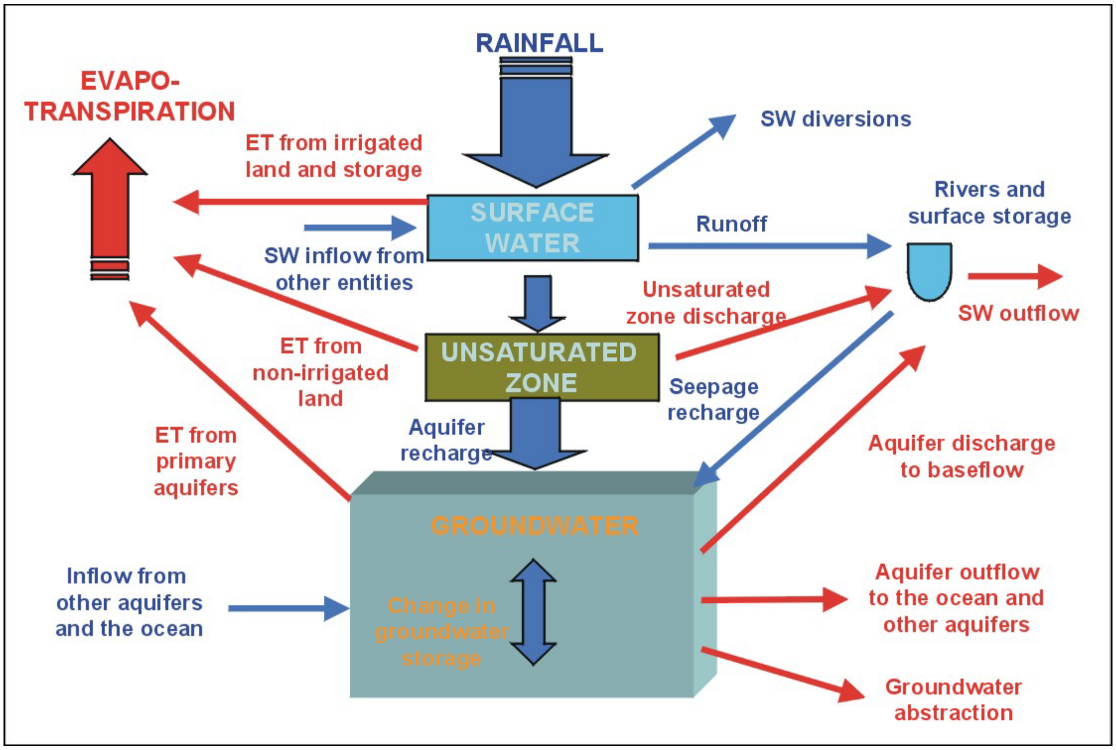


**Figure 2-2 Hydrological processes, interactions and fluxes, relevant for model approach**

Based on the hydrogeological analysis of the study area and the three purposes of the study as outlined above, the following models are considered necessary to address the issues and questions above, relevant to water availability and compulsory licensing. They can be grouped into the following categories:

- Basin-scale conceptual groundwater model to identify aquifer-specific flow paths, geometry, recharge/ discharge, surface water / groundwater interaction zones
- Aquifer-specific regional water balance model for aquifer-specific estimation of recharge, discharge, storage, groundwater use and potential yield
- Primary (coastal and alluvial) aquifer models to refine the water balance, quantify surface water / groundwater interaction and assess impact of abstraction
- TMG fractured-rock aquifer models to refine the water balance and quantify surface water / groundwater interaction
- Surface water yield model with upgraded groundwater input to assess the surface water / groundwater interaction.

The models are required at different scales and dimensions. To ensure consistency and common data between these models a clear model hierarchy and structure is used, whereby the regional model feeds relevant data into an intermediate scale model or the local models.

The different steps in a groundwater flow model are discussed in some detail below, in order to facilitate a summary approach to presenting model input and results in Section 3.

### 2.3.2 Modelling process

Initially simple box models that are of the correct aquifer proportions (but not necessarily shape or internal complexity) are configured and we proceed, step by step, to make the model more complex as we test the impact of each assumption on model results. This is an important process in understanding model behaviour during calibration and securing confidence in model output. It is essential to state what the model assumptions are so that, in due course, as additional real world data becomes available, it is possible to upgrade and improve the model and if needs be re-calibrate using different boundary conditions. It is good modelling practice to test different boundary conditions to ensure that they do not prescribe model results.

For example, if one defines a fixed head along a boundary it actually means that there is a constant source of water entering the model here, and the rate at which it enters the model is a function of how the head conditions within the model vary in relation to it. If this condition is not true to the real world, the model results may be very good - even calibrate - but they will be defined by the boundary condition and not reflect the real world. It is preferable to use simpler boundary conditions that do not impact model results, especially if there is limited data and it is necessary to make many model assumptions, rather than more complex conditions that are perhaps a better representation of real-world physical processes. This makes it easier to test the impact of different model assumptions and concepts on model results.

Different conceptual models or views on what the essential elements needed to reproduce the real world in a model are, can be tested by generating increasingly fine and more complex meshes, internal and external boundary conditions, until the basic processes that are observed in the real world are reproduced at a spatial and temporal scale that is appropriate to the decision to be made. This can often depend on the decision that will be taken based on model results.

For example, a simple box model can be configured to test whether or not a layered aquifer can be represented as a single layer with a vertically averaged K, in order to represent the movement of a contaminant in one or more layers of higher than average conductivity. A single-layer model may be adequate for a simple, robust steady-state mass-balance model and to motivate for the design of an aquifer protection protocol, but not good enough to assist in the design and evaluation of specific impacts of contamination on a well field (e.g. to answer the questions; where does the contaminant go? and how fast?). In deciding whether or not this is an acceptable simplification of the real world, the cost-benefit advantage of a more complex (time-consuming) model must be sufficiently different between the two models to warrant the extra effort with regard to available data on the individual layers, geological complexity (lateral and vertical) and the required detail of the model results. Physically realistic does not necessarily signify physically exact.

Limited data is not necessarily an inhibition to modelling. The quality, distribution and temporal relevance of the data are more important. Whether model input parameters are appropriate can be relatively easily resolved through scenario testing and reference to internationally accepted ranges in these values. As field data of improved quality becomes available the calibration can be improved and the model itself becomes more complex. Where data is not available reasonable inferences based on known geological characteristics and empirical observation constrain the range and value of hydraulic parameters input to the model. These inferences must be documented as model assumptions as they also inform the mesh and boundary conditions and the impact can be assessed. This is the modelling approach adopted in this study and why a sound physical basis for all decisions is considered important to avoid a blackbox approach to modelling; in short good data does not itself secure a good model. Field knowledge, geological and hydrogeological insight, thought and understanding do.

The storage model (see Volume 4) and numerical model configuration (Volume 5 & 6) requires insight into structural, marine and sedimentary geology processes and products in order to construct plausible 3D scenarios as to the most likely aquifer geometry and character. These are cross-referenced against available earth science and hydrogeological field information and refined. If a single scenario does not emerge as the preferred scenario a number of different models would be configured to establish the sensitivity of the model result to the conceptual model. The storage model is based on actual data documented in geological maps and informed 3D interpretation thereof. Assumptions are made as to regional dip of aquifer lithology at depth based on accepted structural geology principles and mechanics of brittle failure. The details of this modelling are contained in Volume 4 Section 4.

There is often emphasis on having to use available or published point source data to avoid the unhappy situation of "garbage in, garbage out" when modelling. Less emphasis is placed on testing the conceptual model although this can have a greater negative impact on model results than using an inferred input parameter that is plausible, but unpublished. All data made available, whether published in peer-review journals, theses, consultant reports or other grey literature was evaluated on its own merits in the context of the conceptual model, which may or may not have been similar to those used by the various authors who designed the data collection process. Data that was not made available before December 2007 is not used in this study. This decision was taken at study management level after repeated requests to various parties had not yielded results and was delaying initiation of numerical and GIS modelling.

Selected numerical model scenarios adequately account for a range of values in model input parameters. Parameter testing in the model process indicates model sensitivity to possible errors in input parameters and is addressed when confidence in model results is discussed in the reports. This highlights the critical importance of the conceptual model and the use of the best available expertise, experience and knowledge of the theory and field conditions as well as insight into the relationship between geology, hydrogeology and hydrological processes and product.

## 2.4 AQUIFER-SPECIFIC CONCEPTUAL MODEL

The three critical steps in building a conceptual model (Anderson and Woesner, 1992) are:

- Defining the hydrostratigraphic units;
- Defining a flow system
- Preparing a water balance.

### 2.4.1 Defining the hydrostratigraphic units

Definition of the hydrostratigraphic units (see **Table 2-2**) is the first step, based on the lithological characteristics and hydraulic properties of different units, and their 3D spatial relationship to each other (cf. Volume 3, Section 3.4 and Table 3-4). There is however an iterative nature to the second and third steps, because it is not possible to prepare a water balance without defining a flow system and it is not possible to define a flow system without understanding the process relationship between the different hydrostratigraphic units, the hydroclimatology, empirical field evidence of groundwater movement and the surface-water flow systems.

Ensuring that any identified recharge zone can be connected physically via a defined flow path to an identified discharge zone is most important in any calculations of an aquifer-specific mass balance and or catchment mass balance. There is simply an inherent flaw in any mass balance for surface-water and groundwater that is not undertaken on a physical scale appropriate to this process. The first step in realizing physically real mass-balance numbers is to define the recharge areas based on aquifer outcrop areas underlying rainfall isohyets. The second step is to iteratively correlate the known discharge sites (considering volume, water quality, isotopic character and temperature) with likely flow paths defined by 3D structural geology and hydrostratigraphic relationships. Cross checks as regards temperature, chemistry and isotopic character of discharge water allow qualitative evaluation of the conceptual flow model.

Without an overt and explicit conceptual model of the real world it is not possible to evaluate model results or to design a monitoring network, the output of which can be used to test this understanding. The mesh design and boundary conditions are the model elements that numerically define our understanding of the most important elements of the real world. The mesh is defined by the element size(s) and the geometric organization of one layer of elements with respect to the other. The boundary conditions represent our key model assumptions about actual physical processes that we wish to reproduce using the model. Oversimplification or failing to represent the relevant scale of process in a model will result in physically incorrect patterns in the model result. Failure to appreciate the scale of the process that a calibration data set represents will result in incorrect model results or a model that will not calibrate. These factors combine to represent our understanding of the aquifer geometry and process complexity and they constrain the model results accordingly.

The different conceptual models for the fractured - rock aquifers of the Table Mountain Group (TMG) and the coastal primary aquifers are summarised below. The approach to determine the input parameters in the mass balance equation for these aquifers is considered an element of the conceptual model. Working from first principles requires an individual or team of individuals who are able to work at fairly specialist level in remote sensing, structural geology, physical hydrogeology, hydrochemistry, isotope hydrogeology and both flow and GIS modelling, each having reasonable insight into the different aspects through a background in basic geology, hydrogeology and hydrology.

**Table 2-2 Hydrostratigraphy of the Study Area**

| Superunits | Units | Subunits |
|---|---|---|
| | | |
| | Bredasdorp Aquifer | Various discrete alluvial aquifers |
| | | Langebaan/Springfontyn Subaquifers |
| | | Local (unnamed) aquitards(s) |
| | Sandveld Aquifer | Varswater Subaquifer |
| | | Local (unnamed) aquitards(s) |
| | | Elandsfontyn Subaquifer |
| | *Mainly underlain by aquicludes of Malmesbury Group and or Cape Granite Suite in western part of Berg WMA; alluvial Sandveld is locally underlain by TMG and higher units in eastern part* | |
| | | |
| | 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 ?<br>(not yet separately mapped throughout Berg WMA) |
| | | Leeukop Subaquifer ?<br>(not yet separately mapped throughout Berg WMA) |
| | | Graafwater Meso-aquitard |
| | | Piekenierskloof Subaquifer (localized) |
| | Aquicludes | [Klipheuwel Group]<br>[Cape Granite Suite]<br>[Malmesbury Group] |

### 2.4.2 Conceptual Model for the Table Mountain Group Aquifers

Because of the strategic importance and the escalating demand, development and use of the significant volumes of groundwater stored in the TMG, much effort was spent on resolving the preferred flow paths in the Skurweberg Aquifer and the Peninsula Aquifer. It is not readily appreciated that the groundwater in these extensive and very thick fractured rock aquifers, primarily flows in the highly fractured zones bordering wide regional-scale, often annealed fault zones that can extend for hundreds of kilometres (see **Figure 2-3**). These tectonic features transect fourth-, third- and second-order catchments, Water Management Areas (WMAs) and in some cases discharge groundwater at or beyond the coastline. In a few areas of the West Coast, the TMG underlies the Bredasdorp and Sandveld sediments (see **Table 2-2**) that include the coastal primary aquifers, such as the area around the Piketberg.

At a regional scale, groundwater in a fractured rock does not necessarily flow perpendicular to topographic gradient or in strictly parallel lines. Flow lines may converge or diverge in zones of structural complexity and hydraulic heterogeneity, and will tend to follow the strike of distinct structural lineaments, but can be spatially averaged to approximate a traditional flow net. These structural features are preferred flow paths (see **Figure 2-4**) and, within deep confined artesian basins, they can provide natural mechanisms for interbasin or intercatchment transfer, which can complicate the calibration of both surface and groundwater models, especially at quaternary scale and in those catchments with perennial streams fed by springs emerging from the confined Peninsula Aquifer.

At a scale smaller than the large megafault zones, vertical and subvertical flow within the aquifer can occur along bedding planes, depending on the dip of the strata on the valley walls, and within joint sets orientated perpendicular to bedding. Depending upon the topography and lithological contacts, groundwater flow may be directed along or across the bedding strike (see **Figure 2-4**).

In general the aquitards maintain their hydraulic integrity and effectively separate the main aquifer units. In selected and readily identified areas, however, the Skurweberg may be downfaulted against the underlying Peninsula, and the two aquifers may therefore be hydraulically connected through a network of faulting and fracturing. In the synclinal valleys the aquifer strata dip inwards to the valley axis at angles varying from sub vertical to only a few degrees. These bedding planes, together with associated joint and fracture systems, create shorter - length flow paths for rainfall to infiltrate and reach the larger scale transecting fault zones that create the large preferred flow paths and have a different orientation and scale.

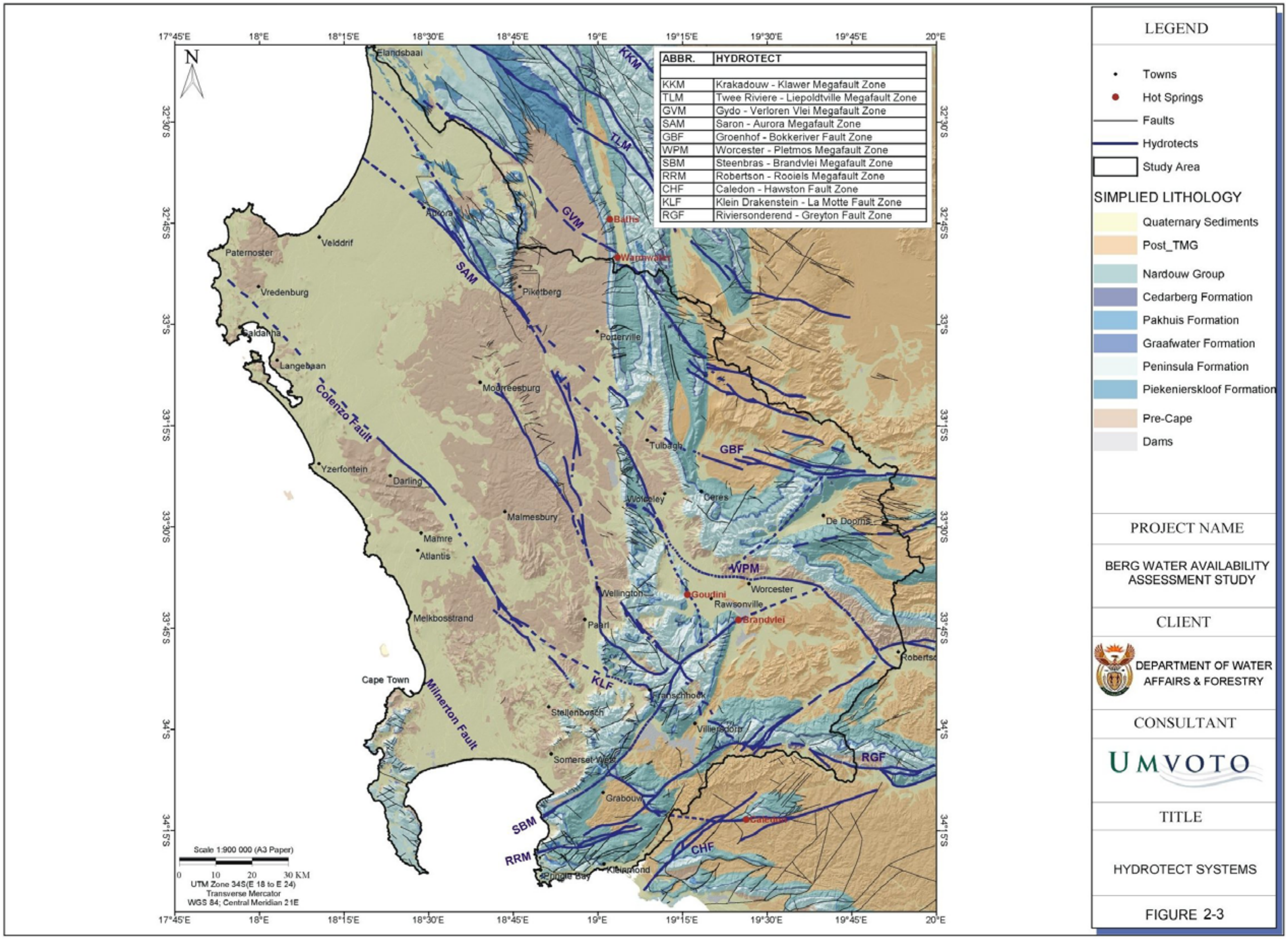


**Figure 2-3 Hydrotect Systems transecting the study area**

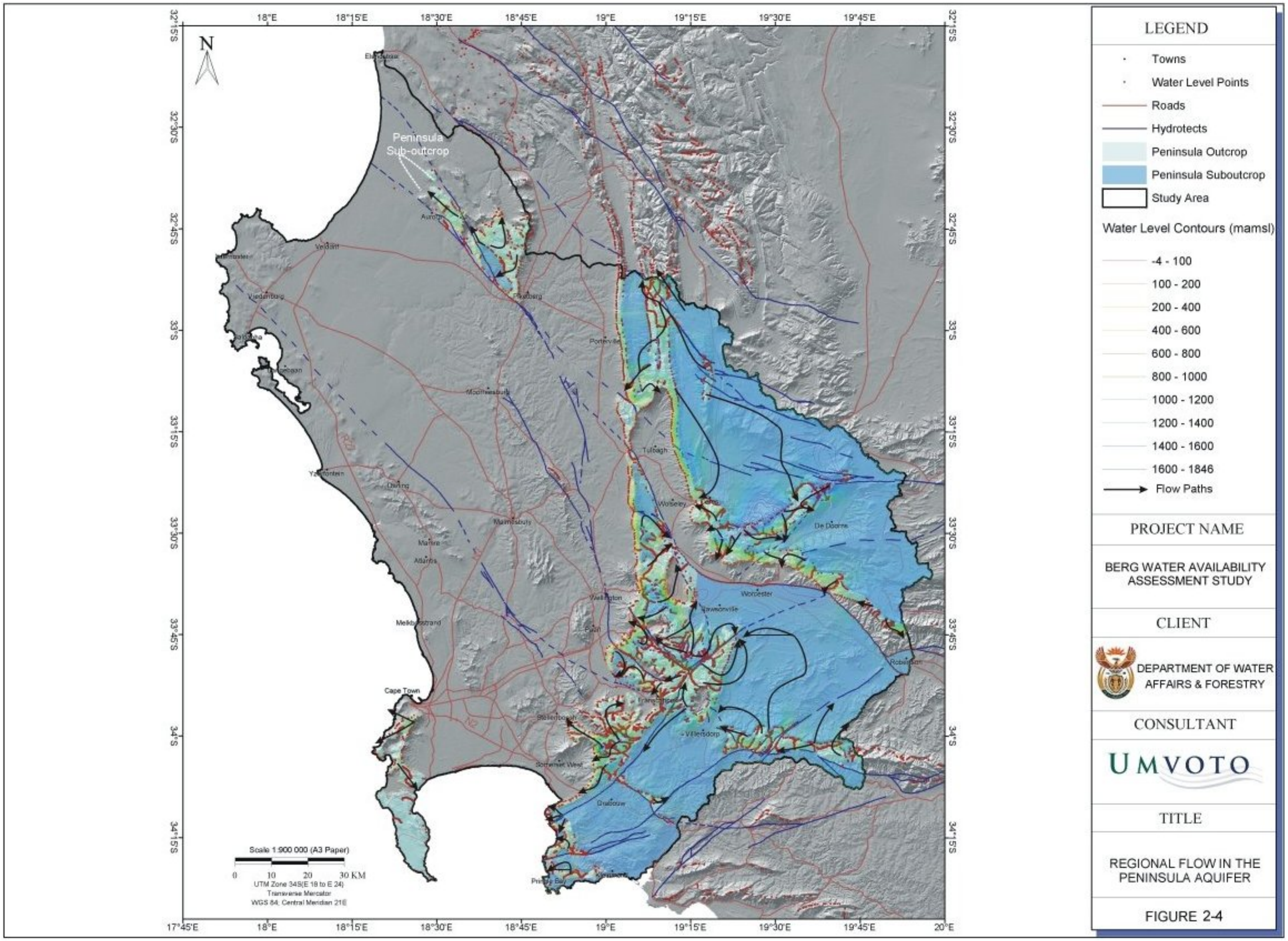


**Figure 2-4 Regional Flow for Peninsula Aquifer**

### 2.4.3 Conceptual Model for the coastal primary aquifers

The outline of the conceptual model for the smaller - scale model domains is given in Volume 3 of this report (DWAF, 2007b). This broad conceptual model was developed through an analysis of marine, fluvial and aeolian processes operating at various times in the geological history of the coastal regions, along with changes in the water cycle and vegetation associated with past climate change and sea-level variation (see **Figure 2-5**), that have resulted in particular sedimentary products or erosion patterns common to the Cape Flats and West Coast areas.

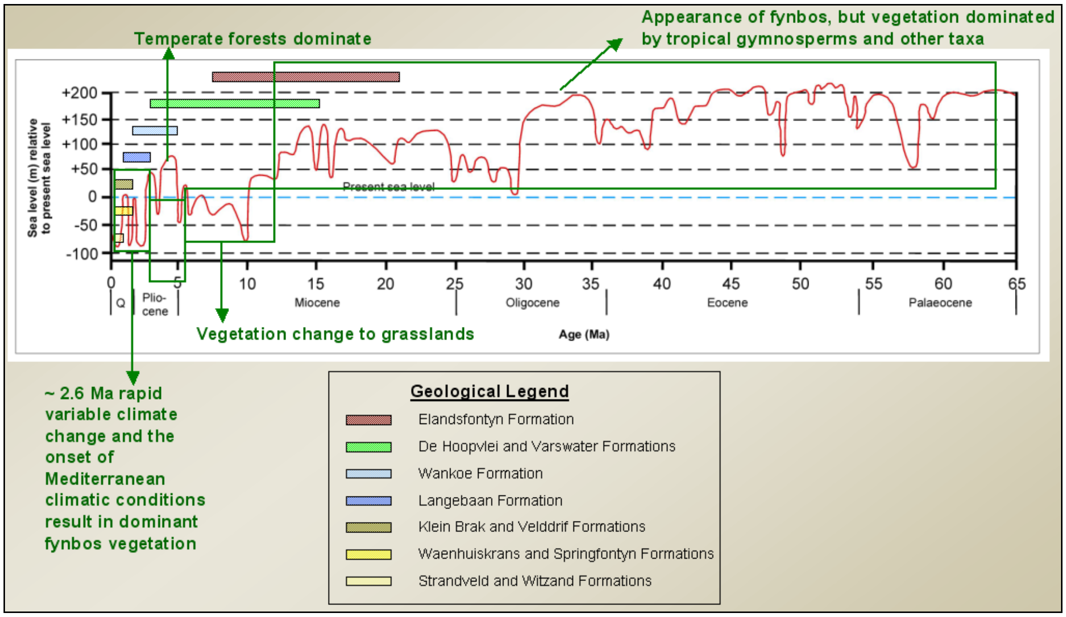


**Figure 2-5 Climate and sea-level variation along the West Coast**

The main geohistorical features are generally warmer climate; sea levels higher than present and tropical vegetation prior to ~12 Ma, associated with older strata of the Sandveld aquifers (see **Table 2-2**). After 12 Ma in the Late Miocene period, growth of the Antarctic ice sheet was associated with a fall in sea-level, and incision of the Sandveld (early Miocene; 25-12 Ma) drainage systems across the coastal plain and continental shelf. A warmer period in the early Pliocene period (after ~5 Ma) saw a recovery of high sea - level stands and the flooding and burial of older fluviatile deposits by upper Sandveld marine and estuarine strata, associated with temperate - forest vegetation (see **Figure 2-5**).

Climatic deterioration and general aridification associated with the Pleistocene growth of the southern and northern ice-caps after ~2.5 Ma resulted in the evolution of the fynbos vegetation and the invasion of the coastal plain by large-scale windblown (aeolian) sands that constitute the younger, Bredasdorp aquifer system. The deposition of these units was controlled by the dominant trade-wind directions and, because parabolic dune systems migrate upslope from the shoreline, occurred across the pre-existing Sandveld topography and drainage trends, which were buried by these younger sedimentary units.

Groundwater flow in the older, confined Sandveld aquifer units occurs from an inland direction, centred around regional, fluviatile palaeo-channels, routed towards the coast in typical drainage patterns where they enter the sea, generally at high angles to the coastline (see **Figure 2-6**). Inland, recharge occurs primarily as infiltration from rainfall through thin overlying Bredasdorp sands or, at certain favourable locations, as flood recharge from transecting rivers. Only in the case of the Piketberg area is there interaction with another groundwater source from the underlying Peninsula Aquifer. Shallow groundwater flow in the superficial, unconfined Bredasdorp aquifers is controlled by water - table gradients that follow in subdued form the local topography of the active or fossilized dune systems.

### 2.4.4 Mass Balance input parameters

**Recharge**

Unlike the preferred flow paths, lithological changes, small-scale structural and sedimentary features as well as the fold structures of the Table Mountain Group control the recharge rate in the TMG terrain. Recharge is usually considered an important element in hydrogeological modelling because, within the hydrological and hydrogeological communities, there is commonly adherence to the concept that that sustainable pumping should not exceed the recharge rate in a given aquifer, which belief has been called the “Water Budget Myth” (Bredehoeft et al. 1982; Bredehoeft, 2002; Devlin and Sophocleus, 2005). Despite the early presentation of conclusive theoretical proof and supporting discussions (e.g., Theis, 1940) to show that the concept is erroneous, the idea has been particularly persistent - even enshrined in legislation in some jurisdictions - that, if one can estimate the recharge to a groundwater system, one can determine the size of a sustainable development therein.

However, the sustainable abstraction rate of a groundwater development usually depends on when and how much of the discharge from the system is "captured" by the development (Bredehoeft, 2002; Bredehoeft and Durbin, 2009): ‘‘Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in the ground-water discharge into streams, lakes, and the ocean, or from that component of evapotranspiration derived from the saturated zone’’ (Lohman, 1972). Capture is independent of the virgin rate of recharge and depends on the dynamic response of an aquifer system to development. The study of the response dynamics of groundwater systems is one of the principal reasons for the creation of hydrogeological models (Bredehoeft, 2002).

Under natural conditions and on a time-scale of centuries, aquifers evolve towards a state of dynamic equilibrium in which wet years, when recharge exceeds discharge, are offset by dry years, when discharge exceeds recharge. Development of and abstraction from groundwater wells upsets this natural equilibrium by inducing a loss from aquifer storage and an approach to a new state of dynamic equilibrium when there is no further loss or minimal loss from storage. The new equilibrium is accomplished either by an increase in recharge, a decrease in natural discharge, or a combination of the two (Sophocleus, 2002); in other words, by capture.

A new wellfield developed at some distance from a recharge source forms a funnel-shaped drawdown in the water-table (or potentiometric surface), which deepens and expands as groundwater is taken from storage. When the periphery of the drawdown funnel arrives at the recharge zone(s) of surface-groundwater interaction, surface water starts to flow into the aquifer. With continued pumping from the wellfield, the drawdown perimeter continues to expand until a new equilibrium is reached, in which induced recharge balances the pumping.

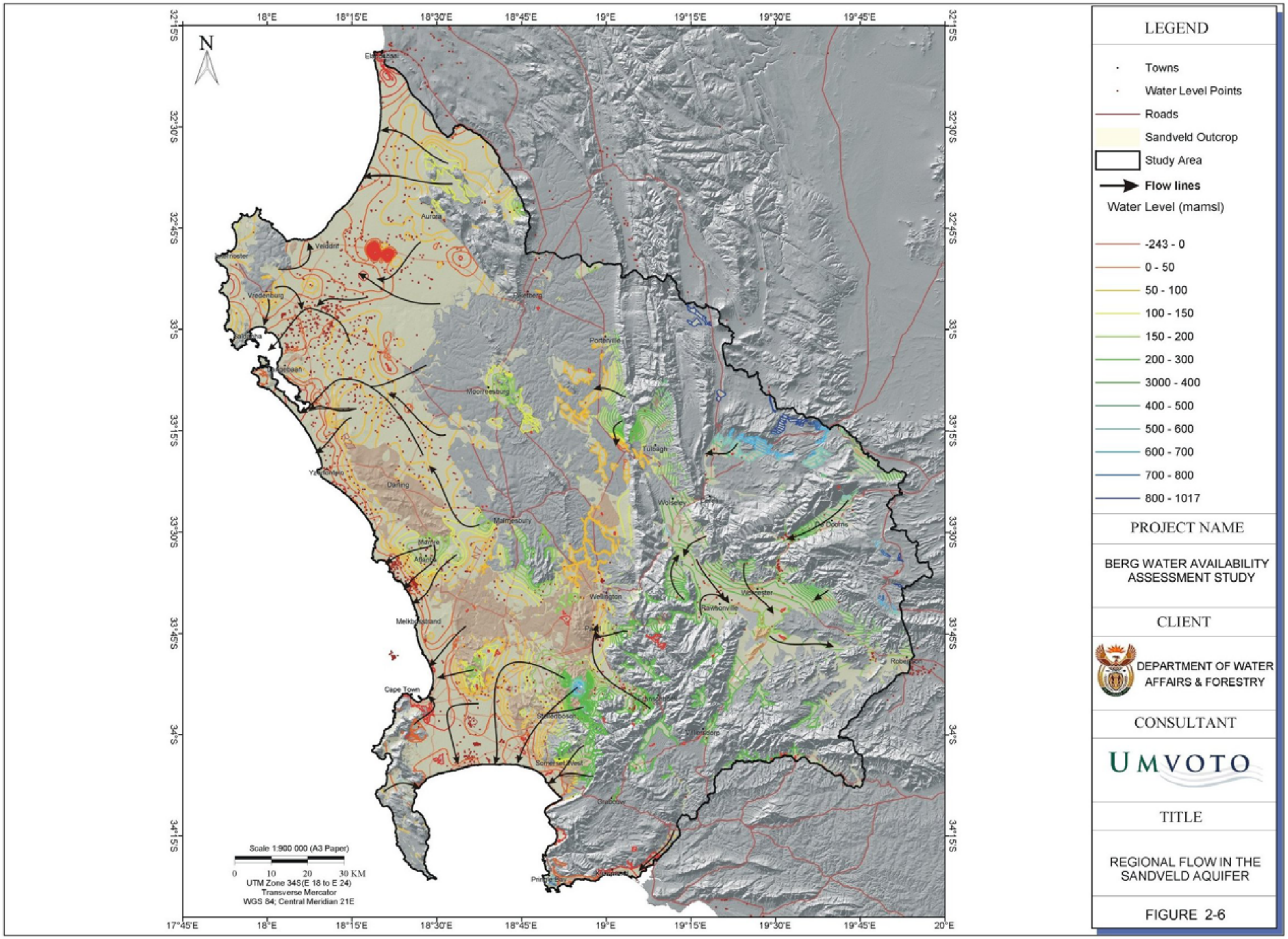


**Figure 2-6 Regional Flow in the Sandveld Aquifer**

Until the perimeter of the cone reaches a discharge/recharge source, the volume of the cone represents a volume of water that has been taken from storage in the aquifer, i.e., the "groundwater depletion" or drawdown, over and above the subsequent diversions from that source. "Thus, groundwater sources include groundwater (or aquifer) storage and induced recharge of surface water. The timing of the change from groundwater depletion (or "mining") to induced recharge from surface - water bodies is key to developing sound water - use policies … Aquifer drawdown and surface - water depletion are two results of groundwater development that affect policy. Both are fundamentally related to pumping rate, aquifer diffusivity, location, and time of pumpage. The natural recharge rate is unrelated to any of these parameters. Nonetheless, policy makers often use natural recharge to balance groundwater use, a policy known as safe yield." (Sophocleus, 2002, p. 62).

These strictures on the uncritical acceptance of the water budget myth do not, however, imply that recharge is not worth any consideration in the study and modelling of groundwater sustainability. Responsible groundwater development involves more than sustainable pumping, but also water quality, ecology and socio-economic considerations; all or many of which aspects may depend on recharge rates. Furthermore, the management use of numerical modelling for the estimation of sustainable pumping rates requires information on both the quantity of recharge and its spatio-temporal distribution, and simulation results are highly sensitive to these inputs (Sophocleus and Devlin, 2004). Accordingly there remains an obvious need to collect site-specific and temporal data and to prepare the best possible estimates of recharge to ensure that the models accurately represent the simulated systems. Many models can indeed be calibrated without exact knowledge of recharge inputs, as a pragmatic trade - off is always possible between accuracy of representation, on the one hand, and the cost and technical challenge of obtaining accurate recharge data, on the other.

**Discharge**

The above sections briefly describe why it is critical to understand what the flow and process hypothesis is and what physical and likely temporal scale you are working at, when designing a field investigation into ground truth mapping of flow paths in the TMG, determining rates and patterns of recharge, impact of abstraction on either surface water bodies or on the ecology and for hydraulic characteristics for which it is necessary to understand whether one is monitoring confined or unconfined behaviour. There are obvious implications for mesh design and selection of boundary conditions depending on the model purpose and available data.

When working at a regional scale it is not necessary to have enough data to prepare an idealised flow net which is relatively easy to obtain in a laterally extensive, homogenous primary aquifer. It is necessary to know what is physically possible and what is improbable. To this end, effort was expended in Task 7 and 12 in deepening the understanding of the available data, e.g., whether there was agreement with previous interpretations documented in various reports and peer reviewed journals, whether and where it was appropriate to use the elevations of known and inferred springs as more reliable datum points if the flow paths towards those springs could reasonably be inferred from geological data and 3D interpretation, cross referenced to the surface water information and records (especially of flow gauges).

A relatively straightforward reasoning on this basis, and use of empirical and measured data combined with an insight into the complexities of structural fabric at various scales in the TMG, underpins this conceptual model. The primary assumption adopted in this study is that the primary or "matrix" porosity of the quartzites that constitute the Peninsula and Skurweberg Aquifers is close to zero, meaning that for all practical purposes, water does not flow within the matrix but through the secondary pore spaces created by fractures and cracks in the rock mass.

The regional conceptual model and selection of Integrated Water Resource Model domains, drawn on the above basis, is aimed at providing reasonable confidence in the boundary conditions adopted for the different model domains and an overt understanding of the configuration and scale of acceptable simplifications in the numerical model that nevertheless still adequately represent the real world.

## 2.5 INTEGRATION OF GROUNDWATER INTO THE PITMAN AND WRYM

The integration of the actual and potential yield from the TMG aquifers into the WRYM poses certain challenges. It was agreed by consulting teams and the study management that the "Sami model" was not suitable for use in the Pitman model in the TMG-dominated terrain. This had obvious consequences for the integration of groundwater into the WRYM, in particular the large volumes of water stored in confined as well as in the unconfined TMG aquifers, the latter being those most developed. It was accepted that these challenges would not be entirely overcome in this study but a combined effort to develop an alternative approach based on first principles was integrated into the various study tasks. In-depth discussions as to the importance of quantifying key springs emerging from the confined portions of the Peninsula Aquifer and how this was currently conceived in the Pitman model highlighted the importance of revisiting the approach to integrating groundwater into the existing surface water paradigms. The details of how groundwater was integrated into the Pitman and the WRYM are available in Report 8 of this study and summarised below.

Based on a practical evaluation and a conceptual analysis of whether and how different aquifers exchange water with the tributaries and main stem of the river in each catchment in the study domain, it was concluded that the Sami model is not appropriate to use in 84% of the quaternary catchments in the Berg WAAS area. In all of these catchments the groundwater flow regime is truly 3D and cannot in any meaningful way be simplified to 1D. In the remainder of the quaternary catchments, the Sami model can possibly be applied, although it is also not recommended.

In light of the findings of this evaluation, three possible approaches to facilitate the modelling of surface water-groundwater interaction in both the catchment and system models were considered viz.:

- Conventional Pitman modelling (Sami groundwater model disabled)
- Pitman modelling with Sami model enabled
- Pitman model with external source representing groundwater contribution to discharge and "dummy" groundwater reservoir representing aquifer storage in the system model.

Although the conceptual approach does not attempt to simulate all the groundwater processes that are treated as standard in conventional groundwater models, it is considered to be the most appropriate methodology within the context of the Berg WAAS and it is recommended that this approach be implemented.

For the integration of groundwater into the WRYM groundwater was treated as an external source of water, adding to the river flow and dam yield. Pumping groundwater continuously might maximize the yield but could result in unnecessary spillage during wet periods, if conveyed via the existing dam infrastructure. Different operating rules for maximizing the yield and minimizing the pumping from the groundwater were investigated. Annual base flow sequences for each of the different abstraction scenarios in the WRYM are calculated from a dynamic storage model, which is based on the understanding of the TMG Aquifer behaviour and considers the potential impact of temporal variation in rainfall and abstractions in the TMG Aquifer system having time lags of a number of years on this base flow. The fluctuation in hydraulic head was calibrated against the available data and detailed groundwater model results.

# 3. KEY RESULTS

## 3.1 REGIONAL MODEL RESULTS

### 3.1.1 Conceptual Model

An aquifer-specific conceptual model across the study area was developed with the aim to generate a 3D view of the aquifer geometry, hydraulic properties and preferred flow paths, and to identify zones of surface water / groundwater interaction and interaction between aquifers. This requires identification of the groundwater recharge and discharge zones, the preferred flow paths linking these two zones, and the preparation of piezometric maps for each aquifer. The conceptual flow relationship between groundwater and surface-water regimes is based on the 3D characterisation of the aquifers, their likely spatial and temporal relationship with the stream-drainage system, as well as any lateral and vertical recharge between bounding aquifers.

An aquifer-specific approach was adopted to support regulatory decisions (such as compulsory licensing) about sustainable aquifer, well field or borehole yield as well as the impacts of abstraction. The major aquifers considered in this study are the Peninsula and Skurweberg aquifers (i.e. fractured aquifers) as well as the coastal and inland alluvium aquifers (i.e. intergranular aquifers). To meet one of the core requirement of the study, viz. to understand and map surface and groundwater interaction and to quantify it as far as possible, to be able to integrate groundwater into the Pitman and the WRYM models, the groundwater study boundaries were defined by areas called Integrated Water Resource Management Domains (IWRM Domains).

| **Box 1: Definition of an Integrated Water Resource Management Domain** |
| --- |
| An IWRM domain is a defined geographic area within which both the surface water and the groundwater resources, together with water-dependent ecosystems, can be quantitatively assessed, monitored, modeled, and managed in an integrated fashion through the development of conjunctive-use schemes. An IWRM domain aims to integrate the surface-water, groundwater and ecological dimensions of resource management within a unified geographical framework, where these elements share common physiographic and hydro meteorological boundary conditions but may respond on different temporal scales. |

The delineation of IWRM domain boundaries requires an understanding of the overall three-dimensional aquifer geometry and geography to define the storage, distribution and fluxes between aquifers. In addition knowledge of the spatial patterns of surface-water and groundwater interaction between the drainage network (rivers and streams) and the different (unconfined and confined) aquifer systems is necessary. Surface-water catchments and watersheds are therefore important in delineating IWRM domains, together with the 3-D geological understanding required to predict the groundwater flow paths.

The regional conceptual model and selection of 15 IWRM domains (9 classified as fractured, 3 classified as intergranular, and 3 classified as intergranular-fractured; see **Figure 3-1**) resulted in reasonable confidence in the boundary conditions selected for the different model domains and an overt understanding of the reasonable simplification to adequately represent the real world in the model configuration (DWA, 2007b).

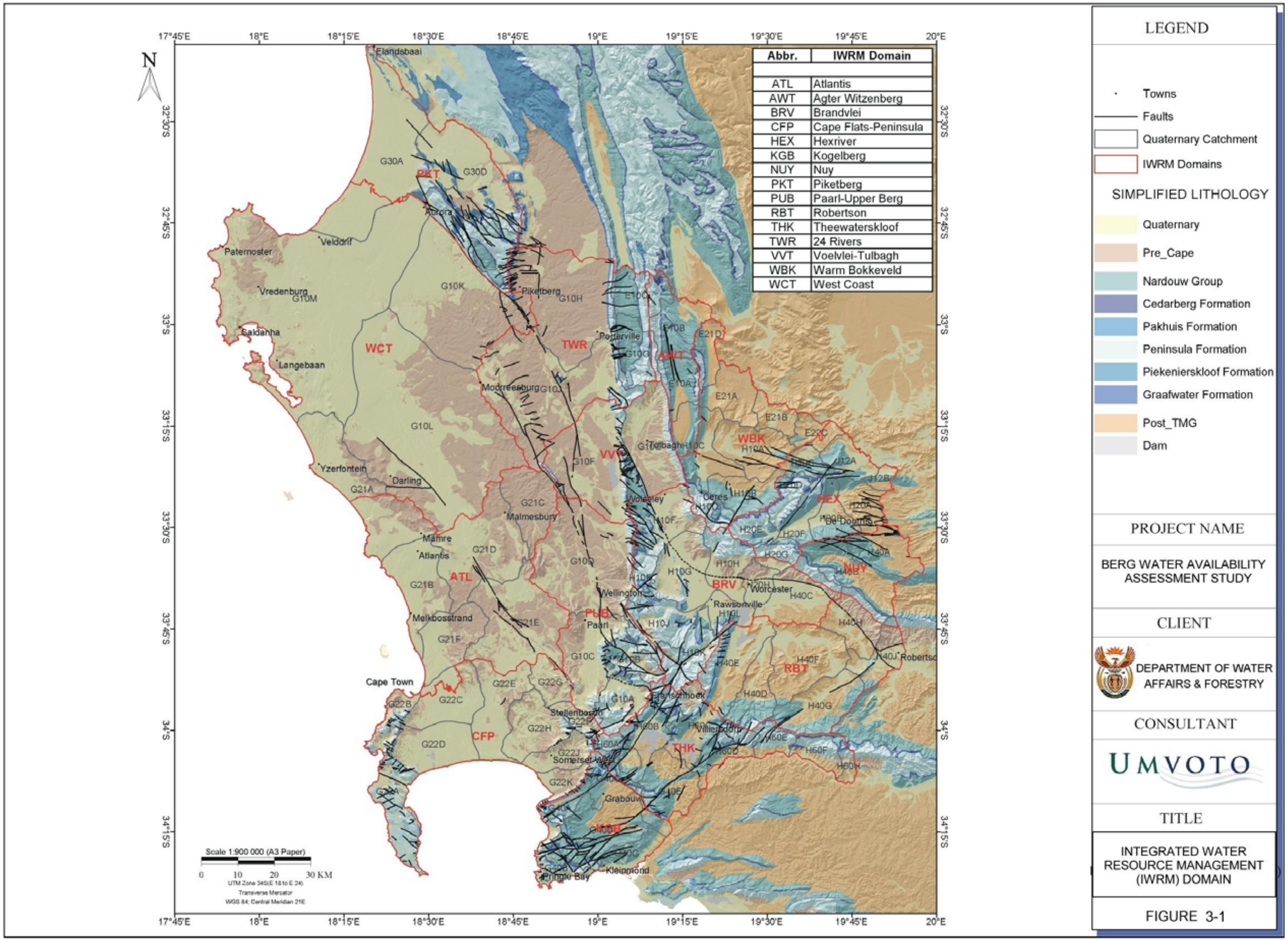


**Figure 3-1 The 15 IWRM domains in the Berg WAAS study area**

The surface water flow and groundwater flow paths reflect the structural features of the TMG. It is also an advantage that the nature of brittle failure of TMG rock is a fractal process as this supports extrapolation of patterns and data at different scales. The distinct seasonal patterns of supply and demand for both urban and agricultural users together with large confined fractured rock aquifers that show a distinctly seasonal 1 – 2 m fluctuation in the piezometric surface, facilitates an uncommon opportunity to water resource planners to consider and plan for conjunctive use in an area with a Mediterranean climate. Such an approach would facilitate adaptation to climate change (focus on storage to overcome increased variability and extremity of climate) but also support the implementation of riverine upgrade and the environmental reserve under the National Water Act (Act 36 of 1998).

### 3.1.2 Regional Water Balance Model Results

Within each of these domains the recharge, discharge, current usage and potential usage were calculated at different scales using different approaches for each of the key aquifers of the different aquifer types as defined in the 1:500 000 Hydrogeological maps at a regional scale. The regional conceptual model and selection of Integrated Water Resource Model domains that were drawn on the basis of this work resulted in reasonable confidence in the boundary conditions selected for the different model domains, an overt understanding of what complexities, at what process scale, could be simplified to adequately represent the real world in the model configuration.

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 / verified against 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 confined Peninsula Aquifer, based on known and *inferred three dimensional* model of the geological structure and the behaviour of confined aquifers;
- Aquifer-specific natural discharge, based on groundwater contribution to base flow 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 (see section below);
- Groundwater potential, based on recharge, baseflow and groundwater use.

A regional-scale two-dimensional (2D) GIS-based model was configured to calculate recharge, discharge, water demand, available and potential yield of specific aquifers using base maps of 1:250 000. The three-dimensional (3D) geometry of the Table Mountain Group Aquifers was derived from 1:50 000 geology maps using local scale detail (1:10 000) where this was available. A quasi-3D XL spreadsheet model was developed to calculate the yield from these aquifers under different head and management scenarios.

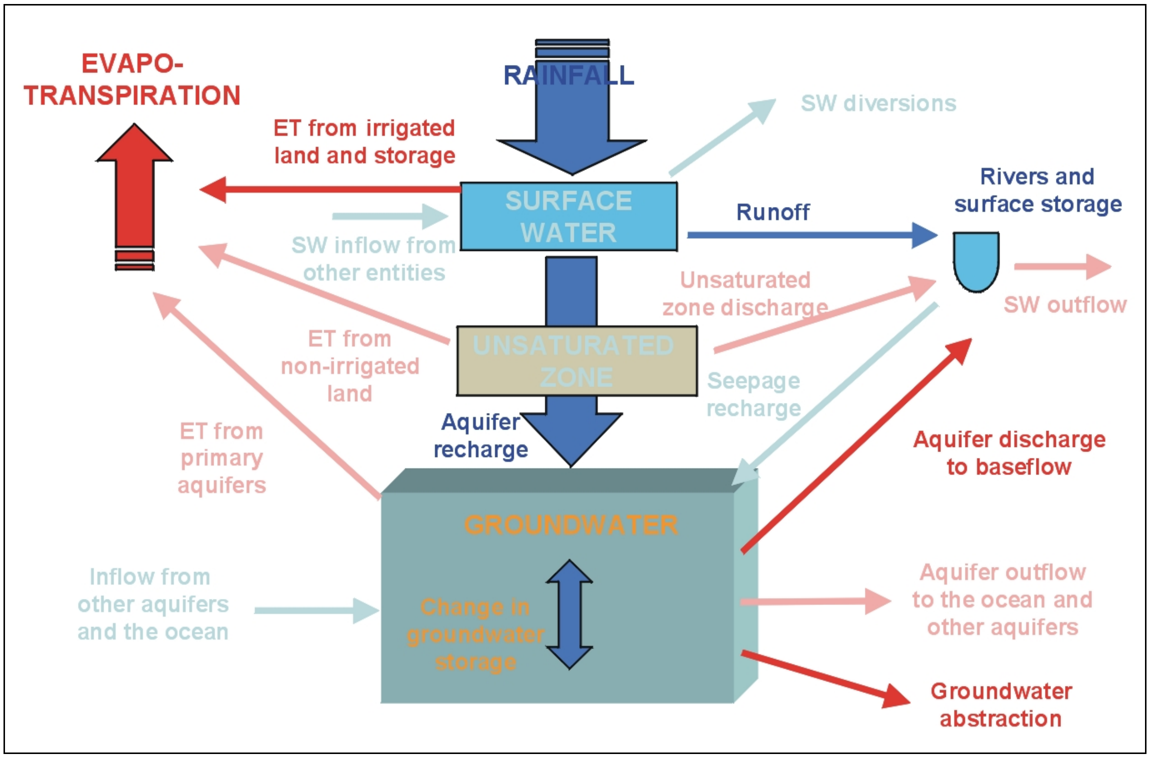


**Figure 3-2 Hydrological processes, interactions and fluxes in water balance model**

The water balance and yield model suggests a total remaining groundwater potential of 869 million $m^3$/a within the study area (see **Table 3-1**). The recharge estimation for the Peninsula and Nardouw aquifers are considered very conservative and a higher groundwater potential from these aquifers can be expected, once the model is calibrated.

**Table 3-1 Summary results of groundwater potential per aquifer for study area (in million $m^3$/a)**

| Aquifer | Recharge | Baseflow | Recharge - Baseflow | Groundwater Use | Groundwater Potential (Re – BF - Use) |
|---|---|---|---|---|---|
| Intergranular | 355 | 41.1 | 314 | 92.6 | 222 |
| Intergranular fractured | 267 | 39.2 | 228 | 58.4 | 170 |
| Fractured | 8.0 | 0.7 | 7.3 | 0.6 | 6.7 |
| Nardouw | 226 | 46.2 | 180 | 20.6 | 159 |
| Peninsula | 390 | 69.7 | 320 | 8.6 | 312 |
| Total | 1247 | 197 | 1050 | 181 | 869 |

On the other hand, the recharge for the intergranular aquifer, and hence the groundwater potential, appears to be high, especially along the West Coast and the Cape Flats. These estimates need to be verified prior to further groundwater development, water allocation or licensing.

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

**Table 3-2 Estimated groundwater potential and over allocation of groundwater in selected quaternary catchments (all values in $Mm^3/a$)**

| Quaternary Catchment | Peninsula | Nardouw | Intergranular-fractured | Intergranular | Total Groundwater Potential |
|---|---|---|---|---|---|
| E21A | 0.04 | 0.20 | 3.24 | **-0.27** | 3.21 |
| G21B | 0.00 | 0.00 | 0.95 | **-1.65** | **-0.70** |
| H10B | 0.00 | 1.00 | **-1.31** | 0.29 | **-0.02** |
| H10C | 0.08 | 1.77 | **-8.29** | **-1.49** | **-7.93** |
| H10F | 4.52 | 1.52 | **-2.39** | 2.41 | 6.06 |
| H10G | 2.04 | **-0.60** | 2.07 | **-1.48** | 2.02 |
| H10J | 9.46 | **-0.83** | 1.15 | 1.58 | 11.36 |
| H10L | 0.52 | 0.47 | 0.49 | **-3.38** | **-1.90** |
| H20B | 0.00 | 1.51 | 1.28 | **-0.67** | 2.12 |
| H20E | 4.25 | 0.67 | 0.40 | **-0.83** | 4.48 |
| H20F | 2.35 | 2.22 | 0.57 | **-6.95** | **-1.80** |
| H20G | 3.45 | 0.94 | 0.75 | **-2.49** | 2.65 |
| H40B | 1.08 | 10.02 | 4.85 | **-0.23** | 15.71 |

* negative values indicate deficit or over allocation

The intergranular aquifer is the most developed and utilised across the study domain. There are the following areas of concern:

- Over allocation of groundwater from the intergranular aquifer at least in the Hex River IWRM domains;
- Very high groundwater use (> 50% of Recharge – Base flow) in the Brandvlei, Nuy and Warm Bokkeveld IWRM domains;
- High groundwater allocation (> 20% of Recharge – Base flow) in the Atlantis, Kogelberg, Paarl-Upper Berg and West Coast IWRM domains;
- High groundwater use from the Nardouw Aquifer in the Brandvlei, Hex River and Warm Bokkeveld IWRM domains.

The Peninsula Aquifer and in certain catchments the Nardouw Aquifer are mostly un- or underutilised, but have the potential to supply significant quantities of water out of their evaporation-free storage, which is 2 to 3 orders of magnitude higher than the capacity of the surface water storage facilities in the study domain.

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 published 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 need to be revised. The results indicate a storage capacity within the Peninsula Aquifer alone of 366 705 million $m^3$, which are 2 to 3 orders of magnitude higher than the capacity of the surface water storage facilities in the study domain. By utilising the storage capacity of the confined portions alone, the Peninsula Aquifer can deliver a yield of between 158 and 633 million $m^3$, depending upon the acceptable average draw down of 5 m and 20 m, respectively (DWA, 2008a).

**Table 3-3 Potential yield of the Peninsula Aquifer for the IWRM domains, based on the storage yield model (Effective Storativity based on Specific Storage)**

| IWRM Domain | Effective Storativity | Pore Volume Million $m^3$ | Volume per head decline of: | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 m | | 5 m | | 20 m | |
| | | | Million $m^3$ | % | Million $m^3$ | % | Million $m^3$ | % |
| AWT | 6.89E-03 | 13 163 | 1.58 | 0.01 | 7.90 | 0.06 | 31.58 | 0.24 |
| BRV | 7.03E-03 | 31 672 | 3.80 | 0.01 | 19.00 | 0.06 | 76.02 | 0.24 |
| CFP | 8.47E-03 | 230 | 0.03 | 0.01 | 0.14 | 0.06 | 0.55 | 0.24 |
| HEX | 6.71E-03 | 31 568 | 3.79 | 0.01 | 18.94 | 0.06 | 75.75 | 0.24 |
| KGB | 6.70E-03 | 31 749 | 3.81 | 0.01 | 19.05 | 0.06 | 76.18 | 0.24 |
| NUY | 6.84E-03 | 24 406 | 2.93 | 0.01 | 14.64 | 0.06 | 58.58 | 0.24 |
| PKT | 7.93E-03 | 3 632 | 0.44 | 0.01 | 2.18 | 0.06 | 8.72 | 0.24 |
| PUB | 6.71E-03 | 2 796 | 0.34 | 0.01 | 1.68 | 0.06 | 6.71 | 0.24 |
| RBT | 7.03E-03 | 69 925 | 8.39 | 0.01 | 41.96 | 0.06 | 167.85 | 0.24 |
| THK | 7.23E-03 | 37 802 | 4.54 | 0.01 | 22.69 | 0.06 | 90.75 | 0.24 |
| TWR | 7.73E-03 | 12 206 | 1.46 | 0.01 | 7.32 | 0.06 | 29.29 | 0.24 |
| VVT | 6.88E-03 | 2 720 | 0.33 | 0.01 | 1.63 | 0.06 | 6.53 | 0.24 |
| WBK | 6.65E-03 | 34 109 | 4.09 | 0.01 | 20.46 | 0.06 | 81.85 | 0.24 |
| **Total** | **6.19E-03** | **328 664** | **31.63** | **0.01** | **158.15** | **0.05** | **632.59** | **0.19** |

## 3.2 DETAILED MODEL RESULTS – 2D

### 3.2.1 TMG Piketberg Model

The water balance and yield model, developed for the regional scale, was applied at finer scale for the TMG Aquifer in the Piketberg area, and suggests a total remaining groundwater potential of approximately 33 million $m^3$/a within the Piketberg area, applying the average recharge estimation (see **Table 3-1**). The recharge estimations for the Peninsula and Nardouw aquifers are considered conservative.

**Table 3-4 Summary results of groundwater potential per aquifer in the Piketberg area (in million $m^3$/a)**

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

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

The very high groundwater potential for the intergranular and intergranular - fractured aquifers does not take into account the exploitability and the suitability for domestic or agricultural use. The groundwater quality in large areas of the Sandveld primary aquifer as well as the Malmesbury and Granite regolith aquifers does not comply with the drinking water standards and is not or only to a degree suitable for consumption without expensive water treatment.

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 3-5 Potential Yield of the confined Peninsula Aquifer in the Model Domain, based on the storage yield model (Effective Storativity based on Specific Storage)**

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

### 3.2.2 TMG Witzenberg – Nuy Model

The water balance and yield model, developed for the regional scale, was applied at finer scale for the TMG Aquifer in the Witzenberg - Nuy area and suggests a total remaining long - term averaged groundwater potential of 144 million $m^3/a$ within the Witzenberg - Nuy area, based on a comparison of the average recharge estimation, base flow and current groundwater use (see **Table 3-6**).

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.

**Table 3-6 Summary results of groundwater potential per aquifer in the Witzenberg-Nuy area (in million $m^3/a$)**

| 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** |

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

| Model Sub-domain | Effective Storativity | Pore Volume Million $m^3$ | Volume per head decline of: | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 m | | 5 m | | 20 m | |
| | | | Million $m^3$ | % | Million $m^3$ | % | Million $m^3$ | % |
| 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** |

## 3.3 DETAILED MODEL RESULTS – 3D

### 3.3.1 Overview

Three-dimensional numerical modelling of groundwater flow was carried out for the Cape Flats, Langebaan Road and Breede River Alluvial aquifers. The Cape Flats and Langebaan aquifers were modelled using finite element software, Feflow. The former emphasis arises from the need to assess the potential contribution of the Cape Flats Aquifer to future water supplies of the City of Cape Town. The latter follows the proposed pilot implementation of aquifer storage and recovery (ASR) to increase the yield of the Langebaan Road Aquifer and the importance of evaluating the potential impacts on the lower reaches of the Berg River and surface water allocations. The complex interactions between the TMG aquifers, the Breede River Alluvium and the Breede River and tributaries were modelled in 3D using Modflow.

The results of these different models confirmed the order of magnitude for the estimated groundwater potential, refined the estimates of groundwater fluxes from and to surface water bodies and indicated areas for potential groundwater development with minimal impact on the surface water regime and the environment.

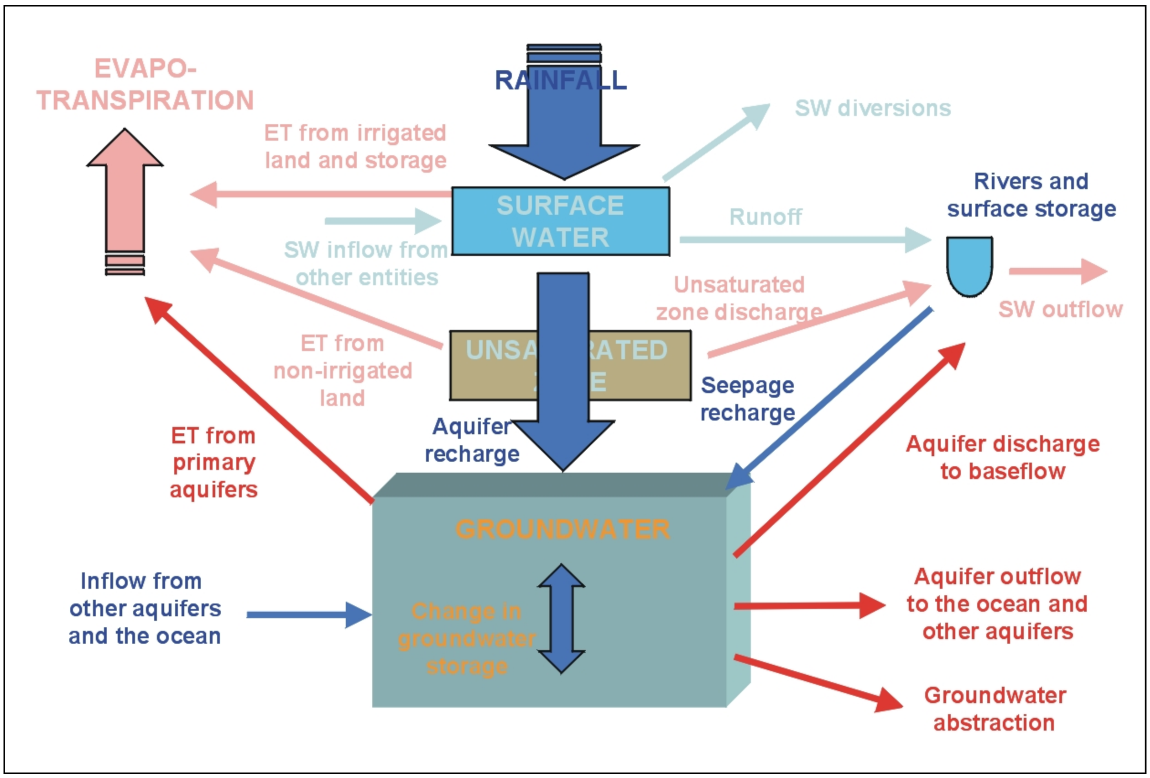


**Figure 3-3 Hydrological processes, interactions and fluxes, considered in detailed groundwater flow models**

Various input data sets are common to all numerical models. Bedrock topography for each of the alluvial models is a key model input and was constructed from various data sources:

- Borehole depths from the 1:50 000 geological map series,
- Borehole depths or bedrock contour maps provided in literature and
- Spot height on bedrock outcrops as shown in the 1:250 000 geological maps.

The recharge data used in the models is generated through the BRBS method (DWA, 2002a). Time series recharge was calculated by combining the BRBS recharge (which can be taken as a long-term average) with point data (weather stations) in the area. WARMS data was used for current abstraction. Groundwater levels for calibration were taken from the NGDB database. The database was sifted for points with water level and geology information. DWA flow gauging stations were used for surface water levels and combined with 20 x 20 m DEM data to convert into meters above mean sea level.

A calibration standard of modelled water levels within 10% average error to observed point data is set. The model is calibrated to this standard with the use of groundwater fluxes and groundwater as compared to topography as an additional guide.

### 3.3.2 Breede Alluvium Model

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

**Model Results**

The modelled water levels are compared to the observed water levels based on a comparison with mapped data. The major features of the flow regime are replicated in the model. Groundwater flows from the valley sides towards the Breede River, and also through the valley towards the southeast. The observed groundwater gradients are also broadly replicated. The model replicates the flow regime at a regional scale and gives expected mass balance numbers. Model runs showed that the equivalent hydraulic conductivity in the valley must be in the range of 10-100 m/d. The seasonal variation of the aquifer was simulated in transient modelling. The modelled groundwater fluxes are shown in **Table 3-8**.

**Table 3-8 Modelled groundwater fluxes for Breede Alluvium Model**

| | Influx | | Discharge | |
|---|---|---|---|---|
| | Vertical Recharge | TMG fed tributaries | Breede River | Balance |
| $m^3$/day | 62 982 | 8 144 | -71 062 | 64 |
| Million $m^3$/a | 22.99 | 2.97 | -25.94 | 0.02 |

Abstraction scenario testing on the transient model suggests that the aquifer is relatively fast to respond to major changes in the in - fluxes or out - fluxes applied to the aquifer. Inputting the assumed current abstraction to the transient model shows that the system re-adjusts to the lower net recharge conditions and achieves stability after ~10 years of this continued abstraction.

This re-adjustment to a new equilibrium is highlighted in **Figure 3-4** below. From time zero, an abstraction of 18 million $m^3$/a is applied, hence the net recharge is reduced from 23 million $m^3$/a to 5 million $m^3$/a. The 'balance' curve highlights aquifer storage: if the balance is negative more water leaves the aquifer than enters. This shows that initially, in the first years, water is provided for the abstraction from aquifer storage. Over time the 'balance' gradually tends to zero – i.e. tends to a position where equilibrium is attained and the inflow to the aquifer (recharge) equals the new discharge (abstraction and baseflow to the Breede). The effect is to reduce water levels in the aquifer which increases the head between water in TMG fed tributaries thus increasing the recharge from the alluvial fans. To achieve the new equilibrium, baseflow to the Breede River has decreased from ~21 million $m^3/a$ to ~12.5 million $m^3/a$. The question of whether an abstraction of 80% of recharge is sustainable cannot be evaluated in terms of the proportion of recharge that this abstraction volume is (~80%), but rather the appropriate analysis for whether this is sustainable is a decision on whether reducing baseflow by 8.5 million $m^3/a$ is acceptable in terms of potential impacts on river flows, and associated users. (Note: the graph does not show a reduction in aquifer storage as 'Balance' does not reflect a storage volume, it reflects the difference in the aquifer fluxes for each year.)

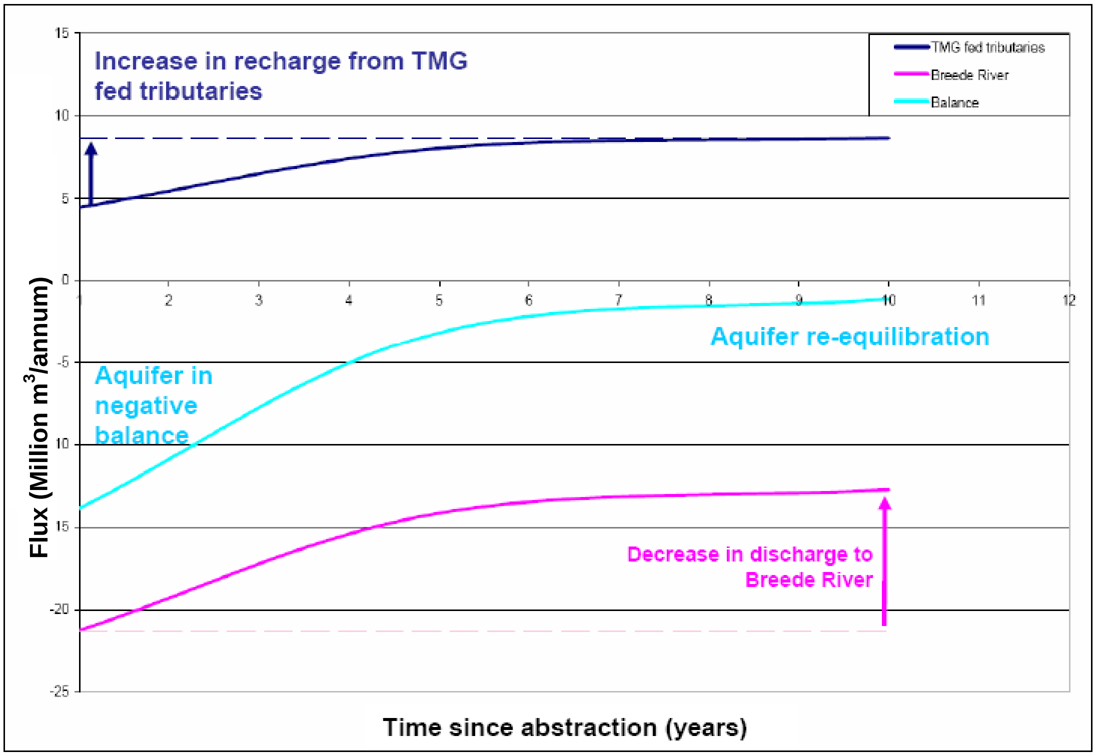


**Figure 3-4 Aquifer fluxes over time since major abstraction began. Negative fluxes are fluxes out of the aquifer, positive are fluxes into the aquifer. (Adapted from Figure 5.12, Volume 9)**

The modelled system returns to the natural situation of flows within 1 year after maximum and minimum surface water levels taken from flood and low flow records are applied, suggesting the aquifer can act like a sponge to flood waters, and buffer low flow periods. The relationship suggests that the alluvium can readily take up excess surface water, and that the time lag between groundwater recharge and discharge to the Breede River could be optimised to store winter flood water for use within the following summer dry period. The ASR scenario showed that there is a potential for significant storage within the aquifer, away from the centre of the valley. Local - scale mapping of water levels as depth to water is required to quantify such available storage.

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

### 3.3.3 Cape Flats Aquifer Model

A 3D finite element model is developed for a ~350 $km^2$ area with >61 000 nodes and ~100 000 prismatic elements. The elements are 60 - 450 m in length. The landward boundaries of the numerical model lie along rivers as transfer boundary conditions. For the upper unconfined aquifer the ocean acts as a constant head in the south and for the lower confined aquifer the point at which hydraulic equilibrium is reached with the ocean (at the extent of the palaeochannel) is used as a constant head. The model is 4 - layered.

**Model results**

The numerical model results confirmed what was assumed in the conceptual model, viz. that the basal gravels have higher hydraulic conductivity than the rest of the aquifer as the model calibrated with higher hydraulic conductivity in the basal layer, existing only within palaeochannels. It has been possible to replicate the general features of the observed water - level data but the modelled water level is typically smoothed with respect to the observed water - level data. The model basal layer within the palaeochannels calibrated with a horizontal hydraulic conductivity of 84 m/d. Above the high hydraulic conductivity palaeochannels an area of low horizontal hydraulic conductivity was input to the model, of 0.1 m/d. The remainder of the model has a horizontal hydraulic conductivity of 10 m/d. The model calibrated with the vertical hydraulic conductivity an order of magnitude less than the horizontal hydraulic conductivity.

Various model scenarios were developed because of the uncertainty of various data sets which inform the conceptual model. ‘Scenario A’ is based on the ‘base case’ situation and assumes hydraulic disconnection between surface waters and groundwater in the model, based on the observed canalisation of river courses with concrete lining. The efficacy of the canalised sections of rivers is not known and the potential for transfer between groundwater and surface water was addressed in ‘Scenario B’. Some of the point data used for calibration represented local groundwater highs and the model could not match these data, highlighting the difficulty in using point data (relative to the local scale) to calibrate regional models. ‘Scenario C’ tested the model sensitivity to an alternate calibration data set using inferred data points. The model results show the ocean as a dominant sink to the aquifer, and that on average the rivers behave as sinks. The modelled groundwater fluxes are shown in **Table 3-9**.

**Table 3-9 Modelled groundwater fluxes for Cape Flats Aquifer Model**

| Scenario | Mass Balance ($m^3$/day) | | |
|---|---|---|---|
| | To Ocean | Model to rivers | Rivers to model |
| Model Scenario A | 16 000 | 6 610 | 2 320 |
| Model Scenario B | 17 100 | 7 500 | 4 180 |
| Model Scenario C | 19 200 | 8 590 | 3 960 |

Surface water - groundwater fluxes are presented per quaternary (see **Table 3-10**). The fluxes differ significantly between Scenario A, B and C (by up to 70%), due to the key difference in assumptions for connectivity between surface and groundwater. To refine the estimates site - specific data on location of canalised portions of rivers, and the efficacy of canalisation are required.

**Table 3-10 Surface water - groundwater fluxes per Quaternary**

*(% are given as compared to the total flux to surface water for that model scenario)*

| Quaternary Catchment | Rivers | Model Scenario | Flux into Model ($m^3/d$) | Flux out of Model ($m^3/d$) | Net ($m^3/d$) |
|---|---|---|---|---|---|
| G22C | Elsieskraal and Vyekraal | A | 0 | -3783<br>57% of flux to SW from aquifer | -3783 |
| | | B | 0 | -4094<br>55% of flux to SW from aquifer | -4090 |
| | | C | 0 | -4843<br>56% of flux to SW from aquifer | -4843 |
| G22D | Lotus, Rondevlei and Zeekoevlei | A | 1572<br>68% of flux from SW to aquifer | -1074<br>16% of flux to SW from aquifer | +498 |
| | | B | +3441<br>82% of flux from SW across | -1700<br>23% of flux to SW from aquifer | +1741 |
| | | C | +3232<br>82% of flux from SW across | -1833<br>21% of flux to SW from aquifer | +1399 |
| G22E | Kuils | A | +743<br>32% of flux from SW across | -1755<br>27% of flux to SW from aquifer | -1012 |
| | | B | +743<br>18% of flux from SW across | -1720<br>23% of flux to SW from aquifer | -977 |
| | | c | +729<br>18% of flux from SW across | -1958<br>22% of flux to SW from aquifer | -1229 |

The effect of the current abstraction regime on the aquifer, compared to a naturalised situation with zero abstraction was tested in the model and is shown in **Table 3-11**, for scenario C. Results are shown for the situation where a new equilibrium is gained and the ‘Balance’, representing change in storage, is zero.

**Table 3-11 The effect of abstraction on modelled water balance fluxes**

*The difference is calculated as a % change, from no abstraction to abstraction.*

| | Flux into Model ($m^3/d$) | | Flux out of Model ($m^3/d$) | | |
|---|---|---|---|---|---|
| | Recharge | Rivers | Rivers | Ocean | Abstraction |
| Abstraction | +31 022 | +3 960 | -8 590 | -19 200 | -10 794 |
| Zero Abstraction | +31 022 | -2 890 | -11 000 | -26 000 | 0 |
| Difference caused by abstraction | - | Increase of 37% | Decrease of 22% | Decrease of 26% | - |

The seasonal variation of the aquifer was simulated in transient modelling. Two possible hypothetical wellfield scenarios were tested and suggest that there is a resource available for additional abstraction, and that additional abstraction could be effective in reducing water levels enough that winter flooding is reduced or mitigated. The results suggest an additional "safe yield" of ~2 million $m^3/a$ is available, from the northern palaeochannel area.

### 3.3.4 Langebaan Road Aquifer Model

A fully 3-dimensional finite element model was developed for a ~2 000 $km^2$ area with ~7 135 triangular prismatic elements. The elements are 500–1 200 m in length. The landward boundaries of the numerical model lie along topographical divides or across observed groundwater contours, and are no-flow boundary conditions. The ocean acts as a constant head in the southeast and northwest. The model is 5-layered.

The numerical model was considered calibrated with the following parameter set; the model basal layer within the palaeochannels calibrated with Kx=Ky of ~10 m/d. A discontinuous low K layer overlies the basal layer, at Kx=Ky of 0.01 m/d. The upper layer dominantly has a K of 10 m/d, with some area in the south at ~1 m/d. The model calibrated with vertical K an order of magnitude less than horizontal K.

**Model results**

The basement topography has a strong influence on the flow regime. The speed of groundwater flow increases in the palaeochannels as the groundwater is funnelled into the deep narrow incisions. The modelled groundwater flow replicates the major features of the observed groundwater flow. The higher water levels in the southeast are replicated, and flow from the southeast occurs towards the Elandsfontein aquifer system (EAS) and northwest into the Langebaan Road Aquifer System (LRAS).

The results show the ocean as a dominant sink to the aquifer, and that on average (i.e. the steady - state model) the Berg River behaves as a sink. The modelled groundwater fluxes are shown in **Table 3-12**.

**Table 3-12 Modelled groundwater fluxes in Langebaan Road Aquifer Model**

| Flux into Model ($m^3/d$) | Flux out of Model ($m^3/d$) | |
|---|---|---|
| Recharge | Ocean | Rivers |
| 59,800 | -32 800 | -27 100 |

The effect of the current abstraction across the aquifer is shown in **Table 3-13**. Abstraction is focussed at the West Coast Wellfield and **Figure 3-5** below shows a cross section of water levels across this wellfield.

**Table 3-13 The effect of Abstraction**

| | Flux into Model ($m^3/d$) | | Flux out of Model ($m^3/d$) | | | Balance ($m^3/d$) |
|---|---|---|---|---|---|---|
| | Recharge | Rivers | Ocean | Rivers | Abstraction | |
| Abstraction (i.e. standard model case) | 59 800 | 0 | -29 500 | -21 200 | -10 100 | -1 000 |
| Zero Abstraction | 59 800 | 0 | -32 800 | -26 900 | 0 | -100 |
| Difference caused by abstraction | - | - | Decrease of 10% | Decrease of 22% | - | Increase of 900% |

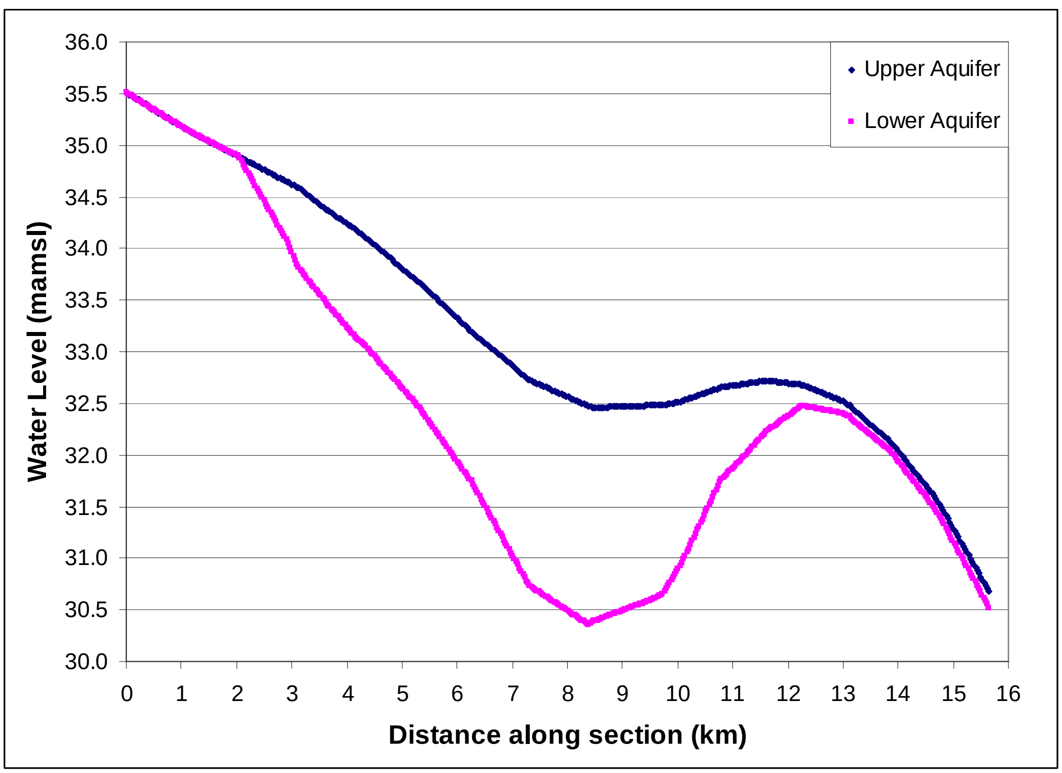


**Figure 3-5 The modelled effect of abstraction at the West Coast Wellfield (taken from Figure 5.8 Volume 6)**

*The cross section of water levels is taken across the wellfield areas and the drawdown cone is clearly visible. The impact on water levels in the lower aquifer where abstraction occurs is ~2m higher than the impact on the upper aquifer. The impact in the upper aquifer is ~1m.*

Scenario testing on the transient model suggests there is a large storage volume available: significant variations in rainfall, increased abstraction, ASR scenarios all have little effect on the regional mass balance numbers, simply affecting the storage (causing a negative or a positive balance). Significantly, there is a potentially under-exploited resource in the Elandsfontein Aquifer System and the wellfield scenario showed that water levels close to the Langebaan Lagoon wouldn't be affected by the abstraction which could supplement water from the West Coast Wellfield. The potential for seawater intrusion is small.

## 3.4 INTEGRATION WITH SURFACE WATER MODEL

### 3.4.1 Overview

When it became evident that the groundwater – surface water interaction and the integration of groundwater potential and use into the water resource planning could not be achieved reliably with the current groundwater modules in the Water Resources Yield Model (WRYM), an alternative approach, as mentioned in Section 2.5 above, was agreed upon between the client and the study team.

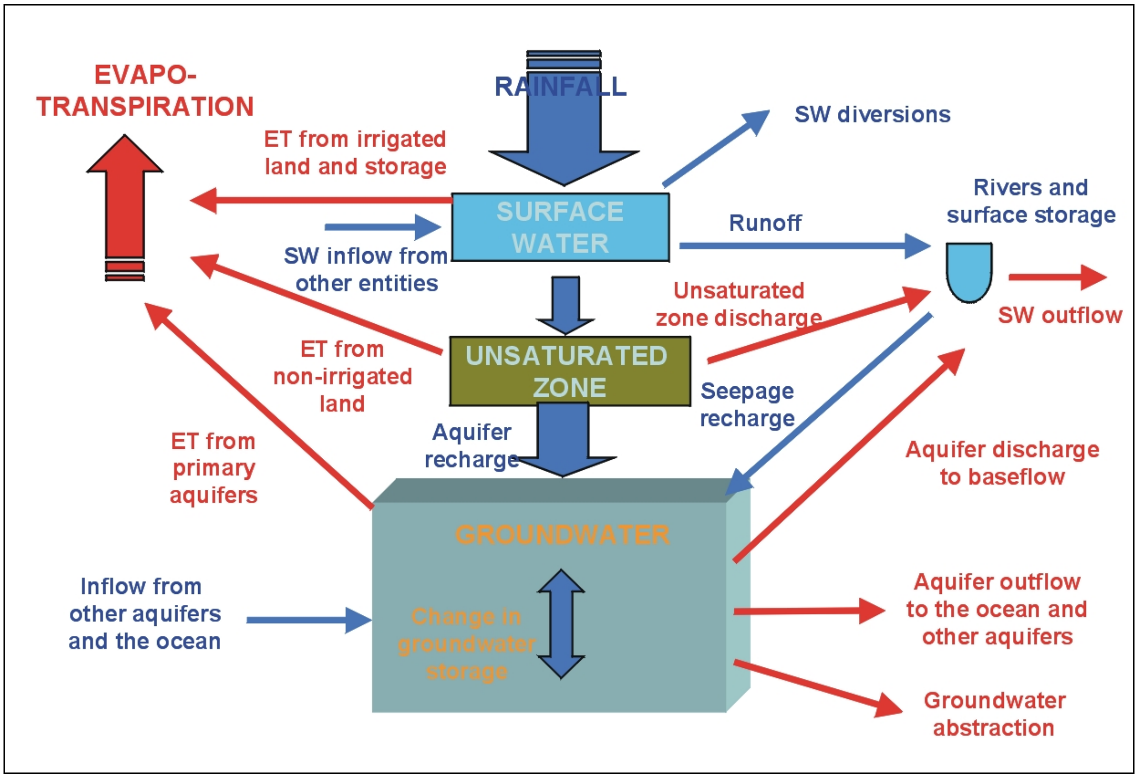


**Figure 3-6 Hydrological processes, interactions and fluxes, considered in the Integrated Water Resource Model**

The integration of groundwater into the WRYM was tested for abstraction scenarios from the TMG Aquifer, which has a huge storage volume that can be used for climate change adaptation and potential for augmenting the supply to the City of Cape Town. Groundwater was treated as an external source of water, adding to the river flows and dam yields.

Llamas (2004) has noted that "… in recent decades groundwater over-exploitation has become a kind of 'hydromyth' that has pervaded water resources literature. A usual axiom derived from this pervasive 'hydromyth' is that groundwater is an unreliable and fragile resource that should only be developed if it is not possible to implement the conventional large surface water projects." However, when corresponding surface resources such as rivers or man - made reservoirs may be unable to provide enough water, aquifers - natural underground reservoirs that can have enormous storage capacity much greater than even the largest man - made reservoirs - are convenient sources enabling timely use of water, which can be pumped out during exceptionally dry periods.

For an idealized, two-dimensional, homogeneous, and isotropic groundwater system, there exists a *transition* or *growth curve*, defining the rate at which dependence on groundwater storage (left portion of **Figure 3-7**) converts to dependence on surface - water depletion (right portion of **Figure 3-7**), which is highly variable and is particular to each case. In non-dimensional form, where the percentage of groundwater withdrawal derived from groundwater storage is plotted on the *y*-axis against dimensionless time [$t^*=\{4(T/S)/x^2\}t$; see **Figure 3-7** for T, S, x definitions] on the *x*-axis, its general shape is retained in systems with apparently different boundaries and parametric values. The initial and final phases of the transition curve are separated in time by a factor of nearly 10 000, hence *full* reliance on indirect (induced) recharge takes an extremely long time (Sophocleus, 2002).

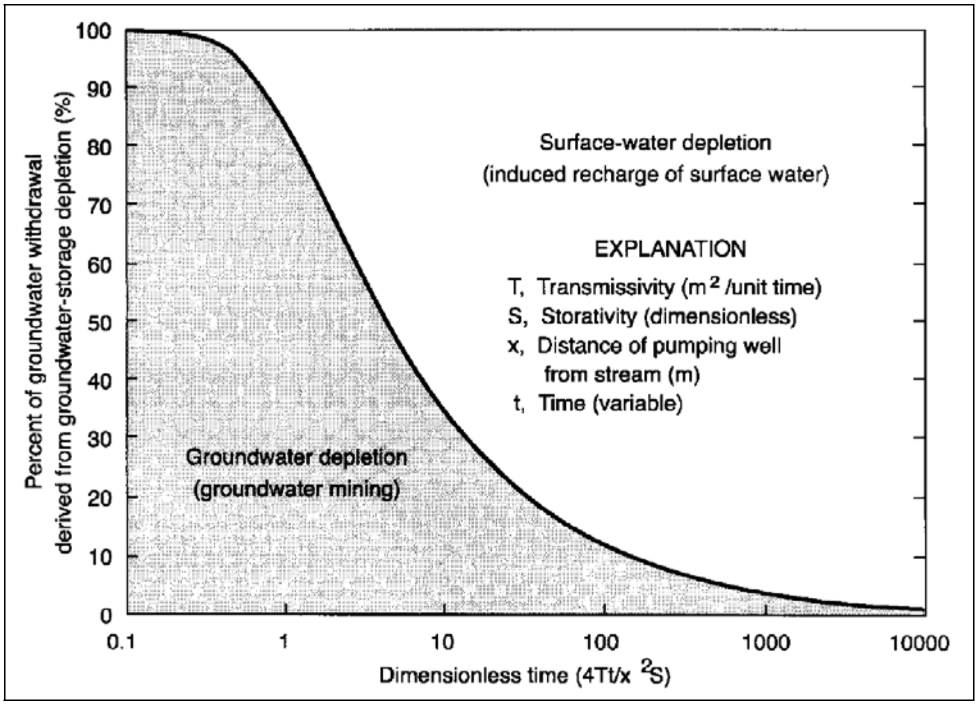


**Figure 3-7 Transition from reliance upon groundwater storage to induced recharge of surface water (from Sophocleus, 2002, Fig. 9).**

The distinct category of "groundwater mining" depends entirely upon the time frame, but *in their initial stages all groundwater developments mine water*. In a large regional aquifer system, such as the Peninsula Formation of the TMG, where a typical transmissivity (T) may be 50 $m^2$/day and storativity (S) may be 0.005, and a particular wellfield location can be relatively remote (x =10 km) from the nearest surface water recharge/discharge source, the characteristic "time to early capture" [t for unit $t^* = x^2/4(T/S)$] is 2500 days or 6.74 years. Thus, in this example, groundwater storage is still the major part (~ 85%) of the water source after ~7 years of pumping (i.e. at dimensionless time 1 in **Figure 3-7**), but ends up being ~15% of the water pumped after 700 years, while the major part then derives from reduced surface water run-off (i.e. at dimensionless time 100 in **Figure 3-7**).

Parts of the TMG aquifer system are so relatively large that a transition to "full capture" and a new steady-state condition may take several millennia. Such large systems pose a challenge to the water manager, especially one who is committed to attempting to reach a new equilibrium state in which water levels will stabilize and the system can be maintained indefinitely

(Bredehoeft and Durbin, 2009). As the characteristic time equation shows, the duration to equilibrium depends upon: (1) the aquifer diffusivity (i.e., the ratio of aquifer transmissivity to storativity, T/S), which is a measure of how fast a transient change in head is transmitted throughout the aquifer system; and (2) the distance, x, from the well to the surface-water source of induced recharge. For radial flow of groundwater, a tenfold increase in distance from the surface - water body causes a 100-fold delay in the response time, whereas a change in diffusivity is linearly proportional to the response time (Sophocleus, 2002).

Groundwater depletion is the inevitable and natural consequence of withdrawing water from an aquifer, but in cases where recharge is either unavailable (“fossil” aquifers) or unable to refill drained pore spaces (compacting aquifers), it effectively constitutes permanent “groundwater mining”. In renewable aquifers, depletion is indicated by persistent and substantial head declines (Konikow and Kendy, 2005).

Huge reserves of fresh groundwater are justifiably exploited where the amounts of renewable surface - water resources are relatively small: “In such situations, groundwater mining may be a reasonable action if various conditions are met:

1) the amount of groundwater reserves can be estimated with acceptable accuracy;
2) the rate of reserves depletion can be guaranteed for a long period, e.g. from fifty to one hundred years;
3) the environmental impacts of such groundwater withdrawals are properly assessed and considered clearly less significant than the socio - economic benefits from groundwater mining; and
4) solutions are envisaged for the time when the groundwater is fully depleted” (Llamas, 2004, p. 25).

The identification, development and implementation of an appropriate “exit strategy” by the time the aquifer is substantially depleted, implies that “… society will have used the mined groundwater to advance economically, socially and technically so as to enable future generations to develop substitute water sources at tolerable capital and operational cost. But it could equally mean strengthening the capacity of existing water-users to cooperate in managing water resources more efficiently.” (Al - Eryani et al., 2006, p. 26).

To better prepare communities to cope with increasing water stress as aquifer storage is depleted, particularly for a “non - renewable groundwater resource” – recently defined as one “… available for extraction, of necessity over a finite period, from the reserves of an aquifer which has a very low current rate of average annual renewal but a large storage capacity” (Margat et al., 2006, p. 14), there is an obvious need for socio-economic planning of the exploitation. A socially-sustainable, “planned depletion scenario” is described as the “…orderly utilization of aquifer reserves (of a system with little pre-existing development), minimising quality deterioration and maximising groundwater productivity, with expected benefits and predicted impacts over a specified time - frame. The overall goal should be to use groundwater in a manner that maximises long-term economic and social development of the community and decreases, over time, the frequency and severity of threats to society, leaving people better prepared to cope with socio-economic stresses associated with increasing water scarcity as aquifer storage is depleted. This will often entail the initiation and expansion of high added-value economic activities that are not water intensive.” (Al-Eryani et al., 2006, p. 26).

The foregoing planning scenario contradicts another common ‘hydromyth’ (Llamas, 2003, 2004), related to the water budget myth, namely, that groundwater mining – the intentional development of non - renewable groundwater resources – is always an over-exploitation that is offensive to basic ecological and ethical principles. It is, however, indeed often the case that, when a non-renewable aquifer is shared by a number of different users, the “unwritten rule of shared resources” usually applies, i.e., “… that what is left today will not necessarily be saved for tomorrow, but will be exploited by other partners” (AbuZeid and Elrawady, 2008). In order to achieve the best scenario for sustainable development, the strict implementation of continuous monitoring – including the sharing of annual extraction data, representative electrical conductivity (EC) measurements, and water - level measurements at every extraction site - within a regional information network for cooperation and knowledge exchange, including regional thematic maps and a regional mathematical model, is necessary.

In contexts where some large aquifers that have undergone groundwater mining or “overdrafting” for many decades, pumping data is hardly reliable and the extent of overdraft has not been adequately analysed for decades. “It is perhaps the lack of willingness to monitor, rather than overdraft *per se* that may constitute the greatest intergenerational threat for groundwater resources” (Llamas et al., 2006).

Despite its vital contribution to as many as two billion people who depend directly upon aquifers for drinking water, and to groundwater-irrigated agriculture that produces around 40 per cent of the world’s food, the “recognition of the pivotal role of groundwater in human development is relatively recent and still patchy. This omission is understandable; water stored in the ground beneath our feet is invisible and so its depletion or degradation due to contamination can proceed unnoticed, unlike our rivers, lakes and reservoirs, where drying-up or pollution rapidly becomes obvious and is reported in the news media” (Morris et al., 2003, p. 1). It is indeed the “world’s hidden water resource”, constituting about 95% of fresh water on the planet (exclusive of polar ice-caps).

“Groundwater systems have value not only as perennial sources of water supply, but also as reservoirs for cyclical injection and withdrawal to modulate the variability inherent in surface - water supplies. Management approaches increasingly involve the use of artificial recharge of excess surface water or recycled water by direct well injection, surface spreading, or induced recharge from streams. As predictive links between hydrology and climate improve (e.g., prediction of El Ninõ conditions), opportunities exist to make better use of the storage capacity of groundwater systems. Many scientific challenges remain to understand more fully the long-term hydraulic response of aquifer systems, subsurface chemical and biological changes of the injected water, and geochemical effects of mixing waters of different chemistries …. With time and extensive use, much of the local groundwater may be derived from artificial recharge … a further indicator of the dynamic nature of groundwater systems” (Alley et al., 2002, p. 1990)

### 3.4.2 Dynamic Storage Model

A dynamic storage model was developed, which provides annual base flow sequences for each of the different abstraction scenarios in the WRYM. The spreadsheet model is based on the understanding of the TMG Aquifer behaviour and considers the potential impact of temporal variation in rainfall and abstractions in the TMG Aquifer system having time lags of a number of years on this base flow. The fluctuation in hydraulic head was calibrated against the available data and detailed groundwater model results.

**Figure 3-8** shows the simulated annual variation in recharge and discharge, based on the annual rainfall sequence for the selected TMG outcrop area and using a fixed rainfall – recharge relationship. The discharge is calculated based on a non-linear storage volume – discharge relationship.

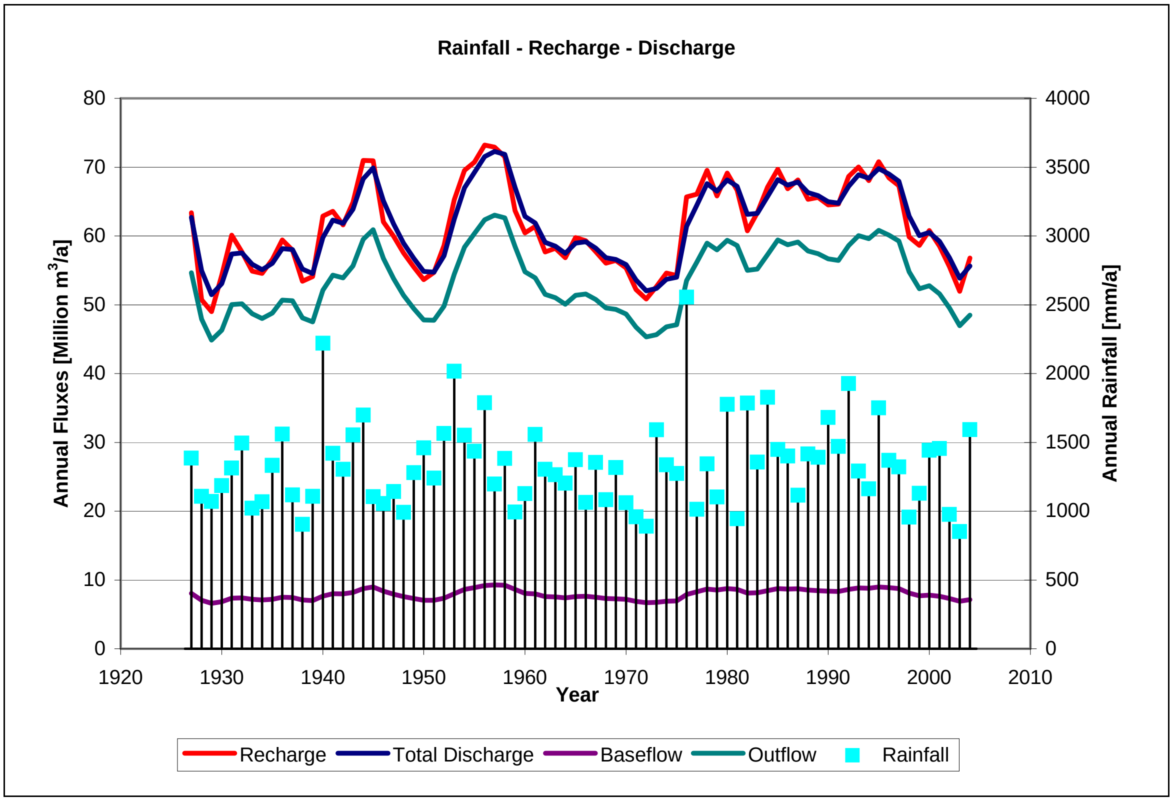


**Figure 3-8 Simulated annual recharge and discharge sequences, based on annual rainfall sequence**

The final change in storage volume (see **Figure 3-9**) is then calculated with a simple water balance equation, taking the storage volume of the previous year as well as the calculated influx and outflow into account. Since groundwater abstraction reduces the volume of water in storage, the impact of abstraction on discharge can be simulated and hence the change of storage volume due to abstraction calculated per year (see **Figure 3-10**).

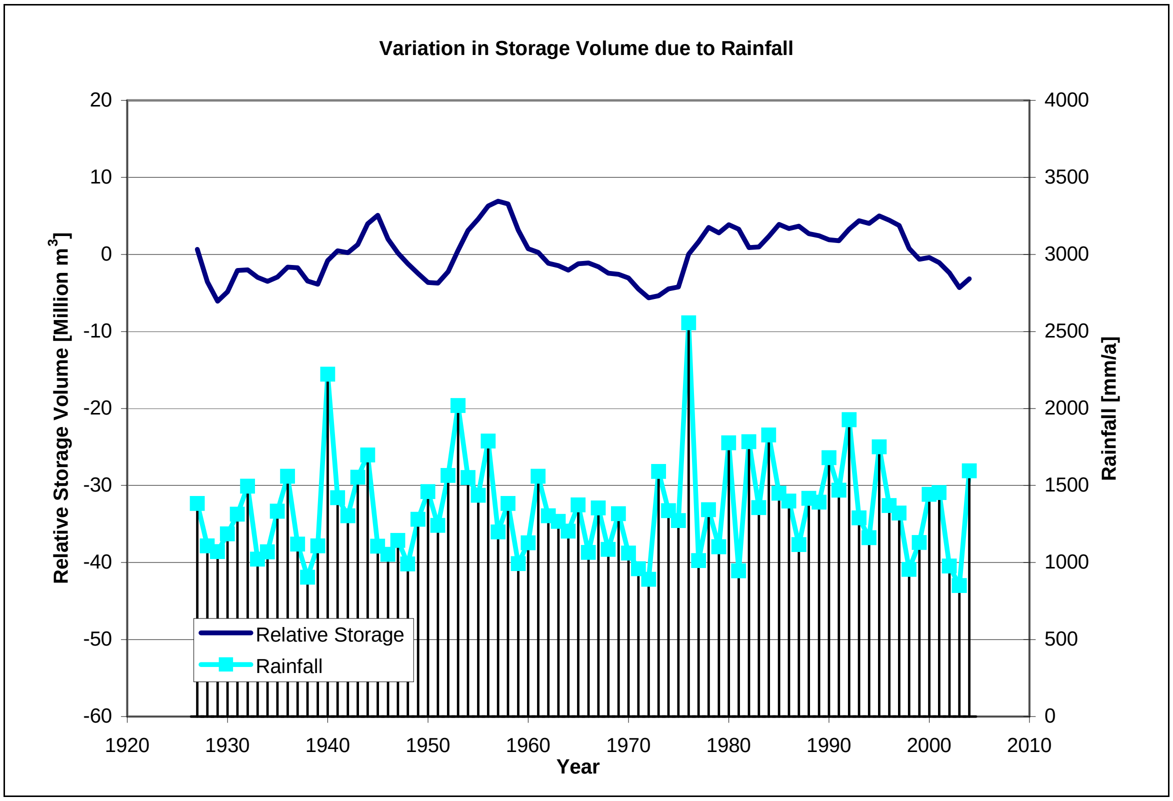


**Figure 3-9 Simulated variation in relative storage volume, due to rainfall, recharge and natural discharge**

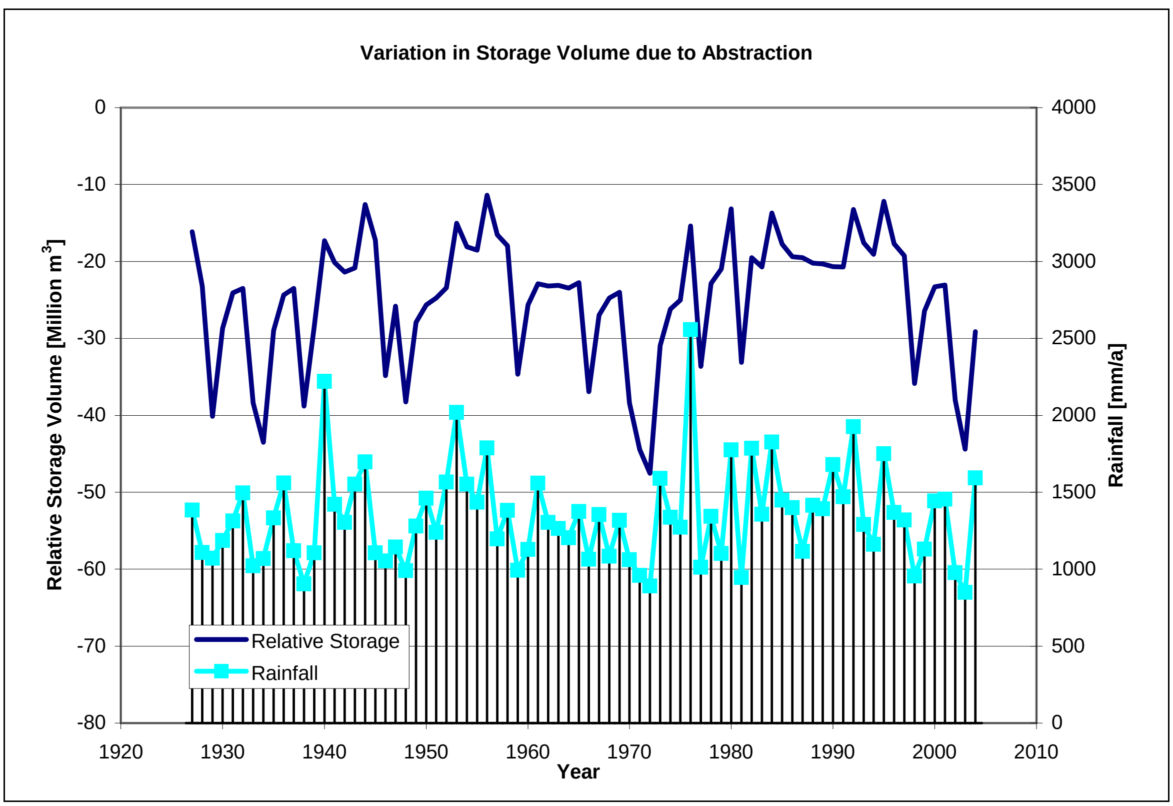


**Figure 3-10 Simulated variation in relative storage volume, due to rainfall, recharge, discharge and abstraction**

### 3.4.3 Integration into the WRYM

The second outcome of the dynamic storage model is an annual sequence of base flow that is used in the WRYM to refine the initial estimates of the contribution to the yield from groundwater.

Pumping groundwater into dams might maximize the yield but could result in unnecessary spillage during wet periods, if conveyed via the existing dam infrastructure. Different operating rules for maximizing the yield and minimizing the pumping from the groundwater were investigated (see **Figure 3-11**). This is detailed in Report 8 of this study.

The increase in yield from conjunctive use is actually greater than the average volume pumped, especially when using operating rules with a low spillage risk. The difference between the yield and the volume pumped was termed the “conjunctive” component of the yield. The ratio of the conjunctive yield to the total yield varies from 35-40%, if the system is operated at a low spillage risk, down to about 5-10% if the system is operated at a high spillage risk. For the scenario of intermittent groundwater abstraction during dryer periods, the yield increase is about twice the average abstraction from groundwater.

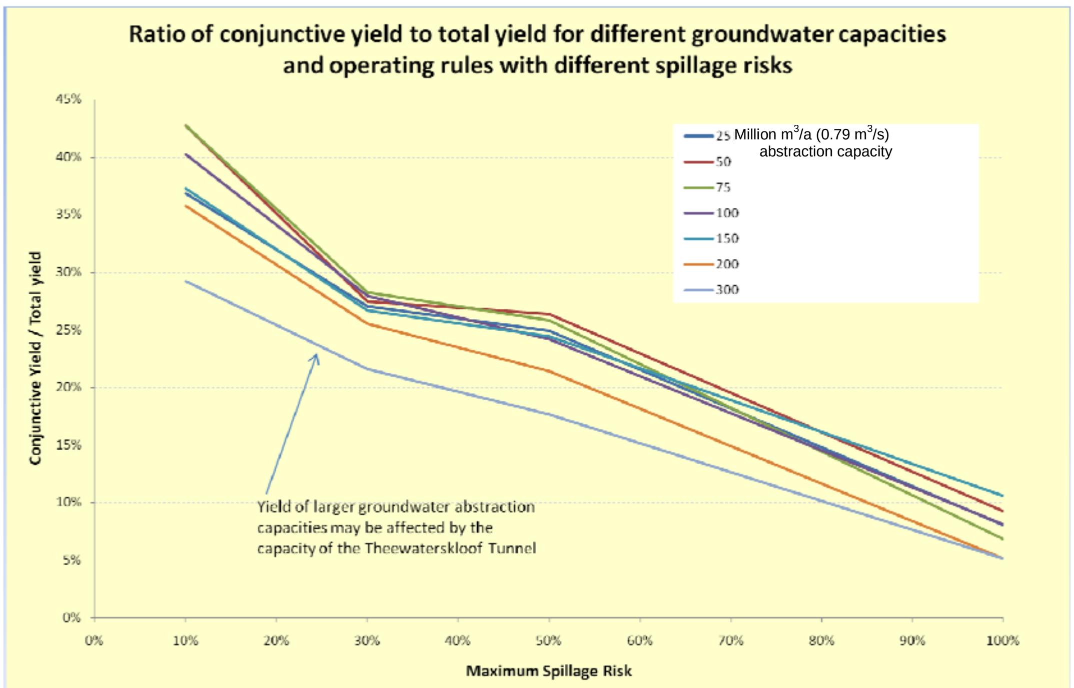


**Figure 3-11 Yield increase due to conjunctive use**

## 3.5 CONFIDENCE AND CONSTRAINTS

### 3.5.1 Overview

The "critical zone", where the hydrosphere, biosphere, geosphere, and atmosphere interact with one another and with the human sphere, presents special challenges to the development of long - term predictive models, despite the substantial progress in recent decades in describing, modeling, and even predicting the behavior of such systems. The inherent complexity of some as yet poorly understood types of critical - zone hydrogeologic systems, including regions of groundwater - surface-water interactions and deep-seated fractured - flow regimes (such as the confined TMG) stretch our knowledge and understanding of, and ability to model, these processes.

The words "verification" and "validation" have a widespread use in the modelling literature. As a response to the evaluation of the predictions of groundwater models by practicing environmental scientists (Konikow & Bredehoeft 1992; Anderson & Woessner 1992), the problem of verification with regard to environmental models has been discussed in detail in a contribution from professional philosophers (Oreskes et al., 1994). In open natural systems, verification or validation of models is impossible, because models of such systems may be non-unique. Only a conditional confirmation is possible, which may depend on errors in the model structure(s), the calibration of parameters or other auxiliary conditions, and also on the period of data used in evaluation (Beven, 2002).

From "postaudit" comparison of prediction to actual behaviour over periods of decades (e.g., Konikow and Bredehoeft, 1992; de Marsily et al. 1992; Bredehoeft and Konikow, 1993), it is evident that the predictive capability of models based on a "history match" (i.e., a calibration to previous hydrologic data) diminishes rapidly for periods longer than that of the historical data (Bredehoeft, 2002). Confidence in the predictive capabilities of hydro(geo)logical models is accordingly limited to no more than several decades in the case of the Berg catchment data (data from 1920), and the limits may arguably be considerably shorter in the most highly complex and poorly understood hydrogeologic settings.

This limitation of modelling has significance for future licensing of groundwater developments over the longer - term. "It is naive to believe that we will somehow validate a computer model so that it will make accurate predictions of system responses far into the future. In a sense, emphasizing validation deceives society with the impression that, by expending sufficient effort, uncertainty can be eliminated and absolute knowledge be attained. Society continually makes operational decisions in the face of uncertainty. These decisions are based upon judgements about future risks and consequences. … (In) the final analysis, society will make a judgement concerning the prudence of what is proposed. We believe society will demand a consensus from the responsible scientific community that the actions being proposed are reasonable. This does not mean that our models were somehow validated; rather, the relevant problems have been investigated and we have assured ourselves that they do not pose unreasonable risks" (Konikow and Bredehoeft, 1992, p. 82).

### 3.5.2 Result Limitations and Uses

The limitations and possible applications of the model results are summarised in **Table 3-14**.

**Table 3-14 Limitations and applicability of the developed groundwater models**

| Model | Limitation | Uses |
|---|---|---|
| Water Balance Model | Does not support compulsory licensing | Water resource evaluation<br>• First Order Water balance,<br>• First Order Yield estimation |
| TMGA Models<br>• Witzenberg - Nuy<br>• Piketberg | | Refinement of water balance, storage and yield<br>Identification of stressed / over allocated aquifers |
| Cape Flats aquifer Model | Does not support individual wellfield / borehole licensing | Quantify temporal and spatial patterns and rate and volume of exchange, of surface and groundwater interaction for natural situations and flood scenarios.<br>Quantify the impact of abstraction for augmentation of water supply in Cape Town on base flow.<br>Investigates the impact of a potential pollution source on Cape Flats Aquifer. |
| Langebaan Aqufier Model | Does not support individual wellfield / borehole licensing | Quantify temporal and spatial patterns and rate and volume of exchange, of surface and groundwater interaction, in the Lower Berg River catchment, for natural situations and flood scenarios.<br>Quantify the impact of abstraction scenarios on base flow.<br>Investigate the impact of a hypothetical wellfield schemes on water levels and saline intrusion.<br>Investigate the impact of the ASR scheme on water levels. |
| Breede Aquifer Model | Does not support individual wellfield / borehole licensing<br><br>The alluvium and the TMG are modelled separately hence the model cannot test the effect of increased abstraction on the inflow from the TMG into the alluvium. | Quantify temporal and spatial patterns and rate and volume of exchange, of surface and groundwater interaction, in the Upper Breede, for natural situations, flood and drought scenarios.<br>Quantify the impact of abstraction scenarios on base flow.<br>Investigate the possibility for an ASR scheme to store surplus flood water |

### 3.5.3 Water Quality

The estimated water availability is only applicable if the water quality is at an acceptable standard. In general, the TMG aquifers are more protected from surface contamination than the alluvial aquifers.

# 4. PROPOSED METHODOLOGY

## 4.1 RECOMMENDED MODELLING APPROACH

### 4.1.1 Overview

Based on the lessons learned, the recommended approach to modelling follows discrete steps to allow for an increasing level of confidence during the process, while the scale of investigation is refined from regional / basin scale to local wellfield and borehole scale. The main elements of this approach are:

- Good conceptual models are tested numerically to design and detail monitoring networks;
- Simple box and/or other storage models are constructed as being most cost-effective for aquifer - specific reconnaissance level;
- 3D aquifer - specific flow models are established for preliminary resource evaluation and assessment of impact of abstraction on surface water regime and existing lawful use;
- Transient (4D space - time) wellfield models are developed to evaluate wellfield design and management scenarios for all commercial or urban use.

As summarised in the following sections of this report, an iterative approach is proposed, as the models are updated with new and more detailed data and information while the scale of investigation gets more detailed.

### 4.1.2 Aquifer - specific conceptual model [2D-4D]

The purpose of conceptual model development is to stimulate creative debate within and among surface water, groundwater and environmental professionals, the external review team and the client about model assumptions and boundary conditions, aquifer definitions, hydraulic parameters, possible flow paths, and groundwater-surface water interactions as well as impacts of abstractions. The various components of the models remain open to fundamental re-evaluation after the collation and analysis of further data, and consideration of alternative interpretations (Bredehoeft, 2005):

> "…The appropriateness of the conceptual model cannot be tested until a numerical model is built and comparisons between field observations and model simulation results are made. Thus one of the most useful things about a numerical model is that it provides a tool to test and improve the conceptual model of a field site. It also provides a guide to future data collection, particularly in those cases where additional data are needed in order to produce a conceptual model consistent with field observations. For this reason, one should not wait until a 'perfect' conceptual model is formulated before starting to assemble the numerical model. Instead, conceptual and numerical modelling should be viewed as an iterative process in which the conceptual model is continuously reformulated and updated… (Bredehoeft, 2005,p. 38)

In this project, the integration of complex concepts of shallow and deep groundwater flow into the numerical models is indeed the most challenging element of a regional - scale model or of modelling individual aquifers in a geologically and topographically complex quaternary or larger - scale model domain. The geoscientific method of "multiple working hypotheses" is therefore most appropriate in this case, where "the effort is to think independently, or at least individually, in the endeavor to discover new truth, or to make new combinations of truth, or at least to develop an individualized aggregation of truth" (Chamberlin, 1890).

#### 4.1.3 IWRM domain delineation [2D/3D]

To meet one of the core requirements of the study, viz. to understand and map surface and groundwater interaction and to quantify it as far as possible in order to be able to integrate groundwater into the Pitman and the WRYM models, the groundwater study boundaries were defined by areas called Integrated Water Resource Management Domains (IWRM Domains).

The delineation of IWRM domain boundaries requires an understanding of the overall three-dimensional storage, distribution and transfers of groundwater between aquifers, in addition to knowledge of the spatial patterns of surface - water and groundwater interaction between the drainage network (rivers and streams) and the different (unconfined and confined) aquifer systems. Surface - water catchments and watersheds are therefore important in delineating IWRM domains, together with the 3-D geological understanding required to predict the groundwater flow paths between different aquifers.

The regional conceptual model and appropriate selection of Integrated Water Resource Model domains produce the likely boundary conditions for the different model domains, an overt understanding of what complexities, at what process scale for both surface and groundwater. These can then be simplified to adequately represent the real world in the model configuration because it inherently limits the risk of double accounting and facilitates conceptual development of conjunctive schemes. Over simplification or failing to represent the relevant scale of process in a model will result in physically incorrect patterns in the model result. Failure to appreciate the scale of the process that a calibration data set represents will result in incorrect model results or a model that will not calibrate.

#### 4.1.4 Aquifer specific water balance model [2D/3D]

It is possible to abstract and simplify to 2D only if the 3D process and geometry is adequately understood. For this reason the 2D GIS model is summed over an IWRM domain to limit potential double accounting inherent in the simplification of a 4D problem to 2D. Lithological units between which there is known to be lateral or vertical hydraulic connection and seasonal exchange of water are treated as a single aquifer and digitised from the 1:250 000 or 1:50 000 geology map depending upon the level of detail required. This reduces errors since the method only accounts for vertical recharge from rain. The rainfall surface is discretized into an annual measure of rain, summed for each rainfall isohyet which overlies these aquifer surfaces. Depending upon the rainfall volume and the aquifer type, a fixed percentage of this volume of water is assumed to recharge the aquifer.

As more detailed ground truth information becomes available, spatial detail about the local variation in recharge depending upon topography, rainfall event type, aquifer characteristics and water table elevation become available spatially. Weighted detail can be included relatively easily. The standard steady - state Mass Balance Equation is applied, using the range of published data for evapotranspiration, surface water runoff and base flow. The range in the value of these variables illustrates uncertainty in model results because evaluating recharge to any aquifer is about calculating a small number by subtracting various large numbers from a single total, viz. rainfall. Thus ensuring that aquifers are defined by geological characteristics and hydrological and hydrogeological processes reduces first - order spatial and potential double accounting errors ignored in non aquifer - specific or 1D approaches, which sum/discretize a total groundwater recharge volume per quaternary.

### 4.1.5 Aquifer specific dynamic storage model [3D/4D]

The steady state mass balance model uses long - term average data for rainfall and base flow. These can be combined with annual rainfall records or predicted data for the development of a dynamic storage model. The model is explained in Section 3.4.1. Although this is not a numerical model the calculated averaged water level responses give an indication of the feasibility of abstraction rates and the possibilities to cover drought periods with conjunctive use scenarios (see Section 4.1.6).

### 4.1.6 Numerical flow model [3D/4D]

Conceptual and semi-quantitative understanding can be tested against available field measurements and records of exploration results. If the conceptual model proves to be robust, careful selection of measured, derived and extrapolated data sets to configure, calibrate and test the steady state model in a predictive mode will support sensitivity analysis of input parameters to model output and the evaluation of uncertainties in model results. Time steps are generally large.

This approach supports the management of uncertainties in groundwater assessment and it also allows the modeller to prepare a physically real mesh yet limit numerical instabilities. Ongoing upgrade and revision of the model configuration and calibration will provide a sound analytical tool to be used in a Model, Monitor and Manage strategy for groundwater resource evaluation, development and management.

### 4.1.7 Aquifer operational /conjunctive use model [4D]

The benefits of conjunctive use of groundwater storage and dams can be evaluated with the Water Resources Yield Model (WRYM). This has the advantage that the groundwater well field accessing this aquifer would be able to use existing storage and conveyance infrastructure.

The following approach should be adopted:

- The conjunctive use scenarios are first evaluated in the Water Resources Yield Model (WRYM) for various groundwater abstraction capacities and operating rules.
- Thereafter, the dynamic storage model is used to provide an initial estimate of the impact of the abstraction scenarios on the TMG and on the contribution of groundwater to surface flows.
- The reduced estimate of the contribution of groundwater to surface flows is then used to adjust the yields obtained in the WRYM.

### 4.1.8 Wellfield design and management model [4D]

The last step in groundwater development and quantifying surface water / groundwater interaction is the development of a local scale, fully 3D transient flow model, which is based on the regional aquifer model to define far field boundary conditions and average hydraulic properties with adequate process insight and data to model at the required fine scale using smaller time steps.

## 4.2 CONCLUSIONS

The greatest error in groundwater resource evaluation and prediction of impacts on surface water and the environment is in unwarranted reduction of a 4D problem to 1D or 2D. To quantify a process in 2D it is necessary to have a 3D conceptual model and insight into the long term temporal patterns. To quantify in 3D (numerical models) it is necessary to have a physically real and verifiable insight into the likely variations in volumes, area and, at least the range in, expected seasonal variations and other factors that could influence this. A rule of thumb is that one can predict future behaviour of a system for double the number of years that one has data for, provided one clearly understands (even conceptually) the spatial detail and temporal pattern that is mapped by that data.

The recommended approach relies on three critical aspects, viz.

- data collection at appropriate spatial position and frequency intervals relevant to the decisions to be taken;
- team interaction between surface water and groundwater specialists that have the necessary skills and knowledge of the earth and water processes, and good communication between the disciplines; and
- timely implementation of relevant monitoring infrastructure and model upgrade.

The applicability and outcome of these models are summarised in **Table 4-1** with reference to the objectives of this study, i.e. water resource evaluation and compulsory licensing.

**Table 4-1 Applicability and outcome of the various models**

| | Conceptual Model | Water Balance Model | Numerical flow model | Wellfield model |
|---|---|---|---|---|
| **General (applicable to all themes)** | | | | |
| Design of 2D & numerical models | X | | | |
| Design of monitoring networks | X | | Refinement | |
| Evaluation & Assessment of data | X | | | |
| Evaluation & Assessment of Model Results | X | | | |
| **Water Resource Evaluation** | | | | |
| First order 'planning' numbers | | X | | |
| First order impact assessment | | X | | |
| First Order loss/gain to rivers to update WRYM | | | X | |
| Operational yield assessment | | | X | X |
| Rapid Reserve determination | | X | X | |
| **Compulsory Licensing (requires Water Resource Evaluation)** | | | | |
| Intermediate or comprehensive Reserve determination | | | X | X |
| Aquifer yield estimate for license (not of borehole) | | | X | |
| Estimate of impact of surface water usage on groundwater in storage | | | X | |
| Estimate of impact of groundwater abstraction on surface water flow | | | X | |
| Wellfield / Borehole licensing | | | | X |
| **Conjunctive Scheme Development (requires Water Resource Evaluation and Licensing)** | | | | |
| Scheme Concept & Design | X | | X | X |
| Scenario testing for (conjunctive) scheme options | | | X | |
| Wellfield management | | | | X |

# 5. WAY FORWARD

## 5.1 RECOMMENDATIONS FOR UPGRADE OF REGIONAL MODEL [2D/3D]

The results of the Water Balance Model show that uncertainty of the data input as well as the method applied 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.

### 5.1.1 Monitoring

A monitoring programme and additional data collection is detailed in the recommendations of the Data Availability Report (Volume 2; DWA, 2007a) and the Conceptual Model Report (Volume 3; DWA, 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.

The upgrade of the flow gauging station network with regards to low flow and flood flow measurements at key points in the river network is suggested and detailed in the Flow Gauge Assessment Report (DWA, 2006a). This assessment needs to be extended to the Hex and Nuy rivers for increasing the confidence in the reported MAR values for these catchments.

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

- Rainfall sampling and chemical / isotope analysis in selected recharge areas for calibration of the recharge model with the Chloride Mass Balance and Isotopes;
- Seasonal and event response sampling of rainfall, spring flow and groundwater for calculation of residence time and interflow/rejected recharge;
- Monitoring of key abstraction points for aquifer response to abstraction for considering the impact of existing groundwater use with 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 therefore suggested to develop a comprehensive monitoring programme for the Berg WAAS area that comprises all the above aspects in an integrated and optimised manner.

### 5.1.2 Modelling

It is recommended to align the discretisation for the surface water modelling with the boundaries of the groundwater regime to ensure that the surface water modelling scale ties in with groundwater flow path scale effects within each relevant aquifer and to account for subsurface transfer across catchment boundaries. The proposed IWRM domains allow for this integration and are considered the scale for the WRYM, which would also allow for the design of groundwater or conjunctive use schemes. However, the WRSM modelling should be undertaken on the scale of sub-domains that are aquifer and quaternary - catchment specific.

It is recommended to update the Water Balance Model, once additional data as outlined above is available, to verify the model and increase the confidence in the model results. This updated Water Balance Model can then replace the GRA II data for the Berg and upper Breede WMA.

## 5.2 RECOMMENDATIONS FOR UPGRADE OF DETAILED MODELS [2D/3D]

The results of the Water Balance Model for the TMG Aquifer in the Piketberg and Witzenberg-Nuy model domains 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 comprehensive data collection and monitoring programme. The following activities are required for increasing the confidence in the model outputs of any model updates or refinements.

### 5.2.1 Data collection requirements

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

### 5.2.2 Monitoring

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

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

### 5.2.3 Site specific concerns

If further exploitation of the aquifers in the **Piketberg area** is considered;

- a feasibility study is recommended that comprises the development of a flow model on the wellfield scale, based on long-term monitoring data, as described above.

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.

## 5.3 RECOMMENDATIONS FOR UPGRADE OF DETAILED MODELS [3D]

### 5.3.1 Breede Alluvium Model

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

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

### 5.3.2 Cape Flats Aquifer Model

Recommendations fall under the broad purposes of further model testing, and data collection to support further modelling. These recommendations can be summarised as:

- Test the robustness of the conceptual model by investigating whether significant groundwater flow occurs to the northwest and discharges to Table Bay. This requires additional water - level data in the northwest of the Cape Flats in order to interpret directions of groundwater flow. Additional basement data would be required in the northwest, from borehole logs and geophysical investigation.
- Hydraulic testing in which boreholes are drilled, logged accurately, and the basal layer targeted in the pump test. This would provide information on the extent of the basal gravels and additional basement-elevation data. The response of different layers of the aquifer, in response to pumping the basal gravels, is required. Stratigraphy - specific hydraulic parameters would further refine the model and increase confidence.
- Hydrocensus data collected across the Cape Flats area: water levels and borehole use, accurate X,Y and Z coordinates.

- Additional data should be sourced or collected in fieldwork on the river geometries, typical bed sediments, and most importantly the river stages.
- Smaller scale models are to be constructed for the purpose of optimisation of positions for additional abstraction, and to determine effect on other users / surface waters.
- Data on alien vegetation water usage and aerial extent is required in order to explicitly quantify evapotranspiration.
- Undertake model upgrade based on the above results, such that the model can be used as a predictive tool, supporting medium to long - term upgrade of the hydrological data and WRYM.

### 5.3.3 Langebaan Road Aquifer Model

Recommendations fall under the broad purposes of further model testing, and data collection to support further modelling. These recommendations can be summarised as:

- Hydrocensus data should be collected across the Langebaan area: water levels and borehole use, accurate GPS of X,Y,Z coordinates
- Undertake model upgrade based on the above results, such that the model can be used as a predictive tool supporting medium to long-term upgrade of the hydrological data and the WRYM.
- Additional modelling at a smaller scale in order to understand the hydraulic nature of the aquifers and replicate differing flow directions at different depths. In the vicinity of the Berg River this will generate a better understanding of the nature of the surface water – ground water interaction.
- Additional modelling at a smaller wellfield scale in order to manage the West Coast Wellfield abstraction.
- Smaller - scale model to be constructed for the purpose of optimisation of abstraction volume and rate, and positions, for additional potential wellfields and licensing thereof.
- Smaller - scale model to be constructed for the purpose of optimisation of ASR injection volume and rate, and borehole positions.

## 5.4 KEY RECOMMENDATIONS FOR INTEGRATED NUMERICAL SURFACE WATER – GROUNDWATER MODELLING

The most significant obstacle in the accurate regional scale quantification of surface water – groundwater exchange is the lack of data to a common datum. Groundwater is measured using sea level as a datum, and reported in metres above mean sea level. Surface water is typically measured as a flux. DWA has a network of surface flow gauges where river stage is monitored. However, measurements are taken as a height above a certain point (the v notch). These are not surveyed hence not comparable to metres above mean sea level. Once surveyed, the input data to the models developed here can be upgraded and the mass balance numbers revised.

## 5.5 SCOPE OF WORK

In order to facilitate the upgrade of models and further studies, the above mentioned recommendations are grouped into activity groups and detailed further. The proposed Scope of Work as contained in Appendix C is structured according to priorities and logical sequence of activities:

- Data Acquisition and Database Compilation
- Design and Implementation of Monitoring Network
- Ongoing Monitoring
- Data Analysis and Interpretation
- Modelling
- Review and Revision

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# APPENDICES

# APPENDIX A: VOL. 2 – 9: EXECUTIVE SUMMARIES

# GROUNDWATER MODEL REPORT VOLUME 2
# DATA AVAILABILITY AND EVALUATION

# EXECUTIVE SUMMARY

## INTRODUCTION

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

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

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

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

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

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

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

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

Volume 6: Langebaan Road Aquifer

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium

This report is Volume 2 in the project series. Volume 2 and 3 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.

**DATA SETS**

In order to determine the groundwater available in the WCWSS area by means of deterministic and numerical models, a variety of data is required for the different methods and modelling approaches employed. The required data sets refer to the 3D physical, chemical and biological conditions in the study area and the changes thereof over time. These parameters are grouped into the following categories:

- Topography,
- Hydrology,
- Hydroclimatology,
- Geology,
- Hydrogeology,
- Land Cover, and
- Water Use.

**Topography**

The 20 m Digital Elevation Model (DEM) was purchased for this project and is considered adequate for the groundwater tasks.

**Hydrology**

<u>Catchments</u>

Current catchment areas are defined by hydrological divides or watersheds. However, surface and groundwater catchment areas may not coincide and there is not a formally accepted delineation of how, in the IWRM context, these differences can be addressed when establishing a water balance for any one quaternary catchment. The delineation of IWRM domains for use as model domains for this study will be addressed in the Regional Conceptual Model Report (Volume 3).

<u>River flow and water level</u>

The river flow and water level data are only available from selected gauging stations and there are no hydrodynamic data along river reaches. The elevation between flow gauging stations will be automatically estimated in the GIS using the natural gradient of the river based on the 1:50 000 and 20 m DEM.

There are a number of rivers in which no flow gauges are available. Data from existing flow gauges will be used in model calibration for quaternary catchments without gauging stations under Task 8 to Task 10. Umvoto will use the model results for the groundwater modelling.

<u>Geometry and geological context of surface water bodies</u>

There is no site-specific or detailed data available on the geometry of river reaches, i.e what they look like in cross section, in the study area. However, these can be inferred from topographic and geological information. The basic geological context of a river reach – i.e. the stratigraphy underlying the river, can be determined from topographic and geological maps.

<u>Run-off</u>

The run - off data is only available as mean annual values per quaternary catchment. Time series data is only available as river flow at flow gauging stations at the downstream end of catchments. Since this parameter is important for the water balance model, it will be required to undertake a GIS model of the spatial distribution of run - off as a function of rainfall, altitude and slope.

Baseflow

There are no aquifer - specific values of baseflow, as the published data are summed per quaternary catchment. Additionally the published data display a huge range of values, depending upon the author and methodology.

In the fold terrain of the Western Cape it is unlikely that the aquifer, which outcrops on the valley sides, is in direct hydraulic contact with the river, except along specific reaches of a river where either the Skurweberg or the Peninsula Formation comprise both the valley sides as well as the valley floor and or the Rietvlei Formation is not overlain by the Gydo Formation of the Bokkeveld Group in the valley floors. These circumstances can be established from aerial photos, 1:50000 topographical and geological maps or at a more local scale from an orthophoto, if available.

The methodology adopted for this study comprises the following:

- As 1st order estimate the values for groundwater contribution to baseflow, as given in the GRDM software (DWA, 2006c), will be used.
- An attempt will be made to disaggregate these baseflow values within each catchment, based on outcrop area, location of springs, aquifer - specific recharge distribution and geological reasoning.
- The values will be updated during the study in an iteration process, based on results from both the surface water and groundwater modelling.

**Hydroclimatology**

Rainfall

There is sufficient rainfall data available, both as spatial distribution of mean annual and mean monthly values and as time series (daily or monthly) at several rainfall stations. However, due to inconsistencies between the MAP distribution from the CCWR in the high mountainous areas and the MAR values for these catchments, it was decided to develop a revised spatial distribution of MAP, based on additional rainfall data and rainfall stations. This revised MAP distribution will be used in the study.

Temperature

There are only few time series temperature data from selected weather stations in the study area available. However, there are spatial distributions of mean monthly temperature from the Agrohydrology data set that will be used for the project. The spatial distribution reflects the relationship between temperature and altitude. Mean monthly data are sufficient for estimation of actual evapotranspiration.

Evapotranspiration

The only available data are measurements and spatial distribution of potential evaporation. However, the actual evapotranspiration can be modelled, based on monthly temperature and monthly rainfall, applying the formula by Turc (1954) as adapted by Santoni (1964) for use in Mediterranean climate. In addition, transpiration data or water requirements for different vegetation types can be used to estimate spatial and seasonal distribution of evapotranspiration if this is required.

**Geology**

Lithology

The lithological data as digitised from the geological maps in 1:50 000 obtained from the Council for Geoscience (CGS) combined with the in - house local knowledge is sufficient for the purpose of this project.

Structural Features

The existing information and data on faults are sufficient and can be refined in the detailed model domains, if required, from structural analysis of existing data. However, the currently available data about the fracture network is very detailed in some areas of the study area, e.g. Piketberg and Hottentots Holland, while the data is not available at the required scale in other areas, especially in the northern part around Tulbagh, Ceres and Hex River. The information about fracture distribution and density is crucial for determining hydraulic parameters, hydraulic relevant thickness and interaction with surface water bodies.

It is therefore recommended to undertake a fracture mapping in the study area to fill these data gaps in all areas relevant for detailed modeling and for groundwater – surface water interaction.

Aquifer geometry

The aquifer thickness or saturated thickness values given in the GRA II data sets are unrealistic for the primary aquifers and the TMG aquifers. They do not take into account the vertical extent of water-bearing fracture systems in the TMG and the structurally controlled variability in thickness of the primary aquifers. Furthermore, the possibility of multi-layered aquifer systems and the occurrence of unconfined and confined aquifers are not considered.

The currently published information on paleochannels in the primary aquifers of the West Coast (SRK, 2004) and the Cape Flats does not coincide with the conceptual understanding of the geological processes for developing these paleochannels. Therefore, the bedrock topography will need to be revised, based on borehole information and first principles of geological processes.

For the purpose of this study the aquifer thickness of the relevant TMG aquifers will be modelled in the GIS from lithological contacts, faults, dip and strike information and geological reasoning.

**Hydrogeology**

Hydraulic Parameters

The regional parameter values given in the GRA II database are not reasonable and will not be used in this project. The spatial distribution does not take the different aquifers and the 3$^{rd}$ dimension into account. The preferred flow paths in the fractured rock aquifers are not considered.

However, there are sufficient localised data for the different aquifers under consideration, e.g. Cape Flats Aquifer, Langebaan Road Aquifer, Atlantis Aquifer, Peninsula Aquifer in Hermanus, Piketberg, Hex River and Citrusdal. The adopted approach can be summarised as follows:

- It is envisaged for the regional scale model to apply reasonable average values for different aquifers, based on local knowledge, literature, geological reasoning and actual measurements.

- For the detailed model areas, existing field data, additional field measurements, local knowledge and geological reasoning will be used to provide reasonable estimates of the relevant parameters and to develop spatial distribution maps for these.
- Finally, the transmissivity or hydraulic conductivity will be calibrated during the detailed numerical models and become a model output.

Recharge

The available spatial distribution of recharge does not take into account the behaviour and infiltration capacity of the different aquifers. Furthermore, there is no distinction between recharge and discharge areas of the different aquifers.

The approach adopted to estimate aquifer-specific recharge values is scale dependent, as described in the Inception Report (DWA, 2005a). The following steps will be undertaken to estimate recharge on a regional scale:

- Applying the aquifer-specific recharge model, as developed for the ISPs;
- Applying map-centric recharge simulation model with modelled distribution of run-off and actual evapotranspiration (see above). This type of model was originally developed in the CAGE project (DWA, 2000) and calibrated in the recent Clanwilliam project (DWA, 2006d). The original methodology will be revised and tested in this study area.
- Create time series data for monthly recharge values, based on monthly rainfall data, and apply seasonal changes to spatial distribution from map - centric simulation.

Groundwater levels

The national scale spatial distribution of groundwater levels from the GRA II project is not realistic, as it does not take into account the occurrence and 3$^{rd}$ dimension of the different aquifers. However, there are sufficient point data of groundwater level measurements on the NGDB and from local hydrocensus surveys for the detailed model domains.

- For the regional scale model it is envisaged to apply reasonable average values for different aquifers, based on local knowledge, literature, geological reasoning and actual measurements
- For the local scale models a spatial distribution of average values, based on field measurements, local knowledge and geological reasoning will be established as input into the models.
- The time series data from field measurements will be applied to transient model runs.
- Both the spatial distribution and the time series data are then used as reference data for the calibration of the models.

Springs

There is insufficient information about the distribution of distinct discharge sites and the actual discharge at springs. Additionally, the use of water from springs is often not registered with the DWA and therefore the uptake is not recorded, other than via allocation in the surface water system.

It is envisaged using the currently mapped springs and starting points of perennial rivers as 1$^{st}$ order indication of groundwater discharge sites. An estimation of discharge rates will be obtained by extrapolating flow records from hydrocensus data and the NGDB. The discharge sites will be assigned to the different aquifers, based on geological mapping and reasoning.

Hydrochemistry

There is no coherent data set on hydrochemistry for the whole study area available. There is good data coverage for EC and TDS as indicators of water quality, while only isolated data on other parameters exist. The importance of good hydrochemistry data is threefold:

- The fitness for use depends upon the chemical constituents in the water;
- Chloride and isotope data can be used to support recharge estimation and therefore the water resource evaluation;
- Macro and trace elements and isotope data can be used to distinguish between water from different aquifers as well as between surface water and groundwater.

The available regional water quality data are sufficient as indicators of fitness for use and will be used to determine the quantity of potable water. Sampling and analysis of groundwater and rainfall for Chloride is undertaken in several areas within and outside of the study domain and the data are considered sufficient on the regional scale.

Thermal Data

There is no comprehensive mapping of thermal springs available. There are also no time series data of temperature changes at hot springs. It is therefore envisaged to use the limited thermal data for the groundwater flow modeling as follows:

- Applying thermal data from the NGDB and TMGAA hydrocensus as indicators for the regional flow model
- Applying thermal data from selected boreholes and springs within the TMG Aquifer domain for calibration of heat and groundwater flow models.

**Land Cover**

Soil Cover

The scale of the available soil type map from the WR90 is very coarse. This information will only be used as background information and to qualitatively evaluate the recharge model results.

Vegetation Cover

There are two different existing data sets with vegetation data available, viz. the natural vegetation cover after Acocks and the land cover from the NLC 2000 project. Since the land cover represents the most recent situation of vegetation cover and land use, the NLC coverage will be used as support parameter for the recharge estimation and water use calculation. The results of both estimations will be qualitatively checked against the pattern of land use.

**Water Use**

Groundwater

The information on groundwater use in its current format is not sufficient for the purpose of this project. The data are averaged or summed per quaternary catchment (GRA II) or per cadastral farm (WARMS) and are therefore not aquifer specific.

There is also no information in these sources that indicates the seasonal fluctuations of groundwater use, the historical growth (or decline) in groundwater use, or in the case of WARMS from which aquifer the water is being abstracted. The following is envisaged to overcome these problems:

- Spatial disaggregation of water use data per catchment with respect to aquifers, based on registered usage, borehole distribution, land use, aquifer properties and local knowledge;

- Estimation of seasonal fluctuation of groundwater use, based on the assessment of irrigation requirements and percentage split between sectors;
- Indication of historical change in groundwater use, based on boreholes drilled per year, increase in agricultural areas, population growth and general development.

Surface water

There is sufficient spatial information about the allocation from surface water and the capacities and yields of dams. However, the actual consumption is monitored only in terms of the major dams and mainly in terms of domestic and urban use. The uptake by farmers for irrigation can only be estimated from land use, irrigation requirements and actual climatic conditions.

**CONCLUSIONS AND RECOMMENDATIONS**

The main conclusion that can be drawn from the assessment of available data is that there is adequate data to initiate modelling, to configure the proposed models, and to run these models to contribute to an improved groundwater resource evaluation.

Conceptual and semi-quantitative understanding can be tested against available field measurements and records of exploration results. If the conceptual model proves to be robust, careful selection of measured, derived and extrapolated data sets to configure, calibrate and test the model in a predictive mode will support sensitivity analysis of input parameters to model output and the evaluation of uncertainties in model results.

This approach supports the management of uncertainties in groundwater assessment and it also allows the modeller to prepare a physically real mesh yet limit numerical instabilities. Ongoing upgrade and revision of the model configuration and calibration will provide a sound analytical tool to be used in a Model, Monitor and Manage strategy for groundwater resource evaluation, development and management.

The required parameters, data sources and specific comments are documented in **Table E-1** below.

**Table E-1: Summary Table of Parameters and Data Sources used in the Project**

| Parameter | Data used | Comment |
|---|---|---|
| | | |
| **Topography** | | |
| Digital elevation model (DEM) | ComputaMaps | |
| | | |
| **Hydrology** | | |
| Quaternary catchments | WR90 | |
| IWRM Domain | | Model Output |
| Surface Water Bodies | CDSM | |
| Rivers | CDSM | |
| Flow gauges | WR90, NS | |
| Stream flow records | DWAF, NS | |
| Run off | WR90, NS | Model Output |
| Baseflow | Different Sources | |
| Groundwater contribution to Baseflow | GRDM | Model Output |
| | | |
| **Hydroclimatology** | | |
| Mean Annual Precipitation | NS | |
| Median monthly rainfall | Agrohydrology | Adjusted with NS MAP |
| Rainfall stations | SAWS, NS | |
| Rainfall time series | NS | |
| Mean Annual Temperature | Agrohydrology | |
| Mean monthly maximum Temperature | Agrohydrology | |
| Temperature time series | SAWS | |
| Mean Annual Evaporation | Agrohydrology | |
| Mean Monthly Evaporation | Agrohydrology | |
| Mean Annual Evapotranspiration | | Model Output |
| Mean Monthly Evapotranspiration | | Model Output |
| | | |
| **Geology** | | |
| 1:50000 geology maps | Council for Geoscience | |
| 1:250000 geology maps | Council for Geoscience | |
| Folds | | Umvoto mapping |
| Faults | Council for Geoscience | Re-interpreted |
| Fractures | | Umvoto mapping |
| Bedrock topography for Cape Flats | Different sources | Re-interpreted |
| Bedrock topography for West Coast | Different sources | Re-interpreted |
| Bedrock topography for Breede Alluvium | Different sources | Re-interpreted |
| Porosity | Different sources | |
| Aquifer thickness | Different sources | Model Output |
| | | |
| **Hydrogeology** | | |
| Aquifer yield | Combined Database | Model Output |
| Groundwater Storage | | Model Output |
| Transmissivity $m^2$/day | Combined Database | |
| Hydraulic conductivity | Combined Database | |
| Borehole yield | Combined Database | |
| Storage coefficient | Combined Database | |
| Specific Yield | Combined Database | |
| Spring locations | Combined Database | Re-interpreted |
| Recharge | Combined Database | Model Output |

| Parameter | Data used | Comment |
|---|---|---|
| Waterlevel (mamsl) | Combined Database | |
| Waterlevel (mbgl) | Combined Database | |
| Water chemistry data | Combined Database | |
| Water temperature data | Combined Database | |
| | | |
| **Land Cover** | | |
| Land Cover | NLC 2000 | Updated by NS |
| Soil Cover | WR90 | Partially updated by NS |
| | | |
| **Water Use** | | |
| Groundwater abstraction, water use | Combined Database | Re-interpreted |
| Annual groundwater abstraction | DWAF / GRA II | |

The assessment of the data available for use in this study and the development of the conceptual models and approach at a regional and at an individual aquifer scale (see Volume 3) have highlighted the following data gaps:

- location of perennial springs
- time series for spring flow
- spring hydrochemistry (macro and trace)
- isotopic characterization of spring and seep zones and groundwater
- thermal measurements of springs and groundwater
- event response changes in spring flow and groundwater level
- widely-distributed hydraulic parameters for the TMG Aquifer
- bedrock topography along the West Coast
- volume and pattern of groundwater use per aquifer
- uniform scale of fracture mapping
- geological anomalies in the 1:50 000 geological field sheets.

It is therefore recommended that the following data collection activities be undertaken in a follow up study:

- Comprehensive spring hydrocensus
- Borehole hydrocensus
- Fracture mapping in TMG terrain
- Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg aquifers
- Mapping of paleochannels and bedrock topography in West Coast and alluvium aquifers
- Hydrochemical sampling at specific river reaches
- Review and revise monitoring network
- Review and revise geological mapping in selected areas.

Since it is not expected that these will be undertaken and or become available in time for use in this study, preliminary assumptions will be made as part of this study.

# GROUNDWATER MODEL REPORT VOLUME 3
# REGIONAL CONCEPTUAL MODEL

# EXECUTIVE SUMMARY

## INTRODUCTION

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

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

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

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

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

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

These volumes are:

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

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

Volume 6: Langebaan Road Aquifer

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium

This report is Volume 3 in the project series. Volume 2 and 3 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.

## AQUIFER PRINCIPLES

This Conceptual Model Volume outlines a strategic aquifer-specific approach to groundwater resource assessment at a regional or a local scale and documents a methodology that can be applied in any other geographic region since it is based on first principles. It is necessary to adopt an aquifer-specific approach to support regulatory decisions (as compulsory licensing) about sustainable aquifer, wellfield or borehole yield as well as the impacts of abstraction.

The aquifers considered here include the regionally relevant Table Mountain Group (TMG) aquifers viz. the Skurweberg and the Peninsula Aquifers ("fractured rock aquifers") and also the larger and more significant primary aquifers within the study domain which are the Sandveld (Langebaan and the Cape Flats) and the Breede Alluvium Aquifers ("Intergranular aquifers"). The "fractured-and-weathered" or regolith zones are largely disregarded in this study, except where they might interface laterally with, or grade into, the afore-mentioned aquifers.

## STUDY DOMAIN

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. About 17% of the total water requirements in the Breede WMA are estimated to be supplied from groundwater, while the estimation for the Berg WMA is about 6% (DWAF, 2003).

The topography, drainage, hydroclimate, land-use and even the agricultural crops are largely determined by the underlying rock type and its structural character. This strong geological control also exerts an influence on the local climate and land-use potential, through orographic control over precipitation and the widely variable geochemical composition of the different formations. The western half of the study area is host to predominantly Pre-Cape basement including rocks of the **Malmesbury Group** and the intrusive **Cape Granite Suite**, overlain by quaternary sediments of the **Sandveld Group**. The Cape Fold Belt comprising rocks of the **Table Mountain Group** (TMG) and the overlying Post-Cape **Bokkeveld** and **Witteberg Groups** as well as **Karoo Supergroup** dominate the eastern half of the study area.

## REGIONAL CONCEPTUAL MODEL

The purpose of the present modelling study is to provide a sound quantitative basis for water resource assessment in the future. The process for calculating the aquifer-specific mass balance and or catchment mass balance is as follows: The recharge areas are defined based on physically measurable aquifer outcrop areas underlying rainfall isohyets. These are correlated to the known discharge sites (considering volume, water quality, isotopic character and temperature) with likely flow paths defined by 3D structural geology and hydrostratigraphic relationships. Cross checks as regards temperature, chemistry and isotopic character of discharge water allows qualitative evaluation of the conceptual flow model.

The TMG is well known for the occurrence of numerous spring systems, discharge points of groundwater flow. The study area is host to several hot springs, among them Brandvlei and Goudini. Water temperature measurements in springs, boreholes and streams provide a potentially important source of information about deep groundwater flow paths within the TMG aquifer system.

As part of the groundwater flow-path investigations, eleven definite structural zones of increased hydraulic conductivity (so-called "hydrotects") were identified. The evidence for their existence takes the form of a definite spatial association between springs and high-yielding boreholes, on the one hand, and major geological fracture systems, on the other hand. These hydrotects are the preferred flow paths that link the major recharge zones to the discharge sites within any one aquifer.

Groundwater and surface water interact at many places throughout the landscape. These interactions can be highly dynamic as they respond to the variations and changes in the hydraulic gradients which drive the flows between them.

**INTEGRATED WATER RESOURCE MANAGEMENT**

During the Hydrogeological Reconnaissance Report for the City of Cape Town (CCT) Table Mountain Group Aquifer Feasibility Study and Pilot Project (CMC, 2004), the concept of an Integrated Water Resource Management (IWRM) domain was introduced. The purpose for establishing IWRM domains is to "initiate the planning for the groundwater modelling as well as the Water Resource Yield Model (WRYM) development and to promote the integration of surface water groundwater and ecological monitoring within a domain that conceivably responds differently in time but has the same boundary conditions". Each of the fifteen IWRM domains are chosen such that they can effectively be considered isolated units. This was done with an understanding of the spatial and temporal distribution of both surface and groundwater flow, in addition to knowledge of the water recharge, storage and discharge areas.

**DETAILED MODEL DOMAINS**

Five detailed model domain areas were selected and delineated as part of the requirements of this study.

| Small Model Domain | Aquifer of Interest |
|---|---|
| | |
| Cape Flats | Cape Flats "Intergranular" Aquifer |
| Langebaan Road and Geelbek | Langebaan Road and Geelbek "Intergranular" Aquifers |
| Piketberg | Peninsula "Fractured-Rock" Aquifer and<br>Sandveld "Intergranular" Aquifer |
| Witzenberg-Nuy Valley | Peninsula and Skurweberg "Fractured-Rock" Aquifers |
| Breede River Alluvium | Breede River Alluvial "Intergranular" Aquifer and<br>Peninsula and Skurweberg "Fractured-Rock" Aquifers |

**CONCLUSIONS**

- Recharge to the TMG aquifers occurs in the high-lying mountainous ranges of the Cape Fold Belt.
- Recharge to the Sandveld aquifers occurs in the areas of aquifer exposure as well as through lateral and flood recharge.
- The groundwater from the different aquifers discharges either into rivers and streams via springs or along river reaches, or direct into the ocean. In some areas groundwater from the TMG discharges into the alluvium aquifers.
- Groundwater flow in the TMG aquifers follows structurally-controlled preferred flow paths, called hydrotects.
- Groundwater flow in the Sandveld aquifers is controlled by the current surface topography and the bedrock topography, forming palaeo channels.

**RECOMMENDATIONS**

The following data collection activities are recommended for verification of model assumptions and to increase the confidence of hydraulic parameters and hence model outputs.

- Spring hydrocensus
- Borehole hydrocensus
- Fracture mapping in TMG terrain
- Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg aquifers
- Mapping of palaeo channels and bedrock topography in West Coast and alluvium aquifers
- Hydrochemical sampling at specific river reaches
- Review and revise geological mapping in selected areas
- Review and revise monitoring network.

The following recommendations are made for the subsequent water balance model and the detailed groundwater flow models:

a) Extend the study area for the groundwater component at the northern boundary to reflect the results of the structural analysis and conceptual flow modelling in these areas.

b) Undertake the water balance modelling for the extended study area on an aquifer-specific basis.

c) Combine the proposed detailed models of Task 15b (TMG Tulbagh – Ceres) and Task 15c (TMG Hex River Mountains) into one model domain, called TMG Witzenberg – Nuy Valley.

d) Restrict the detailed modelling of the West Coast aquifers (Task 14a) to the Langebaan Road and Geelbek aquifers.

e) Extend the model domain for the detailed model of Task 15d (TMG Piketberg) towards the coast to include the interaction with the primary aquifer in the Verlorenvlei palaeo channel.

f) Set-up, configure and run the detailed groundwater flow models for the revised model domains:

   - Cape Flats aquifer
   - Langebaan Road and Geelbek aquifers
   - Piketberg TMG and Verlorenvlei palaeo channel aquifers
   - TMG Witzenberg – Nuy Valley aquifers
   - Breede Alluvium

# GROUNDWATER MODEL REPORT VOLUME 4
# REGIONAL WATER BALANCE MODEL

# EXECUTIVE SUMMARY

## INTRODUCTION

The Assessment of Water Availability in the Berg Catchment (WMA19) by means of Water Resource related Models (short title: Berg 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). 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.

This report is Volume 4 in the project series. Volume 3 and 4 are to be read in conjunction with each other as the conceptual model has informed the delineation of IWRM domains and the breakdown into aquifer types, as used in the water balance model.

## STUDY DOMAIN

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. About 17% of the total water requirements in the Breede WMA are estimated to be supplied from groundwater, while the estimation for the Berg WMA is about 6% of the total water requirements (DWAF, 2003b).

The topography, drainage, hydroclimate, land-use and even the agricultural crops are largely determined by the underlying rock type and its structural character. This strong geological control also exerts an influence on the local climate and land-use potential, through orographic control over precipitation and the widely variable geochemical composition of the different formations. The western half of the study area is host to predominantly Pre-Cape basement including rocks of the **Malmesbury Group** and the intrusive **Cape Granite Suite**, overlain by quaternary sediments of the **Sandveld Group**. The Cape Fold Belt comprising rocks of the **Table Mountain Group** (TMG) and the overlying Post-Cape **Bokkeveld** and **Witteberg Groups** as well as **Karoo Supergroup** dominate the eastern half of the study area.

The aquifers considered here include the regionally relevant Table Mountain Group (TMG) aquifers viz. the Skurweberg and the Peninsula Aquifers (“Fractured rock aquifers”) and also the larger and more significant primary aquifers within the study domain which are the Sandveld (Langebaan and the Cape Flats aquifers) and the Breede Alluvium Aquifers (“Intergranular aquifers”). The “fractured-and-weathered” or regolith zones are largely disregarded in this study, except where they might interface laterally with, or grade into, the afore-mentioned aquifers.

## REGIONAL WATER BALANCE MODEL

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

### Storage

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

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

The results indicate a storage capacity within the Peninsula Aquifer alone of 366,705 million $m^3$ (see **Table E-1**), which are 2 to 3 orders of magnitude higher than the capacity of the surface water storage facilities in the study domain.

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

| Peninsula Aquifer | Area ($km^2$) | Rock Volume (Million $m^3$) | Pore Volume (Million $m^3$) |
|---|---|---|---|
| | | | |
| Unconfined portion | 1 750.27 | 1 414 520 | 70 726 |
| Confined portion | 5 112.44 | 5 919 580 | 295 979 |
| Whole Peninsula Aquifer | 6 862.71 | 7 334 100 | 366 705 |

### 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 Chloride Mass Balance method and the Saturated Volume Fluctuation method, are applied in localised areas to compare with the regional estimation.

From the comparison of the different recharge methods, as shown in **Table E-2**, it is evident that the map-centric simulation results in very 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 water balance method developed for the ISP studies results in high recharge to the TMG aquifers and lower recharge to the intergranular and intergranular-fractured aquifers. For comparison, the results of both methods will be used for further analysis in the water balance and yield model, as best and worst case, respectively.

**Table E-2 Comparison of recharge estimations**

| Aquifer type | Recharge [million $m^3$/a] | | | | | |
|---|---|---|---|---|---|---|
| | Fixed % | BRBS | ISP | GRA II | Map-centric | SVF conf |
| | | | | | | |
| Peninsula | 404 | 406 | 511 | 433 | 214 | 384 |
| Nardouw | 140 | 215 | 275 | 241 | 196 | N/a |
| Fractured | 7 | 7 | 10 | 6 | 11 | N/a |
| Intergranular-fractured | 123 | 223 | 222 | 323 | 348 | N/a |
| Intergranular | 147 | 375 | 363 | 326 | 350 | N/a |
| Total aquifer specific | 822 | 1 227 | 1 381 | 1 328 | 1 119 | N/a |

**Discharge**

Discharge from the aquifer systems occurs as natural discharge via springs or baseflow, and as groundwater abstraction. For both, the currently available regional estimates are disaggregated into aquifer specific values, using assumptions and knowledge about distribution of discharge sites and boreholes. A comparison between the GRA II data sets on groundwater use and the WARMS database shows significant differences in both the aquifer specific distribution and the total volume (see **Table E-3**). The data from the WARMS are considered conservative and will be used in determining the groundwater potential.

**Table E-3 Estimated groundwater use per aquifer**

| **Source and Method** | Peninsula Aquifer *Million $m^3$/a* | Nardouw Aquifer *Million $m^3$/a* | Other Fractured Aquifers *Million $m^3$/a* | Intergranular fractured Aquifers *Million $m^3$/a* | Intergranular Aquifers *Million $m^3$/a* | **Total Groundwater use** *Million $m^3$/a* |
|---|---|---|---|---|---|---|
| **Disaggregating of GRA II** | 14.57 | 23.83 | 1.48 | 51.40 | 58.48 | **149.76** |
| **WARMS / NGDB** | 8.58 | 20.60 | 0.60 | 58.44 | 92.63 | **180.86** |

**YIELD MODEL**

The water balance and yield model suggests a total remaining long-term averaged groundwater potential of 741 million $m^3$/a within the study area, based on a comparison of the map-centric recharge estimation, baseflow and current groundwater use (see **Table E-4**). The results for applying the recharge estimation based on the water balance method developed for the ISP studies suggest a total groundwater potential of 1 003 million $m^3$/a. Using the average of the different recharge estimations, the total groundwater potential is estimated at 869 million $m^3$/a. A significant part of the groundwater potential is lost either to the sea or as rejected recharge, if not utilised.

**Table E-4 Summary results of groundwater potential per aquifer [million $m^3/a$]**

| Aquifer | Method | Recharge | Baseflow | Recharge - Baseflow | Groundwater Use | Groundwater Potential (Re – BF - Use) |
|---|---|---|---|---|---|---|
| **Intergranular** | Map-centric | 350 | 41.1 | 309 | 92.6 | 217 |
| | ISP | 363 | 36.6 | 327 | 92.6 | 234 |
| | **Average** | **355** | **41.1** | **314** | **92.6** | **222** |
| **Intergranular fractured** | Map-centric | 348 | 54.1 | 294 | 58.4 | 236 |
| | ISP | 222 | 28.5 | 194 | 58.4 | 135 |
| | **Average** | **267** | **39.2** | **228** | **58.4** | **170** |
| **Fractured** | Map-centric | 10.8 | 0.6 | 10.2 | 0.6 | 9.6 |
| | ISP | 9.6 | 0.9 | 8.7 | 0.6 | 8.1 |
| | **Average** | **8.0** | **0.7** | **7.3** | **0.6** | **6.7** |
| **Nardouw** | Map-centric | 196 | 43.2 | 152 | 20.6 | 132 |
| | ISP | 275 | 49.3 | 226 | 20.6 | 205 |
| | **Average** | **226** | **46.2** | **180** | **20.6** | **159** |
| **Peninsula** | Map-centric | 214 | 57.9 | 156 | 8.6 | 148 |
| | ISP | 511 | 81.6 | 429 | 8.6 | 420 |
| | **Average** | **390** | **69.7** | **320** | **8.6** | **312** |
| **Total** | Map-centric | 1119 | 197 | 922 | 181 | 741 |
| | ISP | 1381 | 197 | 1184 | 181 | 1003 |
| | **Average** | **1247** | **197** | **1050** | **181** | **869** |

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 158 and 633 million $m^3$, depending upon the acceptable average drawdown of between 5m and 20m respectively.

The results of the water balance and yield model will be used as input to the WRSM and WRYM. The review of the applicability of the Sami Module (DWA, 2007d) revealed that the module has inherent assumptions that are not met in most of the study area. There are only few catchments within the Berg WAAS area, where most of the assumptions are met and the module therefore might work. The assumptions are summarized as follows:

1. Single homogenous aquifer in catchment, with uniform gradient and isotropic parameter distribution
2. Shallow aquifer, water table near surface, that is connected to surface water body along the whole length of the river reach
3. Unconfined aquifer
4. Well-established initial water level for starting month of simulation period
5. Groundwater flows directly towards single main stem; no asymmetry in perennial tributary pattern
6. Catchment free of endorheic drainage areas.

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

In addition to the data collection activities as recommended in the Data Availability Report (DWAF, 2007a) long-term monitoring should be initiated for the following aspects:

- Rainfall sampling and chemical / isotope analysis in selected recharge areas for calibration of 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 suggested to develop a comprehensive monitoring programme for the Berg WAAS area that comprises all relevant aspects in an integrated and optimised manner.

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 Water Resources Simulation Model (WRSM) and Water Resources Yield Model (WRYM). Hence, the development of alternatives to these modules is strongly suggested that comprises:

- Applying the aquifer specific distribution of groundwater contribution to baseflow in the Pitman model
- Applying the aquifer specific storage volumes in the WRYM as per scheme spatial and operational definition.

# GROUNDWATER MODEL REPORT VOLUME 5
# CAPE FLATS AQUIFER 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 (DWA, 2005a):

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

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

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

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

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

These volumes are:

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

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer  - Steady State

Volume 5b: Cape Flats Aquifer – Transient State

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

**THE CAPE FLATS STUDY AREA**

The Cape Flats covers an area in excess of 400 $km^2$ (Hay, 1981, DWA, 2005), extending from False Bay in the south to the Tygerberg Hills in the northeast and Milnerton in the northwest. It is bounded by Table Mountain in the west and the hills of Kanonkop at Brackenfell in the east. As the name suggests, the topography is relatively flat with elevations ranging from 0 mamsl in the south to only 110 mamsl in the northeast. Drainage patterns are controlled by the surface topography and the main rivers (the Kuils and the Lotus) flow in a north-south direction towards False Bay. The Elsieskraal flows from the northeast to the west and discharges to the north of Table Bay.

Cape Town and environs has a Mediterranean climate. Mean annual evaporation exceeds precipitation by more than double. The rain falls in the winter and April to September is the wettest 6-month period. Analysis of monthly rainfall data within the Cape Flats model area shows 82% of the rainfall occurs in these months.

The Quaternary Sands that form the relatively thin Cape Flats Aquifer comprise fluvial, marine and aeolian deposited sands. The sands overlie the weathered Malmesbury and granite basement rocks which act as an aquiclude. The Quaternary Sands are heterogeneous multi-layered sands, consisting of interbedded sands, clay, clayey sand, limestone, sandstone, coarse gravels and peats. Distinct stratigraphic groups have been described within the Quaternary Sands but the lateral continuity across the Cape Flats is questionable. A summarised general geological section is presented detailing basal fluvial channel gravels present in palaeochannels, overlain by a fining upward sequence, overlain by a sand unit which has an interbedded calcrete layer.

Focussing on geological features salient to the hydrogeology, and on the basis that the Cape Flats model is a large-scale model, it is accepted that at the largest scale a broad distinction of 2 discrete layers is possible. Below the approximate depth of sea level, the sand unit has a greater abundance of coarse sediment layers. Above this level, the sands have more peat.

The near-surface groundwater-flow direction parallels the surface water drainage. Groundwater generally flows in a semi radial fashion from the higher lying basement in the northeast near Durbanville, toward Table Bay to the northwest and the False Bay coast to the south. The basement topography shows a palaeochannel of the Kuils River aligned north-south roughly in the west of the model domain. Coarser-grained deposits of fluvial sands and gravels in this palaeochannel provide a preferred flow-path southwards. The hydraulic nature of the aquifer is scale dependent. The sands are considered to be dominantly unconfined with regard to the largest spatial scale. At the smaller scale the aquifer will have a complex multi layered semi confined nature.

There is direct interaction between surface water and groundwater flow. In winter, elevated rainfall and surface water run-off recharges the groundwater in the aquifer. As the water table rises the groundwater begins to recharge the overlying rivers. During summer the groundwater levels reduce as recharge ceases and discharge continues, and in due course the rivers recharge the aquifer again until the next winter. The main rivers (the Kuils, the Elsieskraal, and the Lotus) that flow through the Cape Metropolitan Area have in part been channelized and lined with concrete but are not necessarily impermeable to the aquifer. This direct interaction between surface water flow in the rivers and groundwater flow in the aquifer has implications with regard to contamination of the aquifer by pollution in the form of industrial and urban waste in the rivers.

## CONCEPTUAL MODEL

The conceptual model assumes that:

- The aquifer is dominantly unconfined. The degree to which any confinement may exist is dictated by the difference in hydraulic conductivity between layers, which is a calibration parameter.
- The aquifer is underlain by impermeable basement.
- Water is sourced by rainfall, and leaves the aquifer through outflow to the ocean, abstraction and rivers. Recharge is assumed net (accounting for evapotranspiration).
- Canalised reaches of rivers are hydraulically disconnected from the aquifer.
- Deep groundwater flows to the south discharging to False Bay, shallow groundwater and surface water flows to the northwest discharging to Table Bay.

## NUMERICAL MODEL

A fully 3D finite element model is developed of an ~350 km$^2$ area with >61 000 nodes and ~100 000 prismatic elements. The elements are 450 – 60 m in length. The landward boundaries of the numerical model lie along rivers as transfer boundary conditions. The ocean acts as a constant head in the south. The model is 4-layered.

The following data sets were used to construct the bedrock topography:

- Borehole depths from the 1:50 000 geological map series,
- Borehole depths provided by Wessels and Greeff, 1980, Henzen 1973, and Rogers 1980.
- Spot height on bedrock outcrops as shown in the 1:250 000 geological maps

The recharge data used in the model is generated through a modified version of the BRBS method (DWA, 2002). Recharge over the modelled area is 31 000 m$^3$/d or 11 million m$^3$/a.

WARMS data was used for abstractions. The total abstraction over the modelled area is 10 000 m$^3$/d or 3 million m$^3$/a.

As per the model assumptions that the rivers act as sinks to the aquifers the river stages were set below the groundwater level. River stages were set on average at 4.5 m below topography in the river node.

A calibration standard of modelled water levels within 10% average error to observed point data is set. The model is calibrated to this standard with the use of groundwater fluxes and groundwater as compared to topography as an additional guide.

The numerical model results confirmed what was assumed in the conceptual model viz. that the basal gravels are higher hydraulic conductivity than the rest of the aquifer as the model calibrated with higher hydraulic conductivity in the basal layer, existing only within palaeochannels. The model basal layer within the palaeochannels calibrated with a horizontal hydraulic conductivity of 84 m/d. Above the high hydraulic conductivity palaeochannels an area of low horizontal hydraulic conductivity was input to the model, of 0.1 m/d. The remainder of the model has a horizontal hydraulic conductivity of 10 m/d. The model calibrated with the vertical hydraulic conductivity an order of magnitude less than the horizontal hydraulic conductivity.

## MODEL RESULTS

Three model scenarios are developed:

Scenario A: the base case, attained through calibration of K and transfer rate. All canalised rivers in the real world are assumed hydraulically disconnected in the model.

Scenario B: tested the uncertainties in efficacy of canalisation and the uncertainty in flow out of the model domain along the western boundary by making selected rivers in the northwest and along the western boundary able to transfer water into or out of the model.

Scenario C: tests the model sensitivity to the application of observed point data as known groundwater levels in the model.

The results show the ocean as a dominant sink to the aquifer, and that on average the rivers behave as sinks. The modelled groundwater fluxes are shown in **Table E-1**.

**Table E-1 Modelled Groundwater Fluxes**

| Scenario | Mass Balance ($m^3$/day) | | |
|---|---|---|---|
| | To Ocean | Model to rivers | Rivers to model |
| Model Scenario A | 16000 | 6610 | 2320 |
| Model Scenario B | 17100 | 7500 | 4180 |
| Model Scenario C | 19200 | 8590 | 3960 |

Surface water- groundwater fluxes are presented per quaternary (**Table E-2**). The fluxes differ significantly between Scenario A, B and C (by up to 70%).

**Table E-2 Surface water - groundwater fluxes per Quaternary**

*(% are given as compared to the total flux to surface water for that model scenario)*

| Quaternary Catchment | Rivers | Model Scenario | Flux into Model ($m^3/d$) | Flux out of Model ($m^3/d$) | Net ($m^3/d$) |
|---|---|---|---|---|---|
| G22C | Elsieskraal and Vyekraal | A | 0 | -3783<br>57% of flux to SW from aquifer | -3783 |
| | | B | 0 | -4094<br>55% of flux to SW from aquifer | -4090<br>- |
| | | C | 0 | -4843<br>56% of flux to SW from aquifer | -4843 |
| G22D | Lotus, Rondevlei and Zeekoevlei | A | 1572<br>68% of flux from SW to aquifer | -1074<br>16% of flux to SW from aquifer | +498 |
| | | B | +3441<br>82% of flux from SW across | -1700<br>23% of flux to SW from aquifer | +1741<br>- |
| | | C | +3232<br>82% of flux from SW across | -1833<br>21% of flux to SW from aquifer | +1399 |
| G22E | Kuils | A | +743<br>32% of flux from SW across | -1755<br>27% of flux to SW from aquifer | -1012 |
| | | B | +743<br>18% of flux from SW across | -1720<br>23% of flux to SW from aquifer | -977<br>- |
| | | c | +729<br>18% of flux from SW across | -1958<br>22% of flux to SW from aquifer | -1229 |

The effect of abstraction is shown in **Table E-3**.

**Table E-3 The effect of Abstraction on modelled water balance fluxes**

*The difference is calculated as a % change, from no abstraction to abstraction.*

| Scenario | | Flux into Model ($m^3$/d) | | Flux out of Model ($m^3$/d) | | | Balance ($m^3$/d) |
|---|---|---|---|---|---|---|---|
| | | Recharge | Rivers | Rivers | Ocean | Abstraction | |
| A | Abstraction | +31022 | +2320 | -6610 | -16,000 | -10,794 | -225 |
| | Zero Abstraction | +31022 | +1735 | -8830 | -23,900 | 0 | -1 |
| | Difference caused by abstraction | - | Increase of 33% | Decrease of 25% | Decrease of 33% | - | - |
| B | Abstraction | +31022 | +4189 | -7495 | -17,172 | -10,794 | -250 |
| | Zero Abstraction | +31022 | +3067 | -9897 | -24,200 | 0 | -8 |
| | Difference caused by abstraction | - | Increase of 37% | Decrease of 24% | Decrease of 29% | - | - |
| C | Abstraction | +31022 | +3960 | -8590 | -19,200 | -10,794 | 0 |
| | Zero Abstraction | +31022 | -2890 | -11,000 | -26,000 | 0 | 0 |
| | Difference caused by abstraction | - | Increase of 37% | Decrease of 22% | Decrease of 26% | - | - |

The seasonal variation of the aquifer was simulated in transient modelling. The best fit was achieved using a specific yield of 3%, very low for a dominantly sand aquifer. Scenario testing on the transient model suggests that there is a resource available for additional abstraction, and that additional abstraction could be effective in reducing water levels enough that winter flooding is reduced or mitigated. The results suggest an additional “safe yield” of ~2 million $m^3$/annum is available, from the northern palaeochannel areas.

## RECOMMENDATIONS

The following recommendations are made in order to upgrade the model in the future.

| Purpose | Aspect | Information required | Source of information |
|---|---|---|---|
| Boundary Conditions and Conceptual model refinement | Investigate whether significant groundwater flow occurs to the northwest discharging to Table Bay. | Basement elevation data, especially in the northwest | Geophysical investigation<br>Borehole logs<br>New boreholes |
| | | Water table surface map | Additional water level point data, especially in northwest |
| | Investigate whether groundwater mounds exist across the water level surface or whether these are topographic imprints. | Water table surface map More data | Additional and more reliable water level point data across the Cape Flats |
| | Detail the hydraulic nature of the aquifer and the nature of confinement or not | Pump test results;<br>Downhole geophysics;<br>Estimates of porosity to refine model layers;<br>Field estimates for different layers. | Pump test conducted in the central palaeochannel;<br>Layer specific monitoring |
| Improve confidence in numerical model | Test reliability of numerical model boundary conditions and uniqueness of model solution for SW-GW interactions;<br>Run model scenario with rivers as internal boundaries, and no flow boundaries at the aerial limit of the aquifer | Information above required to populate the larger model domain (especially to the northwest) | As above. |
| | More accurate representation of rivers | Actual data on river stages, and river widths, thus reducing the potential range of transfer rate parameter and improving confidence in the SW-GW interaction numbers | Field measurements of actual river widths;<br>River stage data |

All original input data directly used in the model and the final model files (Feflow files in “fem” format) are presented in the companion CD. Input data generated within the model files (such as boundary conditions) are stored within the Feflow files. These can be produced in non-Feflow format on request.

# GROUNDWATER MODEL REPORT VOLUME 6
# LANGEBAAN ROAD AND ELANDSFONTEIN AQUIFER SYSTEM MODEL

# EXECUTIVE SUMMARY

## INTRODUCTION

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

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

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

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

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

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

These volumes are:

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

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer Model

Volume 6: Langebaan Road and Elandsfontein Aquifer System Model

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium Model

This report is Volume 6 in the project series. Volumes 2 and 3 can be read as a background to this report as the available data has informed the regional conceptual model, and the regional conceptual model has informed the delineation of individual model domains, data selection for model input and calibration.

**THE LANGEBAAN ROAD AND ELANDSFONTEIN STUDY AREA**

Wave-cut terraces overlain by aeolian dunes dominate the topography of the Langebaan area, with sand covered plains, fixed dunes and surface limestone ridges forming the visible landscape. Intrusive granitic plutons are responsible for raised highlands and koppies, which reach up to heights of 450 mamsl.

The perennial Berg River is the most significant river in the region, and is located along the northeastern boundary of the study area. The Berg River drains northwestwards into the Atlantic Ocean near Velddrif, with its lower courses subjected to tidal influence (Timmerman, 1985b).

Langebaan and its environs have a Mediterranean climate, with evaporation exceeding rainfall, and most of the rainfall occurring between the months of May to August. Average annual rainfall for the study area ranges between < 100 mm to ~ 500 mm, with most of the region having an annual rainfall of less than 280 mm.

Focussing on geological features salient to the hydrogeology, the Langebaan region is dominated by semi- to unconsolidated Cenozoic sediments that unconformably overlie basement rocks. The oldest Cenozoic deposits, the fluvial lower Elandsfontyn gravels, occur within the deeper basement areas of the palaeochannels. (Note: the Elandsfontyn gravel unit is not to be confused with the Elandsfontein Aquifer System, which is named after a farm in the area.) The lower Elandsfontyn gravel deposits were subsequently covered with clays and peats. Overlying the Elandsfontyn gravels, the aeolian sands of the Bredasdorp Group form the palaeo- and currently active dunes.

The palaeotopography reflects the palaeoclimatological interpretation that a marine transgression dammed up Proto-Berg Rivers, which previously exited to the southwest coastline. Two clear palaeochannel systems are evident in the basement. Previous workers have published basement elevation maps of the area which show these palaeochannels as enclosed basins rather than continuous channels. The interpretation suggested here is that the palaeochannels are continuous to the southwest coast.

Each of these palaeochannels comprise (semi-) separate aquifer systems. The southern palaeochannel in the area encompasses the Elandsfontein Aquifer system (EAS) and the northern palaeochannel, the Langebaan Road Aquifer System (LRAS). The sedimentary succession can be separated into 3 significant hydrogeological units:

- the basal gravels of the Elandsfontyn, forming the lower aquifer unit, LAU,
- the clay layer of the upper Elandsfontyn, which acts to (semi) confine the basal aquifer,
- the variably consolidated sands and calcretes, with interbedded peat clay of the Bredasdorp, the upper unconfined aquifer unit, UAU.

These 3 units are present in each aquifer system. The basal unit is separate between systems, and the UAU is continuous. Flow in the LAU is controlled by topography of the basement, flowing southwest towards the coast. Flow in the UAU is more controlled by surface topography and flows from a recharge high in the south, semi radially, towards the Berg River northeast, towards the LRAS to the north, and into the EAS to the southwest. The LAU is recharged in areas where the head difference between upper and lower aquifer is large enough to drive vertical recharge downwards (via leakage through clay if clay layer is present).

There is a direct interaction between the UAU and the Berg River. The regional gradient is towards the Berg River and hence on average the Berg River gains from groundwater. However during winder flood events, this gradient is likely to reverse and flood waters recahrge the aquifer.

**CONCEPTUAL MODEL**

The conceptual model assumes that:

- It is assumed that the palaeotopography is representative of ancient fluvial systems and continuous palaeochannels are inferred.
- The geology can be interpreted as 3 distinct hydrostratigraphical units:
    1. The upper unconfined aquifer unit comprising the Bredasdorp formation sediments and Varswater sediments if present;
    2. The confining layer (Upper Elandsfontyn clay)
    3. The lower (semi-) confined aquifer unit (Elandsfontyn sediments)
- The aquifer is underlain by impermeable basement.
- The UAU is recharged directly from rainfall.
- The LAU is recharged in via leakage through the clay unit.
- The UAU discharges to the Berg River, to the coastline at Saldanha Bay and the coastline at Langebaan Lagoon and south of the lagoon.
- The Berg River acts as a recharge source to the aquifer during flood events.
- Flow in the LAU is basement controlled and occurs along the axes of the palaeochannels.
- The LAU discharges to the coastline at Saldanha Bay and the coastline at Langebaan Lagoon and south of the lagoon.
- The Berg River is in direct hydraulic connectivity with the UAU only.

**NUMERICAL MODEL**

A fully 3-dimensional finite element model is developed of an ~2 000 $km^2$ area with ~7 135 triangular prismatic elements. The elements are 500 – 1 200 m in length. The landward boundaries of the numerical model lie along topographical divides or across observed groundwater contours, and are no-flow boundary conditions. The ocean acts as a constant head in the southeast and northwest. The model is 5-layered.

The following data sets were used to construct the bedrock topography:

- Borehole depths from the NGDB data set, using records of shale and granite as indications of basement rocks.
- Offshore basement data of De la Cruz (1978).
- Spot heights on bedrock outcrops as shown in the 1:250 000 geological maps.

The recharge data used in the model is generated through a modified version of the Breede River Basin Study (BRBS) method (DWAF, 2002). Recharge over the modelled area is ~22 million $m^3$/a.

Water-use Authorisation and Management System data was used for abstractions. The total abstraction over the modelled area is 3.6 $Mm^3$/a.

As per the model assumptions that the rivers act as a sink to the aquifer and the river, stages were set below the groundwater level. As an initial estimate of the modelled groundwater levels the topography and the measured water level distribution was used and river stages were input relative to this water level distribution, between 1-3 m below it.

A calibration standard of modelled water levels within 10% average error to observed point data is set. The model is calibrated to this standard with the use of groundwater fluxes and groundwater as compared to topography as an additional guide.

The numerical model was considered calibrated with the following parameter set; the model basal layer within the palaeochannels calibrated with Kx=Ky of ~10 m/d. a discontinuous low K layer overlies the basal later, at Kx=Ky of 0.01 m/d. The upper layer dominantly has a K of 10 m/d, with some area in the south at ~1 m/d. The model calibrated with vertical K an order of magnitude less than horizontal K.

## MODEL RESULTS

The results show the ocean as a dominant sink to the aquifer, and that on average (i.e. the steady-state model) the Berg River behaves as a sink. The modelled groundwater fluxes are shown in **Table E-1**. There is an imbalance of 100 $m^3$/d between the flux in and out of the model.

**Table E-1 Modelled Groundwater Fluxes**

| Flux into Model ($m^3$/d) | Flux out of Model ($m^3$/d) | |
|---|---|---|
| Recharge | Ocean | Rivers |
| 59,800 | -32 800 | -27 100 |

The effect of abstraction is shown in **Table E-2**.

**Table E-2 The effect of Abstraction**

| | Flux into Model ($m^3$/d) | | Flux out of Model ($m^3$/d) | | | Balance ($m^3$/d) |
|---|---|---|---|---|---|---|
| | Recharge | Rivers | Ocean | Rivers | Abstraction | |
| Abstraction (i.e. standard model case) | 59 800 | 0 | -29 500 | -21 200 | -10 100 | -1000 |
| Zero Abstraction | 59 800 | 0 | -32 800 | -26 900 | 0 | -100 |
| Difference caused by abstraction | - | - | Decrease of 10% | Decrease of 22% | - | Increase of 900% |

The seasonal variation of the aquifer was simulated in transient modelling. The best fit was achieved using a specific yield of 2%. Scenario testing on the transient model suggests that there is a resource available for additional abstraction in the EAS, and that it is possible to abstract small quantities without affecting the water levels at potentially sensitive receptors such as the Langebaan Lagoon. An ASR scenario suggests that it is possible to site injection boreholes within the cone of depression and raise water levels, reversing some of the depression.

## RECOMMENDATIONS

The following recommendations are made:

*Summary Recommendation 1: Hydrocensus data collected across the Langebaan area: water levels and borehole use, accurate GPS of X,Y,Z coordinates*

*Summary Recommendation 2: Make surface water data available to all disciplines by allowing it to be converted to a universal datum. All gauging stations are required to be surveyed at the point at which the measurements are taken.*

*Summary Recommendation 3: Additional modelling at a smaller scale in order to understand the hydraulic nature of the aquifers and replicate differing flow directions at different depths. In the vicinity of the Berg River this will generate a better understanding of the nature of the SW-GW interaction.*

*Summary Recommendation 4: Additional modelling at a smaller wellfield scale in order to manage the current situation of abstraction from storage.*

*Summary Recommendation 5: Smaller- scale model to be constructed for the purpose of optimisation of abstraction volume and rate, and positions, for additional potential wellfields and licensing thereof.*

*Summary Recommendation 6: Smaller scale- model to be constructed for the purpose of optimisation of ASR injection volume and rate, and borehole positions.*

# GROUNDWATER MODEL REPORT VOLUME 7
# TMG AQUIFER, PIKETBERG MODEL

# EXECUTIVE SUMMARY

## INTRODUCTION

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

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

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

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

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

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

These volumes are:

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

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer

Volume 6: Langebaan Road Aquifer

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium

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

**STUDY DOMAIN**

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

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

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

**PIKETBERG WATER BALANCE MODEL**

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

**Storage**

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

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

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

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

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

### Recharge

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

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

**Table E-2 Comparison of recharge estimations**

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

### Discharge

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

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

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

| Quaternary catchment | Peninsula Aquifer *Million $m^3/a$* | Nardouw Aquifer *Million $m^3/a$* | Other Fractured Aquifers *Million $m^3/a$* | Intergranular fractured Aquifers *Million $m^3/a$* | Intergranular Aquifers *Million $m^3/a$* | **Total Groundwater use** *Million $m^3/a$* |
|---|---|---|---|---|---|---|
| G10K | 0.45 | 0.10 | 0.06 | 0.06 | 0.02 | 0.69 |
| G30A | 0.06 | | 0.11 | 0.02 | 1.86 | 2.05 |
| G30D | 0.19 | | 0.21 | 0.37 | 1.80 | 2.57 |
| **Total** | **0.69** | **0.10** | **0.38** | **0.44** | **3.69** | **5.30** |

**YIELD MODEL**

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

**Table E-4 Summary results of groundwater potential per aquifer [in million $m^3/a$]**

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

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

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

**CONCLUSIONS**

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

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

**RECOMMENDATIONS**

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

- Spring hydrocensus including diverse hydrochemical sampling to verify discharge rates;
- Continuous flow monitoring of selected springs, e.g. Aurora spring;
- 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 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 wrt refining unused potential estimates;
- Monitoring of ambient boreholes in different aquifers to establish seasonal fluctuation of water levels for calibration of recharge estimation;

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

# 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 (Million $m^3$) | Pore Volume (Million $m^3$) |
|---|---|---|---|---|
| | | | | |
| 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 ($km^2$) | Rock Volume (Million $m^3$) | Pore Volume (Million $m^3$) |
|---|---|---|---|---|
| | | | | |
| 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 | |
|---|---|---|---|---|---|---|---|
| | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Mm/a* |
| 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 | Nardouw Aquifer | Other Fractured Aquifers | Intergranular fractured Aquifers | Intergranular Aquifers | **Total Groundwater use** |
|---|---|---|---|---|---|---|
| | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/a* | *Million $m^3$/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 [in million $m^3/a$]**

| 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** |

## 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.

# GROUNDWATER MODEL REPORT VOLUME 9
# BREEDE RIVER ALLUVIUM AQUIFER MODEL

# EXECUTIVE SUMMARY

## INTRODUCTION

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

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

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

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

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

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

Volume 1: Overview of Methodology and Results

Volume 2: Data Availability and Evaluation

Volume 3: Regional Conceptual Model

Volume 4: Regional Water Balance Model

Volume 5: Cape Flats Aquifer Model

Volume 6: Langebaan Road and Elandsfontein Aquifer System Model

Volume 7: Table Mountain Group Aquifers – Piketberg area

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

Volume 9: Breede River Alluvium Aquifer Model

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

## BREEDE RIVER ALLUVIUM AQUIFER MODEL

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

The main aims in development of the model are:

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

## CONCEPTUAL MODEL

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

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

## NUMERICAL MODEL

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

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

## MODEL RESULTS

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

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

**Table E-1 Modelled groundwater fluxes**

| | Influx | | Discharge | |
|---|---|---|---|---|
| | Recharge | Constant heads | Rivers | Balance |
| $m^3$/day | 62 982 | 8 144 | -71 062 | 64 |
| Million $m^3$/annum | 23 | 3 | -26 | 0 |

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

## RECOMMENDATIONS

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

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

# APPENDIX B: GLOSSARY

Aquifer — a consolidated or unconsolidated geologic unit (material, stratum, or formation) or set of connected units that yields a significant quantity of water of suitable quality to wells or springs in economically usable amounts.

Confined (or artesian) - an aquifer that is immediately overlain by a low-permeability unit (confining layer). A confined aquifer does not have a water table.

Unconfined (or water-table) - the upper surface of the aquifer is the water table. Water-table aquifers are directly overlain by an unsaturated zone or a surface water body.

Aquitard — a geologic material, stratum, or formation of low permeability (a confining unit) that transmits significant amounts of water on a regional scale or over geologic time.

Conceptual model — a clear, qualitative physical description of how a hydrogeological system behaves.

Drawdown` — the drop in head from the initial head caused by pumping from a well or set of wells.

Hydraulic conductivity (K) — the volume of fluid that flows through a unit area of porous medium for a unit hydraulic gradient normal to that area.

Hydraulic head (h) — the elevation in a well in reference to a specific datum; the mechanical energy per unit weight of water [L].

Permeability — the ease with which a porous medium can transmit water or other fluids.

Porosity (n) — the volume of the voids divided by the total volume of porous medium [-]. While effective porosity is the interconnected porosity which contributes to groundwater flow. Often used synonymously with specific yield although the two terms are not synonymous.

Pump test — one of a series of techniques to evaluate the hydraulic properties of an aquifer by observing how water levels change with space and time when water is pumped from the aquifer.

Recharge — the process by which water enters the groundwater system or, more precisely, enters the phreatic zone.

Safe yield — the volume of water that can be annually withdrawn from an aquifer (or groundwater basin or system) without 1) exceeding average annual recharge; 2) violating water rights; 3) creating uneconomic conditions for water use; or 4) creating undesirable side effects, such as subsidence or saline water intrusion.

Specific storage (Ss) — the volume of water released per unit volume of aquifer for a unit decrease in hydraulic head [$L^{-1}$].

Specific yield (Sy) — the volume of water that a saturated porous medium can yield by gravity drainage divided by the volume of the porous medium.

Storage — water contained within an aquifer or within a surface-water reservoir.

Storativity (S) — the volume of water released per unit area of aquifer for a unit decline in head. In a confined aquifer, S is essentially the specific storage (Ss) times aquifer thickness; in an unconfined aquifer, S is essentially equal to the specific yield or the effective porosity

Transmissivity (T) — the discharge through a unit width of the entire saturated thickness of an aquifer for a unit hydraulic gradient normal to the unit width, sometimes termed the coefficient of transmissibility [$L^2\ t^{-1}$]

| | |
|---|---|
| Water table | a surface at or near the top of the phreatic zone (zone of saturation) where the fluid pressure is equal to atmospheric pressure. In the field this is defined by the level of water in wells that barely penetrate the phreatic (saturated) zone. |
| Yield | generically, the amount of water pumped from a well (or bore). In Australia, there is a narrower definition - the maximum sustainable pumping rate such that the drawdown in a well after 24 hours does not exceed a specified percentage (typically ~2%) of the column of water above the base of the aquifer. This assumes that the well is fully penetrating and screened over all permeable intervals of the aquifer. The units of yield are volume per time [$L^3$ $t^{-1}$], e.g. l/s. |
| Data | observations made from monitoring the real world |
| Raster | system of tessellating rectangular cells in which individual cells are a representation of point, line, area and network surfaces |
| Vector | a spatial data model using two-dimensional Cartesian (x, y) co-ordinates to store the shape of spatial entities |

Taken from:

Sharp, John M., Jr., 1999, A Glossary of Hydrogeological Terms: Department of Geological Sciences, The University of Texas, Austin, Texas, 35p.

Department of Water Affairs and Forestry (2006b) *Groundwater Dictionary.* Developed by the Institute for Groundwater Studies (IGS).

# APPENDIX C: REVIEW COMMENTS AND REPLIES

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| **Volume 2** | **Data Availability** | |
| Chapter 1 Introduction | This chapter provides background. It is well written. | |
| Chapter 2 Parameters | Can groundwater quality not be used in the calibration of the models (Table 2.1)? | In theory yes groundwater quality can be used. However these models are flow only and not transport. |
| Chapter 4 Topography | There is no legend for topography in Figure 4.1. | For readability figure 4.1 doesn't include labelling of contours. Figure 4.2 supports figure 4.1, where elevations are colour coded and can easily be read. |
| Chapter 5 Hydrology | In Section 5.2.3 it is stated that the actual evapotranspiration will be modelled. In which documents are the results of this modelling discussed? | In Volume 4, the Water Balance Model report, actual evapotranspiration is calculated. |
| Chapter 6 Geology | On page 36 the authors state that fracture mapping is relevant for groundwater – surface water interaction – please explain why? | If a river flows over a geologic formation there may not be a direct interaction, for example if there are no fractures to act as major conduits for discharge from the formation. Details on the fractures are therefore necessary to understand the spatial extent of surface groundwater interactions. |
| | Prof van Tonder and Prof Xu have estimated porosity values for the TMG – it would be interesting to compare them to the values documented in Table 6.4. | There was an extensive data collection phase at the start of the project. UWC &IGS were contacted for relevant data but limited information was received. In agreement with the study manager at DWAF, it was agreed that the data collection phase could end and the team uses data available at that time. |
| | Table 6.8 – there is more information available than documented in this Table. | The team is fully aware that there is additional information available however the data in the table provides the range of expected parameter values. |
| | Figure 6.7 – there is more pumping test information available. | As above |
| | On page 49 two methods to determine recharge are proposed – must evapotranspiration not be included in the latter? | The mapcentric model does include evapotranspiration, see Volume 4. |
| Concluding | When looking through the list of geohydrological reports available for the study area, it is a concern that so little information can be extracted from these reports. In addition there are many more reports not listed – however I can understand that it is difficult to obtain reports from consultants etc. | This was the experience of the project team. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| **Volume 3** | **Conceptual Model** | |
| Chapter 1 Introduction | This chapter provides background. It is well written. | |
| Chapter 2 Study Area | The dams in Figure 2.2 are not clear. | Noted |
| | Colours in Figure 2.6 do not agree with the legend. | Using the DEM as the background to the figure makes the colours appear darker than in the key. Noted as a limitation |
| Chapter 3 Geology | Colours in Figure 3.1, 3.4 and 3.5 do not agree with the legend. | |
| | The statement on page 37, second paragraph under Fractured-rock aquifers does not make sense (i.e having significant fracture porosity and a permeability greater than $10^{-16}$ $m^2$). | The TMG quartzites are aquifers (i.e. having significant fracture porosity and a permeability greater than $10^{-16}$ $m^2$) of stratabound character, 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. |
| | Figures 3.7, 3.8, 3.10 and 3.11 are incorrect fault position are missing, flow directions are missing/incorrect and the piezometeric level is missing or incorrect. | The figures are conceptual cross-sections to illustrate the different types of spring settings and deep aquifer flow in the TMG domain. The team cannot see any incorrect or missing information. |
| Chapter 4 Conceptual Flow | Under Section 4.1 the authors list the different types of recharge occurring in the area. However no mention is made of surface water – groundwater interaction. | The main recharge, which is considered as surface water – groundwater interaction, is flood recharge. The team is aware that there are tributaries, which are losing water to the underlying aquifer in specific river reaches, even under normal conditions. However, these are not relevant for the regional scale flow model and are addressed in the detailed model domains. |
| | There are numerous typing errors/spelling mistakes in this chapter. | Corrected in final version |
| | Water level contours are not clear on Figure 4.6 & 4.9. Groundwater flow must be perpendicular to the contours which is not the case in the sketches. It is however noted that the lineaments will play a role in the flow direction. | Yes, groundwater flow must be perpendicular to water level contours, in an isotropic aquifer. However, the TMG aquifers are anisotropic, fractured aquifers, in which the positions of fractures and faults determine the groundwater flow direction. In addition, these figures are conceptual diagrams on a regional scale and are not intended to simulate local flow directions. |
| | Were groundwater levels ever plotted against topography to obtain a correlation? If they were is there a correlation? | The relationship between topography and water levels informed the interpretation of the contour and were used to add additional data, where no measured data was available. The contour maps reflect this approach, in that groundwater flow in the unconfined aquifer mostly follows the topography. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| Chapter 5 IWRM | No comment concerning the delineation of IWRM domains. | |
| Chapter 6 Detailed Model Domains | Why were groundwater levels not taken into account in the delineation of IWR? | Groundwater levels were taken into account implicitly. However, the main parameters for the delineation were surface water drainage and aquifer boundaries (i.e. geological contacts). |
| | Aquifer parameters and recharge values should be specified for the conceptual models. | These are specified in the detailed model reports. |
| | Once again the flow paths must be perpendicular to the groundwater level contours, even though lineaments will influence the flow path. | See above |
| | Graphics in Figure 6.6 is not clear | Not sure what the reviewer refers to. The authors cannot see anything wrong with the figure. |
| | Why are there 2 cones of depression in the north-eastern section of Figure 6.9 and in areas in Figure 6.15? | Incorrect data points that were mistakenly not removed. |
| | Why are the aquifers going into the sea in Figure 6.10? | These two channels show the extent of the confined parts of the Langebaan Road and Elandsfontein Aquifer. These are confined by low permeable sediments which extend into the sea. The extension into the sea is also confirmed by drilling results in the Saldanha Bay. |
| | The flow directions in Figures 6.24 and 6.25 are incorrect when considering the piezometric gradient. | These are conceptual cross-sections to show the major flow paths. The flow direction will vary locally from these. Figure 6.25 contains the flow directions for the Nardouw Aquifer, but mistakenly the piezometric level for the Peninsula Aquifer. |
| Concluding | My main concern with this document is the flow directions in the cross-sections which don't always make sense. | See above |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| **Volume 4** | **Water Balance Model** | |
| Chapter 1 Introduction | This chapter provides background. It is well written. | |
| Chapter 2 Study Area | In chapter 2 it is not clear how slope distribution and terrain roughness are taken into account in the water balance. Flat areas don't necessarily have to be discharge areas – they can also be recharge areas depending on the composition of the underlying materials. | The use of slope and terrain roughness in the map-centric recharge model is described in Chapter 5. Not all flat areas are assigned as discharge areas, this depends upon the surrounding area. |
| | It is important for the authors to note that the GRAII datasets are under review. | Noted. |
| | Under Section 2.3.2, the authors state that the TMG quartzites are starbound aquifers (i.e. having significant fracture porosity and a permeability greater than $10^{-16}$ $m^2$). Please check this statement. | See reply under Vol 3 above |
| Chapter 3 WBM Approach | It will be useful to have a definition for storage as this is not a standard groundwater term. | The term "storage" is used as per traditional English definition ("space reserved for storing") and as per hydrological and engineering definition. The term is also used in geohydrology; e.g. DK Todd refer to storage volume of an aquifer |
| | Figure 3.1 does not make sense – it indicates the cycle only works in one direction. However surface water can also recharge groundwater systems etc. | We agree that flow between surface water and groundwater can be in both directions. Figure 3.1 is a schematic diagram to illustrate the main processes that are taken into account in the WBM |
| Chapter 4 Storage | In Box 1, it is total porosity introduced in the equation for specific storage and not effective porosity. | |
| | In Section 4.2 an additional limitation is the lack of data. | The limitation of the model is determined by the scale of input data. The model results could be improved with drilling results |
| | Porosity values obtained by Profs van Tonder and Xu must be included in the study. Have the authors conducted a sensitivity analysis on the excel model. Where are water levels brought into the equation? | These were unfortunately not available at the time of the data collection. The authors would welcome receiving these data for comparison. A sensitivity analysis was undertaken for the yield model (Chapter 7) with a range of porosity and compressibility values<br><br>Water levels were not taken into account in the storage model, as the result of the model indicates the total amount of water that can be stored in the aquifer. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| | I do not agree with the porosity values. | What are “correct” values in the reviewer’s opinion? |
| Chapter 5 Recharge | Is Equation 1 correct? What about interflow and other processes than take place in the unsaturated zone? | Equation is a simplified version of the water balance equation. Interflow, baseflow etc. are implicitly considered, as they form part of MAR. |
| | I don’t agree with the recharge values. | Which ones? What are “correct” values in the reviewer’s opinion |
| Chapter 6 Discharge | Did the authors validate the baseflow values obtained from the different databases? Was there any scaling performed for the various reaches within a river? | It was outside the scope of work for the regional water balance model to validate input data that were developed on a regional scale. The scale of the calculations did not allow for disaggregation to river reaches. |
| | Were the numerical models not supposed to be used for the baseflow estimations? | The WBM gives the regional scale estimates, based on regional scale data. These are verified / updated in the numerical models – not other way around. |
| | The hydraulic connectivity shown in Figures 6.1 & 6.2 must be explained. | Explained in text on page 67 |
| | It is unclear if groundwater used by vegetation is included in the calculations. | Groundwater abstraction by vegetation is not included in the calculation of discharge, as it is taken into account in the recharge estimation methods. |
| Chapter 7 Yield | The third paragraph of this chapter states “A frustration of, and currently the most limiting factor, in groundwater resource development is the perception that if confined portions of the Peninsula and Skurweberg Aquifers are pumped that springs and seep zones will significantly be impacted upon” does this not depend on the type of spring? | The authors agree, whether a spring or seep will be significantly impacted upon by abstraction from the TMG depends on the geological setting of the spring. However, it remains a frustration that this distinction is often not made in environmental assessments. |
| | I don’t agree with the storage yield model parameters and results. | Which parameters are incorrect? What would be “correct” values? |
| Concluding | I do not agree with a number of parameters and methods (specifically the storage model) used in the regional water balance. | Which parameters are incorrect? What would be “correct” values? What technical aspect of which method is incorrect? |
| **Volume 5** | **Cape Flats Aquifer** | |
| Chapter 1 Introduction | This chapter just provides background to the study and study area. | |
| | The conceptual model for the study area is summarised in the chapter. However the conceptual model will not be reviewed in this document as it is documented in the review of Volume 3: Regional Conceptual Model. | |

| **Report / Chapter** | **Comments external reviewer (Dr Ingrid Dennis)** | **Umvoto response** |
|---|---|---|
| | Under Section 1.2.1 the authors list a number of issues to be addressed in the report however no mention is made concerning drought management. | The issues listed are those tasked to the team in the Berg WAAS ToR and documented in the inception report. |
| | Figure 1.3 depicts groundwater flow directions – how were these determined as they do not seem to follow the topography which contradicts the text. | The reviewer is confusing drainage and shallow groundwater flow with the major groundwater flow. The text states that drainage (ie rivers) and shallow groundwater flow is controlled by surface topography, and that major groundwater flow is controlled by basement topography – as depicted in Fig1.3 |
| Chapter 2 Study Area | The legend of Figure 2.4 does not coincide with the colours shown on the map. | Using the DEM as the background to the figure makes the colours appear darker than in the key. Noted as a limitation |
| | It would be interesting to include the method utilised for the generation of groundwater contours in Figure 2.9. Was Bayesian interpolation considered? | Agreed - interpolation method employed should be noted. Bayesian interpolation was not used. |
| | The recharge for Atlantis is known to be 23% so the Cape Flats should be approximately 25%. | We used the best available published estimates, including BRBS / GRDM / GRAII methods. Using the high recharge values, as proposed by Gerber, resulted in unrealistic high hydraulic conductivity (k) values. |
| | Are pit latrines not a major source of pollution on the Cape Flats? | Yes, informal settlements are listed as pollution sources. |
| Chapter 3 Conceptual | No comment concerning the conceptual model. | This Chapter is considered the crucial aspect of the model report. Paul Seward had requested comments from a second reviewer on this, as he did not feel competent enough for commenting. |
| Chapter 4 Input data | A specific yield of 0.2 was assigned which is approximately equal to effective porosity so why is a low value being assigned for what is assumed to be total porosity i.e. 0.15? | Total porosity is not used in numerical flow model. Agreed that specific yield should be equal or less than porosity. |
| | The initial recharge used in the model is too low! | As above. It is within the range of published recharge figures, taken the local conditions into account. |
| | In Table 4-6 storage coefficient should be specific storage. | Agreed |
| | What vertical hydraulic conductivity values were used? | This chapter is input data only – the initial hydraulic conductivity values are irrelevant as it is a key calibration parameter. It is stated that an initial hydraulic conductivity value of 10m/d is used. As there is no discussion of anisotropy at this point, it is assumed that horizontal and vertical hydraulic conductivity are equal. Detailed description of the various hydraulic conductivity settings is given in chapter 5. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| Chapter 5 Steady State | The boreholes used in the steady state calibration – which of the 3 water levels (i.e. which layer) were they calibrated to? | The 3 layers are required as a numerical model representation of the natural system – but they do not pertain exactly to geological strata. This is not possible in groundwater models where layers must be continuous across model areas. Chapter 5.3: Calibration data explains the calibration procedure:<br><br>"There is no separate calibration data set available for the potentially confined or semi confined layer of the aquifer in the palaeochannel. The degree of confinement, if any, may be in the order of centimetres (see Section 2.4.1). Thus it was considered acceptable to use this data set to calibrate all layers and to test the sensitivity of the model to the presence or absence of a confining layer overlying the palaeochannel by varying K in the relevant layer" |
| | It would be interesting to include anisotropy in the xy direction. | This was tested in the modelling but did not improve the calibration (as were many other factors which aren't reported on as it is a lengthy process). Once a solution (parameters) is attained which meets the calibration criteria the model is deemed sufficiently calibrated. |
| | From Figure 5-10 it seems as though the simulated recharge is too low. | There are several reasons for the observed levels being higher than modelled with the hydraulic conductivity scenario shown in Fig 5.10. In a numerical model recharge and hydraulic conductivity are interlinked parameters. To solve this a recharge distribution was assumed, based on best available information, and the K parameter set calibrated which best matches observed water levels. The relationship K and recharge is evident in table 5.2 which details certain K scenarios where the modelled levels are greatly higher than observed. The reason is not that the recharge is too low. The effect of scale is likely to be more important – at this regional scale model the steep local water level changes (which point data reflect) cannot be replicated. |
| | The authors must ensure that if they include abstraction in the steady state model – the abstraction rates must be for the input steady state water levels. | The abstraction rates and the water levels are all current data so yes they are correspondent. |
| | It is suggested that a steady state model first be run and calibrated without abstraction. | It was decided to include abstraction in the steady state because the observed water levels are affected by abstraction. To calibrate to a naturalised system would require naturalised water levels, which were not available. |

| **Report / Chapter** | **Comments external reviewer (Dr Ingrid Dennis)** | **Umvoto response** |
|---|---|---|
| Chapter 6 Transient | The specific storage seems low for the study area. | The transient model was calibrated with changing the specific yield. The specific storage as stated in Chapter 6.4 was not changed during calibration, as a dominantly unconfined aquifer was assumed. However, the value assigned is in the range of published data. |
| | It is suggested that the authors just reduce the recharge during the dry months and not make it zero | It was decided to set recharge in summer months to zero to account for the effect of evapotranspiration. |
| | Section 6.3 contradicts assumptions made in Section 6.1. | The authors cannot see any contradiction – please qualify. 6.1 states that monthly recharge will be entered and that a homogeneous distribution is assumed (i.e. spatially the same number each month). |
| | Section 6.3 – the recharge values still seem too low. | Comments above apply. The recharge is not changed between Steady state and transient simulation. |
| | It would be interesting to plot a time series of observed versus simulated water levels | Noted. Figure 6.3 and Figure 6.5 in combination with paragraph 2 of section 6.6.2 seemed sufficient. |
| | Can Cape Town International and the industries in the vicinity thereof not be considered as a pollution source? | Yes. |
| | It would be interesting to highlight all potential polluters in the study area to assess how much of the area could actually be polluted. | Agreed. However, this level of detail was deemed out of the scope of this project, and is included in the recommendations. |
| Concluding | There are too many model scenarios included in Chapters 5 & 6, move some to an Appendix as it is confusing to work through all of them. | They are agreed key deliverables of this project. |
| | It would be useful for the authors to include a section on how the results documented can assist in obtaining a compulsory licence and assist in the other issues listed in Chapter 1. | Will be addressed in summary report. |
| | One final question to the authors – taking into consideration all the unknowns, could the 3D model not be compacted into a 2D model? Would the answers differ significantly? | The regional scale 3d model could probably be compacted into a 2d model without significantly altering the results. This would be an interesting teaching exercise for comparison of model set-up. However, for refinement of the model in localised area, e.g. flow towards the sea, and for optimisation of the scenarios a 3D model would be required. Hence, it is best practice to develop the basic model in 3D. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
| --- | --- | --- |
| **Volume 7** | **Piketberg Model** | |
| Overall | Before discussing the contents of the document, the authors of the document must be congratulated on a well written report. Each Chapter in the review document will be discussed separately in the following sections. However before discussing the Chapters in detail it is suggested that the authors replace groundwater model in the title with water balance. | This is Volume 7 in the range of the Groundwater Model Report for the Berg WAAS, which includes different types of groundwater models, e.g. conceptual, water balance and numerical. |
| Chapter 1 Introduction | This chapter just provides background to the study and study area. The conceptual model for the study area is summarised in the chapter. However the conceptual model will not be reviewed in this document as it is documented in the review of Volume 3: Regional Conceptual Model. It is however suggested that the authors ensure all abbreviations used in this chapter are included in the list of abbreviations. | It would have been useful to have a review of the conceptual model in this document. However, it is assumed that the conceptual model for the area is accepted by the reviewer, as no area specific comments were noted in the review of Volume 3. |
| Chapter 2 Study Area | In Section 2.1.3 the authors state that the valleys are considered as discharge areas and that no recharge occurs in these areas. Is this true discharge occurs at the rivers but that does not mean recharge does not occur in the valleys. Recharge adjacent rivers can be higher. | It is stated as model assumption that recharge is set zero in these valleys that are identified as discharge areas. Although recharge can occur close to the rivers, it is considered to be taken up by quick discharge to the river and or evapotranspiration and hence neglected in the calculations of effective recharge. |
| | It is unclear in the document how the slope analysis results were included in the final estimation of run-off as under Section 2.2.2 only WR90 and WR2005 runoff values are quoted. | The slope distribution was used in the map-centric recharge simulation, as is stated in text. Section 2.2 describes the currently available data. |
| | Under Section 2.3.2: Fractured-rock aquifers it is stated: The TMG quartzites are stratabound aquifers (i.e. having significant fracture porosity and a permeability greater than $10^{-16}$ $m^2$) is the statement concerning permeability correct? Is the unit for permeability not length/time? | The unit for hydraulic conductivity is length/time [m/d]. The unit for permeability is area [$m^2$]. |
| | It is difficult to follow the discussion on the relationship between aquifer type and topography as the axes of Figure 2-10 are not labelled correctly i.e. normalised what? Slope (degree or percentage?). | As stated in the text, the axes show normalised distribution of slope. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| Chapter 3<br>WBM | The approach will not be reviewed here. The approach will be discussed in the review of Volume 4: Regional Water Balance Model. | |
| Chapter 4<br>Storage | The storage model will not be reviewed here. The model will be discussed in the review of Volume 4: Regional Water Balance Model. | |
| | It is assumed that the porosity of 5% applied in the model is effective porosity? Is this used for an estimation of specific yield? Were the same value applied for the confined and unconfined sections – this can not be true? | The porosity value refers to effective porosity. As stated in Section 7, Yield Model, porosity was one of the parameters to estimate the storage coefficient for the confined portions. The yield model was not applied to the unconfined portions. |
| | Why was the integranular Sandveld Aquifer not taken into account? | The Sandveld Aquifer was taken into account in the water balance model. Hence, it is an unconfined aquifer with limited storage capacity compared to the annual recharge, it was decided that a separate storage model would not yield significant more information |
| | Transactions of the Geological Society of South Africa document an average total porosity for the study area of < 2%. The effective porosity must then be between 0.5 – 1%. Prof Xu has conducted many tests to assess porosity in the study area. Maybe the project team should contact him more accurate estimates. The values documented in Table 4-2 are incorrect – they are too high! | The authors have used values available to the team at the time of the study. Prof Xu and the UWC were approached for data and information during the data collection phase (see Volume 2), but did not provide the information referred to above. The authors would be glad, if the reviewer could assist in obtaining these reports for a comparison. |
| Chapter 5<br>Recharge | A recharge value of 23% is too high for the study area – that is the recharge for an unconfined porous aquifer such as Atlantis. From testing the data used in the GRDM software it was found that the recharge values are too high, rather indicating a total recharge and not an effective recharge (taking into account evapotranspiration etc). Once again the authors are referred to Prof Xu, who has been researching these values. | A variety of methods and published values were used in the recharge estimation. 23% might seem high, but is in line with the values developed by the GRAII and used in the GRDM. Evapotranspiration was taken into account explicitly in the map-centric recharge simulation and the ISP method, while it is implicitly considered in the GRAII method. |
| Chapter 6<br>Discharge | There are hydrographs available for the study area. It is suggested that the GRDM values be validated. | The authors fully support the notion that the GRDM values and all other baseflow estimations should be validated, as the estimation procedure are subjective and depend upon the definition used for baseflow.<br>There are hydrographs from the Hol River (G3H005) and the Kruis River (G3H001) available, both of which clearly indicate the ephemeral character of the rivers originating in the Piketberg Mountains. In both there is no river flow recorded during the summer months. Hence, the authors decided to estimate groundwater contribution from known springs in the area. |

| Report / Chapter | Comments external reviewer (Dr Ingrid Dennis) | Umvoto response |
|---|---|---|
| | Can no lateral discharge- recharge estimations be made with simple Darcy calculations? | Theoretically it is possible to calculate the groundwater flow across the aquifer boundaries, based on gradient and conductivity, assuming that both aquifers are fully connected. However, the lateral discharge – recharge from the Peninsula Aquifer into the overlying primary aquifer depends mainly upon the fracture network and fracture connectivity in the Peninsula Aquifer at the contact zone with the primary aquifer. This information is not readily available and observation from other areas indicate the possibility of zones with low connectivity. |
| Chapter 7<br>Yield Model | It is important that the authors check the values used in their water balance. | See comments above |
| | Under Section 7.2 the authors speak about effective storativity – a definition of this term would be useful. | Storativity is defined by Kruseman & de Ridder as Specific Storage times Thickness. The authors the terms Effective Storativity to highlight the fact that effective porosity was used for the calculation. |
| | The storativity values documented in Table 7-3 are too high. | What would be 'correct' values or accepted values in the reviewer's opinion?<br>The storativity of 7.5 E-03 is in the order of acceptable and published values for the TMG aquifers (e.g. 0.001, Rosewarne, 2002) and considered reasonable. |
| Concluding | The data used in this assessment mostly come from national coverages, very little data validation was documented, where actual field data have been used to confirm the national coverages. It is important for the authors to note that the national coverages are currently being reviewed. Input data for calculations must be checked. | Information and data that was available to the authors at the time of undertaking the model was used. As mentioned above, other site specific data was not made available. |
| | It would be useful for the authors to include a section on how the results documented can assist in obtaining a compulsory licence. The inclusion of a confidence analysis would be useful in this regard. | Will be addressed in Summary Report |

# APPENDIX D: SCOPE OF WORK

# SCOPE OF WORK

## INTRODUCTION

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 plus 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 (DWA) has 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 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. It will ensure that the necessary infrastructure or other interventions are implemented in good time to reconcile supply with the future demands. This Strategy will be updated regularly.

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

- 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 comprised two phases: Phase 1 (Inception) and Phase 2 (Model configurations for assessment of current water availability and selected augmentation options). Phase 2 comprised 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 overarching strategic management intent established for the Berg River catchment and the WCWSS, a number of models were developed for evaluating the groundwater availability on a regional and IWRM Domain scale.

Volume 2 (Data Availability and Evaluation) and Volume 3 (Regional Conceptual Model) of this series were prepared in iterative and parallel fashion. On completion of these reports the model domains and approach to both the coastal and fractured rock TMG aquifers were revised. It was agreed in a series of discussions between the client (DWAF Head Office and Regional Office), the surface water and the groundwater team, documented in the relevant project meeting minutes and correspondence, that:

- Fully 3D numerical models were developed for the coastal aquifers (Volume 5: Cape Flats Aquifer Model; Volume 6 Langebaan Road and Elandsfontein Aquifer System Model) using Finite Element (FE) software (FeFlow; Version 5.3)
- 2D and quasi 3D (in-house Storage Model) GIS based models were developed for the TMG aquifers (Volume 7: TMG Aquifer – Piketberg Model and Volume 8 – TMG Aquifer, Witzenberg-Nuy Model) using the same approach taken to develop an aquifer specific regional mass balance (Volume 4: Regional Water Balance Model) presenting results at a quaternary scale, but the geological and hydrogeological mapping and storage modelling would be done at a finer scale, thus increasing confidence in the output.
- ModFlow, a Finite Difference (FD) quasi-3D software was used to model various scenarios to better understand the spatial and temporal patterns of surface and TMG groundwater interaction in the middle to upper Breede basin where there is limited hydrological data with which to calibrate surface water models. (Volume 9: Breede River Alluvium Aquifer Model)

The assessment of available data and the approaches to overcome critical data gaps and shortcomings highlighted the impact of limitations of existing data bases, particularly the baseflow and groundwater usage values. In the smaller aquifers and in those areas where significant or distinct seasonal surface and groundwater interaction is a feature, these relatively small numbers can introduce significant uncertainty to resource allocation decisions; viz., there is groundwater available for allocation or there is not. This illustrates the principle that resource evaluation and management is risk management, and that management and monitoring strategies must be directed towards reducing and or better defining the risks.

The following data gaps were identified:

- location of perennial springs
- time series for spring flow
- spring hydrochemistry (macro and trace)
- isotopic characterization of springs and seep zones and groundwater
- thermal measurements of springs and groundwater
- event response changes in spring flow and groundwater level
- widely distributed hydraulic parameters for the TMG Aquifer
- bedrock topography along the West Coast
- volume and pattern of groundwater use per aquifer
- uniform scale of fracture mapping
- geological anomalies in the 1:50 000 geological field sheets.

It is required to fill these data gaps for any reasonable updating of the existing models, as would be required for reducing uncertainties and enhancing the confidence in these models.

## GENERAL REQUIREMENTS

The different activities required to upgrade the models can be grouped into the following tasks and will be detailed in the sections below:

- Desktop Data Acquisition
- Field Surveys
- Design and Installation of Monitoring Networks
- Ongoing Monitoring
- Data Analysis
- Modelling Upgrade
- Review and Revision of Monitoring Network

Further details regarding aquifer specific considerations and requirements are given in Section 3 for primary aquifers and 4 for the TMG aquifers.

### DESKTOP DATA ACQUISITION

Some additional desktop data acquisition is required for developing and upgrading relevant monitoring networks, as well as upgrading the existing models for water resource evaluation and groundwater development.

#### Geological mapping

There are some uncertainties regarding the published geological mapping that need attention. These can be undertaken as desktop study using aerial photos, satellite images and digital elevation models. In particular, it is recommended

- Mapping the extent of the paleochannels within the Cape Flats Aquifer, the Langebaan Road Aquifer, the Elandsfontein Aquifer and the Atlantis Aquifer (See Section 3.1);
- Revision of the 1:250 000 and 1:50 000 geological mapping of the TMG Aquifer, where required (see Section 4.1); and
- Undertaking lineament mapping (see Section 4.1)

#### Evapotranspiration

The numerical models have not explicitly quantified loss of water to evapotranspiration, only assumed an effective recharge. The regional Water Balance Model developed an estimate of evapotranspiration, which was based on natural vegetation.

Further quantification of water lost to evapotranspiration requires data on the water usage by alien vegetation (not yet available) and different crop types, and mapping of the extent of alien vegetation and agricultural land. From this data an alternative recharge distribution could be generated and tested in the models.

#### Groundwater use

The available groundwater use data from the WARMS database are not spatially correct and aquifer specific. An attempt was made in the Berg WAAS to calculate aquifer specific data. However, this needs to be refined and the registered and actual groundwater use determined, preferably per borehole. This will be concluded by a field verification process (see Section 2.2).

## FIELD SURVEYS

### Borehole hydrocensus

The assessment of the NGDB and WARMS databases indicates that there is some inconsistency in the data about groundwater use and the number of boreholes in some areas of the study domain. It is of utmost importance for the estimation of groundwater abstraction per aquifer to verify borehole locations and groundwater use. Furthermore, the hydrocensus allows for gathering additional vital information about the aquifer, such as water level, water chemistry, water temperature etc.

There has been a recent blanket hydrocensus undertaken in the Berg River catchment (Parsons, 2003) but no hydrocensus was undertaken during the Breede Basin Study. It is necessary to upgrade the NGDB with a particular focus on obtaining borehole abstraction rates and schedules from all private and municipal users, detailing the aquifer from which the groundwater is abstracted and undertaking selective comprehensive hydrochemical and isotope sampling and analysis (see below). The temperature of different waters is necessary as is selective sampling and mapping of temperature and hydrochemical variations at certain river reaches selected on the basis of prior hydrogeological interpretation of flow paths.

### Surface water and groundwater sampling

The groundwater discharge to rivers along river reaches can be mapped with the aid of chemical and isotope analysis, as some trace elements and isotope signatures are aquifer specific. It is therefore recommended to sample the surface water along selected river reaches to verify whether groundwater discharges into the surface water body. It might be required to also take groundwater samples in the vicinity of the river to determine isotope and trace elements signatures for the relevant aquifers. This work should be planned together with the spring hydrocensus and interpretation of results must take spring localities and hydrochemistry into account.

### Surface water datum

There is a vast resource of reliable surface water data held within the DWAF flow gauging station records. These are continuously monitored, some even hourly. However, this data is of limited use to integrated water resource planning, as it is not measured from a universal datum. In order to really understand and quantify surface – groundwater interactions, data on both storage units (the surface water and the groundwater and water stores) is vital.

All gauging stations are required to be surveyed at the point at which the measurements are taken to allowing all waterlevel data to be converted to a universal datum.

## DESIGN AND INSTALLATION OF MONITORING NETWORKS

It is suggested to develop a comprehensive monitoring programme for the Berg WAAS area that comprises all the requirements in an integrated and optimised manner. Some details of envisaged monitoring are outlined below.

### Review and revise Monitoring Network

Groundwater monitoring programmes must involve regular measurements of:

- water levels,
- water quality (macro and trace elements and biological indicators),

- abstraction volumes,
- climatic variables - rainfall, temperature, potential evaporation and snowfall
- hydrologic variables – spring flow (altitude, volume, water quality, seasonal and or climate event-related variation), baseflow and water quality variations in rivers.

Such systematic programmes are generally implemented for particular groundwater or conjunctive-use schemes, mostly tied to production boreholes. There is an imperative need for strategically placed observation boreholes exclusively dedicated to groundwater monitoring in locations distant from production wellfields.

Groundwater level, as monitored at one or more observation wells (piezometers), is the most important indicator of the state of the resource. Even just one suitably located well, preferably placed furthest from outflow boundaries to surface waters and/or away from sites that are likely to be affected significantly by surface abstraction or by local (artificial) recharge from surface irrigation, can provide substantial information about the overall state of the resource, because the dynamic variability of groundwater levels observed in that suitably located well reflects that of the surrounding aquifer.

There is currently not one consistent monitoring network within the Berg WAAS study area. It is therefore recommended to review and revise the monitoring network and data collection process as well as the actual location (longitude, latitude, elevation, depth) of monitoring boreholes on basis of this project to ensure that the monitoring boreholes are in the right place and monitor different processes at different scales in relevant aquifers.

**Hydrological monitoring**

The upgrade of the flow station network with regards to low flow and flood flow measurements at key points in the river network is suggested and detailed in the Flow Gauge Assessment Report (DWAF, 2006h). These recommendations are to be reviewed and need to be extended to the Hex and Nuy rivers for increasing the confidence in the reported MAR values for these catchments.

**Hydroclimatic monitoring**

Hydroclimatic parameters play a vital role in understanding and quantifying groundwater resources as well as surface water – groundwater interaction. The available network of weather stations does not take into account the recharge and discharge zones for different aquifers and, hence, needs enhancement. The following activities are envisaged:

- Select sites in key recharge areas of major aquifers
- Install network of rainfall collectors in the recharge areas
- Install appropriate weather stations at different altitudes

**Hydrogeological monitoring network**

Based on the revised monitoring network, the establishment of dedicated hydrogeological monitoring sites and installation of adequate equipment is required. At least the following is envisaged:

- identification of key springs for installation of continuous flow metering (see spring hydrocensus, Section 4.2)

- purpose-designed and drilled boreholes equipped for continuous water level monitoring (see Section 3.3 and 4.3)
- strategically sited boreholes for water quality monitoring if the above boreholes are not suitable (see Section 3.3 and 4.3)

**ONGOING MONITORING**

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,
- Seasonal and event response sampling of rainfall, spring flow and groundwater;
- Monitoring of water level in selected key abstraction boreholes;
- Monitoring of water level in ambient boreholes in different aquifers;
- Monitoring of groundwater use as an imperative data set for assessment of the available resource
- hydrochemical and isotopic characterisation of the various aquifer units

**DATA ANALYSIS**

All collected monitoring data will be evaluated and analysed on a regular basis. The following analysis is intended:

- Calibration of the recharge models with other methods;
- Calculation of residence time and interflow/rejected recharge;
- Determining the impact of existing groundwater use;
- Establishing seasonal fluctuation of water levels;
- Establishing trends of water level fluctuations in different aquifers,
- Re-assessment of the available resource
- Quantification of surface water – groundwater interactions

**MODELLING UPGRADE**

The required updates and upgrades for the various groundwater models are discussed in Section 3.6 and 4.6.

Since the Sami Groundwater Module is not applicable throughout the study domain, it is recommended to develop an alternative to the Sami Groundwater Module that comprises:

- Applying the aquifer specific distribution of groundwater contribution to baseflow in the Pitman model
- Applying the aquifer specific storage volumes in the WRYM

It is further recommended to align the discretisation for the surface water modelling with the boundaries of the groundwater regime to ensure that the surface water modelling scale ties in with groundwater flow path scale effects within each relevant aquifer and to account for subsurface transfer across catchment boundaries. The proposed IWRM domains allow for this integration and are considered the scale for the WRYM, which would also allow for the design of groundwater or conjunctive use schemes. However, the WRSM modelling should be undertaken on the scale of sub-domains that are aquifer and quaternary-catchment specific.

### REVIEW AND REVISION OF MONITORING NETWORK

Based on the results from the upgrade and re-run of the various groundwater models, it is recommended to review and revise the monitoring network. This would assist in identifying existing data gaps and optimising the data collection process.

## PRIMARY AQUIFERS

In the following sections the additional requirements for the primary aquifers under considerations are discussed.

### DESKTOP DATA ACQUISITION

#### Palaeochannel mapping

The location and depth of the palaeo channels along the West Coast and underneath the alluvium aquifers determine the groundwater flow pattern in these aquifers. Reasonable inference can be made in the Cape Flats and Langebaan Aquifers based on both offshore and onshore data. No detailed information is available about palaeo channels north of the Berg River estuary. These have previously been inferred from regional structural geology and 1:10 000 topography, as well as knowledge of sea level rise and fall.

Mapping of these palaeo channels would confirm and or refine the present model configurations. It is therefore recommended to undertake airborne or surface geophysical measurements along the West Coast and over the Breede River alluvium.

### FIELD SURVEYS

#### Hydraulic nature of the aquifer

A more detailed understanding of the hydraulic nature would be necessary in order to place reliance on the model results, or to generate a model useable as a well-field model. A full pump test is recommended. This should involve the drilling of new boreholes, which are accurately logged to provide information of the deeper channel deposits and on the lateral extent of the basal gravels. Information on the palaeochanel deposits would confirm whether the calibrated model represents equivalent K's or whether the basal gravels are extensive. Grain size analysis or lab testing of samples, especially in the gravels and overlying finer sediments could provide ranges of likely K to act as a restraint on further model refinement. The model is sensitive to the basement topography. New boreholes would add data points to the basement topography surface and increase model confidence.

Undertake pump testing in which boreholes are drilled, logged accurately, and the basal layer targeted in the pump test. This would provide information on the extent of the basal gravels and additional basement-elevation data. Samples should be laboratory tested for K to provide a typical range useful in restraining the model solution. The pump test must be of long enough duration to conclude whether the aquifer is confined or unconfined. The water response of different layers of the aquifer, in response to pumping the basal gravels, is required. Stratigraphy specific hydraulic parameters would further refine the model and increase confidence.

### Surface water- groundwater interactions

The modelled fluxes between groundwater and surface water are dependent on the river geometry (width and thickness of bed sediment), the riverbed hydraulic conductivity, and the river stages. Each of these in the model has been used as a calibration factor. In order to place more certainty on these calibrated fluxes, field data is required. Information on the river stages is desirable in a transient model to reasonably model the seasonal variation in fluxes between groundwater and surface water. Hence, additional data is sourced or collected in fieldwork on the river geometries, typical bed sediments, and most importantly the river stages.

## DESIGN AND INSTALLATION OF MONITORING NETWORKS

The focus of the monitoring networks for the primary aquifers is on better understanding the groundwater flow paths and the groundwater discharge. Hence, monitoring boreholes are required within and in close vicinity to the paleochannels. In addition, monitoring boreholes close to the rivers and river flow gauges would assist in quantifying the surface water – groundwater interaction.

## ONGOING MONITORING

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

- Rainfall sampling and chemical / isotope analysis in the recharge areas,
- Sampling and chemical / isotope analysis of river reaches,
- Seasonal and event response sampling of rainfall, stream flow and groundwater;
- Monitoring of water level in selected key abstraction boreholes;
- Monitoring of water level in ambient boreholes in different aquifer units;
- hydrochemical and isotopic characterisation of the various aquifer units

## DATA ANALYSIS

The field survey data and ongoing monitoring data will need to be processed and analysed on a regular basis to provide the relevant input for the model upgrades that are recommended below.

## MODELLING UPGRADE

The model upgrade recommendations, given in the different modelling reports, require the above-listed field surveys, ongoing monitoring and data analysis. The recommendations are listed below for quick reference.

### Cape Flats Aquifer (CFA)

- Test reality of the conceptual model by investigating whether significant groundwater flow occurs to the northwest and discharging to Table Bay.
- Smaller scale models are to be constructed for the purpose of optimisation of positions for additional abstraction, and to determine effect on other users / surface waters.

### Langebaan Road Aquifer and Elandsfontein Aquifer systems (LRA/EAS)

- Additional modelling at a smaller scale in order to understand the hydraulic nature of the aquifers and replicate differing flow directions at different depths. In the vicinity of the Berg River this will generate a better understanding of the nature of the SW-GW interaction.

- Additional modelling at a smaller wellfield scale in order to optimise the management of abstraction from storage.
- Smaller-scale model constructed for the purpose of optimisation of abstraction volume and rate, and positions, for additional potential wellfields.
- Smaller-scale model constructed for the purpose of optimisation of ASR injection volume and rate, and borehole positions.

**Breede River Alluvium Aquifer (BRA)**

**Conceptual model testing**

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

**Conceptual ASR schemes**

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

**Develop wellfield management scenarios**

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

## TMG AQUIFER

In the following sections the additional requirements for the Table Mountain Group aquifers are listed.

### DESKTOP DATA ACQUISITION

#### Review and revise geological mapping

The mapping of structural geological features on the 1:250 000 and 1:50 000 geological maps is sufficient for the regional models, but is lacking detail and accuracy as required for detailed modelling. Furthermore, it recently became evident that the mapping of formations is incorrect in some areas. It is therefore recommended to review the geological mapping in the detailed model domains, especially in the TMG dominated domains, with respect to the structural features and stratigraphic detail. If required, the geological mapping will then be revised and updated.

### Fracture mapping

The currently available data about the fracture network is very detailed in some areas of the study area, e.g. Hottentots Holland, Kogelberg, Du Toits Kloof, Hawequas, Winterhoek, Langeberg and Piketberg, while the data is not available at the required scale in other areas, especially in the northern part around Tulbagh, Ceres and Hex River. The information about fracture distribution and density is crucial for determining hydraulic parameters, hydraulic relevant thickness and interaction with surface water bodies. It is therefore recommended to undertake a fracture mapping in the study area to fill these data gaps in all areas relevant for detailed modelling and for groundwater – surface water interaction.

Fracture mapping involves digitizing of linear features as identified on satellite imagery and aerial photos at different scales from 1:100 000 and 1:40 000 (satellite imagery and DEM) to 1:10 000 (aerial or orthophoto).

## FIELD SURVEYS

### Spring hydrocensus

The groundwater is discharged into the surface water via springs, seep zones and lateral or sub-vertical flow into rivers. The study area is unique in that there are ambient, warm to very hot springs in an area of relatively low seismic activity. The springs and seep zones also occur in distinct geological settings which allows comparison with borehole data (depth of water strike, geological formation, geological situation).

The temperature of these springs inform about the maximum likely depth through which the water has moved and therefore also the likely rate of movement from these depths to the surface. This combined with macro and trace chemistry and isotope data, different aquifers having a fairly distinct chemical signature, facilitates definition of flow paths, residence times.

There are currently only a handful of springs in the greater study area that are being monitored. The information about the location of springs, their flow pattern and monitoring data are invaluable in groundwater studies as they provide a direct window into the aquifers themselves.

Ideally, the spring hydrocensus should be approached with an initial desktop study to identify key areas of interest (see Section 2.1), followed by field verification. The desktop study will entail a GIS based methodology combined with remote sensing techniques using high resolution satellite imagery to identify

- local geology,
- geological structures,
- aquifer characteristics,
- surface water patterns, and
- vegetation.

Subsequently field verification will be required as a next phase to determine the validity of the identified potential spring locations and the suitability for installation of automated flow measurements (e.g. weirs, v-notches or flumes), to take water samples for chemical and isotope analysis and to determine field parameters such as water temperature, EC and flow.

**Surface water and groundwater sampling**

The groundwater discharge to rivers along river reaches can be mapped with the aid of chemical and isotope analysis, as some trace elements and isotope signatures are aquifer specific. It is therefore recommended to sample the surface water along selected river reaches to verify whether groundwater discharges into the surface water body. It might be required to also take groundwater samples in the vicinity of the river to determine isotope and trace elements signatures for the relevant aquifers. This work should be planned together with the spring hydrocensus and interpretation of results must take spring localities and hydrochemistry into account.

**Hydraulic Testing**

Aquifer parameters for the Peninsula Aquifer are available from numerous pump tests conducted for up to three weeks in different areas, i.e. the Koo Valley, Hermanus, Citrusdal. There is also long-term data on groundwater level changes from the Olifants-Doring and the Gouritz Basin. Seasonal response to recharge (~1 m) is comparable in these areas. However these is limited pump test data or long-term water level monitoring data for the Skurweberg Aquifer.

The current test pumping results indicate a range of values for transmissivity and storage coefficient. However, there is a need for a better spatial distribution of hydraulic parameter estimations for both the Peninsula and the Skurweberg Aquifer with regards to fracture patterns and vicinity to hydrotects.

It is suggested that selected existing boreholes are test pumped, using tracer tests if appropriate and thereafter equipped with down-hole data loggers. These boreholes will be selected on the basis of the spring and borehole hydrocensus, fracture mapping, revision of flow path definition and the following criteria:

- Location within study domain with regards to model domains
- Geological profile of borehole log
- Proximity to hydraulically active faults
- Existing monitoring network.

The minimum requirements for the hydraulic testing are:

- Pumping at high abstraction rate over an extended period of time (minimum of 5 to 10 days) to stress the aquifer;
- Monitoring of hydraulic head in an abstraction borehole and at least two, strategically placed monitoring boreholes; and
- Identification of boundary conditions and flow regimes based on pumptest data.

**DESIGN AND INSTALLATION OF MONITORING NETWORKS**

The focus of the monitoring networks for the TMG aquifers is on better understanding the groundwater recharge and discharge patterns and volumes, as well as the interaction with other aquifers.

Hence, the monitoring network must comprise of weather stations, rainfall collectors, spring and stream flow gauging stations and monitoring boreholes at strategic locations to achieve the above goal. An important aspect is the use of chemical and isotope samples to verify surface water – groundwater interaction.

**ONGOING MONITORING**

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,
- Seasonal and event response sampling of rainfall, spring flow, stream flow and groundwater;
- Monitoring of water level in selected key abstraction boreholes;
- Monitoring of water level in ambient boreholes in different aquifers;
- Monitoring of groundwater discharge at selected perennial springs,
- Monitoring of groundwater use as an imperative data set for assessment of the available resource
- hydrochemical and isotopic characterisation of the various aquifer units

**DATA ANALYSIS**

The field survey data and ongoing monitoring data will need to be processed and analysed on a regular basis to provide the relevant input for the model upgrades that are recommended below.

**MODELLING UPGRADE**

The model upgrade recommendations, given in the different modelling reports, require the above-listed field surveys, ongoing monitoring and data analysis. The recommendations are listed below for quick reference.

- Update regional water balance model
- Refine dynamic storage model
- Incorporate groundwater model results into WSAM and WRYM
- Evaluate the use of heat flow modelling
- Development of numerical models for selected areas of the TMG

## SUGGESTED PROJECTS

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

1. Desktop geological mapping and field verification
2. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the Upper and Middle Breede to obtain time-series data on fluvial aquifer response to vertical and lateral recharge.
3. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the Cape Flats to obtain time-series data on fluvial aquifer response to recharge and abstraction, and to identify pollution sources.
4. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the Langebaan Road and Elandsfontein aquifers to obtain time-series data on fluvial aquifer response to recharge and abstraction.
5. Design and establish a dedicated groundwater/surface water monitoring network (water levels, abstractions, hydroclimatology and hydrochemistry) in the TMG domains to obtain time-series data on fluvial aquifer response to recharge and abstraction.
6. Hydraulic testing of the aquifers at selected sites to determine aquifer properties including storage potential.
7. Undertake model upgrades based on extensive testing and field confirmation of selected assumptions in the formal model test process, such that it can be used in predictive mode and thereby realise medium to long-term upgrade of the hydrological data and WRYM.
8. Develop small scale models to optimise current abstraction
9. Identify preferred sites for establishing wellfields and or ASR schemes, and prepare detailed models for planning and development of these schemes.
10. Evaluate use of heat flow modelling of TMG aquifers.
11. Upgrade water balance model and the groundwater input to the WRYM.

**Table D-1 Summary of required activities**

| Phase | Activity | Priority |
|---|---|---|
| **Desktop Data Acquisition** | | |
| | Mapping of paleo channels and bedrock topography in West Coast and alluvium aquifers | 1 |
| | Review and revise geological mapping in selected areas | 1 |
| | Fracture mapping in TMG terrain | 1 |
| | Determine aquifer specific groundwater use from WARMS and NGDB | 1 |
| | Data on alien vegetation water usage and aerial extent | 2 |
| | Additional data is sourced or collected in fieldwork on the river geometries, typical bed sediments, etc. | 2 |
| **Field Surveys** | | |
| | Conduct a spring hydrocensus including diverse hydrochemical sampling | 2 |
| | Conduct a borehole hydrocensus | 2 |
| | Hydraulic testing in selected boreholes in both the Peninsula and Skurweberg aquifers | 2 |
| | Hydraulic testing of paleo channels, in which boreholes are drilled, logged accurately, and the basal layer targeted in the pump test. | 2 |
| | Hydrochemical sampling at specific river reaches | 2 |
| | Survey current surface water monitoring sites so as to reduce data to common datum, i.e. mamsl | 2 |
| **Design and Installation of Monitoring Network** | | |
| | Review and revise monitoring network. | 3 |
| | review of sites identified in 2007 for flow gauges relevant to groundwater process mapping | 3 |
| | identification of key springs for installation of continuous flow metering | 3 |
| | purpose-designed and drilled boreholes equipped for continuous water level monitoring | 4 |
| | strategically sited boreholes for water quality monitoring if the above boreholes are not suitable | 4 |
| | Select sites for rainfall and weather stations in key recharge areas | 3 |
| | Installation of weather stations and rainfall collectors | 4 |

| Phase | Activity | Priority |
|---|---|---|
| **Ongoing Monitoring** | | |
| | Rainfall sampling and chemical / isotope analysis in selected recharge areas | 4 |
| | Seasonal and event response sampling of rainfall, spring flow and groundwater | 4 |
| | Monitoring of key abstraction points for aquifer response to abstraction | 4 |
| | Monitoring of ambient boreholes in different aquifers | 4 |
| | Monitoring of spring flow | 4 |
| | Monitoring of groundwater use as an imperative data set | 3 |
| **Data Analysis** | | |
| | Calibration of the recharge model with the Chloride Mass Balance and Isotopes | 5 |
| | Calculation of residence time and interflow/rejected recharge | 5 |
| | Evaluating the impact of existing groundwater use with respect to refining unused potential estimates | 5 |
| | Establish seasonal fluctuation of water levels | 5 |
| | Re-assessment of the available resource | 5 |
| **Modelling Upgrade** | | |
| **CFA** | Test reality of the conceptual model by investigating whether significant groundwater flow occurs to the northwest | 5 |
| | Smaller scale models are to be constructed for the purpose of optimisation of positions for additional abstraction | 6 |
| **LRA** | Additional modelling at a smaller scale in order to understand the hydraulic nature of the aquifers | 3 |
| | Additional modelling at a smaller wellfield scale in order to manage the current situation of abstraction from storage | 3 |
| | Smaller-scale model constructed for the purpose of optimisation of abstraction volume, and positions for additional potential wellfields. | 4 |
| | Smaller-scale model constructed for the purpose of optimisation of ASR injection volume and rate, and borehole positions | 4 |
| **BRA** | Conceptual Model Testing | 3 |
| | Select an alluvial fan at the base of a tributary to the Breede River to evaluate the most suitable site for a pilot ASR scheme | 3 |
| | Develop wellfield management scenarios | 6 |

| Phase | Activity | Priority |
|---|---|---|
| **TMGA** | Evaluate use of heat flow modelling of TMG aquifers | 3 |
| | Develop dynamic storage model for optimising conjunctive use and evaluating the risk of impact | 2 |
| **WRYM** | Develop method to integrate groundwater storage and abstraction into the Pitman model and WRYM | 2 |
| **Review and Revision of Monitoring Network** | | |
| | Ongoing review and revision of monitoring network, based on results from upgraded models | 7 |