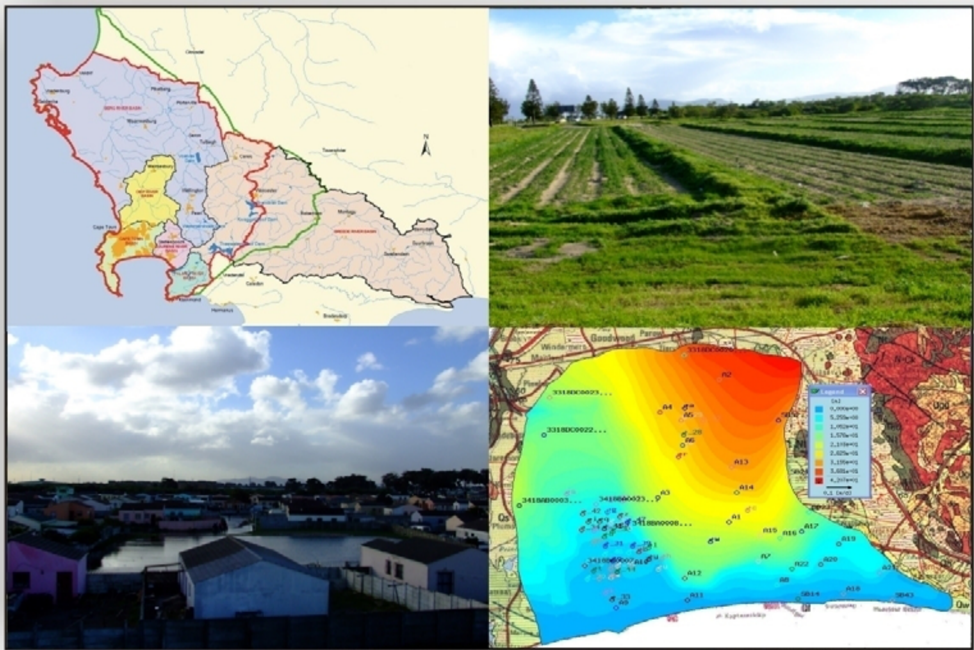
Ref No: P WMA19/000/00/0408

Department of Water Affairs and Forestry

Directorate: National Water Resource Planning

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

GROUNDWATER MODEL REPORT VOL. 5
CAPE FLATS AQUIFER MODEL



Final **August 2008**

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

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APPROVAL

TITLE	:	**The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models :** **Groundwater Model Report Volume 5** **Cape Flats Aquifer Model**
DWAF REPORT NO.	:	**P WMA 19/000/00/0408**
CONSULTANTS	:	**Umvoto Africa in association with Ninham Shand**
AUTHORS	:	**Rowena Hay, Helen Seyler**
REPORT STATUS	:	**Final**
DATE	:	**August 2008**

STUDY TEAM: Approved for Umvoto and Ninham Shand

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

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

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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 - 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, DWAF, 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 (DWAF, 2002). Recharge over the modelled area is 31 000 m^3/d or 11Mm^3/a.

WARMS data was used for abstractions. The total abstraction over the modelled area is 10 000 m^3/d or 3 Mm^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 57% of flux to SW from aquifer	-3783
		B	0	-4094 55% of flux to SW from aquifer	-4090 -
		C	0	-4843 56% of flux to SW from aquifer	-4843
G22D	Lotus, Rondevlei and Zeekoevlei	A	1572 68% of flux from SW to aquifer	-1074 16% of flux to SW from aquifer	+498
		B	+3441 82% of flux from SW across aquifer	-1700 23% of flux to SW from aquifer	+1741 -
		C	+3232 82% of flux from SW across aquifer	-1833 21% of flux to SW from aquifer	+1399
G22E	Kuils	A	+743 32% of flux from SW across aquifer	-1755 27% of flux to SW from aquifer	-1012
		B	+743 18% of flux from SW across aquifer	-1720 23% of flux to SW from aquifer	-977 -
		c	+729 18% of flux from SW across aquifer	-1958 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 Mm^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 Borehole logs 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; Downhole geophysics; Estimates of porosity to refine model layers; Field estimates for different layers.	Pump test conducted in the central palaeochannel; Layer specific monitoring
Improve confidence in numerical model	Test reliability of numerical model boundary conditions and uniqueness of model solution for SW-GW interactions; 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; 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.

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

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ABBREVIATIONS

BRBS	Breede River Basin Study
CDSM	Department of Land Affairs - Chief Directorate Surveys and Mapping
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry
EC	electrical conductivity
E-W	east west
FE	Finite Element
GIS	Geographical Information System
GRA	Groundwater Resources Assessment
GRDM	Groundwater Directed Measures
GW	Groundwater
IWR	Integrated Water Resources
IWRM	Integrated Water Resources Management
K	Hydraulic conductivity
km	kilometre
LRA	Langebaan Road Aquifer
m	metre
MAE	Mean annual evaporation
MAP	Mean annual precipitation
MAR	Mean annual runoff
NGDB	National Groundwater Database
NWRS	National Water Resources Strategy
NWA	National Water Act
op.cit.	work previously cited
RDM	Resource Directed Measures
RQO	Resource Quality Objectives
SAWS	South African Weather Service
SW	Surface water
TDS	Total dissolved solids
TMG	Table Mountain Group
TMGA	Table Mountain Group Aquifer
TOR	Terms of Reference
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
WMA	Water Management Area
WRC	Water Research Commission
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model

WR	Water Resources

1. INTRODUCTION

1.1 THE WAAS PROJECT

1.1.1 Project Background

The Berg River Catchment forms the heart of the Western Cape Water Supply System (WCWSS), whose supply area constitutes the economic hub of the Western Cape and serves a primary export industry based on agricultural produce. The WCWSS serves the City of Cape Town, both urban water users and irrigators along the Berg, Eerste, Lourens, Steenbras and Palmiet Rivers, domestic 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 (DWAF) have initiated two major water resource management and planning undertakings in the environment of the WCWSS:

a) Compulsory licensing in terms of the National Water Act (NWA) - Act 36 of 1998 - is due to be piloted in the Berg WMA, in response to concerns that growing water user demands, as well as streamflow salinity increases, might place parts of the WCWSS in a water-stress condition during the foreseeable future.
b) A Reconciliation Strategy Study has been completed in 2007which reviewed the future water requirements and the options for meeting these demands. The Study identified the most favourable augmentation options and recommended a programme of feasibility studies and other investigations to improve the operation and planning of the system, and to ensure that the necessary infrastructure or other interventions are implemented timeously so as to reconcile the supplies with the future demands.

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

- Reconfigure the existing Water Resources Yield Model (WRYM) configurations at a spatial resolution suitable for allocable water quantification to support compulsory licensing.
- Use reconfigured existing models or newly configured models for allocable water quantification for both surface water and groundwater, where applicable.
- Incorporate changes in concepts, models and approaches, as derived from pilot studies initiated by DWAF elsewhere, if these become available in time.
- Support the Reconciliation 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 south-westerly direction to the south of False Bay.
- The Breede River, which flows easterly to the Indian Ocean and of which the Upper and Middle Breede and the Upper Riviersonderend catchments are focus areas for this Study.

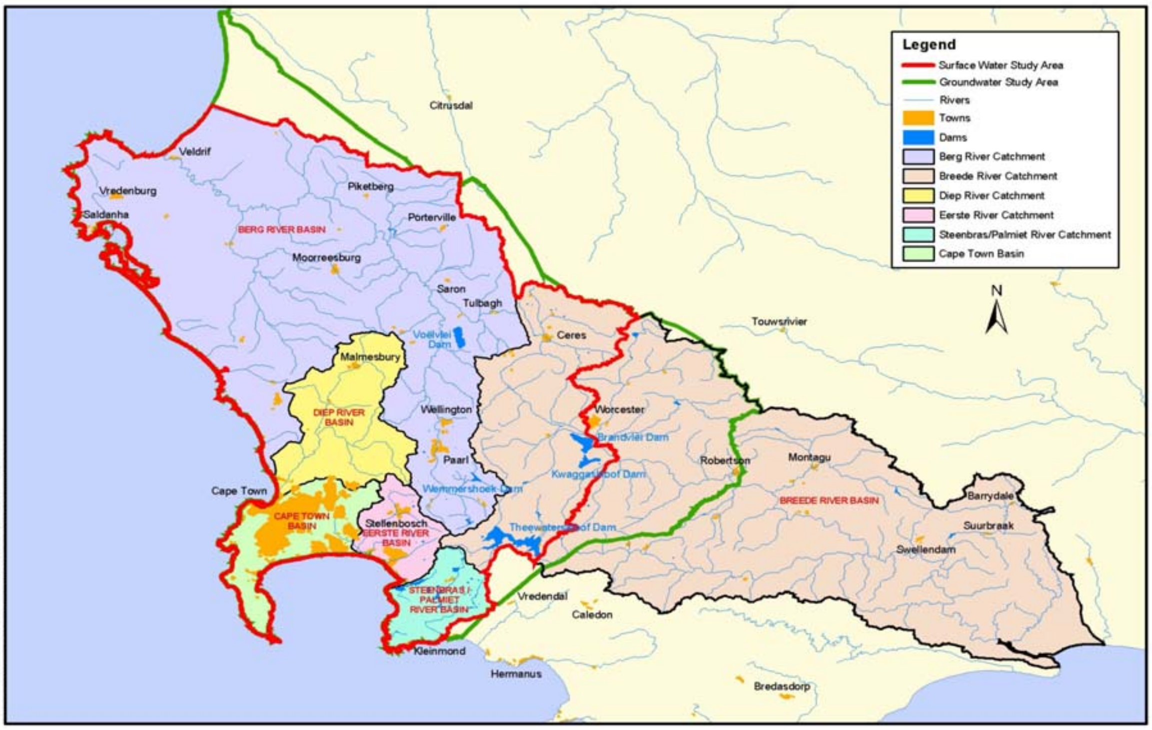

Figure 1-1 Study Area Locality

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

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

1.1.3 Project Components

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

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

1.1.4 Terms of Reference for Groundwater

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

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

Allocation of future surface water involves a 2D analysis of the hydrology and current use. This can easily be simplified to 1D without losing significant physical reality. The impact of future groundwater use on current users and therefore the sustainable utilisation of water in aquifer storage by both user groups can only be assessed if the potential yield rather than the current yield is analysed with appropriate spatial and time series detail. In the Berg WAAS domain this is mostly a fully 3D problem, which cannot be simplified to 1D.

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 impacts on the resource from a source directed and a water quality directed perspective.

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

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

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

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

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

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

These volumes are:
Volume 1: Summary Groundwater Availability Assessment (due at end of project)
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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 form a basis to this report as the available data has informed the regional conceptual model upon which conceptual modelling at the smaller scale of the Cape flats is based and refined, and the conceptual model has informed the selection of data for model input and calibration.

1.2 CAPE FLATS AQUIFER REPORT

1.2.1 Background to the Cape Flats Aquifer Report and Report Purpose

The ultimate purpose of the present Water Availability Assessment and groundwater modeling study is to provide a sound quantitative basis for resource assessment into the future. A regional conceptual model and GIS water balance model has been developed in order to further the understanding of the hydrogeology of the TMG system (Volume 4 of this report, DWAF 2007c). In addition to the regional-scale model, smaller scale modelling is undertaken in selected areas, to characterise and quantify the available water resource with greater confidence at a smaller spatial scale for specific aquifers (DWAF 2005). The conceptual understanding on the regional scale can be iteratively reviewed based on the understanding and knowledge gained from the smaller scale modelling and, in due course on the basis of monitoring data and analysis This report forms the first in the volume series of reporting on these smaller model domains.

The motivation for the Cape Flats to be one of the smaller model domains is economic and also social. Over the past two to three decades the utilisation of the Cape Flats aquifer has been debated. During the late1980s and 1990s increasing informal settlement and expansion of the urban and industrial base have resulted in two factors; increased threat to this aquifer from human as well as industrial waste and the creation of a flood management problem arising from township and informal settlement in low lying areas as well as in areas where the winter groundwater table is above the ground surface. The problems of a high winter groundwater table are exacerbated by losses from the reticulation systems, increased urban storm water runoff and ponding in topographic lows. A possible solution is purposeful lowering of the water table in these areas in the summer to reduce the level of the water table in winter.

The decentralised development of this aquifer lends itself to solving both a social and a natural hazard. The purposeful over abstraction of water in the summer for irrigation of sports fields and green open spaces, and for use as non potable supply to flush toilets, fight fires, create artificial wetlands or recreation areas in natural lows *inter alia* can contribute to holistic water resource management and disaster risk reduction.

The IWRM study undertaken for the City in 2001 (City of Cape Town, 2001) indicated that the cost of water from this aquifer was R162 million with R10 million annual operating costs. The development of the aquifer was not recommended as a high priority in the study. The Western Cape Reconciliation Strategy Study recommended that a feasibility study be conducted in order to assess the usefulness of the Cape Flats aquifer as augmentation to the supply to the City (DWAF, 2005). This report could form a basis for such a feasibility study. More precisely, this report documents:

- Configuration of a numerical model for the Cape Flats Aquifer
- Quantification of surface water – groundwater interaction
- Calibration of recharge estimation and water balance
- Analysis of the rainfall dependency of surface water- groundwater interaction and the water balance
- Scenario for augmenting the bulk water supply to Cape Town
- Scenario for flood management
- Verification of pollution threats within the Cape Flats Aquifer.

A locality map showing the study area boundaries and locality is shown in **Figure 1-1**.

1.2.2 Summary of Cape Flats Conceptual model

The outline of the conceptual model for the smaller scale model domains is given in Volume 3 of this report (DWAF, 2007b). It is summarised below as an introduction to developing the conceptual model through detailed analysis of relevant features in chapters 2 and 3 of this report.

The Cape Flats covers an area in excess of 400 km^2 (Hay,1981; DWAF, 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 to Table Bay.

Unvegetated dunes with older vegetated dunes further inland cover the narrow low-lying coastal plain of the Cape Flats. The dunes are part of the Quaternary sand unit that forms the relatively thin Cape Flats Aquifer. The Quaternary Sands overlie the weathered Malmesbury and granite basement rocks which also act as an aquiclude. The near-surface groundwater-flow direction parallels the surface water drainage. The Cape Flats Aquifer has been extensively studied since the 1970s by various individuals. Varying geological interpretations have been suggested (Henzen,1973; Wessels and Greeff, 1980; Hay,1981). There has been a difference in opinion as to the number of distinct units and whether they are continuous or not across the Cape Flats.

The Cape Flats conceptual model boundaries are shown in **Figure 1-2.** Based on geology, aerial extent of the alluvium, topographic highs, and surface water divides; these boundaries represent the geographic extent of the Cape Flats aquifer. The eastern model boundary follows the contact from the sands to the underlying bedrock. The northern boundary is based on a bedrock high (Gerber, 1980, Rogers, 1980, Hay et al, 1996). The western boundary is based on the contact between the sands and the bedrock. The southern boundary is the coastline.

Water levels relative to mean annual sea level are higher in areas of raised topography around the Durbanville/Tygerberg Hills, Stellenbosch Mountains and environs. Water levels are higher along the footslopes of mountains to the east of the Cape Flats than in those in the west. On the Cape Flats themselves, where the topography is relatively even, the water levels decrease toward the coast at False Bay.

Groundwater generally flows in a semi radial fashion from the higher lying outcrops of basement Malmesbury Shales in the northeast near Durbanville, toward Table Bay to the northwest and the False Bay coast to the south (See **Figure 1-3**). Studies of the basement topography reveal what is interpreted as 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.

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.

1.2.3 Structure of this Report

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

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

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

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

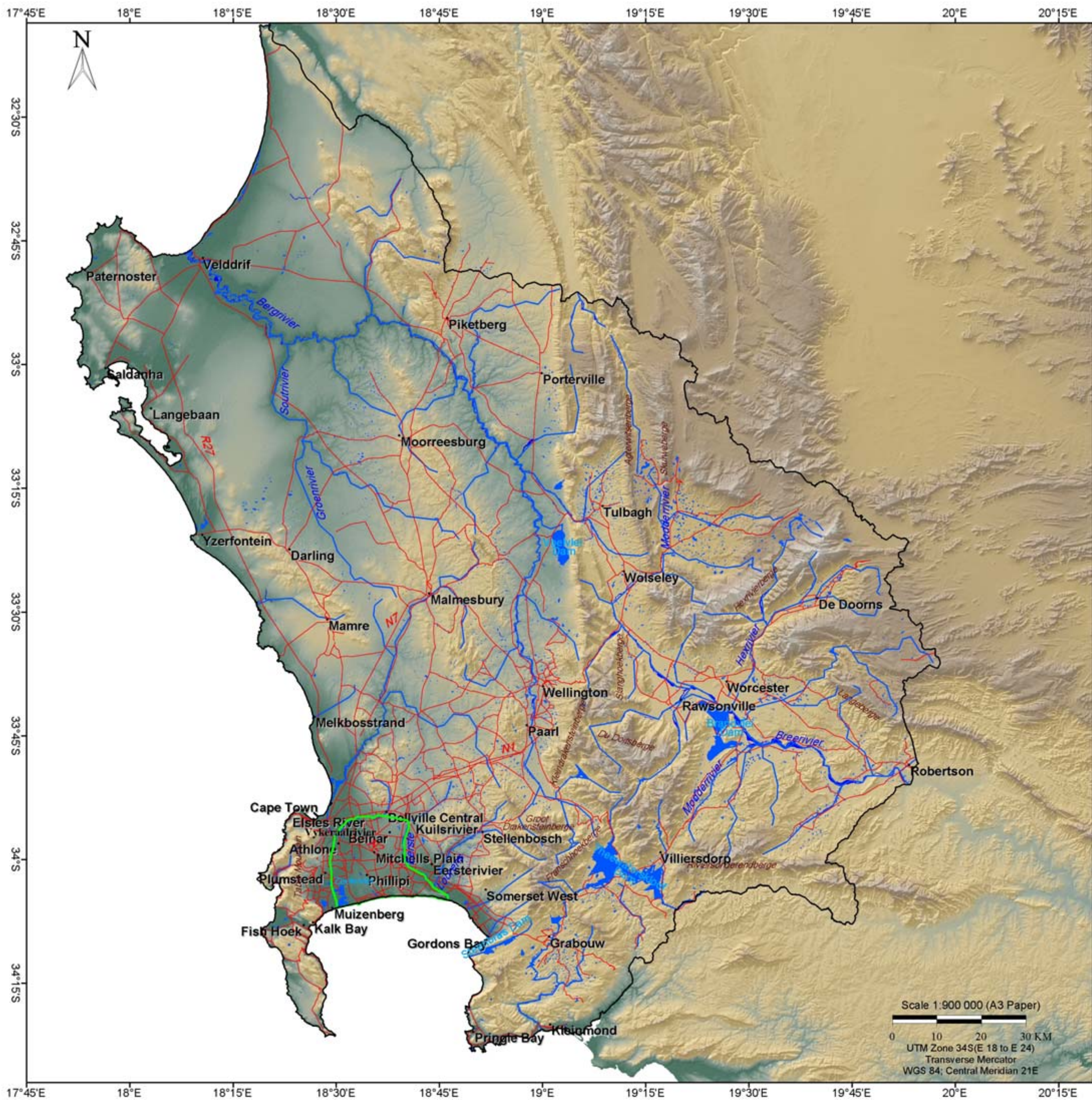
Chapter 4 details available relevant data for the Cape Flats and model data input.

Chapter 5 presents the numerical model results. The steady state model parameter calibration and results are described.

Chapter 6 presents results from calibration of transient modelling.

Chapter 7 details results from using the numerical model scenario testing.

Chapter 8 states the conclusions drawn from the modelling and details recommendations.



LEGEND

- Towns
- Roads
- Major Rivers
- Berg Boundary
- Model Area
- Dams

Elevatiom (mamsl)

2101
1401
1167
934
700
467
233
0

PROJECT NAME

BERG RIVER MODEL STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS

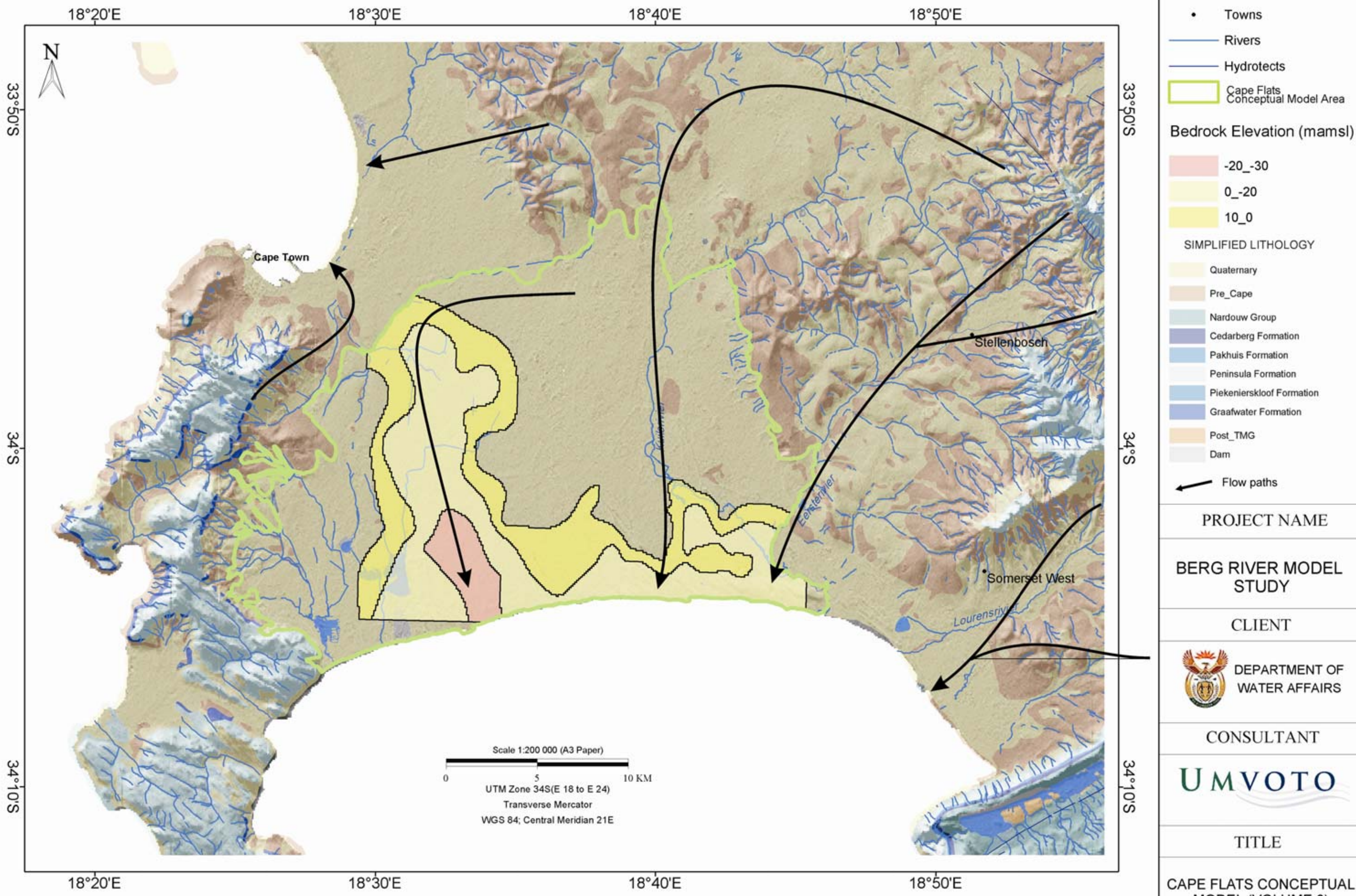
CONSULTANT

UMVOTO

TITLE

LOCALITY MAP

FIGURE 1.2



PROJECT NAME

BERG RIVER MODEL STUDY

CLIENT

DEPARTMENT OF WATER AFFAIRS

CONSULTANT

UMVOTO

TITLE

CAPE FLATS CONCEPTUAL MODEL (VOLUME 3)

FIGURE 1.3

2. DESCRIPTION OF STUDY AREA

2.1 TOPOGRAPHY & DRAINAGE

The Cape Flats area is bounded by the Tygerberg Hills in the North, by the Cape Peninsula in the west and the Bottelary Hills in the east. They cover a large area (400 km^2) from the False Bay coastline in the south, to the suburbs of Bellville in the northeast and Milnerton in the northwest. The topography within the Cape Flats is typical of coastal plain and dune fields and, as the name suggests, variations in topography are relatively minor, with elevations ranging from 0 m above mean sea level (amsl) in the south to 110 mamsl in the north (**Figure 2-1** below).

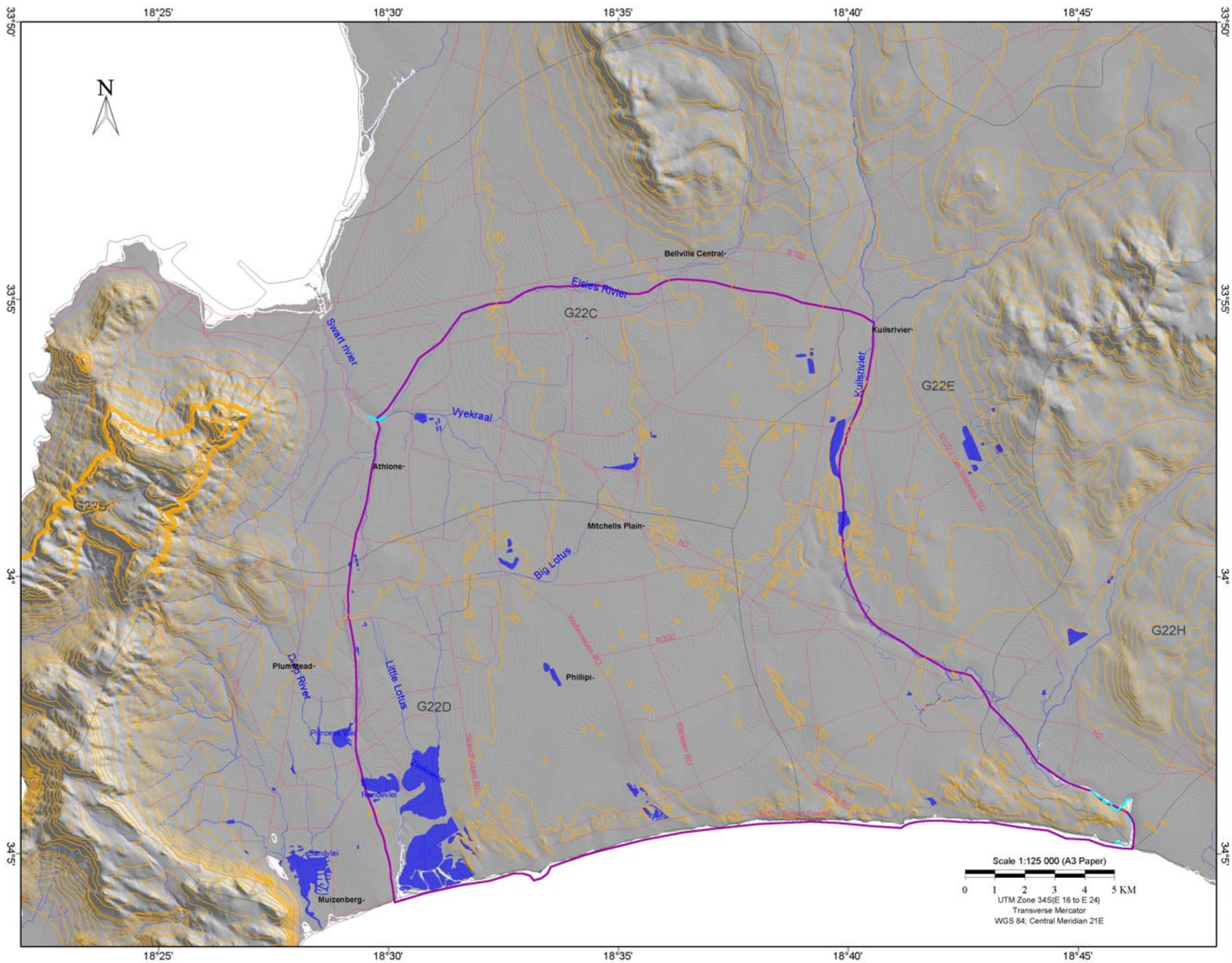
Hay (1981) described the Cape Flats area as having various topographically distinct compartments. These are summarized below:

- A narrow low-lying coastal plain which is covered with unvegetated dunes (i.e. along the coastline), within which elevations range from 0 m to 70 in the south east near Swartklip and Macassar Beach;
- An older vegetated dune field within which the topography varies between 20-70 m ('Cape Flats proper' – i.e., the centre and north of the study area)

The topography and underlying geology of the Cape Flats is continuous to the northwest towards Paarden Island, Milnerton and Bloubergstrand. All rivers drain southwards, except in the northwest where the Black, Salt and Liesbeek Rivers flow in a northerly direction (see **Figure 2-1**). The Elsieskraal River has its origin in the Tygerberg Hills to the northeast of the study area, and drains in a west-southwest direction. Near the intersection of the N2 and the M5 freeways, the Elsieskraal joins the east flowing Vyekraal River, which has its source within the northern Cape Flats area near Guguletu, to form the north flowing Black River. Downstream the Black River joins the Liesbeek River to form the Salt River and flows north discharging to Table Bay. Much of the Elsieskraal runs in a concrete lined channel (Section 2.4.2).

The major south flowing surface drainage features are the Kuils River, Lotus River and Diep River. The Kuils River, in the east of the study area, has its source at the Durbanville golf course and from here drains southwards. Various wetlands are developed along its course, including the area of Vogelvlei just east of Cape Town international airport. Approximately 3.5 km inland from the coast in the east of the study area the Kuils River joins the Eerste River, which flows from the Jonkershoek Mountains east of the area. Where the two rivers meet an area of wetland and marsh is developed, known as the Kuils River Wetlands in Khayelitsha. The Eerste River then flows towards the southeast and discharges at the ocean close to the eastern boundary of the study area. The upper reaches of the Kuils River are degraded and run in a concrete lined channel, and the general water quality is poor.

The Lotus Rivers (Little and Big) have their source within the Cape Flats and drain into Zeekoevlei. The level of Zeekoevlei is artificially controlled and the vlei is drained once a year during winter. These rivers are also canalised for much of their length and water quality is poor. The Diep River has its source on the south-eastern flanks of Table Mountain, and flows across the west of the Cape Flats aquifer, to the west of the Lotus and Zeekoevlei. It discharges to Sandvlei which discharges to the ocean.



LEGEND

- Towns
- Contours
- Rivers
- Roads
- Inland water
- G22C Catchments
- Model Area

PROJECT NAME

BERG WAAS

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

CONSULTANT

UMVOTO

TITLE

TOPOGRAPHY

FIGURE 2.1

2.2 HYDROLOGY AND HYDROCLIMATOLOGY

The WR90 provides certain hydrological and climatological parameters averaged at the catchment scale, which is useful as a first order measure of climate (Midgeley et al, 1994). The Cape Flats cover parts of the following Quaternary catchments (**Figure 2-1**);

- G22C
- G22D
- G22E
- G22H

The WR90 data shows that the only flow gauging stations within the Cape Flats model area are two on the Kuils River (see Volume 2 of this report, DWAF, 2007a). Only one of these, positioned at the north of the Cape Flats model area, has available records. Data was recorded for this flow gauge from 1977-1987. Average monthly total flow volumes range from a minimum of 0.59 Mm^3/month during February, to a maximum of 2.37 Mm^3/month during August. The river flow is at minimum when monthly rainfall is also at minimum. The maximum river flow shows a 2-month delay with respect to the maximum rainfall, which occurs in June (see below).

The rivers on the Cape Flats are known to demonstrate a rapid response to rainfall (local knowledge). This is generated, or at least exaggerated, by the high degree of canalisation and diverting of rainfall into culverts towards the streams away from settlements (local knowledge, see Section 2.4.2). The Lotus and the Vyekraal are reportedly ephemeral and flow in response to high rainfall storm events (Gerber, 1980). Data on groundwater contribution to baseflow is at catchment scale (**Table 2-1**). Comparison of this data to aquifer-specific data for groundwater contribution to baseflow shows that, in most of the catchments throughout the Cape Flats, it comes from intergranular aquifers (Volume 4 of this report, DWAF 2007c). It is not yet possible to know the river-specific contribution to groundwater.

These data provide little information on the specific hydrological behaviour of the rivers traversing the Cape Flats and there are limitations to what can be inferred from it. For example, an ephemeral stream which is groundwater fed at certain times would have a baseflow recorded as zero. (For a full discussion of the GRA II baseflow and groundwater contribution to baseflow see Volume 2 of this report, DWAF, 2007a).

Cape Town and environs has a Mediterranean climate. Mean annual evaporation exceeds precipitation by more than double (**Table 2-2**). 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. This rainfall data is generated by re-calculation of modelled mean monthly values, as given by Agrohydrology data sets (Schultz et al, 1997), to sum to the annual modelled rainfall as used in Volume 4 of this report (DWAF, 2007c). This monthly rainfall data is shown in **Figure 2-2**.

Actual measured monthly rainfall data is also plotted in **Figure 2-2**. This is averaged from data collected between 1927-1979 from a rainfall station in the east of the Cape Flats near the Kuils River (DWAF 2007). The agreement between the ‘modelled’ and ‘measured’ rainfall is good. The magnitude of the ‘measured’ rainfall is less than the averaged as it is in the east of the area, and the mean value incorporates high values from the northwest of the area. The broad pattern of rainfall distribution across the Cape Flats ranges from a minimum of 214 mm/a in the east to ~800 mm/a in the west and central areas of the Cape Flats. The MAP contoured data show a significant rainfall high in Newlands to be extending beyond Athlone. This results in the rainfall being as high as 1500 mm/a in the northwest of the model domain **Figure 2-3**). There are considerations as to the reality of these modelled values.

Table 2-1 Baseflow and Groundwater Contribution to Baseflow per catchment, after GRDM database (DWAF, 2006)

Quaternary Catchment	Base Flow *GRDM*	Base Flow *HUGHES*	Base Flow *PITMAN*	Base Flow *SCHULZE*	GW Contribution to Base Flow *GW_BFLOW*
	mm	mm	mm	mm	mm
G22C	10.0	28.73	2.94	12.00	10.08
G22D	17.0	50.13	4.04	19.30	10.40
G22E	9.0	24.20	2.43	10.60	9.87
G22H	13.0	35.04	3.69	15.00	9.17

Table 2-2 Available hydrological data at Catchment scale (Volume 2 of this report, DWAF 2007a).

Quaternary Catchment	Area	MAP *Berg WAAS*	MAR *WR90*	MAE *WR90*	Run-off Efficiency *WR90*
	km^2	mm	mm	mm	
G22C	254.25	651	92	1400	0.15
G22D	246.01	824	165	1400	0.22
G22E	270.68	562	77	1410	0.13
G22H	227.30	814	111	1415	0.17

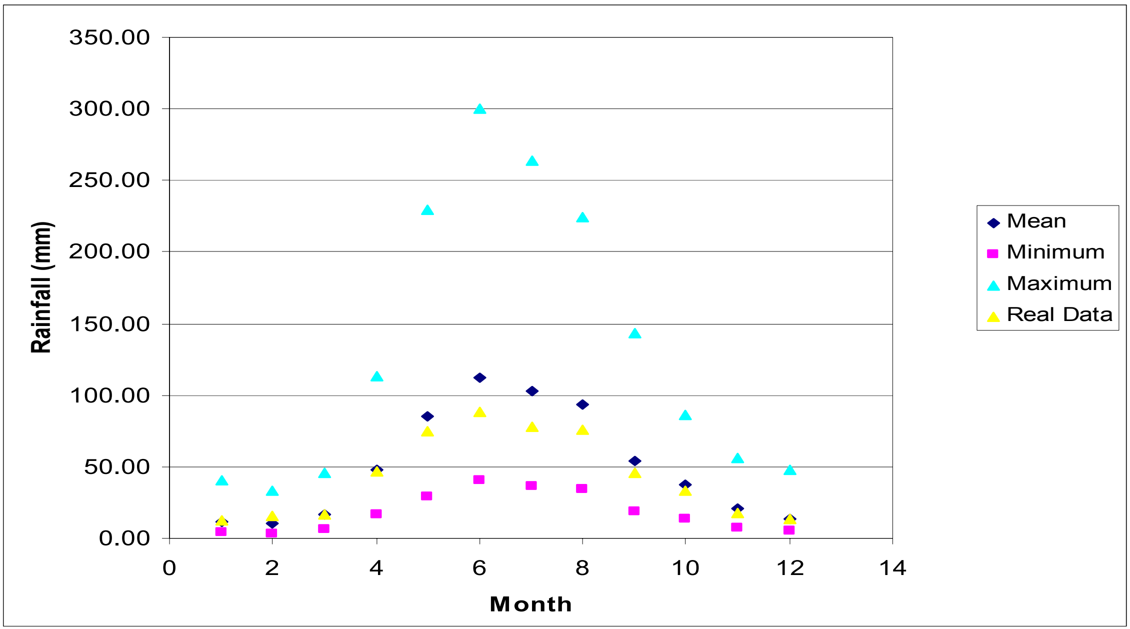
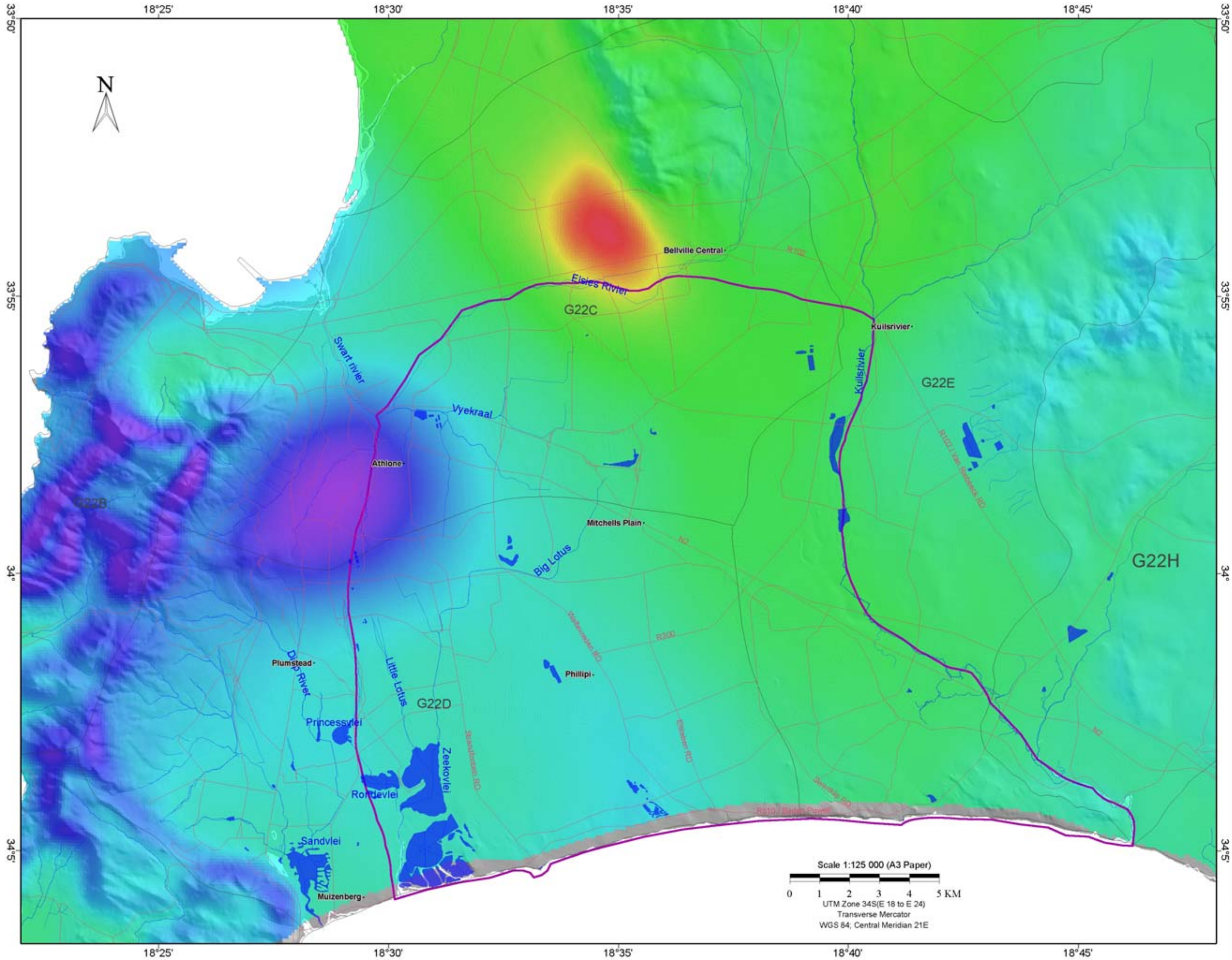


Figure 2-2 Monthly rainfall data for the Cape Flats
(Months from 1 in January to 12 in December)



LEGEND

Towns

Rivers

Roads

Inland water

G22C Catchments

Model Area

Mean Annual Rainfall (mm)

3238

1252

855

457

60

PROJECT NAME

BERG WAAS

CLIENT

DEPARTMENT OF WATER AFFAIRS & FORESTRY

CONSULTANT

UMVOTO

TITLE

MEAN ANNUAL RAINFALL

FIGURE 2.3

2.3 GEOLOGY

2.3.1 Stratigraphy

The stratigraphic sequence present in the Cape Town area comprises rocks ranging from older deposits of the metamorphosed basement Malmesbury Group to the present day wind-blown sands. The full stratigraphic sequence is shown in **Table 2-3** below with the units present in the study domain highlighted.

The Malmesbury Group is a metamorphosed greywacke and comprises phyllite, shale and quartzitic sand and is heavily intruded by the Cape Granite Suite. These outcrop on basement highs at the periphery to the Cape Flats study area (**Figure 2-4**). The Peninsula Formation uncomformably overlies the basement and forms the topographically dominant Cape Peninsula. It is a major unit of the thick sedimentary sequence of the Palaeozoic Cape Supergroup. The older basement rocks and the Peninsula formation are intruded by dolerite dyke swarms with a distinct north-easterly strike. These dykes transect the False Bay as well as the Cape Flats. On the area known as the Cape Flats, the Cape Supergroup is absent, having been eroded away and only the most recent Quaternary Sand deposits overlie the basement Malmesbury and intruded granite/granodiorite (**Figure 2-4** and **Figure 2-5**).

The quaternary unit forms the Cape Flats Aquifer and comprises fluvial, marine and aeolian deposited sands. Theron et al, (1992) described the Quaternary sequence as lower limestone and calcrete or partly cemented calcareous sands, deposited as marine sands in high sea levels, overlain by beach and wind blown deposits of beach sands, white sand with shelly material, loam, sandy loam, and sandy soil. The dune features near the coastal plain are formed by limestone, calcrete and cemented calcareous sands, and the flatter central parts of the Cape Flats are underlain by unconsolidated white sand.

The 3D sedimentology of the Quaternary Sands has been described in detail by many workers through analysis of borehole logs (Henzen, 1973, Wessels and Greeff, 1980, and Hay, 1981). The stratigraphic cross-sections developed by Henzen (1973) document highly heterogeneous multi-layered clean sands with laterally discontinuous layers of various lithologies including, clay, clayey sand, sandy clay, limestone, sandstone, coarse gravels and peats (**Figure 2-6**). The interbedded calcareous deposits (calcrete) near the water table are a result of the high calcium carbonate content of the groundwater (Fraser and Weaver, 2000a). Calcrete deposits occur through the dissolution of shelly material deeper in the stratigraphy followed by re-precipitation of the calcium carbonate.

The detailed cross-sections in **Figure 2-6** show the Quaternary Sands reach a maximum of ~55 m thick. The thickest deposits occur in the palaeochannel running north-south in the south west of the Cape Flats. The clean sand unit is interpreted to be continuous and the interbedded peats, calcareous sands, gravels, clays, etc, are interpreted as laterally discontinuous units by Henzen, (1973).

Table 2-3 Stratigraphy of the Wider Study Area

Age range (Ma)	Supergroup	Group	Formation
0 – 2.5		Bredasdorp	Witzand
			Langebaan
			Velddrif
			Springfontyn
2.5 – 25		Sandveld	Varswater
			Saldanha
			Elandsfontyn
~~ Major unconformity ~~~~~			
65 - 144		Uitenhage	
			Enon
		False Bay Suite	(dolerite swarm)
~~ Major unconformity ~~~~~			
248 - 290	Karoo	Ecca	
		Dwyka	
290 - 354	Cape	Witteberg	(various)
354 - 417		Bokkeveld	(various)
		Table Mountain	Rietvlei
417 - 443			Skurweberg
			Goudini
			Cedarberg
			Pakhuis
			Peninsula
443 - 495			Graafwater
			Piekenierskloof
~~ Major unconformity ~~~~~			
495 - 545	(Saldanian)	Klipheuwel	
		Cape Granite Suite	
545 – >750		Malmesbury	

In contrast to Henzen (1973), Wessels and Greeff (1980), Hay (1981), and also Vandoolaeghe (1989), interpreted the stratigraphy of the sands as comprising discrete continuous to discontinuous layers. The boreholes analysed by Hay (1981) were in a roughly N-S line in the east of the area, ~2 km east of the Swartklip road (**Figure 2-6**). From these Hay (1981) described the Quaternary Sands as comprising 5 distinct layers, as set out in **Table 2-4**.

Table 2-4 Stratigraphy of the Quaternary Sands (after Hay, 1981)

Unit	Group	ORIGIN	DESCRIPTION
A	Bredasdorp Group	Aeolian	Non-calcareous, well-sorted, medium to fine sands underlying surficial shelly sands
B		Aeolian	Calcretised sand (discontinuous unit)
R		Fluvial	Medium to coarse, gravely, angular sand with minor feldspar overlain by fine sandy mud, clay and peat
C		Aeolian	Homogeneous, well-sorted, non-calcareous fine to medium sand
D	Sandveld Group	Marine	Angular to well rounded, poorly sorted, slightly muddy, gravely sand to slightly muddy, sandy gravel

The basal marine unit of gravels pinches out northwards against bedrock (**Figure 2-6**).

Wessels and Greeff (1980) analysed the same line of boreholes as Hay (1981). Their interpretation for the lower stratigraphy is similar as they also map a basal marine gravel. However their interpretation varies slightly as they map one main unit of fine and medium grained sand. Various layers exist within this, for example they map a clay layer within the clean sand, whereas Hay (1981) maps this area as a separate unit, R, which is a sand with clay beds (**Figure 2-6**).

Vandoolaeghe (1989) conducted a comprehensive stratigraphic analysis of ~25 boreholes within a 3 km diameter circular area (the Cape Flats Groundwater Development Pilot Abstraction Scheme). The study area was between the Weltevreden Road and Eisleben Drive (**Figure 2-1**). Vandoolaeghe (1989) coupled his description of the Cape Flats Quaternary Sands, to some degree, to the regional formations shown in **Table 2-3**. His interpretation of the Cape Flats stratigraphy is shown in **Table 2-5**. To a large extent his stratigraphy accords with that detailed by Rogers, 1980.

Table 2-5 Stratigraphy of the Quaternary Sands (after Vandoolaeghe, 1989)

Formation	Formation/ Member	ORIGIN	DESCRIPTION
Bredasdorp	Witzand member	Aeolian	Shelly calcareous sand
	Langebaan Limestone Member	Aeolian	Calcrete and very calcareous sand
	Springfontyn Member	Aeolian	Well sorted and rounded fine to medium clean quartzose sand. Local lenses of clay and peat.
Varswater	Calcareous sand member (CSM)	Marine	Fine to medium, often silty, shelly, calcareous sand
	Shelly Gravel Member (Strandfontein?)	Marine	Coarse shelly gravel and sand
Elandsfontyn	-	Fluviatile	Angular, fine to coarse clayey, silty, angular sand and gravel.

Although Vandoolaeghe marries his lithologies to the regional stratigraphy, analysis of the available borehole details shows the thickness of each unit varies dramatically even at this small scale. For example the Langebaan Limestone member, was only present in 3 of the boreholes. The Springfontyn member varies from 11 m to not present between boreholes that are within 1 km of each other.

Shand (1987) presented a groundwater study of a ~0.5 km^2 area of Mitchells plain, in the south east of the model area. The typical stratigraphy presented for the area is summasrised as a basal fine sand, overlain by a calcrete unit, with a uppermost calcareous sand (**Figure 2-6**).

A discussion of the basement topography is required in order to compare the various geological interpretations and conclude the applicable geological interpretation for this study.

2.3.2 Palaeo-topography

The geological cross-sections (**Figure 2-6**) illustrate a general decrease in bedrock elevation (i.e. a thickening sand unit) towards the south. Data from the geological maps (Theron et al, 1992), borehole logs and maps of basement elevation within previous reports (Wessels and Greeff, 1980, Henzen 1973, Rogers, 1980) have been combined to generate a contour map of the basement elevation, shown in **Figure 2-7**. The basement elevation is highest in the northeast and drops towards the coast in the south. A palaeochannel is evident in the west of the area. The broadly E-W flowing middle section of the Elsieskraal, between Bellville and Pinelands, is not associated with an underlying incised channel in the basement topography. The depth to bedrock is 23 m below ground surface around its course in the Bellville town area, however reduces to 3-6 mbgl between Parow and Goodwood (Hay et al, 1996). It is interpreted that the stream has been diverted near Bellville, from a previous more southerly course. Hence the palaeochannel in the south west of the area is interpreted as a palaeochannel of the Elsieskraal. This diversion is likely to have been generated by the Holocence (<10 Mya) advance of aeolian dune-sand ridges from the shores of False Bay, advancing over the former fluvial topography (Hay et al, 1996).

In a high hydraulic conductivity medium such as unconsolidated sands, flow is likely to be strongly controlled by basement topography and will exploit channels in basement. The basement elevation data **(Figure 2-7)** is sparse in the northwest of the area, however suggests the possibility of a basement low on the northwest at the tip of the Elsieskraal palaeochannel. The two 10 m contours form a channel rather than a closed basin at the northern end of the palaeochannel. If continuous, this suggests that deep groundwater, like surface water in the northwest of the Cape Flats, also flows out to the ocean at the northwest. However data at the Wingfield site show a basement high is present in the north east of the area near Goodwood, beyond the numerical model boundary (Hay et al, 1996). This is shown in **Figure 2-7** by the data points between the 10 and 20 m contour around the northern boundary west of the Elsieskraal River label. Gerber (1980) also suggests that there is a basement high between the north-central Cape Flats and Table Bay. A very high hydraulic head would be required to drive groundwater flow out to the northwest of the model over any basement high. Possible scenarios for groundwater flow at the northwest of the model are described further in chapter 3.

It should be noted that **Figure 2-7** was generated in GIS from a point data set of the basement height. The automatic interpolation has generated some contours that are unrealistic. For example in the northwest the contours around 60 mamsl in Table Bay are generated by the high ground at Table Mountain and the Tygerberg north of Bellville. This high also generated the high contour at 40 mamsl on the northwest boundary of the model. The reader is referred to the data points marked in **Figure 2-7** as a guide to which contours are based on real data. These numerical errors do not occur in the interpolated surface in the model (see Section 4).

2.3.3 Geological Summary and Interpretation

The upper most stratigraphic unit of the Witzand Aeolian shelly calcareous sand, which exists at the surface in parts of the Cape Flats, is common to geological interpretations. Most of the cross sections mapped by Henzen (1973) show a stratigraphy dominated by a sand unit. This is interbedded with lenses of calcrete, clay and peat. The main sand unit mapped by Henzen (1973) is likely to correspond to the Bredasdorp and Varswater units together (**Figure 2-8**). Henzen (1973) therefore mapped the sand with varying shelly contents as simply sand, and not separating, for example, a unit with greater abundance of peat lenses (the Springfontyn member).

The key feature necessary for a comparison of the geological interpretations is an understanding of the scale of the various investigations and appreciation of the sedimentary process during which the different formations were deposited. **Figure 2-8** compares the main features of geological interpretation from selected workers, in order to generate a typical geological section applicable to the Cape Flats. A typical geological section is shown for each worker. The sections are shown in scale order, i.e. the smallest scale of investigation is on the left (section 1, after Ninham Shand, 1987) and the largest scale investigation is on the right (section 5, after Henzen, 1973). Wessels and Greeff (1980) and Hay (1981) mapped continuous geological units from interpretation of a N-S ~14 km length line of boreholes in the east of the area. Vandoolaeghe (1989) concluded continuous stratigraphic units through intensive study of a 3 km area, in the southwest of the Cape Flats, however the actual logs show highly discontinuous sediments (more applicable as lenses).

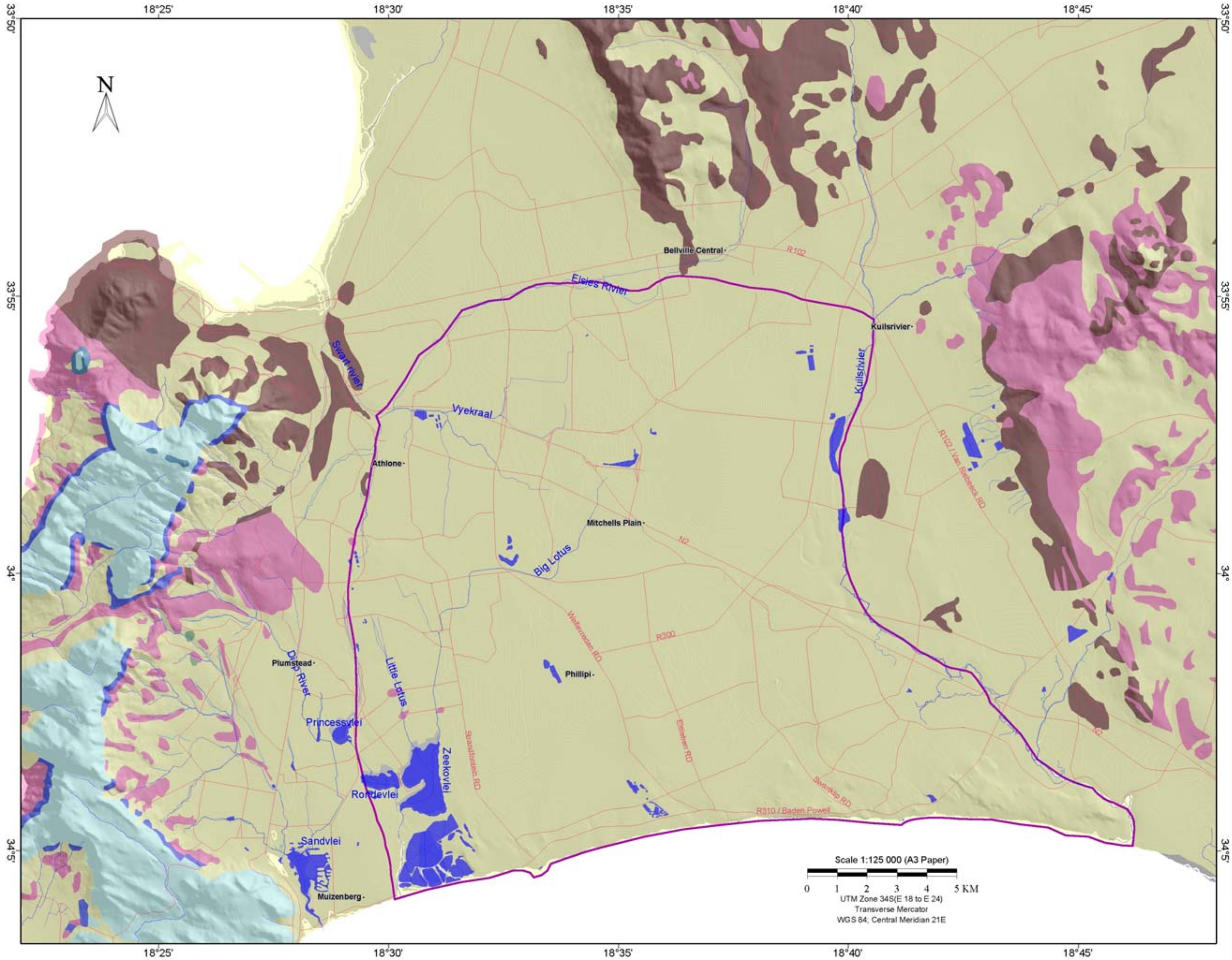
Henzen (1973) shows the most comprehensive collection of cross sections with respect to area covered and density of boreholes included. The study domain of Henzen is comparable to that in this study. It is clear in Henzen's sections that there is greater continuity in the N-S plain rather than the E-W, which is expected for the N-S oriented river systems. The distinction of the Quaternary Sands into multiple discrete layers is unlikely to be applicable to the whole model area because it is unlikely that there is continuity in the E-W plain. However given a typical meandering river system sediments would be continuous in the E-W plain within the confines of the river valley and flood plain but not beyond.

Within the deepest basement, i.e. in the main Elsieskraal palaeochannel, a clean gravel and pebble bed is mapped at or near the base of the section (**Figure 2-6**: Henzen's sections BH 36, 31, 43, 14, 7). Adopting a more geologically real interpretation of the units logged by Henzen (1973), it is suggested that the basal clean gravel is continuous in the confines of the palaeochannel, as a basal fluvial deposit (**Figure 2-8**). The deepest units in Henzen's sections are ~-25 mamsl, however the basement data extends to –30 mamsl, therefore it is interpreted that the basal gravels fill channels to this depth. This is also confirmed by an NGDB borehole in the northwest of the palaeochannel which logs boulders at the deepest level.

Vandoolaeghe (1989) maps the basal layer in his sections as fluvial clayey silty sand and gravel. Vandoolaeghe's boreholes are positioned out of the main palaeochannel in the east. The basement topography presented by Vandoolaeghe at a much finer scale shows his boreholes were within a small scale tributary to the main channel. The sediment, which was described as a fluvial deposit, is typical of a flood plain deposit rather than a main channel deposit. The basal layer described by Hay (1981) and Wessels and Greeff (1980) is a muddy marine deposit, and indeed comparison of the regional basement topography with the position of the boreholes shows that the boreholes are outside of the palaeochannel. It is interpreted that the palaeoenvironment in which the basal fluvial gravel and pebble bed was deposited did not extend this far and thus the basal unit “seen” at this position is the marine deposit, which overlies this basal fluvial system, deposited by marine transgression. The complete sequence therefore would be basal fluvial gravel overlain by finer material as the river systems lost energy at the onset of marine transgression, overlain by marine calcareous sand, gravel (the Elandsfontyn and Varswater formations, shown as the Sandveld in **Figure 2-8**). The Bredasdorp formation is mapped similarly by all workers: a marine sand (Springfontyn and Witzand) with discontinuous clayey / calcrete layers (Langebaan).

It is questionable whether the summarised geological section is applicable at the scale of the numerical model. At the smallest scale there is discrete layering, at a larger scale heterogeneity increases and a spatial averaging into a sand unit with discontinuous lenses may be most applicable. 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. It is clear especially in Henzen’s sections, that 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 (**Figure 2-6**).

Whether the system behaves hydraulically as this 2-layered system, or whether complete representation of the geology layering (as shown in **Figure 2-8**) is necessary in order to replicate the natural system, is tested in the numerical model (see Section 3).



LEGEND

- Towns
- Rivers
- Roads
- Inland water
- Model Area

SIMPLIFIED LITHOLOGY

- Quaternary
- Nardouw Group
- Cedarberg Formation
- Pakhuis Formation
- Peninsula Formation
- Graafwater Formation
- Piekenierskloof Formation
- Cape Granite
- Malmesbury Group

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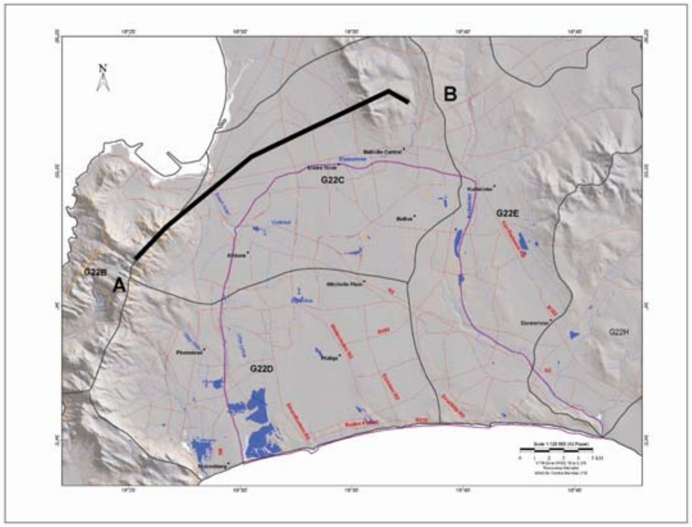
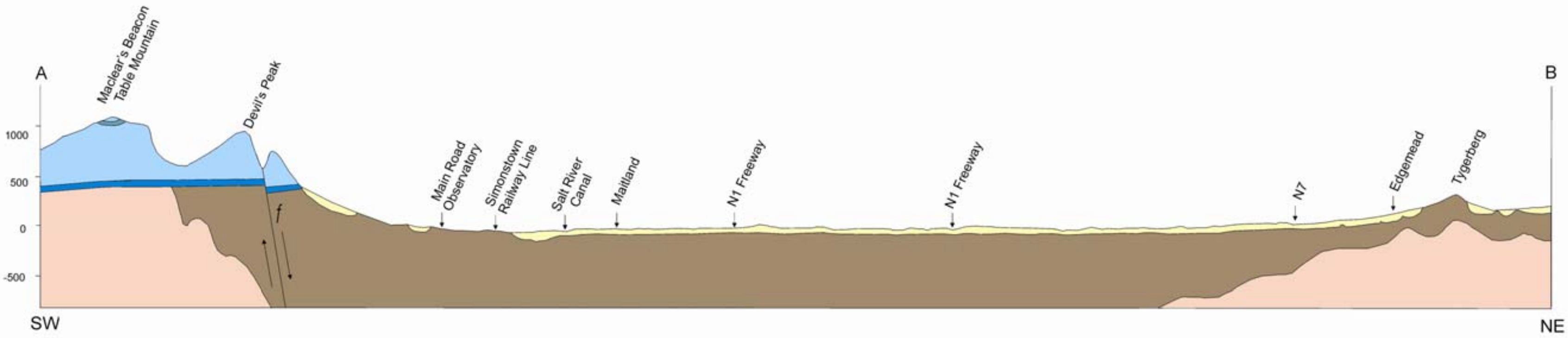
TITLE

REGIONAL GEOLOGY

FIGURE 2.4





No vertical exaggeration
(After 1:50 000 Geological Series, 1984)

LEGEND

f Fault

- Quaternary
- Pakhuis Formation
- Peninsula Formation
- Graafwater Formation
- Cape Granite Suite
- Malmesbury Group

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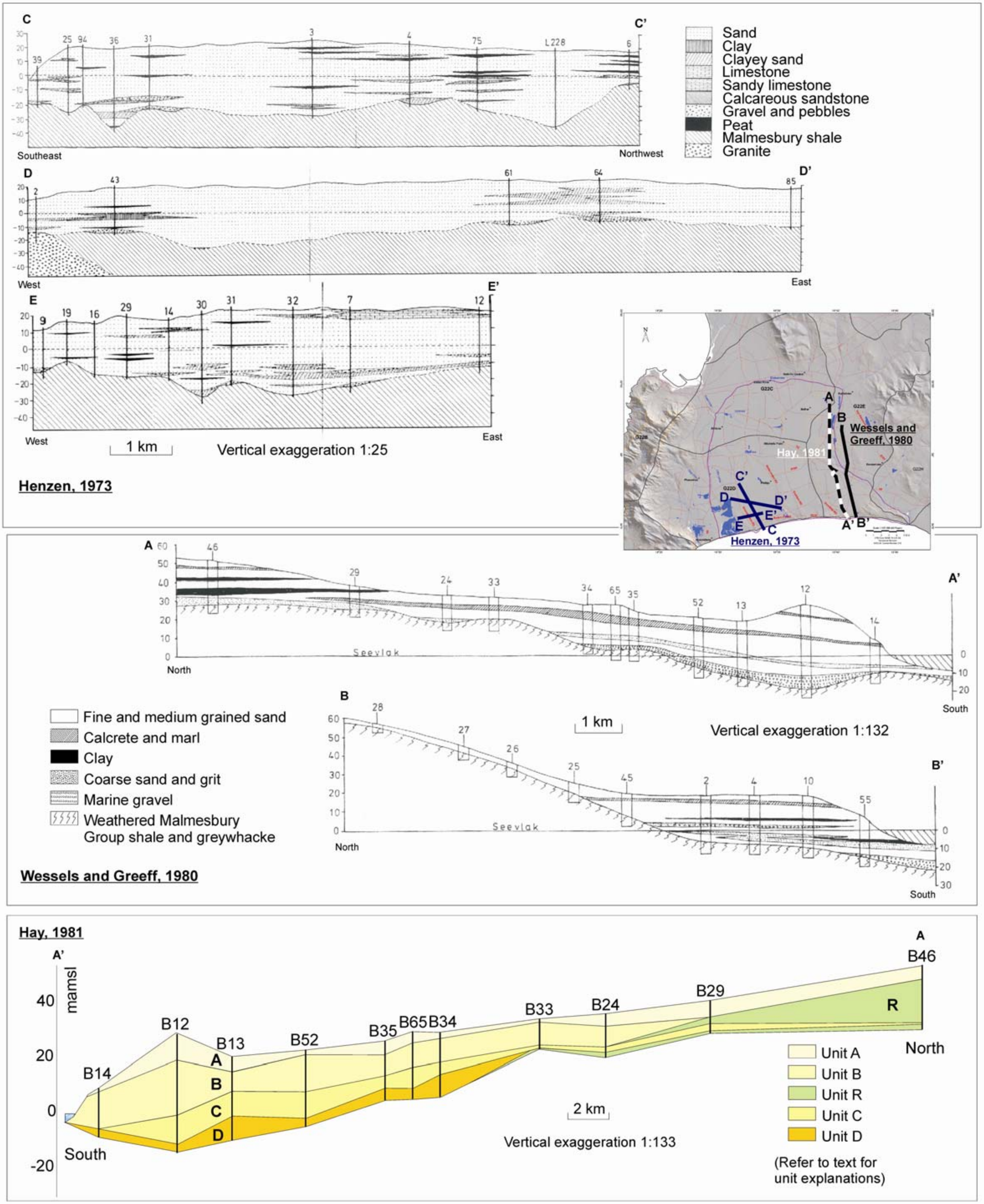
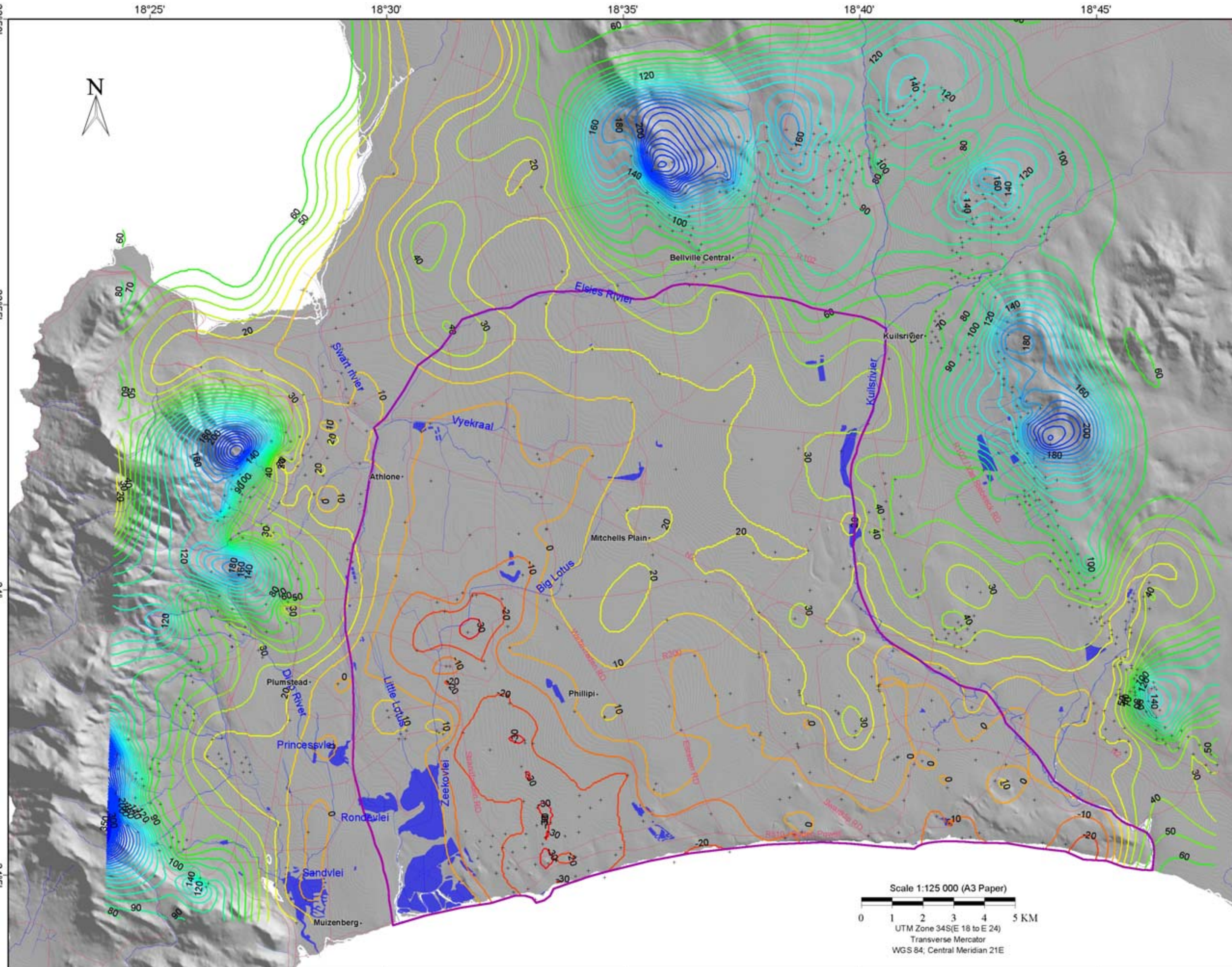
TITLE

SW-NE GEOLOGICAL CROSS SECTION THROUGH THE CAPE TOWN REGION

FIGURE 2.5



PROJECT NAME	CLIENT	CONSULTANT	TITLE
BERG RIVER MODEL STUDY	DEPARTMENT OF WATER AFFAIRS & FORESTRY	UMVOTO	GEOLOGICAL CROSS SECTIONS THROUGH THE QUATERNARY SAND UNIT FIGURE 2.6



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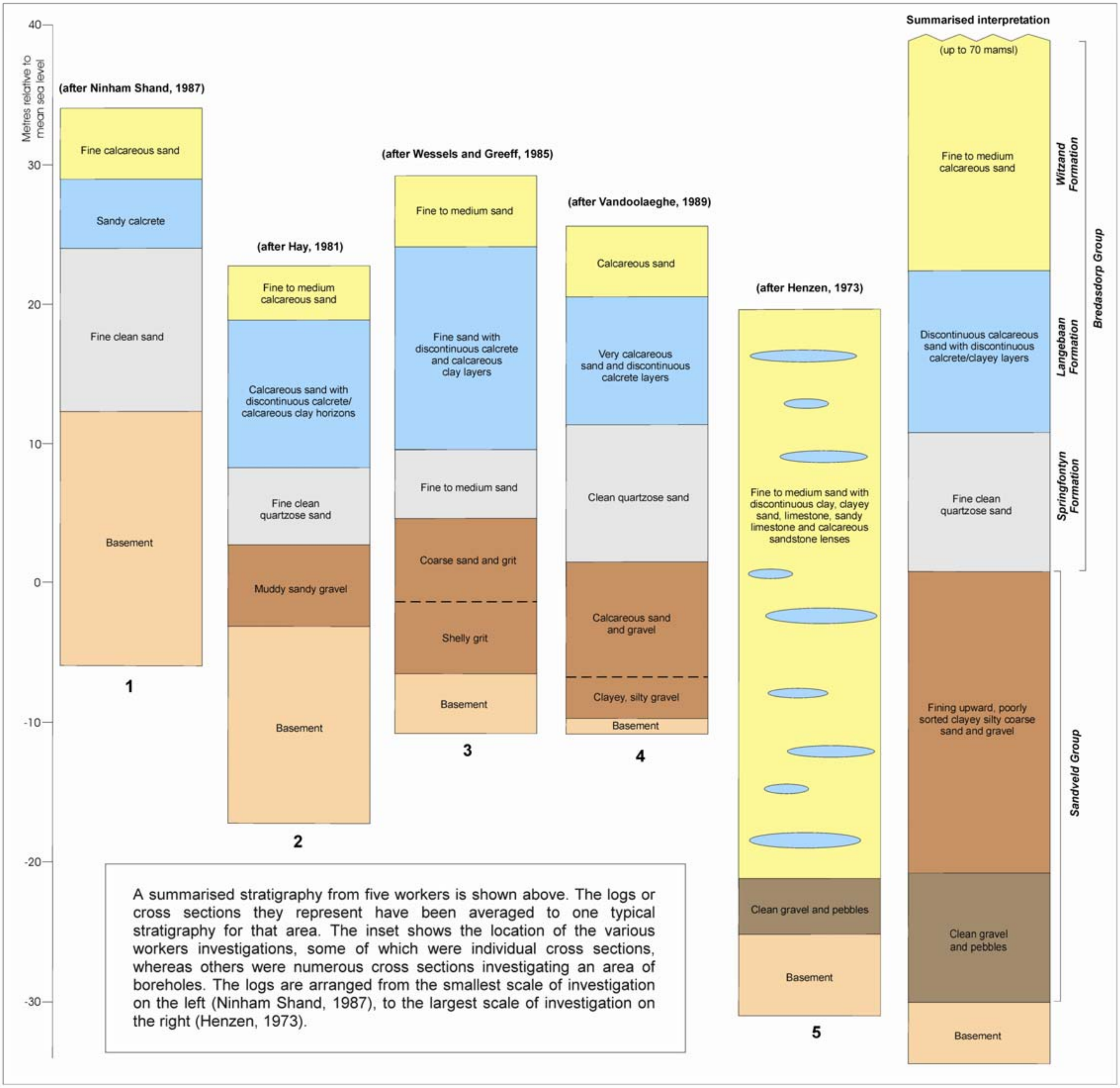
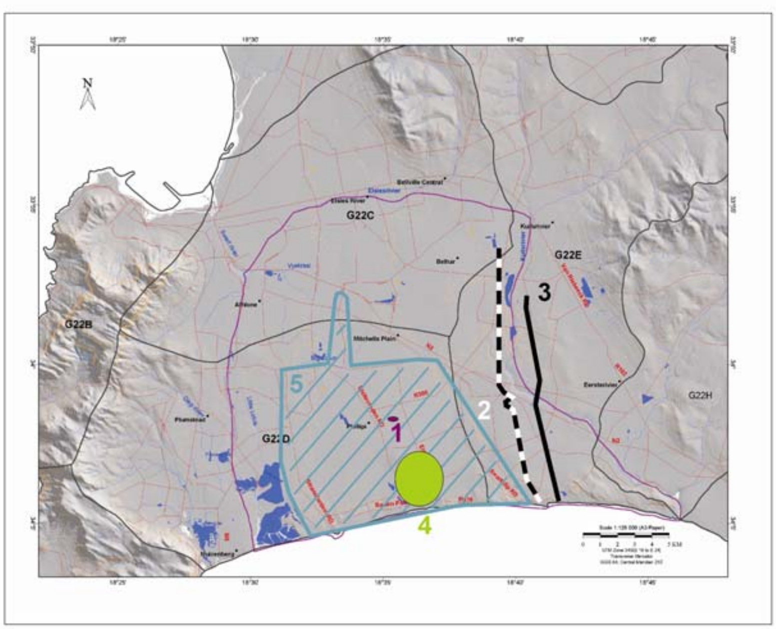
TITLE

PALAEOTOPOGRAPHY

FIGURE 2.7



A summarised stratigraphy from five workers is shown above. The logs or cross sections they represent have been averaged to one typical stratigraphy for that area. The inset shows the location of the various workers investigations, some of which were individual cross sections, whereas others were numerous cross sections investigating an area of boreholes. The logs are arranged from the smallest scale of investigation on the left (Ninham Shand, 1987), to the largest scale of investigation on the right (Henzen, 1973).



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TITLE

CAPE FLATS GEOLOGICAL PROFILES

FIGURE 2.8

2.4 HYDROGEOLOGY

2.4.1 The flow regime

The Cape Flats Quaternary Sands form a primary (intergranular) aquifer. The sands are saturated with water typically to within a few metres of ground level (Fraser and Weaver, 2000a). In low lying areas the upper levels of weathered basement would have been subjected to wave erosion on shallow marine platforms, during numerous Quaternary cycles of marine transgression and regression. This would result in the stripping of the older Tertiary regolith to re-expose the relatively fresh bedrock. Therefore the hydraulic conductivity in the zone of contact between the overlying primary aquifer and the secondary "fractured-rock" bedrock aquifer will have been reduced to the extent that a relatively impermeable aquiclude may separate them (Hay et al, 1996). Flow within this basement can therefore be neglected and the flow regime is considered to exist in the Cape Flats independent of interaction with underlying layers. From test drilling in the Cape Flats it was also concluded by Gerber (1980) that the surface of the bedrock is an impermeable boundary.

The sands are considered to be dominantly unconfined with regard to the largest spatial scale (Fraser and Weaver, 2000a). The magnitude of the difference between the hydraulic conductivities of the 2 layers (Section 2.3.3 above) will dictate the degree to which (if any) the upper layer of lower hydraulic conductivity confines the lower sand. Flow will be concentrated in the lower layer and in the palaeochannels, exploiting the basement topography and the basal higher hydraulic conductivity.

At the smaller scale and where the complete summarised geological section is present (**Figure 2-8 Geological Summary**), the aquifer will have a complex multi-layered nature. The basal fluvial coarse gravel in the palaeochannels may be confined or semi confined by the clayey deposits above it. The lower clean sand (the Springfontyn) will also be semi confined by the calcrete layers above it (Vandoolaeghe, 1989). Only the upper sand unit would be truly unconfined. As described above, it is possible that this geological interpretation is applicable across the model and hence it is possible that semi-confined conditions exist at the regional scale.

Vandoolaeghe (1989) analysed data from pump tests conducted in boreholes within a small area in the south west of the area (Section 2.3.1). These boreholes are situated away from the major palaeochannel and do not penetrate the basal clean gravel, but at their base encounter a flood plain equivalent (Section 2.3.3 above). It was noted as common to all the tests that under the constant discharge test the drawdown reached a maximum only a few minutes into the test. It was concluded that the phenomena indicates vertical flow components to be an important contribution to flow. However due to the short duration of the tests (most just 24 hours) the interpretation is ambiguous. Vandoolaeghe (1989) notes that the drawdown/time curves can be matched to Walton and Hantush methods for semi-confined aquifer but also to Boultan curves which implies semi-unconfined to unconfined conditions. With this short duration it is difficult to say whether the vertical flow is due to leakage through the leaky layer of a semi confined system or due to delayed yield from gravitational drainage in an unconfined system. Vandoolaeghe (1989) states 'the tests were of insufficient duration to observe the end of any potential delayed yield effect and thus conclusive interpretation is made difficult'. It is general practice to pump for 24 hours for a confined system, and longer (say 3 days) for unconfined (Kruseman and de Ridder, 1991), hence 24 hours in order to distinguish between these two is insufficient. The conclusion given by Vandoolaeghe (1989) is that at least at the local scale the aquifer system varies from semi-unconfined to semi-confined.

The borehole logs of the holes pumped in Vandoolaeghe's tests show stratigraphic variation. Some boreholes cased all formations off except the Springfontyn (eg BH 32963) which was screened. Others appear to have screened the full length of the borehole without targeting specific geological layers (eg BH 32978).

The geological interpretation is scale dependent, therefore the interpretation of aquifer nature is also scale dependent. At the small scale where local peat or clay layers exist, the sand beneath is likely to be confined, and a pump test that isolated a lower layer and pumped at a relatively low rate would reflect these conditions. However a pump test of the same stage conducted for longer duration and higher pump rate would have a larger radius of influence, and over the area tested the aquifer may behave dominantly unconfined reflecting an equivalent hydraulic conductivity. For example BH 32963 is essentially screened to represent an unconfined system. Vertical flow in this case would be interpreted to represent delayed yield in an unconfined system. However if the scale of the pump test was small, i.e. of short duration with respect to the hydraulic conductivity, and pumped at a low rate, then it would "see" local effects. Locally there may be discontinuous clay lenses in the upper Springfontyn that generate the semi – confining response. Without the raw data for each individual pump test it is not possible to give a more detailed description than Vandoolaeghe (1989) provides.

Gerber (1980) documents that there is no evidence that interbedded clay/peat layers are effective in providing significant confinement of the aquifer at the scale of investigation conducted – which was an area similar to that under investigation here. Layers of lower conductivity will act to restrict vertical recharge to the aquifer, potentially generating a heterogeneous recharge distribution. The aquifer is likely to be anisotropic, with the north-south direction having a higher hydraulic conductivity than the east-west. The vertical hydraulic conductivity will be reduced.

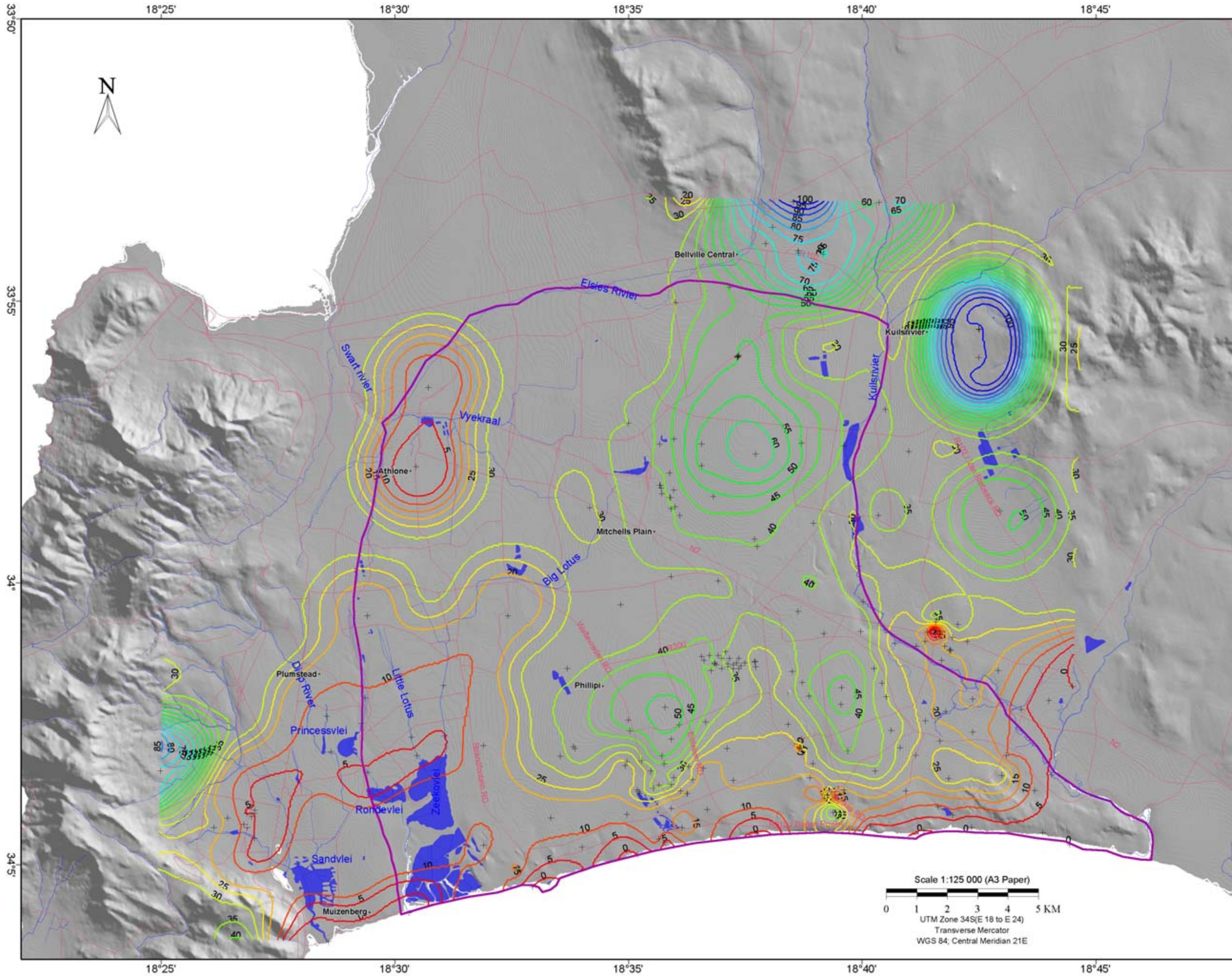
The major source of water to the aquifer is vertical recharge from rainfall onto the Cape Flats. A high hydraulic head in the north of the study area is generated through the higher elevation. Groundwater flow broadly occurs from the high elevation in the north towards the south discharging at the ocean. Algal blooms are common off the coast of the Cape Flats in False Bay, visible as large brown patches. These are caused by diatoms which require dissolved silica for skeleton building and hence are taken as evidence that (silica rich) groundwater does indeed discharge to the ocean (Fraser and Weaver 2000b). Groundwater is likely to discharge along the entire distance of the coastal contact, but concentrated in the palaeochannel. A salinity profile of seawater conducted along the coastline by Henzen (1973) confirms this. Within the spiked amplitude response it is possible to detect a general downward trend from positions west of Zeekoevlei towards the centre of the bay, and rising again towards the eastern point of the Eerste River discharge point, interpreted to represent a greater groundwater flux to the ocean from the central portions of the aquifer. Distinct anomalies where a drop in the salinity occur along the profile, the largest of which are visible east of the Zeekoevlei (west of current sewage works), interpreted to represent the palaeochannel.

It follows from the discussion of geology (Section 2.3.3) and the hydraulic nature of the aquifer above, that water levels in some boreholes will represent atmospheric levels and others may reflect piezometric levels. Due to the limited thickness of the aquifer and its layers, it is likely that the difference between the pressure levels (unconfined and semi to confined) is of the order of centimetres only (Vandoolaeghe. 1989). Therefore data on measured water levels have been included on one water level map. At the regional scale this is sufficiently accurate.

The similarity between measured water levels (shown in **Figure 2-9** below) and basement elevation reveals the control the basement has on water levels. **Figure 2-9** shows that groundwater flow occurs from the high ground in the northeast, towards the west and out to the south of the model. There is a scarcity of data points in the northwest of the model to support or disprove the possibility that groundwater like surface water flows out to the northwest (Section 2.3.2). This water level figure is a combination of data from various sources. NGDB water level data from 175 boreholes was used. Some of this data was time-varying and some had only one measurement for a borehole. Those with time series data were averaged. 47 water level data points from Wessels and Greeff (1980) and specified points at the coastline, were combined with the NGDB data to generate the water level surface.

Interpolation errors in this surface arising from the computer contour process were corrected. A water level low exists in the northwest of the area, based on two water level points from NGDB data, at ~4 and ~8 mamsl. The topography at the points is 16 and 20 mamsl respectively and so these points suggest a groundwater level 12 m below ground level. Henzen (1973) presents a water level surface map for the north of the Cape Flats and this also shows low water levels here (~6-12 mamsl). However there is no information supporting the map such as borehole information and borehole depths. This is unrealistic for the Cape Flats and it is known that groundwater in the northeast is within a few metres of ground level. It is considered that water levels in the northwest are ~1.5 m below topography (L. Groenewald, confirmed by CGS, July 2007). Water levels of ~ 14.5 – 18.5 mamsl in the northwest would generate a similar contour distribution with water flowing from highs in the northeast towards the northwest and south.

The water level surface is discussed further in the selection of calibration data, in Section 5.1.



LEGEND

- Towns
- WL data points
- Rivers
- Roads
- Inland water
- Model Area

Water Level Contours

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
- 40
- 45
- 50
- 55 - 60
- 65 - 70
- 75 - 80
- 85 - 90
- 95 - 100

PROJECT NAME

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CLIENT

Inland water

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TITLE

WATER LEVELS

FIGURE 2.9

2.4.2 Surface water – groundwater interaction

At the broadest scale the aquifer is predominantly unconfined, with groundwater within a few metres of the surface. The rivers in the area are therefore likely to be in hydraulic connection to the groundwater. Where the aquifer is semi-confined (e.g. the deep gravels in the palaeochannels), or at small scales where the aquifer is semi-confined (e.g. at the small scale, the lower clean sand of the Springfontyn may be confined by the calcrete; Section 2.4.1 above) the rivers are likely to be in hydraulic connection with the shallow groundwater in the uppermost unconfined sand unit. In this situation the surface waters can be considered as an outcrop of groundwater, existing where topography drops beneath the level of the hydraulic head in the aquifer (i.e. because of the presence of a channel eroded into the sediment). A typical system would be as follows; in the summer months when rainfall and runoff into the rivers is low, the river flow is sustained by groundwater. In hydraulic terms the head in the aquifer will be greater than the head in the river. As dictated by Darcy's law water will flow from the aquifer to the river. The magnitude of this flow is governed by the hydraulic conductivity and thickness of the riverbed sediments, and the difference in head between the water bodies. In winter when rainfall generates high river flows, especially across high terrain where rainfall and direct runoff to the river will be at its greatest, the stage in the river is likely to be greater than that in the aquifer. A reversal of the flow connection will be observed, hence the aquifer is recharged by the rivers (**Figure 2-10** below). In this typical system the rivers then act as recharge or discharge boundaries to the aquifer.

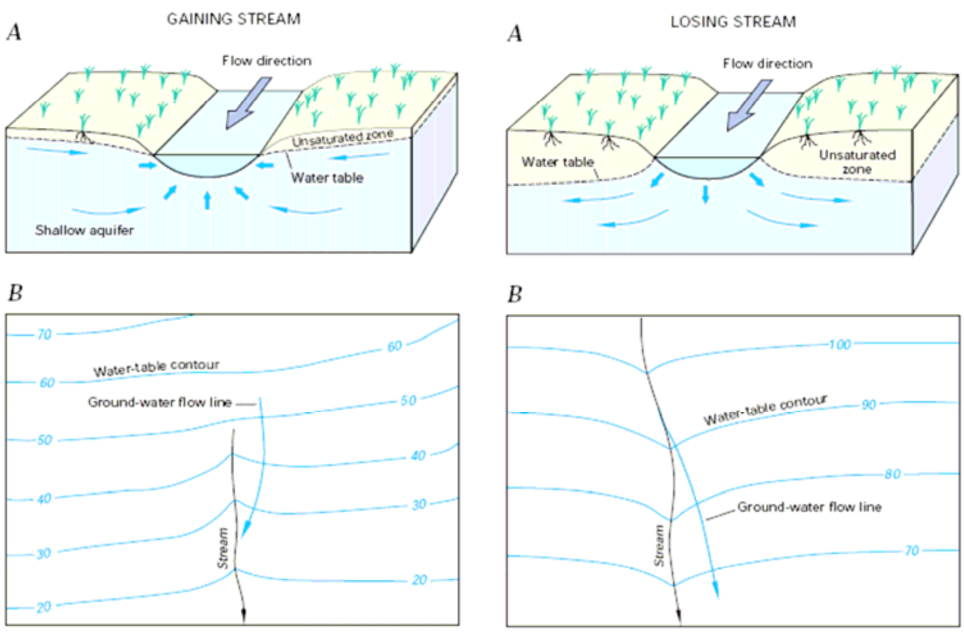

Figure 2-10 Schematic diagram displaying hydraulically connected gaining and losing rivers (Winter et al 1998).

Gerber (1980) states that the Kuils River is the only perennial system in the Cape Flats. However the Kuils, the Elsieskraal, the Vyekraal, and the Lotus are known to flow throughout the year (L. Groenewald, pers comm. July 2007). For flow to continue through the dry season when surface runoff is minimal, the rivers must be sustained to some degree by groundwater contributions to baseflow. Alternatively it is also possible that the rivers are fed by leakages from the reticulation system, either potable or grey water or irrigation return flow (IRF). In this model these rivers are assumed perennial and dependent on groundwater.

The above classical representation of hydraulically connected gaining and losing rivers is complicated in areas such as the Cape Flats where rivers are often canalised. Canalisation vastly reduces any natural connection to the aquifer through replacement of river bed sediments with lower permeability material such as concrete. The canalisation of the rivers in the Cape Flats is shown in **Figure 2-11**. The majority of the Kuils River is natural, except for a 2.5 km length at its northern section. Almost the entire length of the Elsieskraal is canalised and concrete lined. The central sections of the Vyekraal and the Swart rivers, around the confluence of the two, are natural and the remainder of these two rivers run in culverts or composite canals. The most upper reaches of the Lotus (Big and Little), and the Diep River, are canalised or run in a culvert, and the lower reaches (from just north of the Zeekoevlei to the south) are natural (**Figure 2-11**).

Where river reaches have been canalised there are two possible assumptions. Either the lining material is of very low permeability, such that in the canalised reaches the river is no longer in hydraulic connection to the aquifer or given the age of the canals they are permeable but less so than if the river was not canalised. The effect on the flow in the aquifer is depicted in **Figure 2-12.** For a hydraulically connected river it is typical that a regional groundwater system would be sub parallel (towards or away from) to a surface water system, depending on the season. **Figure 2-12** depicts the situation for a river gaining from groundwater. If the influence of the river on this regional system is removed through the addition of an impermeable layer (i.e. the canalisation material) then the influence of the river on the regional flow system is removed and the regional groundwater flow becomes parallel to the canalised river.

The Elsieskraal, Black and Vyekraal rivers drain to Table Bay. This suggests a multidirectional groundwater flow system exists within the study area. Water in the northeast of the study area may flow towards the hydraulic low point of the river rather than to the south to the ocean. Thus at some position a groundwater divide may exist in the north between water flowing into the north flowing rivers and water flowing to the ocean. If there is a disconnection between shallow and deep groundwater (see Section 2.4.1) then this multidirectional groundwater flow system may only occur in the shallow groundwater and deeper groundwater may all flow towards the south.

There are a number of wetland areas in the study area (see **Figure 2-1**). The largest surface water body is the Zeekoevlei. Gerber (1980) documented that the Zeekoevlei is not a major recharge source of water to the aquifer but is partly maintained by groundwater. Significant groundwater contribution to the Zeekoevlei is also documented by Parsons and Harding (2002). It is underlain by low permeability mud and clays, essentially ‘sealing’ its base (Gerber, 1980). The existence of wetlands are therefore considered to be controlled by a combination of the presence of lower permeability layers, and by high groundwater tables.

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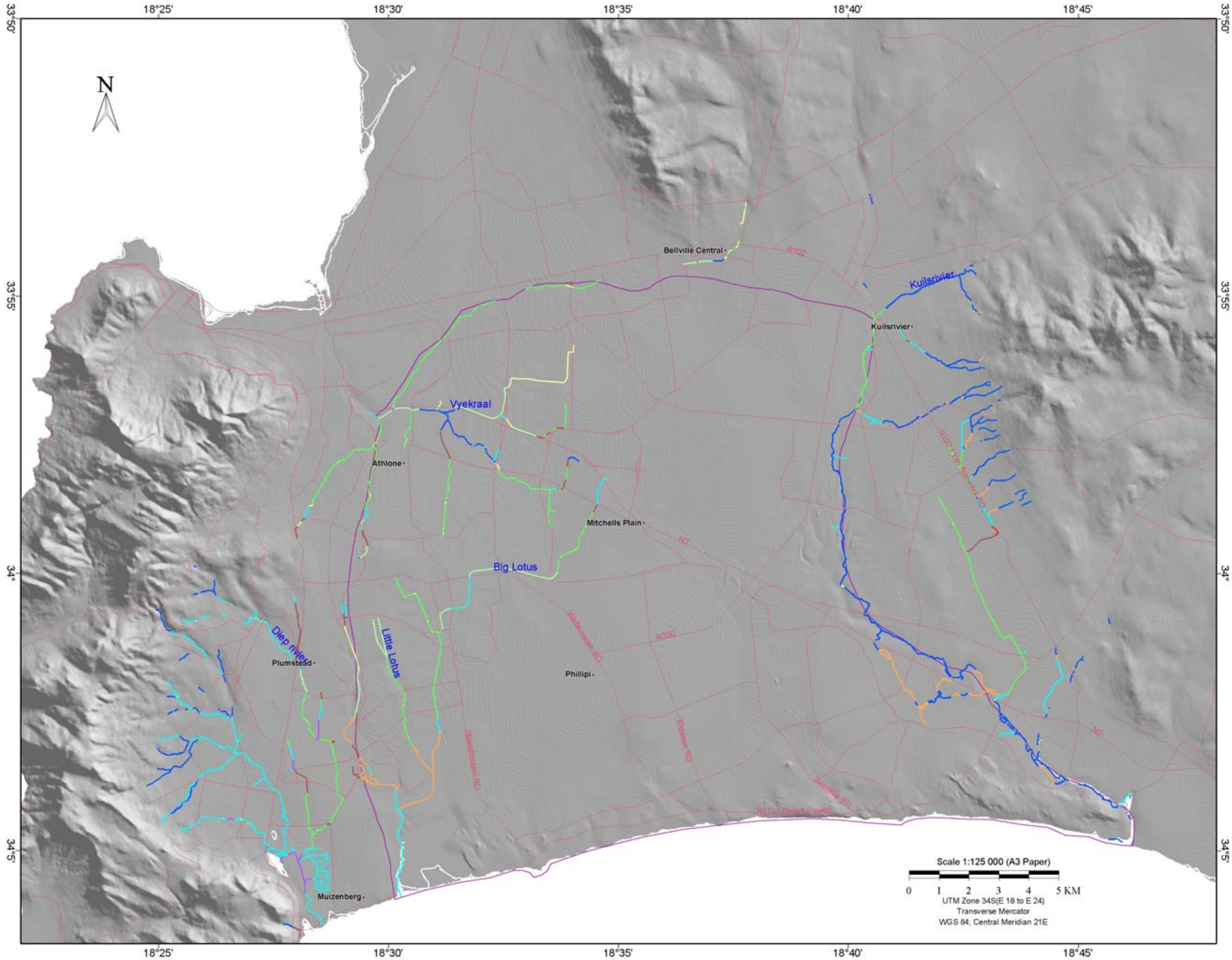

LEGEND

- Towns
- Roads
- Model Area

RIVER LINING TYPE

- composite canal
- culvert
- gap connector/flow path
- lined canal
- natural
- open channel
- storm water pipe
- stream extension
- unknown

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CONSULTANT

UMVOTO

TITLE

RIVER CANALISATION (Ninham Shand, 2007)

FIGURE 2.11

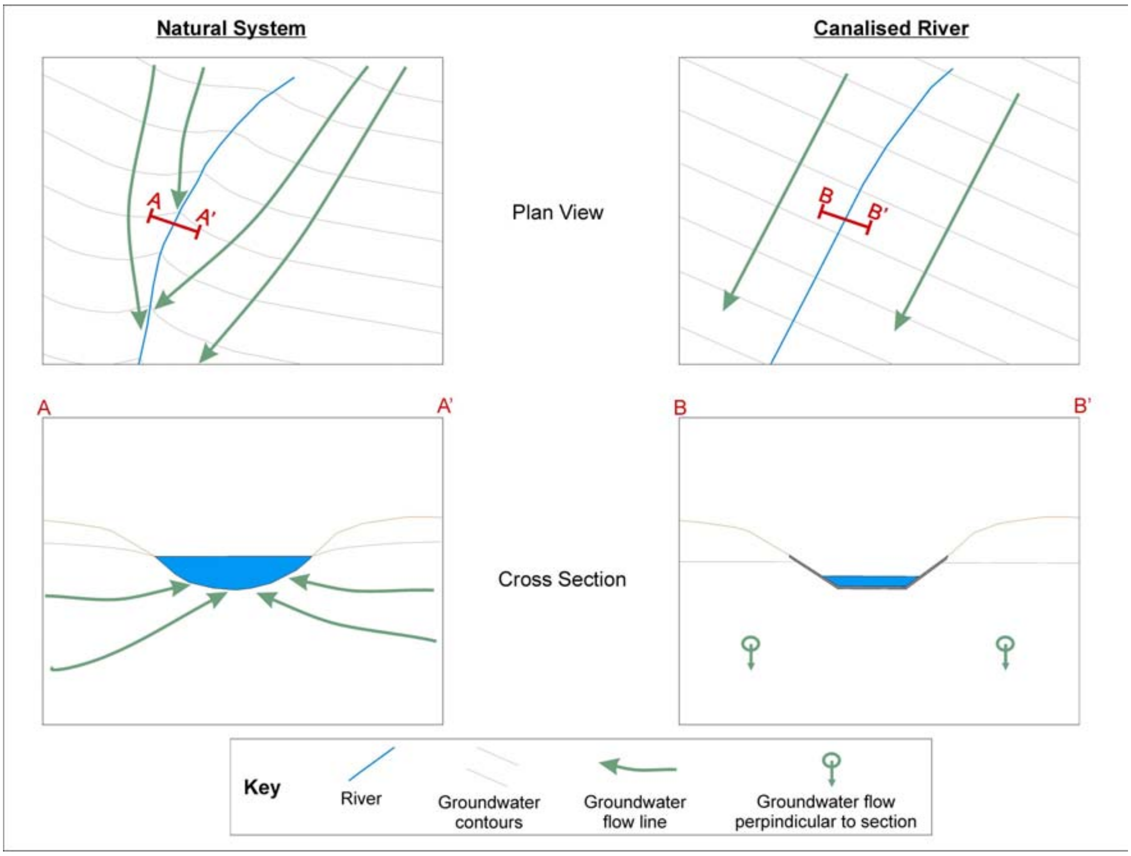


Figure 2-12 Surface water – Groundwater interaction and the effect of canalisation

2.4.3 Recharge

The major recharge source to the aquifer is rainfall. During winter the aquifer will be recharged from the rivers (Section 2.4.2). The stabilization pond system of the sewage treatment scheme southeast of Zeekoevlei represents an additional potential recharge source (Gerber, 1980). However Henzen (1973) concluded that the quantities of recharge from municipal sewage treatment ponds would be so low compared to the daily bulk GW flow as to be negligible. The aquifer pinches out to bedrock at its landward boundaries and hence lateral recharge from other aquifer units is assumed negligible.

Vandoolaeghe (1989) calculated that the 'effective recharge' varies between 15-37% of the annual rainfall. In his calculations of a sustainable yield to the aquifer, he applied an 'average' recharge of 33% of annual rainfall. As an average 'effective recharge' he concludes that this number is lower than 37% to account for potential evaporative losses occurring direct from the aquifer. He also assumes that the 'positive and negative influences on recharge arising from urbanisation are balanced', and that any lateral subsurface gains and losses are insignificant. Gerber (1980) calculated an annual recharge of 154 Mm^3/a for the Cape Flats, over an area similar to that modelled here.

Where groundwater is shallow evaporative losses direct from the aquifer can be significant. Evaporative losses are a function of the depth to groundwater and also the hydraulic properties of the subsurface. They can be estimated to exponentially decrease from the potential rate at the surface to zero at the extinction depth (Van Hoorn and Van Alphen, 1994). An extinction depth of 1.8 m is typical for a highly conductive subsurface such as unconsolidated coarse alluvium (Sholl, 2005). The hydraulic conductivity of material at the surface over the Cape Flats is considered to be of lower hydraulic conductivity (i.e. fine sand, and soil development at the surface) than the subsurface studied by Sholl, (2005). Therefore the extinction depth is likely to be shallower than 1.8 m. With groundwater levels typically around 1-3 m below ground across much of the Cape Flats, direct evaporation is likely to be small or negligible.

It is assumed that any effects of deeper rooting vegetation withdrawing water from the aquifer through evapotranspiration can also be considered small or negligible due to the high amount of urbanisation. The area of the Cape Flats that remains vegetated is the dune field in the south east, and here groundwater is deeper due to the raised dune topography.

It is not possible to adequately represent evapotranspiration effects in the steady state simulation, and it is assumed that the steady state recharge value represents net recharge, that which enters the aquifer after any losses to evapotranspiration. It is further discussed in Section 6.

The GRA II database provides non-aquifer-specific recharge estimates per quaternary catchment (Volume 2 of this report, DWAF 2007a). These have been re-calculated to apply to specific aquifers in Volume 4 of this report (DWAF, 2007c). The estimates provided by GRA II, GRDM, Gerber (1980) and Vandoolaeghe (1989) vary significantly, due to the difference in methods, and are compared in **Table 2-6** below. (The GRA II, GRDM, and BRBS methods are described fully in Volume 4 of this report, DWAF 2007c).

Table 2-6 Recharge estimations from Various Sources (per anum)

Catchment	BRBS Method (DWAF 2002)		GRA II Method[1] (DWAF 2006)		GRDM Method[2] (DWAF 2006)		Local Studies: Vandoolaghe[3] (1989)		Local Studies: Gerber[4] (1980)	
	Mm3	*mm*	*Mm3*	*mm*	*Mm3*	*mm*	*Mm3*	*mm*	*Mm3*	*mm*
G22C	19.62	90.35	14.73	67.84	15.30	70.45	25-58	115 - 267	61.50	283.16
G22D	24.37	112.13	22.78	104.79	24.00	110.41	30-71	138 - 327	N/A	N/A
G22E	12.00	55.05	10.60	48.63	13.50	61.91	23-53	105 - 243	N/A	N/A
G22H	13.90	93.10	9.66	64.68	14.70	98.47	N/A	N/A	N/A	N/A

1) Calculated using average MAP (Volume 4 of this report, DWAF 2007c)

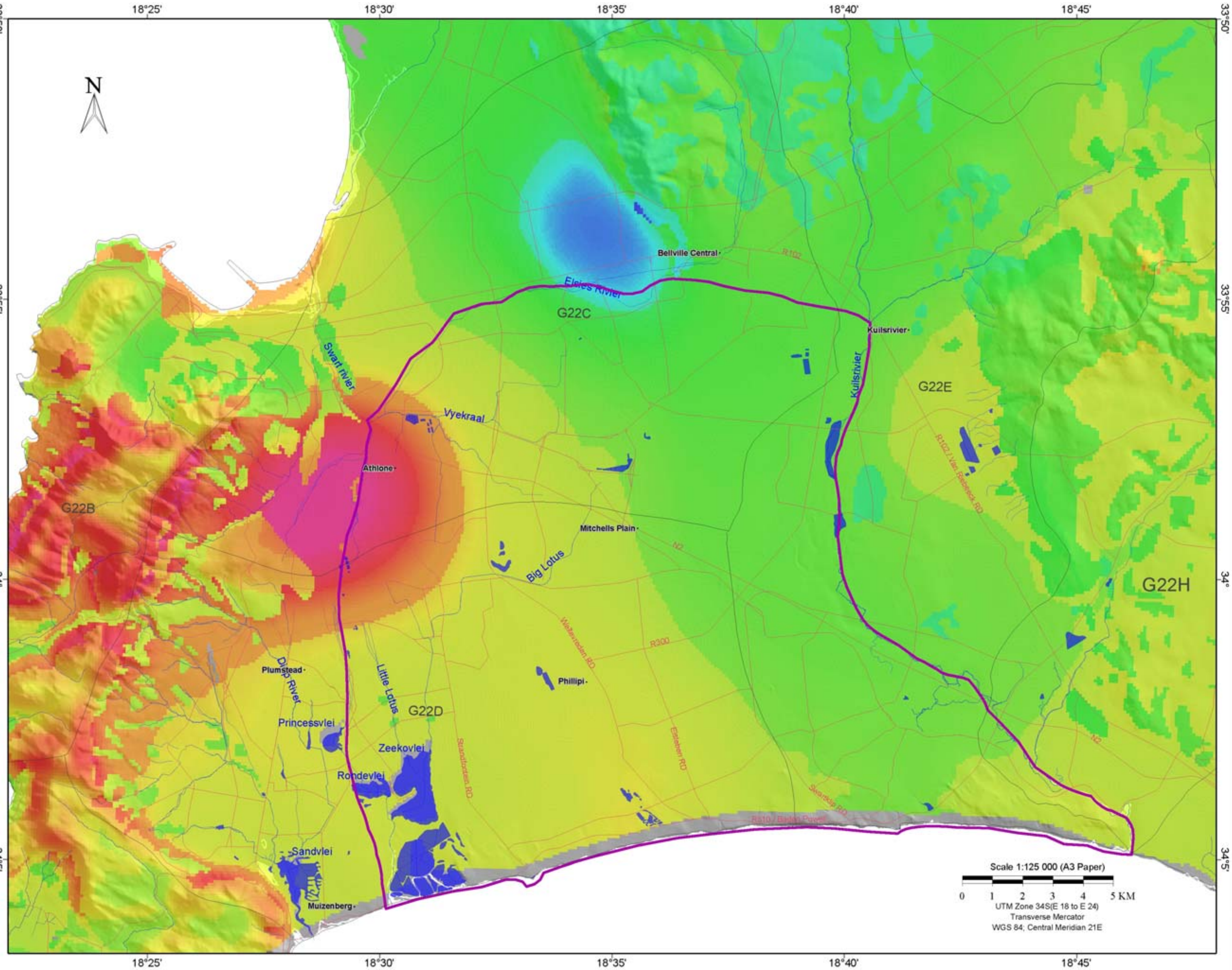
2) GRDM values are given for the whole catchment and are not aquifer specific

3) Values calculated from the recharge percentages, given by Vandoolaeghe (1989)

4) Value given for primary aquifer in Gerber's study area, which equals the catchment size

These quaternary-scale estimates are useful as a first order approximation on the regional scale of the Berg and Breede Basins. At a sub-catchment scale, the recharge distribution over the Cape Flats has been calculated based on the Breede River Basin Study method (DWAF 2002, applied in Volume 4 of this report, DWAF 2007c). Recharge is calculated as a percentage of rainfall, for example for annual rainfall of less than 300 mm, recharge is 3% and for rainfall between 300-600 mm recharge is 6% etc (Volume 4 of this report, DWAF 2007c). The recharge for the Cape Flats calculated with this method is shown in **Figure 2-13.** The BRBS method (DWAF, 2002) also applies a factor to the rainfall as based on the geology, which explains the heterogeneous patterns west of the model boundary. The distribution generated by GRA II is similar as it is also based on rainfall percentages.

The effect of urbanisation on the recharge estimates, and a consideration of how recharge might vary in the future with changing land uses and potential new developments arising in the currently vegetated areas of the Cape Flats is an important consideration for management of the potential future groundwater exploitation in the Cape Flats aquifer. Fraser and Weaver (2000b) suggest that the residential development in the Cape Flats will have a positive impact on the recharge. They propose that recharge will be higher in the urbanised areas than the naturally vegetated areas, reasoning that light rainfall events, which in un-urbanised areas would not result in recharge, would generate recharge events due to concentrated run-off from roofs. Their reasoning takes no account at all of evaporative losses. Because the Cape Flats has a Mediterranean climate with evaporation rates much greater than rainfall, it is considered here that small rain events will evaporate rather than concentrate, hence causing recharge to be reduced in urban areas. The numerical model is configured for a dominantly natural system therefore this effect is not quantified accurately.



LEGEND

- Towns
- Rivers
- Roads
- Inland water
- G22C Catchments
- Model Area

Recharge (mm/a)

1501
201
101
1

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RECHARGE (DWAF Method, 2002)

FIGURE 2.13

2.4.4 Groundwater use

The main groundwater abstraction is for irrigation in the Phillipi farms area (south central of the study area). In general groundwater is pumped into unlined holding dams from where it is then pumped for irrigation. Therefore it is likely that much of the abstracted water is returned to the aquifer directly (IRF). The potential effect the irrigation return flow may be having on the salinity of the aquifer and the soils is of concern with respect to long-term sustainability of the groundwater resource. Holding the groundwater at the surface will allow evaporation and thus the return flow leaking from the base of the holding dam will have an enhanced salinity. Irrigating again with this slightly enhanced salinity groundwater thus allows a positive feedback loop to develop where abstraction and irrigation with saline water cause salinities to continue to increase (Skogerboe and Walker, 1981). Also of concern is the quantity of fertilizer that is infiltrating the aquifer.

Institutions such as schools and hospitals are known to be groundwater users for irrigation of sports fields, but the use is less than that of agriculture. Sand mining is practiced in the dune area in the south east of the model area, but groundwater is not abstracted as the mining is conducted above the water table (L. Groenewald, pers comm., July 2007). Wellpoints are a low cost alternative for municipal water supply for residential property owners. This water use is for small-scale garden use. As it is not a registered use, the magnitude is un-quantifiable, and considered negligible in the model.

Data regarding water use is available from GRA II (DWAF 2006), and from WARMS (see Volume 4 of this report, DWAF 2007c). Water use, summed for each type of use, for each catchment is given in **Table 2-7** and **Table 2-8** below.

Table 2-7 Groundwater use per catchment after GRA II

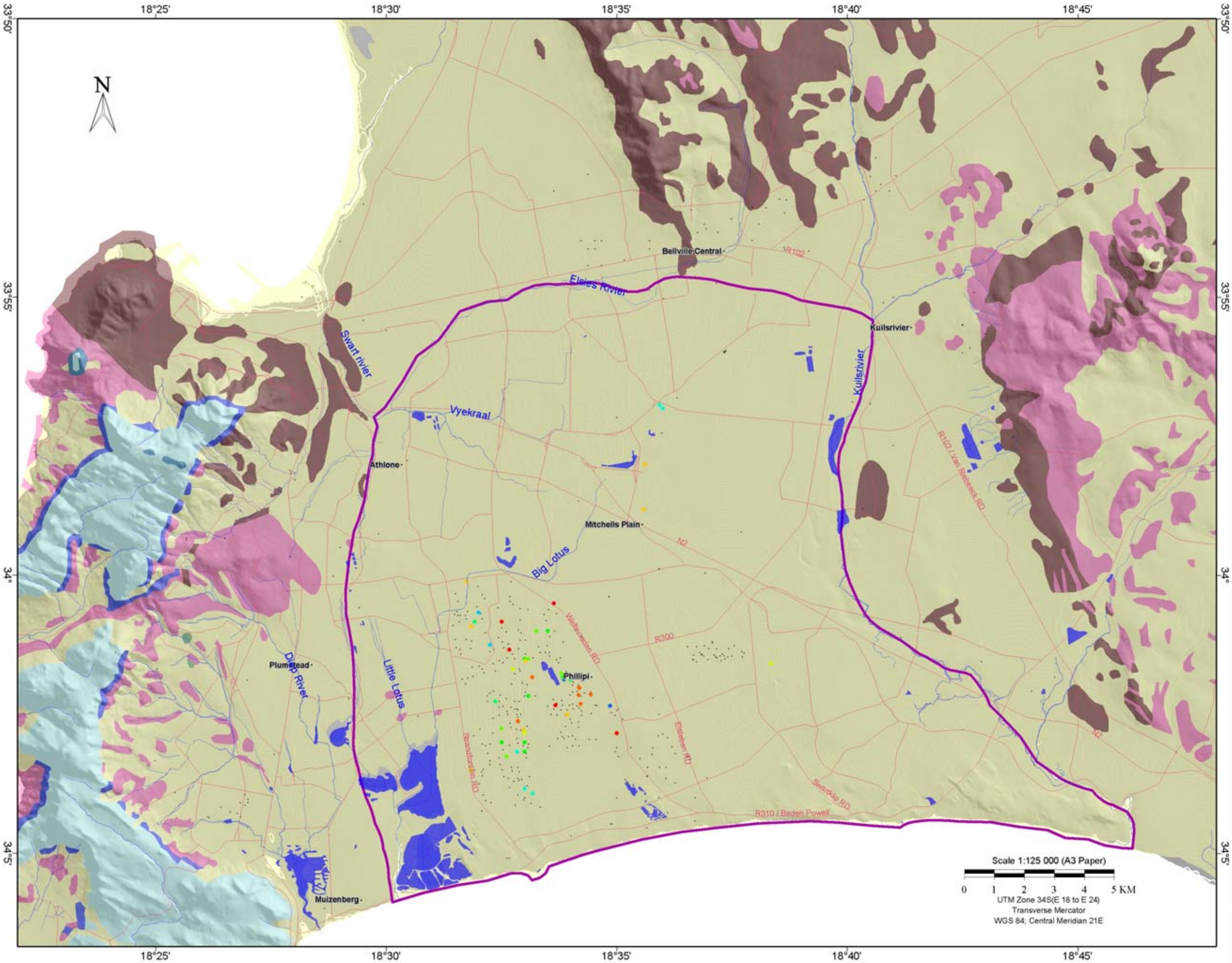
Quaternary Catchment	Groundwater Use [Million m^3/a]						
	Total	Rural	Municipal	Agric. Irrigation	Agric. Livestock	Industry	Aqua
G22C	0.0835	0.0000	0.0000	0.0000	0.0745	0.0090	0.0000
G22D	9.9010	0.0000	5.9474	0.0000	0.0646	3.8890	0.0000
G22E	0.4020	0.0000	0.0000	0.0000	0.0450	0.3570	0.0000
G22H	0.1884	0.0090	0.0000	0.0000	0.0004	0.1790	0.0000

Table 2-8 Groundwater use per catchment after WARMS

Quaternary Catchment	Groundwater Use [Million m^3/a]								
	Total	Industry 2: Rural	Municipal	Agric. Irrigation	Agric. Livestock	Industry 1: Urban	Aqua	Recreation	Schedule 1
G22C	1.803	1.5087	0.0026	0.2917	0.0000	0.00	0.00	0.00	0.0000
G22D	5.134	0.0000	0.0000	5.0962	0.0383	0.00	0.00	0.00	0.0000
G22E	0.867	0.2024	0.0050	0.4976	0.0000	0.00	0.16	0.00	0.0019
G22H	1.296	0.2475	0.0040	1.0439	0.0000	0.00	0.00	0.00	0.0009

There are many differences between these two data sets. For example GRA II shows that within G22D a large proportion of the total 9.9 Mm^3/a abstracted is for municipal water use, and no water is abstracted for agricultural irrigation. The Philippi farms area is within G22D and the WARMS data shows 5 Mm^3/a is used for agricultural irrigation in the area. This supports the conclusion that the WARMS data is more representative. As in the Water Balance Model

(Volume 4 of this report, DWAF 2007c), the WARMS data will be used for the numerical model. The distribution of the WARMS data across the Cape Flats is shown in **Figure 2-14.** For comparison the figure also shows the NGDB boreholes which have water use data associated. Based on the WARMS data, the total active abstraction from groundwater within the Cape Flats model area is estimated at 3.96 Mm^3/a.



LEGEND

- Towns
- NGDB boreholes
- Rivers
- Roads
- Inland water
- Model Area

Registered Volume (m ^ 3 / a)

- 0 - 5000
- 5000 - 10000
- 10000 - 20000
- 20000 - 50000
- 50000 - 75000
- 75000 - 100000
- 100000 - 150000
- 150000 - 2700000

PROJECT NAME

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GROUNDWATER USE (WARMS)

FIGURE 2.14

2.5 WATER QUALITY

2.5.1 Natural background

Groundwater in the Cape Flats Aquifer has a mixed Na Ca\ Alkaline Cl character with most pH falling in the range of 5.76 to 8.8. EC shows a wider range with some waters having an EC of more than 300 mS/m. Most groundwater has an EC between 33 - 150 mS/m (NGDB data set).

A Durov diagram[1] is used to characterise the groundwater in the Cape Flats Aquifer and to compare groundwater chemistry from different areas (see **Figure 2-15**).

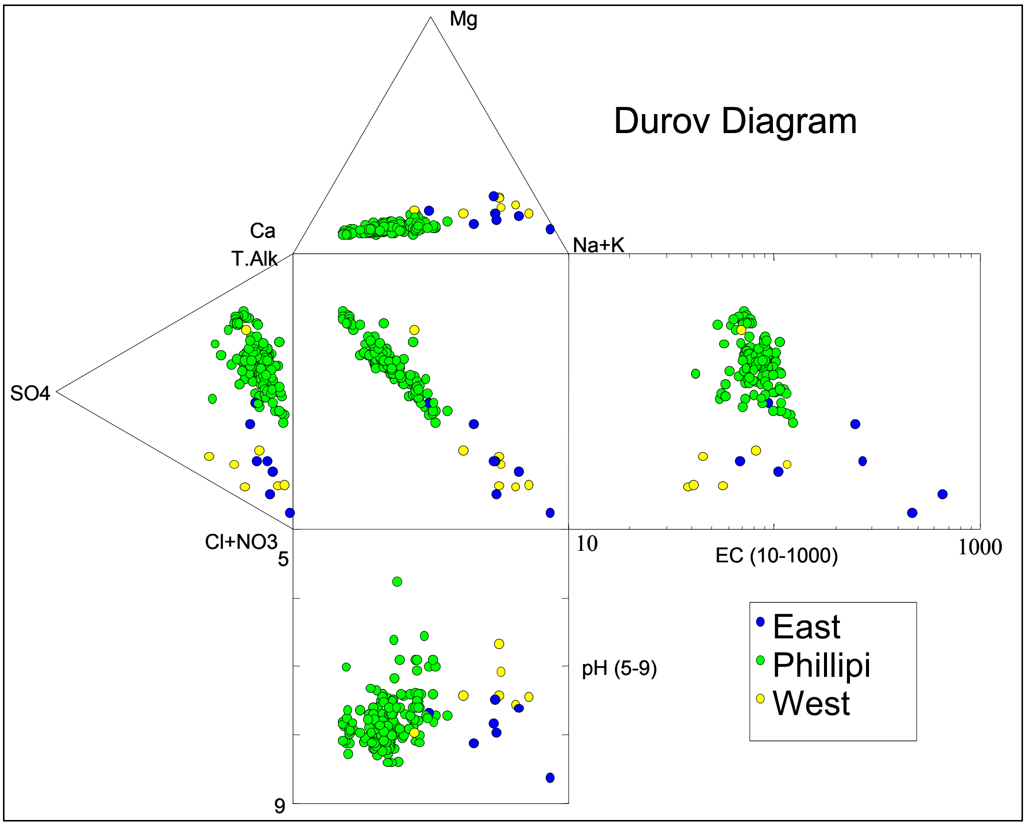


Figure 2-15 Durov Diagram[1]

- Groundwater in the central Phillipi area (green symbols) has a Na Ca-Cl to Ca-Alk character with an EC that ranges between 41.7 and 123.7 mS/m and a pH that ranges from 5.76 to 8.4. The trend between both extremes, as shown in the middle part of the Durov diagram, indicates the effects of rock-water interactions from relatively fresh Na-Cl character rainwater to Ca-Alk water due to dissolution of calcrete and carbonate in the aquifer. The mostly alkaline character of the water is a further indication of this process.

[1] The Durov diagram plots the major ions as percentages of milliequivalents in two base triangles. The total cations and the total anions are set equal to 100% and the data points in the two triangles are projected onto a square grid which lies perpendicular to the third axis in each triangle (Geoafrica website). Also added are EC and pH measurements.

- Groundwater in the eastern part (blue symbols) has mainly a Na-Cl character with an EC that ranges between 68 and 659 mS/m and a pH that ranges from 7.5 to 8.6. The high EC values are most probably influenced by the contact to the Malmesbury Shale, through rock-water interactions at the boundary. Because the aquifer is thinner in the eastern areas the relative influence of Malmesbury Shales is higher.
- Groundwater in the western part (yellow symbols) also has a Na-Cl character slightly tending towards Ca-Alk character with an EC that ranges between 38 and 115 mS/m and a pH that ranges from 6.7 to 8. The low EC values and the Na-Cl character indicate the lack of significant impact from the Malmesbury Shales in the thicker western parts of the aquifer, where the larger volumes of groundwater allow a greater degree of mixing. The difference in water quality from groundwater in the west and east therefore appears mainly due to granites in the west and Malmesbury Shale in the east.

Table 2-9 is a summary of the maximum and minimum values for various constituents of groundwater from the Cape Flats. The higher EC values can most probably be contributed to the boreholes being drilled close to the Malmesbury Formation (as above) but also close to the sea. The maximum values of the Wessels and Greeff (1980) data are mainly from boreholes drilled close to the sea. This is not due to saline intrusion into the boreholes; the proximity to the sea impacts on the chloride concentration in the rainfall. The Wessels and Greeff (1980) boreholes are also close to a zone of bad water quality at the N2 Baden Powell Drive crossing. This poor quality is possibly associated with the sewerage works, or upstream industrial sites, but specific history is unknown.

Table 2-9 Summary of natural water quality in Cape Flats Aquifer

Constituent mg/L	**Tredoux (1984)**	**Wessels & Greeff (1980)**	**NGDB (DWAF 2006)**
EC (mS/m)	73 – 138	33 – 2900	38.3 – 659
pH	6.9 – 7.5	6.9 – 8.8	5.7 – 8.6
Chloride	70 – 255	30 – 9246	28.1 – 2100
Sulphate	25 – 43	4.8 – 1750	5.5 – 350
Alkalinity	261 – 275	112 – 902	8.5 – 437
Sodium	43 – 142	20 – 7000	20.3 – 1048
Potassium	1.5 – 3.3	0.5 – 300	0.66 – 53.6
Calcium	95 – 98	11 – 1370	3.2 – 260
Magnesium	8.4 – 26	6 – 1080	5.4 – 119

2.5.2 Pollution

Table 2-10 is a summary of some water quality guidelines for domestic use. The average concentrations of constituents were used for classifying the water according to the Class of water. The natural groundwater in the Cape Flats Aquifer falls mostly within Class 1. However, pollution threats and actual pollution renders the groundwater unfit for human consumption in specific areas.

Table 2-10 Summary of water quality guidelines for Domestic use.

Constituent	SA Drinking Water Guideline				
mg/L		Class 1	Class 2	Class 3	Class 4
TDS	< 450	450 - 1000	1000 - 2400	2400 - 3400	> 3400
EC (mS/m)	< 70	70 -150	150 - 370	370 - 520	> 520
Chloride	< 100	100 -200	200 - 600	600 - 1200	> 1200
pH	5 - 9.5	4.5 - 5 or 9.5 - 10	4 - 4.5 or 10 - 10.5	3 - 4 or 10.5 - 11	< 3 or > 11

Tredoux (1984) confirmed that pollution of the Cape Flats Aquifer occurs from different pollution sources. He identified three major sources, viz. two waste disposal sites and a sewage works. The results of the detailed pollution study at these three sites is shown in **Table 2-11**.

Table 2-11 Pollution impacts on groundwater quality in Cape Flats Aquifer (after Tredoux, 1984)

	Waste Disposal Sites		Sewage treatment works	
mg/L	Unpolluted		Unpolluted	Polluted
EC (mS/m)	121 – 138	198 – 970	73	220
pH	6.9 – 7.5	6.4 – 6.8	7.2	6.7
Chloride	210 – 255	187 –1150	70	132
Sulphate	27 – 43	35 – 70	25	32
Alkalinity	266 – 275	891 – 3460	261	879
Nitrate	< 0.1	0.2 – 0.6	< 0.1	24
Sodium	123 – 142	146 – 775	43	116
Potassium	1.5 – 3.3	21 – 444	1.7	49
Calcium	95 – 98	53 – 226	97	159
Magnesium	17.7 – 26	41 – 99	8.4	22
Ammonium	0.5	23 – 658	0.5	115

2.6 LANDUSE

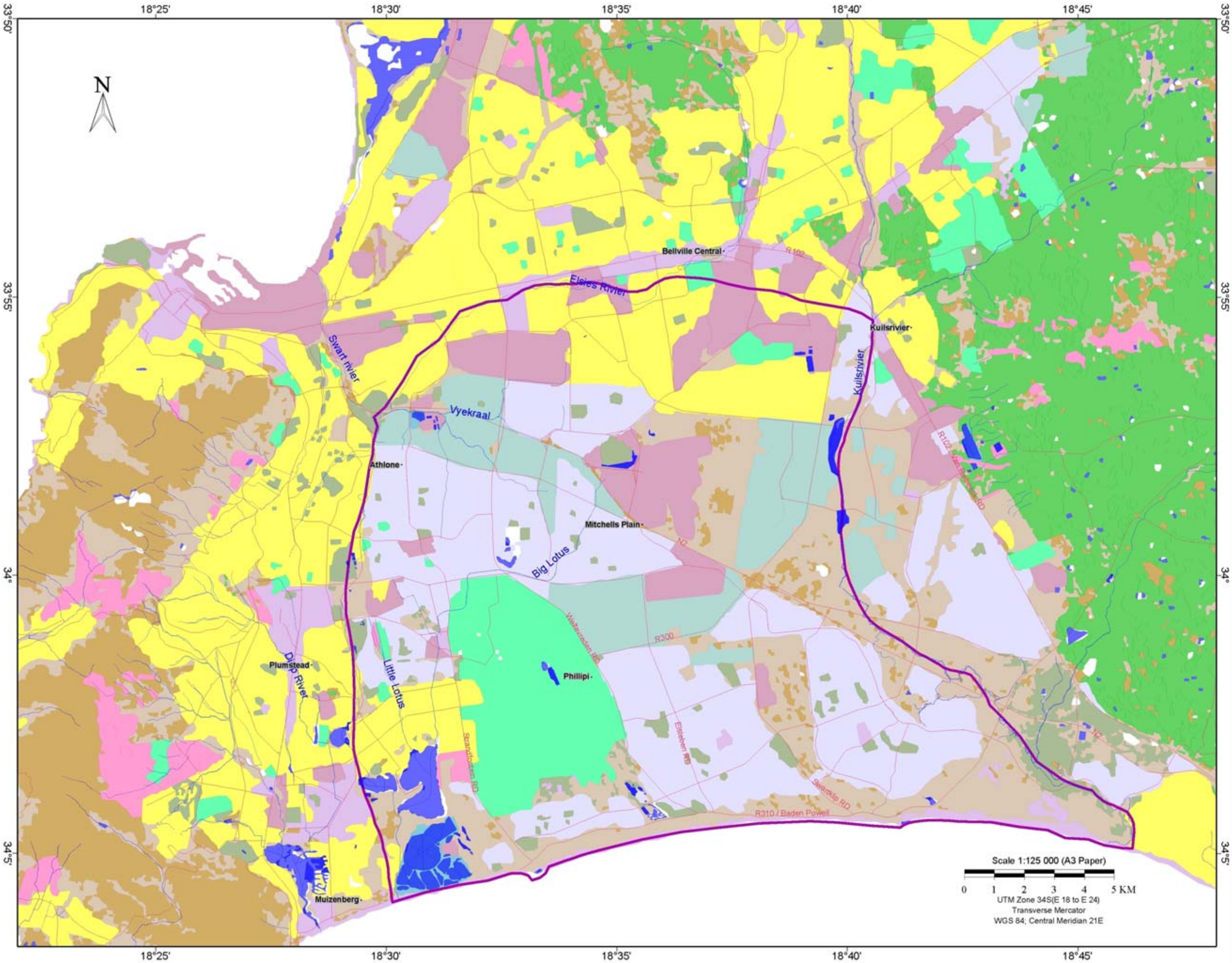
The landuse as mapped from the NLC2000 (CSIR Environmentek, ARC, 2000) is shown in **Figure 2-16** below. The major landuse is housing with formal and informal townships, and thereafter residential. Of these, the formal township is predominant. Second to housing the central and eastern areas of the Cape Flats have large open areas of thicket/bush land or shrub land. Light industrial areas are present in the centre, north and northeast of the area. A large number of small-holdings are present in the south east – the Philippi farms area, which represents land used for cultivation.

Usher et al (2004) identified the major sources of groundwater pollution in urban areas in South Africa. The source prioritization on a national scale shows that on-site sanitation has the highest risk, followed by cemeteries on place 3. There are also several industries listed that are known in the Cape Flats area.

The GRA II developed a risk rating for groundwater contamination, based on the land use, as determined in the NLC, and the vulnerability of the aquifer. The central part of the Cape Flats is grouped as high risk (see **Figure 2-17**)

The pollution threat to the aquifer is further assessed using particle tracking (see section 7). The possible sources are:

- sewage treatment works
- waste disposal sites
- heavy industry area
- informal settlements
- cemeteries.



LEGEND

Towns
Rivers
Roads
Model Area

Landuse

Bare Rock & Soil
Cultivated & commercial
Forest Plantations
Improved Grassland
Mines & Quarries
Shrubland & Low Fynbos
Thicket, Bushland
Residential
Formal Township
Informal Township
Smallholdings
Commercials
Industrial transport
Waterbodies, Wetlands

PROJECT NAME

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LANDUSE

FIGURE 2.16

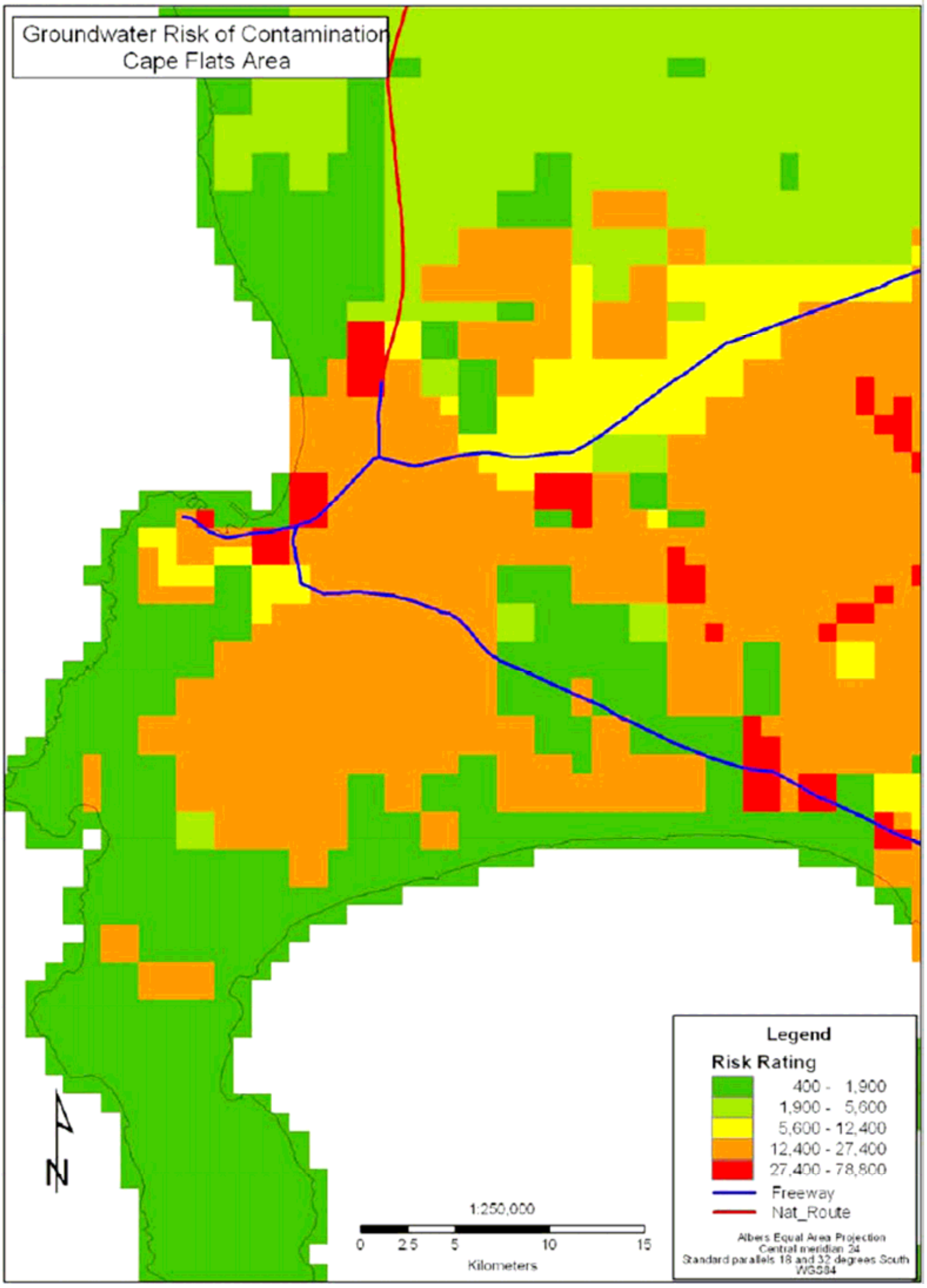


Figure 2-17 Groundwater Risk of Contamination (DWAF 2004)

3. CONCEPTUAL MODEL

3.1 CONCEPTUAL MODEL OF GROUNDWATER FLOW SYSTEM

The aim in model set up is to represent processes as simply as possible, without losing detail of the physics. Physical features and processes that dictate the groundwater flow system form the basis of the conceptual model. The salient conclusions for the groundwater flow system, as detailed in chapter 2, are summarised here. The conceptual model of the groundwater flow regime in the Cape Flats is formed on the assumptions that follow:

The hydraulic nature of the aquifer

There are various possible scenarios for the hydraulic nature of the aquifer, dictated by the interpretation of the geology of the system. The various scenarios will be tested in the numerical model through the process of calibration of the hydraulic conductivity.

- Scenario 1. The Cape Flats aquifer is dominantly unconfined. It is possible that at the largest spatial scale the geology of the system can be represented with a 2-layered system. This assumes that a multi layered or heterogeneous unit can be represented with an equivalent hydraulic conductivity (Hiscock, 2005). The basal layer has a higher hydraulic conductivity and the upper layer has a relative lower conductivity. Flow is concentrated in the lower layer where groundwater flow would be faster.
- The lower layer of higher hydraulic conductivity may be semi-confined depending on the magnitude of the difference between the conductivities of the broadly 2-layered system.
- Scenario 2. The Cape Flats aquifer is multi layered, comprising 2 semi-confined aquifers and an upper unconfined aquifer (**Figure 2-8**). At the local scale, semi-confining conditions exist. In this scenario flow would also be concentrated in the basal coarse gravels that are limited to the palaeochannels.
- The Cape Fats aquifer is underlain by an impermeable basement. Flow within this basement can therefore be neglected.

Sources, sinks and flow direction

- Water is sourced through rainfall as vertical recharge, and also from rivers during winter. The aquifer pinches out to bedrock at its landward boundaries and hence lateral recharge from other aquifer units is assumed negligible.
- The recharge value input is assumed to be net recharge, representing only water that enters the aquifer after any potential losses to evapotranspiration.
- The ocean is a sink throughout the year and the rivers during the summer.
- At a broad scale groundwater flow occurs from the high elevation and high hydraulic head in the north towards the south discharging at the ocean.
- Groundwater flow is controlled by the bedrock topography patterns illustrated by the similarity between water level distribution and basement elevation.
- Water is removed from the system by abstraction. This is quantified by WARMS and will be modelled.

Surface water – groundwater interaction:

- In natural river reaches it is assumed there is complete hydraulic connection between surface and groundwater. In this case rivers act as recharge or discharge boundaries to the aquifer.

- Where the system is natural, it is assumed that the rivers are groundwater fed during the dry season and that the rivers recharge the aquifer during the winter rainy season.
- Time averaged, it is assumed that the rivers act as a sink to the aquifer especially as the groundwater levels are known to be close to the surface, and because there is such an extended 'dry period' where the rivers still flow. Therefore the river stages in a steady state model are required to be lower than the modelled groundwater level.
- Where the rivers are canalised 2 scenarios are possible and tested in the model:
- Scenario 1. Hydraulic connection between surface and groundwater is negligible where rivers are canalised. The river is no longer a hydraulic boundary. The regional groundwater flow is then parallel to canalised sections (Section 2.4.2. **Figure 2-12**). This assumes that the regional groundwater flow at canalised river sections is subparallel and symmetrical on each side of the river.
- Scenario 2. Surface and groundwater are hydraulically connected where rivers are canalised.
- The hydraulic connection between the Zeekoevlei, and other surface water features, and the aquifer is low. This is inferred from the interpretation that their existence is dominated by the presence of low permeability layers. A certain degree of interaction is certain, however the water body is unlikely to act as a dominating recharge or discharge point to the aquifer at the regional scale.

Groundwater flow directions over the depth of the aquifer

In a regional system deep groundwater can flow in a separate direction to shallow groundwater. This is due to the scale of the processes governing the flow characteristics. There is no requirement of the shallow and deep groundwater to be hydraulically separated (e.g. by a low permeability layer) for this type of flow to occur. A schematic diagram depicting shallow and deep groundwater moving in different directions is shown in **Figure 3-1**. Shallow groundwater moves out to the northwest of the model domain due to river capture. There are two possible conceptual scenarios for the deep groundwater flow pattern in the northwest of the Cape Flats (**Figure 3-2**):

- Scenario 1. Deep groundwater flows to the south discharging to False Bay. In this scenario the direction of groundwater flow is dominated by the Elsieskraal River palaeochannel and the hydraulic control the coast at the False Bay coastline generates, causing all groundwater to flow to the south.
- Scenario 2. Deep groundwater in the northwest of the model, like surface water, flows out to the northwest and discharges to Table Bay. The potential continuation of the palaeochannel to the northwest would allow this (Section 2.3.2). However for the flow to be significant the hydraulic head driving deep groundwater to the northwest would have to be high in order to overcome the lateral restriction in the basement.

There are not enough water-level data points in the northwest of the model to prove or disprove either scenario. This model assumes that Scenario 1 is the most applicable and is effectively defined by use of the rivers as boundaries (see below). Any potential continuation in the basement low to the northwest would be narrow as compared to the Elsieskraal palaeochannel to False Bay, hence a high hydraulic head would be required to divert groundwater away from this "path of least resistance".

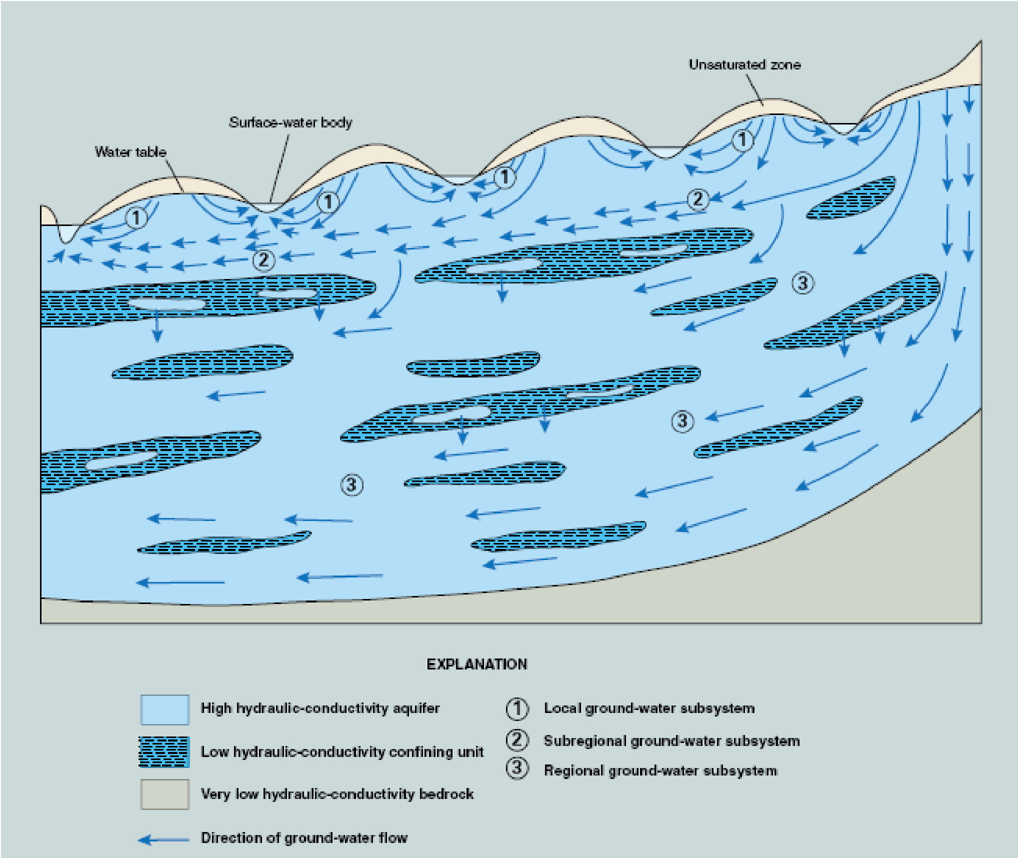
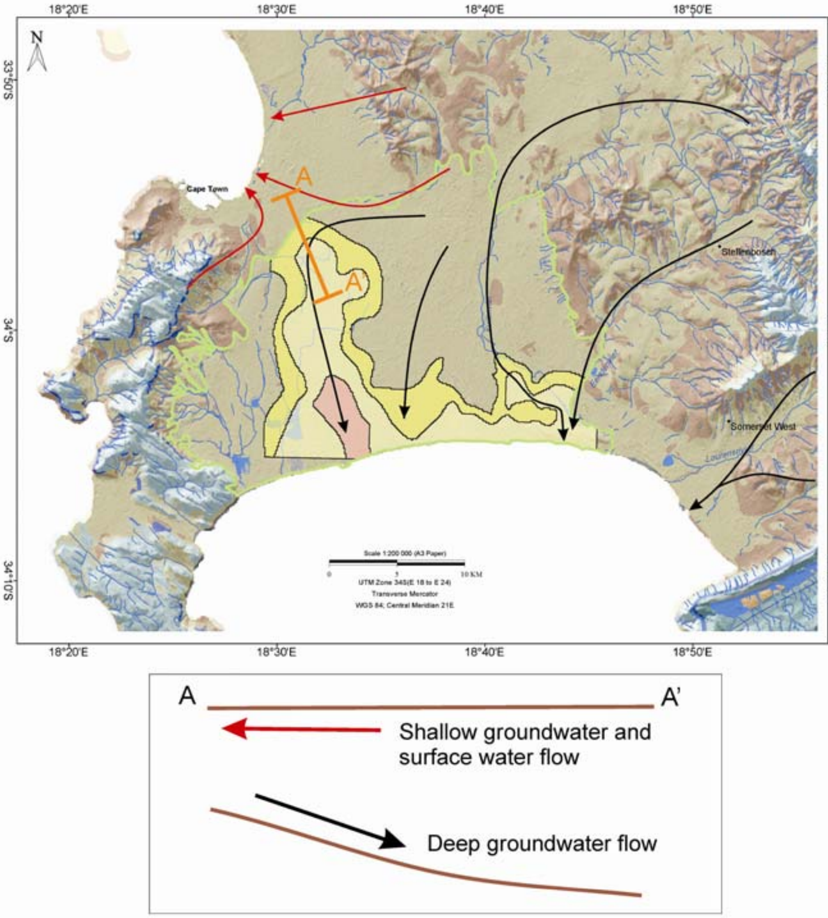
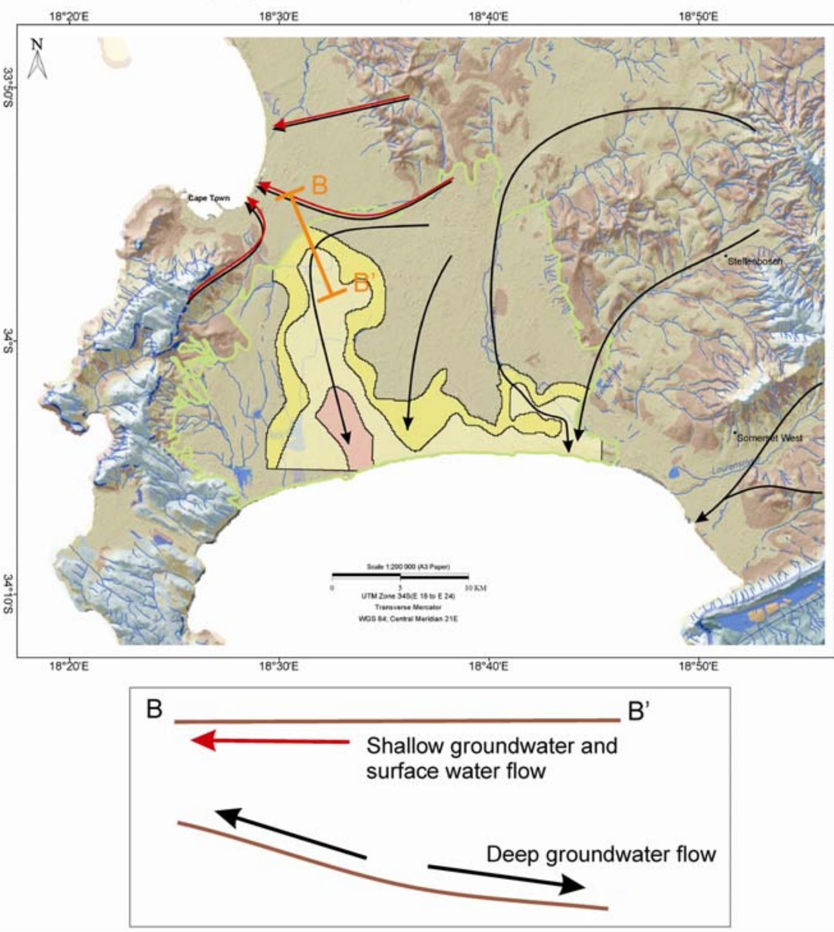


Figure 3-1 Groundwater flow at various scales (Alley et al, 1999)

Scenario 1: Deep groundwater flows to the south discharging in False Bay



Scenario 2: Deep groundwater in the northwest flows to the northwest discharging in Table Bay



LEGEND

- Towns
- Rivers
- Hydrotects
- Cape Flats Model area

Bedrock Elevation (mamsl)

- -20 - -30
- -20 - 0
- 0 - 10

- Shallow groundwater and surface water flow
- Deep groundwater flow

PROJECT NAME

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CAPE FLATS GROUNDWATER FLOW SCENARIOS

FIGURE 3.2

Maps showing two conceptual model scenarios for groundwater flow. Cross sections are schematic and are not to scale.

3.2 TRANSLATION INTO NUMERICAL MODEL

The numerical model is described with a focus on the model boundaries below. Other features of the modelling, for example the representation of rivers as ‘transfer boundaries’, and the input data for model layering, are described further in Section 4. The system is modelled with a finite element groundwater software package Feflow. The mathematics of the finite element package used is beyond the scope of this report and the reader is referred to the Feflow manual (Diersch et al 2006).

Numerical model boundaries are required to be set at positions where a known hydraulic head, known flux of groundwater, or known loss of groundwater from the system can be specified and input to the model. Positions of known fluxes within the model area are also specified as internal boundary conditions.

The southern boundary of the numerical model is set as the ocean. Because it is assumed that the aquifer and the ocean are in hydraulic connection, the hydraulic head of the aquifer at the position of the shoreline must be zero. Therefore the boundary condition along the coastline is a fixed constant head of zero throughout the depth of the aquifer.

The landward boundaries of the original “study area” domain employed in the conceptual model report (**Figure 1-2**) represent the physical aerial extent of the unconfined Cape Flats alluvium aquifer. Numerically representing the aerial extent of the aquifer is feasible in principle as the physical extent represents the point at which there is no groundwater flow, hence a ‘no flow’ boundary could be used. The rivers could also be used as model boundaries and set as Transfer Boundaries. The latter option was chosen, slightly reducing the boundary from the study area (**Figure 3-3**). In areas of the model where numerical instabilities arise because the total aquifer thickness is thin, a minimum thickness of 2 m was specified by reducing basement elevation. The impact on the overall reality of the model results is acceptable since the different geometry generated an increase in the total model volume of only 0.1%.

The Elsieskraal River is set as the northern boundary and the Kuils River the eastern. The western boundary is made up of the North-South running surface water system that feeds into Rondevlei and the M5 canal in the southwest (**Figure 3-4**). Where no rivers exist parts of the landward boundaries are no flow viz. the central area of the western boundary and the length of the northeast boundary. The western boundary is roughly parallel to the assumed dominant flow direction North-South hence flow across this boundary is assumed negligible. The north-eastern boundary is close to the aerial extent of the aquifer and flow across the boundary can be assumed to be negligible. The trace of the river length has been smoothed slightly for the numerical model (evident in **Figure 3-2**) to avoid numerical error. To model exact meanders in river length local scale models would be required

These boundaries exclude certain parts of the aquifer, for example west of the Diep River and Sandvlei. However comparison of basement topography data to land topography (Section 4.3 below) shows that in these areas the aquifer is less than approximately 2 m thick, hence the contribution to bulk water quantity and flow is assumed negligible. Also any water that flows towards the east from the west side of the Diep River would theoretically enter the Diep River.

Shallow groundwater, and also deep groundwater, is free to interact with the transfer boundary. Setting the transfer rate to 0 results in no flow across the boundary therefore flow parallel to the river or the physical boundary can also be modelled.

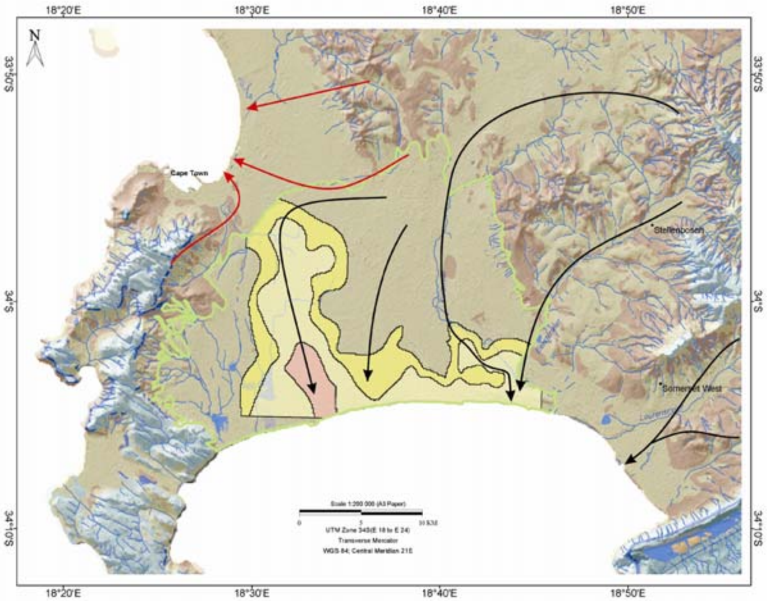
Surface water systems within the model boundaries described above are set as internal boundary conditions, for example the Zeekoevlei and the Lotus River (**Figure 3-3**). Abstractions are also represented as internal boundary conditions.

Figure 3-3 illustrates the Geological Scenario 1 and 2 translated into model layering. The final model set up represents a version of Geological Scenario 2 wherein the middle aquifer layer is not confined. Geological Scenario 1 was tested (see **Table 5-2**).

The model set up as described above, is used for calibration of both the steady state and the transient model. The calibrated steady state model parameters are input to the transient model. The calibration process is described in Section 4.

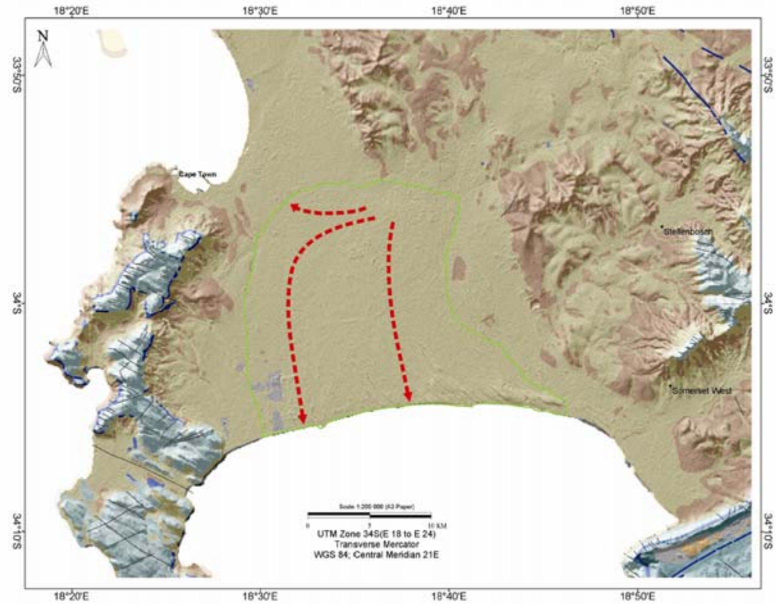
Conceptual Model

Plan View

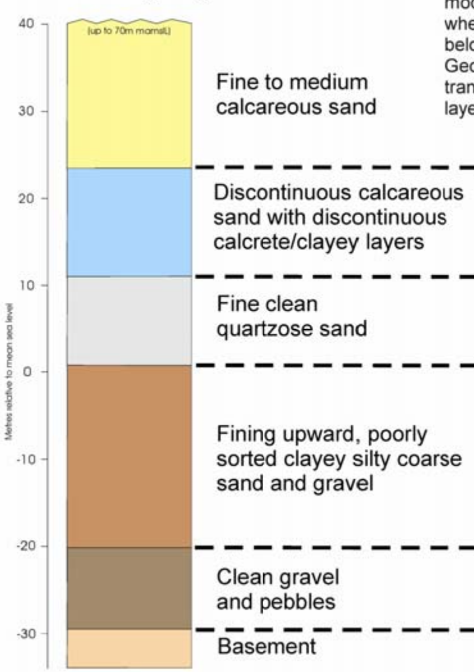


Numerical Model

Plan View

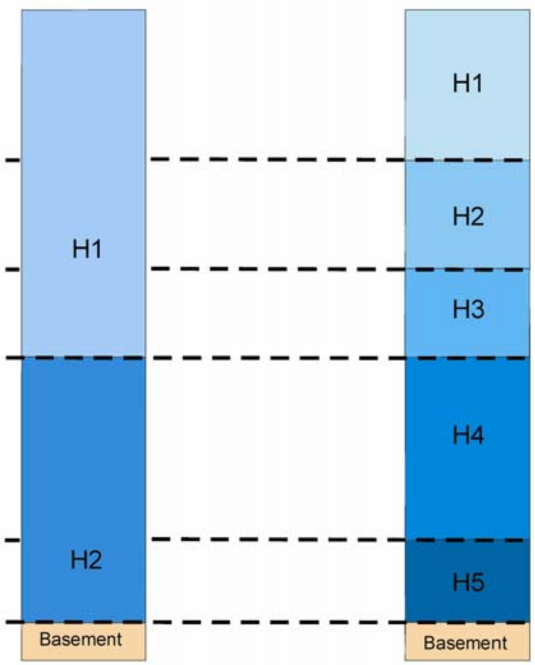


Vertical Layering



The figure shows the translation of the conceptual model into the numerical model, aerially and vertically. Geological Scenario 1 shows the situation where there is a higher proportion of high hydraulic conductivity material below ~0 mamsl, with layer 2 (H2) having a higher K than layer 1 (H1). Geological Scenario 2 indicates the full summarised geological section translated into numerical layers, where H2 and H4 are low K hydraulic layers, H1 and H3 are moderate K layers, and the basal H5 a high K layer.

Geological Scenario 1 *Geological Scenario 2*



LEGEND

- Towns
- Rivers
- Hydrotects
- Cape Flats Model area

Bedrock Elevation (mamsl)

- -20 - -30
- -20 - 0
- 0 - 10

- Shallow groundwater and surface water flow
- Deep groundwater flow
- Numerical model groundwater flow

PROJECT NAME

BERG RIVER MODEL STUDY

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TITLE

TRANSLATION OF CONCEPTUAL MODEL TO NUMERICAL MODEL FOR THE CAPE FLATS

FIGURE 3.3

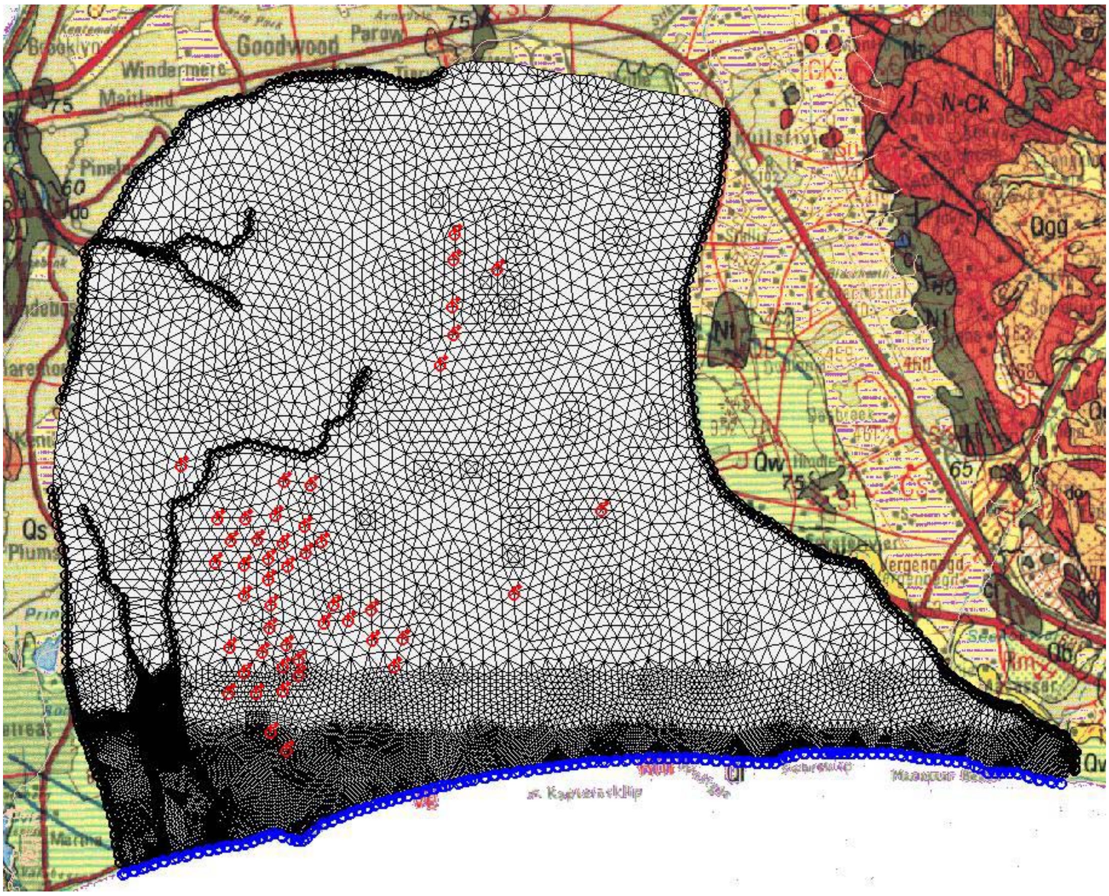


Figure 3-4 Boundary conditions

Red nodes indicate abstraction wells, black nodes represent transfer boundaries and blue nodes indicate constant head boundaries..

4. STEADY STATE MODEL INPUT DATA

4.1 REQUIRED INPUT DATA

A numerical groundwater model requires data for:

- Coordinates of model boundary;
- Top and bottom model surfaces;
- Internal aquifer geometry, dictated by the hydrostratigraphy;
- Porosity data required for contaminant transport modelling;
- Definition of all sources and sinks of water to the aquifer, including recharge, abstraction
- Calibration data is actual field water level measurements, hydraulic properties and specific storage.

Table 4-1 Summary of required input parameters

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

4.2 THE MODEL MESH

The modelled area amounts to ~350 km^2 (less than the total Cape Flats area). The Feflow software uses a triangular mesh. The model is fully 3-D and contains 94 ,596 prismatic elements and has 61 ,080 nodes. The mesh is discretised towards the coast where there are rapid changes in aquifer thickness over small distances. For example the model thickness in the southeast where dunes are present varies from 0 m to >70 m over one element at the coast. Over the majority of the model the prism lengths are generally 250-450 m long, reducing to 175 m in the south, and to ~60 m near the coastline (see **Figure 3-4**).

The model functions by solving the groundwater flow equation at the nodes of the triangles only. The solution for head is then averaged by linear interpolation between nodes to produce a smooth appearance to the contours. Therefore the accuracy of the solution is in part a function of the density of the mesh, and in this case to the scale of ~600 m. The length scale of the problem is 2 orders of magnitude greater than this scale of accuracy and therefore it is deemed sufficient.

Input data can be imported as point data and values are interpolated between so that each model node is specified. This process was applied using an inverse distance weighting of four nearest neighbours interpolation technique.

4.3 TOPOGRAPHY

A 20x20 m DEM was used to construct the model surface topography. In TNT MIPS a grid file-containing point data for each cell of the DEM was created. This process delivered 1.2 million data points for the Cape Flats study area. The point data, because it is based on a 20 by 20 km grid, is much denser than the model mesh, which has nodes separated by ~600 m distance. During data regionalisation a nearest neighbour inverse distance weighting method was used in order to apply topographic data points to the nodes.

Topography ranges, within the model domain, from 0 mamsl at the coast to 72 mamsl in the northeast, near Cape Town Airport.

4.4 BEDROCK

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 1:250000 geological maps

The above data sets were combined. The bedrock elevation, as mamsl rather than depth below surface, was computed by simply subtracting the depth to basement from the topographic elevation at each borehole data point/position (using the 20x20 m DEM). The data distribution generated is shown in **Figure 2-7**.

Certain features are evident in **Figure 2-7** that are a function of the available data and the interpolation process carried out automatically to generate the contours. For example within the palaeochannel of the Elsieskraal River the –30 m contours are closed. This is not typical of fluvial systems and the closed contours are interpreted as a function of the numerical smoothing and interpolation only. In these areas additional common sense data points were entered to ensure a geologically and physically reasonable surface as well as smoothing of sudden changes in elevation. The final basement topography as used in the model is shown in **Figure 4-1.**

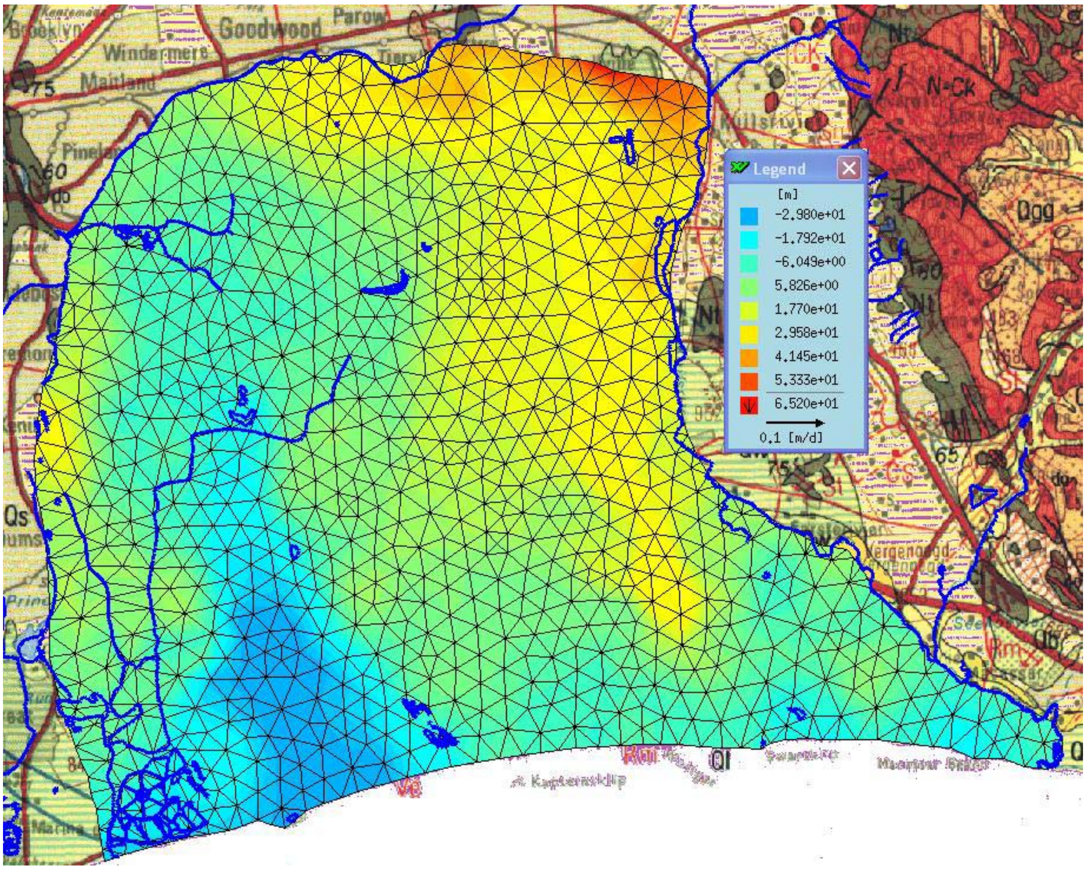


Figure 4-1 Model input data: Bedrock topography, shown as colour field (mamsl)
(a simplified mesh is shown in this figure in order that the colour field is visible, the model mesh is actually more dense, see ***Figure 3-4****)*

4.5 INTERNAL AQUIFER GEOMETRY

The Geological Scenario 1 and a modified version of Scenario 2 (see **Table 4-2** and **Table 4-3** below) were tested in the model, adding a model layer for the purposes of assigning a transfer rate as the transfer boundaries must be set over an aerial face. To represent rivers at a realistic horizontal scale would require a mesh almost 600 times finer than described above. To keep the time needed for each model run acceptable, the transfer boundaries are set across a vertical face to a layer 1 m below the topography hence the uppermost layer in the model. Initial model runs used the simplest layering and complexity was added during calibration.

The upper surface of the basal layer with higher conductivity was set with respect to the basement topography. Feflow cannot model layers that are discontinuous across the model. Therefore in positions where this layer is unlikely to be present, i.e. where basement is greater than 0 mamsl (Section 2.3.3), then the layer pinches out to 0.1 m. Therefore the elevation of the base of layer 2 was set conditionally. If the depth to bedrock at a position was <-0.1 mamsl then the elevation of the slice was set at 0 mamsl. If this condition is not satisfied then the elevation is set at basement elevation +0.1 m. This generates a layer which infills channels but pinches out where basement topography rises from the channel, as the conceptual model states.

Hydraulic conductivity scenarios were tested in a 3-layered system; Geological Scenario 1, (**Table 4-2** and **Table 5-2**) before settling on the 4-layered modified version of Geological Scenario 2 for final calibration (**Table 4-3** and **Table 5-2**).

The numerical solution cannot represent layers that are discontinuous across the model. A layer that is required in reality to be discontinuous (for example the basal layer in **Table 4-2** in places where the basement is higher than 0 mamsl) must be represented in the numerical model as very thin although not present in reality.

The 4-layered model is numerically stable. It does not represent the potential Scenario 2, but allows testing of whether the basal layer is confined, by running model layer 3 with a low hydraulic conductivity. It also allows testing of whether the calcrete beds of the Langebaan Limestone significantly confine the sand unit beneath (the Springfontyn), by running models with a low K in layer 2. The elevation of the modelled layers are not exactly the same as the real positions and thicknesses of the geological units throughout the model domain. Furthermore, because each and every change in vertical sequence is not represented and because lateral continuity is assumed where discontinuity in some layers does happen in reality, the calibrated K values for each layer is an “equivalent hydraulic conductivity”. They cannot be interpreted as the hydraulic conductivities for specific geological formations identified in borehole logs.

Table 4-2 Model Layering: 2-layered hydrogeological scenario: 3-layered numerical model

*(Refer to **Figure 3.3** for geological scenarios)*

Layer	Top	Bottom	K	Comment
1	Topography	Topography – 1 m	H1	Required to represent rivers
2	Topography – 1 m	0 mamsl. 0 mamsl + 0.1 m where basement > 0 mamsl	H1	Represents main sand unit of Bredasdorp and Vaarswater formation
3	0 mamsl. 0 mamsl + 0.1 m where basement > 0 mamsl	Basement topography	H2	Represents higher proportion of higher hydraulic conductivity below 0mamsl, including basal gavels

Table 4-3 Final Model Layering

Layer	Top	Bottom	Thickness	Comment
1	Topography	Topography – 1 m	1m	Required to represent rivers
2	Topography – 1 m	Half way between (topography – 1) and 0 mamsl, or 0 mamsl + 0.1 m	0.45 – 28.0 m	Numerical model layers do not represent geological boundaries exactly.
3	Half way between (topography – 1) and 0 mamsl, or 0 mamsl + 0.1 m	0 mamsl. 0 mamsl + 0.1 m where basement > 0 mamsl	0.45 – 28.0 m	Numerical model layers do not represent geological boundaries exactly.

4	0 mamsl. 0 mamsl + 0.1m where basement > 0 mamsl	Basement topography	0.10 – 29.8 m	Represents higher proportion of higher hydraulic conductivity below 0 mamsl, including basal gavels

4.6 AQUIFER HYDRAULIC PROPERTIES

4.6.1 Hydraulic conductivity

Hydraulic conductivity values vary over more than 10 orders of magnitude in nature (Calver 2001). Typical hydraulic conductivity values are:

- For an unconsolidated silty sand to gravel – 0.01 to 10 000 m/d (Freeze and Cherry 1979)
- For fluvial deposits (alluvium) – 0.1 to 1 000 m/d (Hiscock, 2005).

Selected start up estimates for hydraulic conductivity of the Cape Flats sand aquifer from the literature are shown in **Table 4-4** below.

Table 4-4 Hydraulic conductivity estimates for the Cape Flats

Source	Hydraulic conductivity	Method	Applicability
Shand (1987)	1.9 – 10 m/d	Transient 2D modelling of pump test results.	Local scale processes; Area n/a to palaeochannel; hydraulic equivalent to full thickness of aquifer although semi to confined.
Wessels and Greeff (1980)	15-50 m/d	Hazen grain size formula	Useful as a guide.
Gerber (1980)	1 – 25 m/d	Steady state 2D modelling at regional scale	Modelled equivalent K but laterally variable;
Vandoolaeghe (1989)	Bredasdorp: 30-40 m/d Varswater: 1-10 m/d	Hazen grain size formula Hazen grain size formula, from deposits of similar geological setting to CFA	Conducted on sample of clean sand. Discontinuities and local lenses will reduce K. Useful as guide to relative difference in K between layers.

The conceptual models of previous workers and the numerical set up of previous models varies from that presented here. These results will be used as a guide since there is no indication that these model solutions were unique or verified using independent data sets.

4.6.2 Storage Properties

The volume of water released per unit decline in head in an unconfined aquifer is the specific yield (dimensionless). Water is also released elastically though this volume is much less, and is known as the specific storativity [L^{-1}]. The normal range of specific yield in an unconfined aquifer is from 0.01 – 0.30 (Hiscock, 2005). In agreement with typical literature values the specific yield was assigned to 0.2 and the specific storage to $1E^{-4}$ m^{-1}. Storage parameters affect the transient numerical model, and are described further in section 6.

4.6.3 Porosity

Porosity for fluvial alluvium varies from 0.05 – 0.35 (Hiscock, 2005). A porosity of 0.15 is assumed for the Cape Flats.

4.7 RECHARGE

The recharge for the Cape Flats calculated with the BRBS method (DWAF, 2002) is shown in **Figure 2-13**. This method is based on rainfall only and takes no account of the land use (the method is described in more detail in Volume 4 of this report, DWAF 2007c).

The method applies a factor for geology and uses 1.5 for sand, which the whole of the Cape Flats area is classified as. This effectively increases the recharge above that given by the simple rainfall percentages. Based on the fact that a large proportion of the Cape Flats will have lower permeability at the surface than sand (due to tarmac, soil, upper calcretised layers), a new recharge distribution was generated but did not apply the 1.5 factor for sand (BRBS method). Modelled monthly rainfall data was summed to represent an averaged typical year for each rainfall data point. Percentages as in the BRBS method were applied to these totals. This generates a recharge total over the model area of 12.2 Mm^3/annum, or 36.6 mm. This value is lower than values shown in **Table 2-6**.

The peak in rainfall in the northwest of the model area translated to a peak in recharge. The reality of the modelled rainfall peak is questionable (section 2.2) and the peak was removed, smoothing the recharge distribution. This method generated a total of 31 022 m^3/d, or 11.3 Mm^3/a over the model area which was used as model input. This equates to an average of 33.8 mm. It is assumed a net recharge, minus any potential losses to evaporation / evapotranspiration.

The recharge input to the steady state model is shown in **Figure 4-2**.

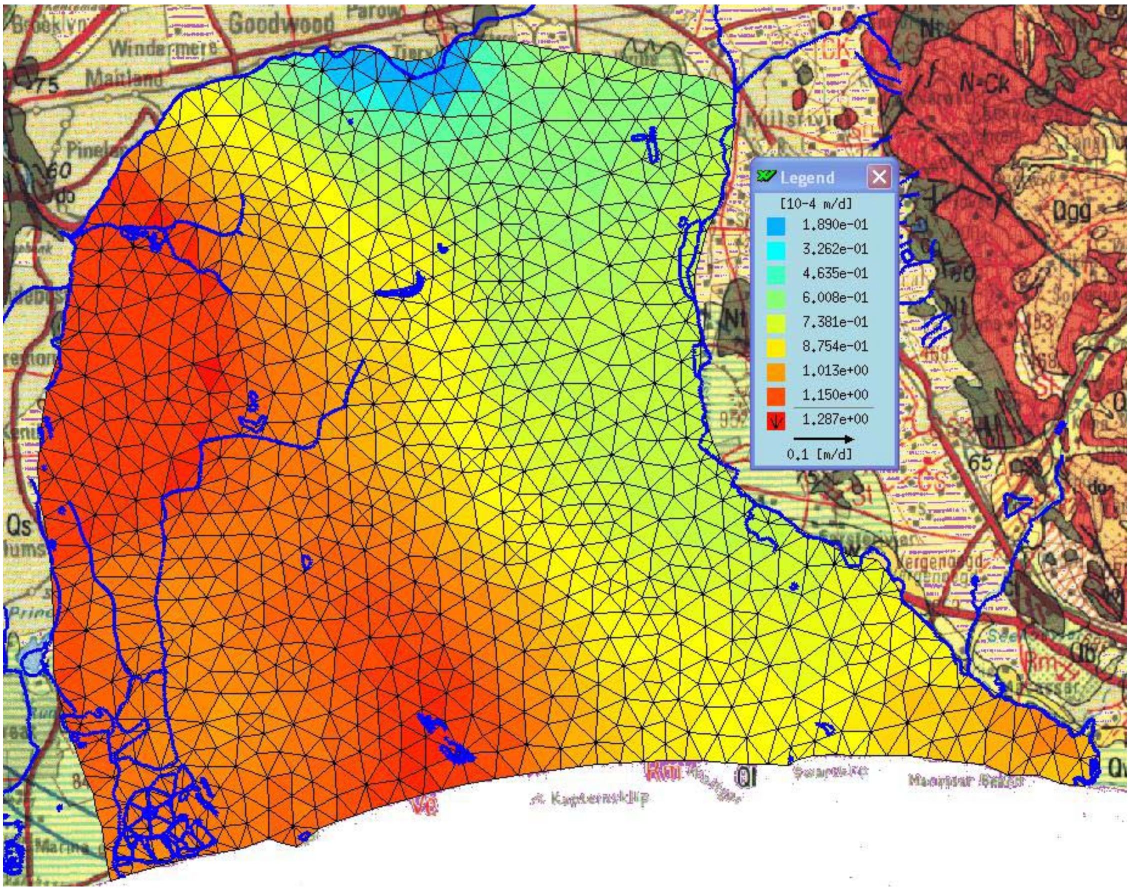


Figure 4-2 Model input data: Recharge shown as colour field (10^{-4} m/d)

4.8 ABSTRACTIONS

The current abstraction in the Cape Flats, as given by WAMRS, is shown in **Figure 2-14**. Boreholes cluster in the area of the palaeochannel; 6 are present in the centre north of the area, and one is present in the east (area 1, 2 and 3 respectively; **Table 4-5**). Abstractions are input to the model as boundary conditions applied to a node, specifying the abstraction rate. This model is concerned with the affect of the current abstraction on the regional flow regime and water levels, not on predicting drawdowns at a specific position. Thus, the total abstraction of every borehole cluster, was summed and averaged over the total number of wells in the cluster/area. The distribution of the total abstraction across the area is shown in **Table 4-5** below, and the boundary condition positions are shown previously in **Figure 3-4**.

Table 4-5 Abstraction input data

Area	Abstraction per borehole	Number of Boreholes	Total Abstraction
1	248.5 m^3/day	40	9940 m^3/day
2	133.2 m^3/day	6	800 m^3/day
3	75 m^3/day	1	75 m^3/day
		Total:	**10 815 m^3/day,** **3.95 Mm^3/annum**

4.9 RIVERS

4.9.1 Positions and river stages

A transfer boundary condition enters a source or sink of water to the selected element based on a simple Darcy calculation between the head in the aquifer beneath the river (H_A) and the river stage (H_S), and the conductance, as follows:

$$Q = \frac{K}{B} \times A \times (H_A - H_s)$$

Where;

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

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

B = bed thickness [L]

A =cross sectional area of flow [L].

The (K/B) term is the conductance of the river, and in Feflow is termed the “transfer rate”.

The river stage Hs and the transfer rate is entered for each transfer boundary node.

In a river scenario the cross sectional area of flow is taken as the horizontal area of the riverbed –the river width times its length. In the classical and simplest representation of surface water - groundwater interaction, applicable at regional scales such as the Cape Flats, this represents the area over which groundwater and surface water can exchange (Rushton and Tomlinson, 1979). In finite difference models such as Modflow it is possible to set this area and within the cells the transfer boundary is entered.

In Feflow the area cannot be manually set. The area for flow is generated by setting transfer nodes over an aerial face, and a vertical layer is used (Section 4.5 above). The river outline follows the actual trace of the river and so the length of the modelled transfer boundary realistic. The vertical thickness of the layer generated for the river represents the width of the river. This layer is set at 1 m thickness, essentially replicating a river 1 m wide. Variations from this width can be accounted for in the calibration of the transfer rate (see below).

As per the model assumptions that the rivers act as a sink to the aquifer, the river stages were set below the groundwater level. As an initial estimate of the modelled groundwater levels the observed groundwater levels and topography were used. River stages were first set at 2 m below the elevation data at the cell (from the DEM). But not all transfer nodes lie in exactly the coordinate position of the physical river. This is especially true along meanders of the Kuils River. In addition to this difference between the model and real world, and because a 20 m DEM is used as the model surface the actual and modelled elevation of the riverbank is not always the same. In general the actual elevation of the river is lower than set in the model.

Because of model scale there can be a highly varying topographic profile along a river reach and therefore varying river stage. Rather than river stages slowly declining downstream, the automatic setting caused sudden jumps to higher stages downstream. This affected the flow regime at the rivers for example if one transfer boundary node had a higher topography than those upstream of it, often by 5 m, then the river stage would also be higher by 5 m, causing a large source to the aquifer.

The average river stage is 4.5 m below topography.

4.9.2 Hydraulic connectivity

The transfer rate accounts for the hydraulic conductivity of the bed sediments divided by the thickness of the bed sediments. A transfer rate of zero signifies zero hydraulic conductivity and the transfer node essentially represents a no-flow boundary. As the transfer rate increases the hydraulic connectivity increases and flux between the aquifer and river flows more freely.

The width of the riverbed is represented by the thickness of layer 1. To accurately represent the width of the river this thickness would have to vary throughout the model which is not possible as the aquifer is thin, a minimum of 2 m, in certain places. It is recommended that the transfer rate be used as the ‘compensation parameter’. It is therefore used as a calibration parameter to be varied to account for changes in river width, as well as changes in bed sediment thickness and hydraulic conductivity.

An initial transfer rate of 1 m/day was set (Transfer rate = K / B = 1 m/d / 0.5 to 1 m = 1-2 d^{-1}) and varied in calibration. In surface water- groundwater Interaction Scenario 1, for river reaches that are canalised, the hydraulic connectivity is reduced such that the boundary is effectively impermeable and the reaches are set to a transfer rate of zero.

4.10 INPUT PARAMETER SUMMARY

The initial input parameter are summarised in **Table 4-6** below.

Table 4-6 Input Parameters

Model Input Parameter	Value	Type
Topography	Range 0 mamsl – 72 mamsl	Fixed
Bedrock topography	Range -30 mamsl – 65 mamsl	Fixed
Layering	3 layers (Table 4.2)	Various possibilities to be tested
Hydraulic conductivity	10 m/d	Calibration
Storage coefficient	$1E^{-4}$ m^{-1}	Transient Calibration
Specific Yield	0.2	Transient Calibration
Porosity	0.15	Fixed
Recharge	Range	Fixed for steady state calibration, varied in scenarios
Abstraction	N/A	Fixed for steady state calibration, varied in scenarios
River Stages	1-3 m below topography	Fixed
Transfer Rate	1	Calibration over natural river sections

5. NUMERICAL MODEL: STEADY STATE MODELLING

5.1 CALIBRATION PROCEDURE

The procedure adopted for calibration is standard to modelling investigations; the simulated steady state heads and flows ("modelled" data) are compared against field-measured values ("real", or "observed" data). This is conducted first for steady state simulations and subsequently for transient simulations (chapter 6). Aquifer parameters are varied until a reasonable fit is generated between modelled and real data selected as calibration data.

The calibration of the model (model geometry refinements and parameter calibration) is described in Section 5.4 below. Initial model runs showed that refinement of the model mesh and layering was required. Subsequent to these variations of the model geometry, calibration concentrated on the boundary conditions and on generating physically realistic behaviour at the river nodes after which calibration of the hydraulic conductivity (K) began.

Within this general process there is iteration that occurs. For example, the major changes were made to the river stages in the sequence described below, however on calibrating hydraulic conductivity, the flow field did change in certain areas and further editing of the river stages occurred. Regardless of the sequence of events, the parameters from the final model are described under each Section of 5.2.

Parameter testing and evaluation of model sensitivity to different parameters is established. A range of values for one or more parameters are input to the model in order to understand the model response to a particular variable, coupled variables or even a group of variables because it is preferable, but not always possible, to establish a unique model solution. However the calibration is always based within the limits of the physically real. Given the inherent uncertainties in this model with respect to the exact nature of the bedrock topography, the rate of transfer between rivers and the aquifer, lateral continuity or otherwise between confining layers at different depths and unknown surface and subsurface discharges arising from the urban environment, a unique model solution was not expected.

A unique model solution is also not necessary as a planning tool. This model aims to test various model scenarios with respect to estimates of the long-term average flux to or from the different rivers, (surface water- groundwater interaction), the ocean and the impact of abstraction on these fluxes.

5.2 CALIBRATION STANDARD

There is no known standard protocol for quantitative evaluation of a model calibration (Anderson and Woessner, 1992). Point data is used here so that a quantitative evaluation is possible, rather than a qualitative visual comparison between contoured maps (which also include any interpolation errors induced on contouring real data). Point data allows scatter plots of the measured against simulated heads to be generated, which for a calibrated model would show a random distribution of points lying closely around the 1:1 line. The difference between the measured and simulated heads can be calculated, and the average of these absolute "errors" ("error" refers to the absolute difference between measured and modelled values) is a useful quantification of the goodness of the fit in the model run (Anderson and Woessner, 1992).

The maximum acceptable value of the calibration error depends on the magnitude of the change in heads over the problem domain (Anderson and Woessner, 1992). Although there is no convention, the following will be used as guidelines:

- All errors should be within 10% of the magnitude of the change in heads across the model (R. Mackay, Pers. comm. February 2005). The water level surface for the model domain (**Figure 2-9**) shows the maximum water level within the model area is 73.1 mamsl, occurring in the northeast where the basement is at 63.3mamsl. The minimum is sea level, therefore 10% of this head drop suggests all point data should be met to within 7.3 m by modelled data in calibration.
- A "small ratio of the RMS error to the total head loss in the system" (Anderson and Woessner, 1992). However no quantitative description of the "small ratio" is given.

The calibration point data is used in combination with all available knowledge (local knowledge of groundwater levels, knowledge gained through literature review). In addition to the point data, model runs will be analysed through comparison of certain "key indicators". These calibration key indicators include:

1. Point data (see below) – the average error to point data and the range in the errors;
2. the maximum modelled water level, to indicate whether any parts of the model are "dry";
3. modelled water levels as compared to ground level, to show if water levels are within a few metres of ground level or above ground level;
4. mass balance numbers including fluxes to the ocean and to and from the rivers.

5.3 CALIBRATION DATA: STEADY STATE WATER LEVELS

The available point data for the model domain is shown in **Figure 2-9**. These are a combination of single points and time series averages (see Section 2.4.1). This water level data required manual amendments in order to generate a usable calibration point data set. The water level surface as shown in **Figure 2-9** mimics topography with ground water mounds in areas of topographic highs (compare **Figure 2-1** and **Figure 2-9**). There is no evidence for recharge sources (such as treatment works) in these areas. It was assumed that these mounds represent the local scale recharge process, a local perched water table or are the result of rapid topographic variation.

Out of the 237 water level points that are available (in **Figure 2-9**), 127 were selected. Points that were in clustered positions were grouped, others were left as single points. This generated a set of 33 points acceptably spread across the model domain. Twenty two (22) of the points represented a group of values and 12 were individual. 26 of these points were used in the final calibration of the model. The 7 points discarded were either situated on the edges of hydrogeological model zones (eg edge of palaeochannel) or associated with local-scale basement highs and not considered representative of the regional groundwater surface.

The remaining points were examined in detail. If a water table elevation was either above model topography or significantly below the known average depth to water table in the area it was adjusted based on best local knowledge (L Groenewald, pers. comm. July 2007). Thereafter the geology of the remaining water level points was analysed (from NGDB records of the Boreholes, and from the logs in Wessels and Greeff, (1980). This showed that:

1. within the clustered areas there was no correlation between geology and water level: the highest water levels in a cluster of boreholes did not pertain to only those boreholes with interbedded clays or calcretes. In certain circumstances the highest water levels were from boreholes in which only sand was logged.
2. the largest variation in water levels for the clustered boreholes occurred for areas associated with variable topography (ie dunes) in the centre, south, and east.

Thus it is an acceptable model assumption that the local groundwater highs representing small-scale recharge patterns and or result from topographically skewed data, which can also not be replicated because a 20 m DEM surface is used or the borehole positions themselves were not correctly recorded in the data base.

There can be simple human error in detailing the X,Y coordinate of a borehole. The regional scale groundwater level surface (Henzen (1973), Gerber (1980)) do not reflect the surface topography detail. They show contours reducing gradually to the south and to the west without distinct groundwater mounds. It is therefore suggested that a topographic bias is introduced in a select number of these water level measurements available in the data base arising from locating the borehole on a 1:50 000 topo sheet in an area of rapidly changing elevation. Water levels, taken as depth below collar, are converted to depth below ground level and this can easily result in a 10 – 20 m error in mamsl. There is less error in flat terrain and or using a 1:10 ,000 orthophoto sheet but boreholes listed prior to the 1980's would have been located using a 1:50 ,000 topo sheet. GPS only became routinely used after about 1995 and only in the last two years have these become accurate in the Z direction with an error of less than 5 m.

This can be corrected by cross checking of the borehole coordinates with topographic context. For example no one would intentionally drill a borehole on top of a dune if they could drill it at the base of the dune. Thus if a borehole plots in an improbable position, the position can be changed using common sense and the water level changed accordingly. In a cluster of boreholes in an area of steeply changing topography and variable water table elevation, the lowest water elevation was taken to represent the group. For clustered points away from varying topography which had a low variation in water levels, the mean of the water level was used

The final calibration point data set is shown in **Figure 5-1** below. 15 points are minimums of clusters; the remaining 9 are single points. 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.

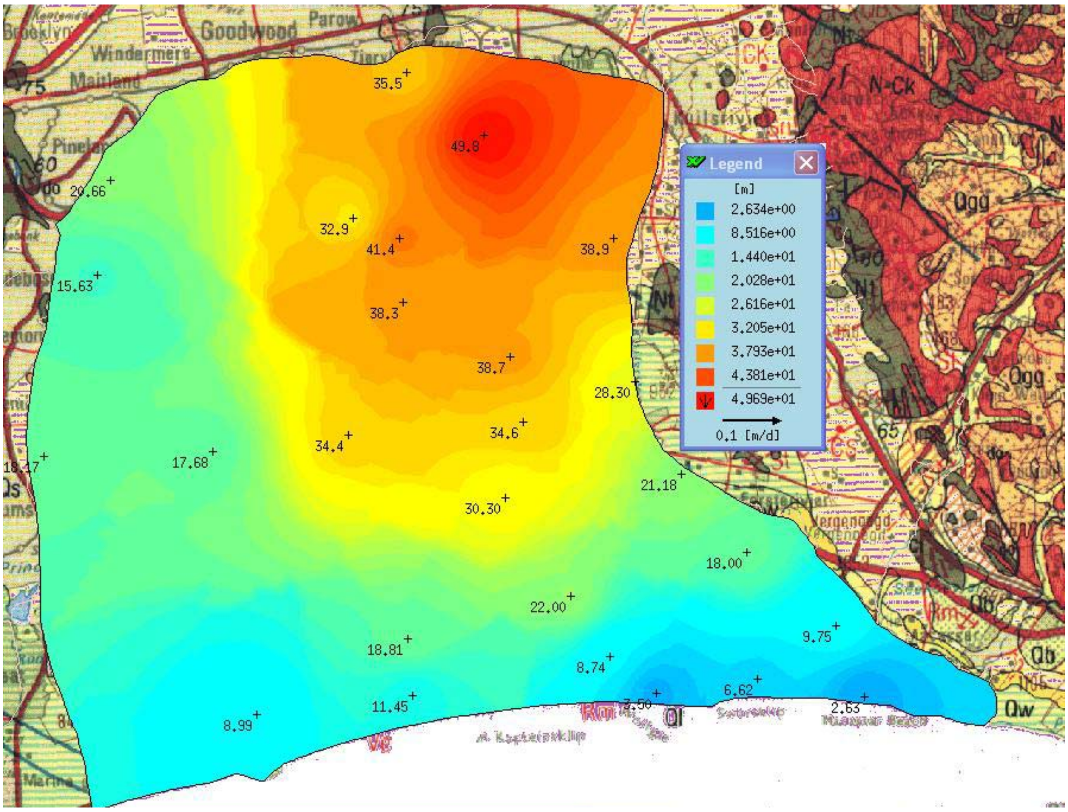


Figure 5-1 Final Calibration Data Points.
The figure shows the data points used in the calibration and a colour field of water level surface interpolated from these points.

5.4 PARAMETER CALIBRATION

5.4.1 Hydraulic conductivity

A summary showing selected key model run results for various distributions of hydraulic conductivity is shown at the end of the discussion of parameter calibration, in **Table 5-2** below. For K scenarios that have a lower K layer overlying higher K layers, the water level is only reported (in **Table 5-2**) for the upper most layer. The average difference in water levels at the point data between layers was a maximum of 0.2 m in these scenarios.

The main features to be drawn from calibration of hydraulic conductivity (Shown in **Table 5-2**) are:

- There is a relatively narrow range in K value in all layers within which the model reproduces a reasonable regional water table and also an acceptable ratio of outflow to the ocean and into the rivers. The minimum K is 10 m/d for either a homogeneous aquifer or an equivalent K taking the net effective of different K in each layer. If K is above ~80 m/d the regional water table gradient generates water levels outside the calibration error.
- There is a close relationship between the variations in K value in different model layers and the flux of water entering the rivers, and the degree of flooding in the northwest and W of the model. The vertical anisotropy in the model impacts on the flux out of the aquifer into the river. The lower Kz the greater the flux to the rivers. The model showed a better calibration fit with Kz an order or magnitude lower than Kx and Ky. Kx and Ky were not varied with respect to each other.

- The numerical models showed that a heterogeneous K was required in order to calibrate to the observation data and hence K was varied between layers and also heterogeneously within layers.
- The numerical model results confirmed what was assumed in the conceptual model: that the basal gravels are higher K than the rest of the aquifer as the model calibrated with higher K in the basal layer, existing only within palaeochannels. **Table 5-2** shows that the high K basal layer is required in order to reduce water levels with respect to ground level.
- It would appear that there is an upper limit to the K in the palaeochannel based on a model assumption that the rivers act as a sink on average over time. A basal layer of ~800 m/d, reasonable for a coarse clean gravel, lowers the water levels in the aquifer and generates a strong outflow to the ocean, such that the rivers become sources to the aquifer.

The model was considered calibrated for this parameter set; high Kx and Ky of (84 m/d) in model layer 4 within the palaeochannels; a very low K (0.1 m/d) in layer 3 in positions overlying the palaeochannels; and a K of 10 m/d in other parts of the model and layers 1 and 2. Kz is 0.1 of these values. This is considered to be the base case or Scenario A.

There are potentially many permutations possible for combinations of K values that may be equivalent to that presented here. The K scenario described above was decided upon as a best fit, because it generated results which fall within the calibration standards set for this modelling exercise (Scenario A **Table 5-2**). The heterogeneous K distribution for layers 3 and 4 is shown in **Figure 5-2** and **Figure 5-3** below.

Since the modelled groundwater levels were ~5 m above ground level in the northwest of the model and there was a difference of up to 12.8 m between the modelled and measured water table in the centre of the model, the calibrated K of Scenario A was used as a base case for further model testing. Various additional scenarios to test model uncertainty were selected. These scenarios are described under the transfer rate section below.

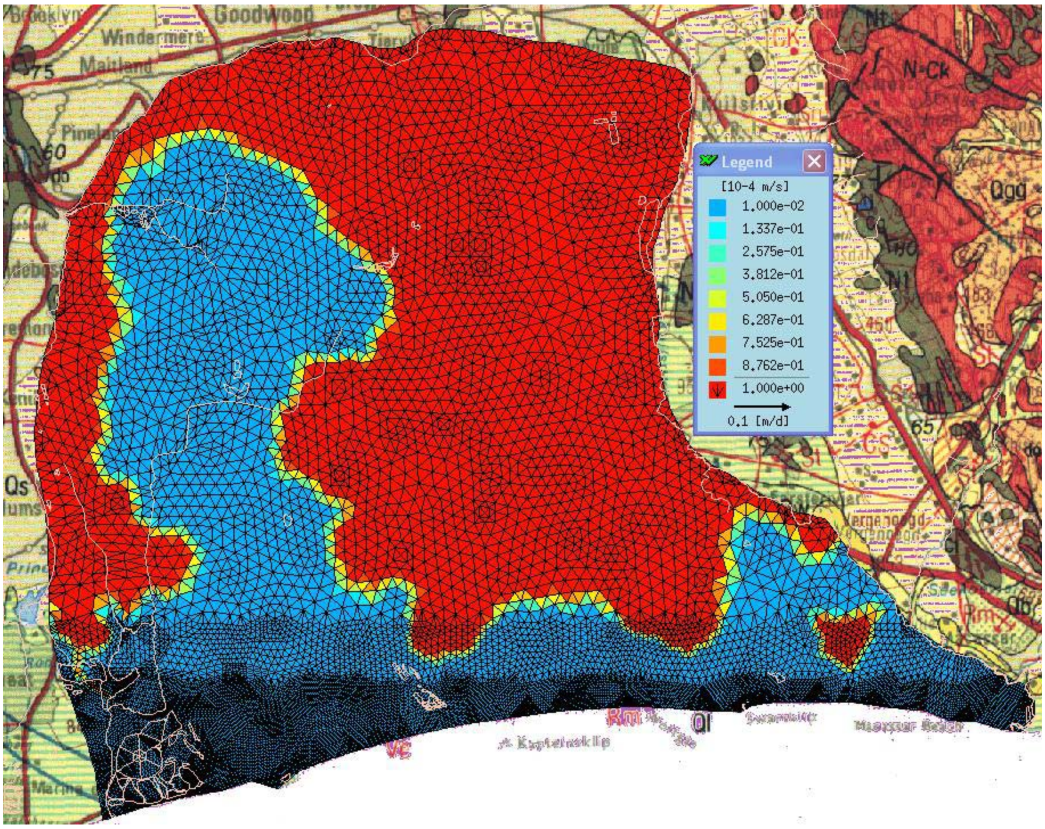


Figure 5-2 Final model hydraulic conductivity distribution for Layer 3 (Kx is shown)

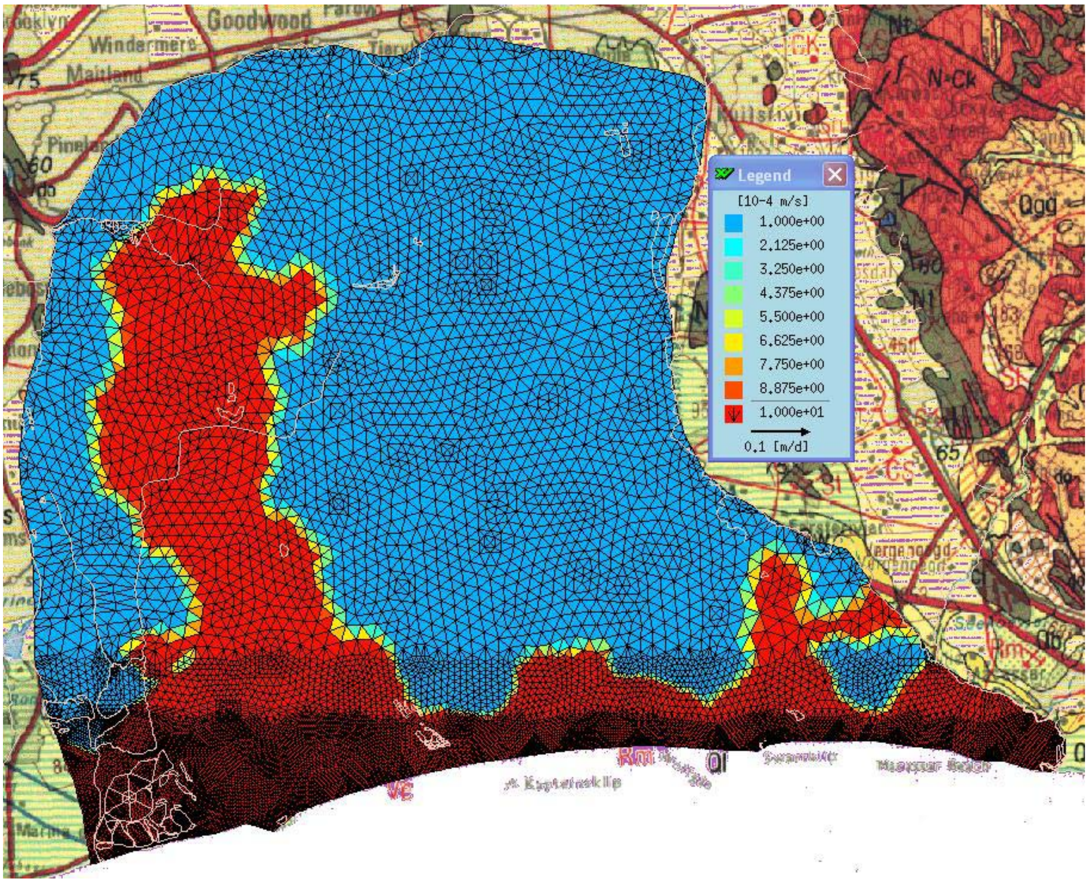


Figure 5-3 Final model hydraulic conductivity distribution for Layer 4 (Kx is shown)

5.4.2 River Transfer Rate

The transfer rate and hydraulic conductivity were varied simultaneously and independently to understand the coupling and independent effect of these parameters. Variations to the magnitude of the transfer rate in steady state simulations have significant effect on the flux of water in and out of the transfer nodes. The effect on the magnitude of the model water levels is less significant. But, although not impacting in the measurement of calibration error it does impact on the model results viz. the surface and groundwater interactions as well as the evaluation of the impacts of abstraction. Thus it is considered a calibration parameter and necessary to establish model sensitivity to variations in it. The transfer rate into and out of a river can be adjusted separately. The transfer rate can also be set at 0 in both directions to simulate a canalised river disconnected from the aquifer.

Initially an input value of 1 d^{-1} over natural sections of river channel was used which generated a broadly realistic flow regime. The Kuils River for example in the model had an effect on the groundwater system up to a distance of around 2 000 m away, but simulated dominant flow to the ocean in the south.

Given the understanding that there is often a greater resistance to flow into an aquifer from a river, than out of an aquifer (Rushton and Tomlinson, 1979) the transfer rate into the aquifer from the rivers was reduced by an order of magnitude compared to the transfer rate out of the aquifer into the rivers (**Table 5.1** below). This maintained the realistic flow regime with regard to the rivers, and improved the mass balance causing the rivers, on average across the model, to act as a sink to the aquifer.

Table 5-1 Transfer Rate Calibration (magnitude)

	Transfer Rate IN	**Transfer Rate OUT**
Initial	1 d^{-1}	1 d^{-1}
Final	0.1 d^{-1}	1 d^{-1}

5.4.3 Three model scenarios

The calibration of hydraulic conductivity and transfer rate described above generated simulated water levels which were consistently higher than ground level in the northwest and west whilst acceptable correspondence held for the rest of the aquifer (See **Figure 5-4**). Realistic ranges and heterogeneous distributions of hydraulic conductivity could not mitigate the flooding.

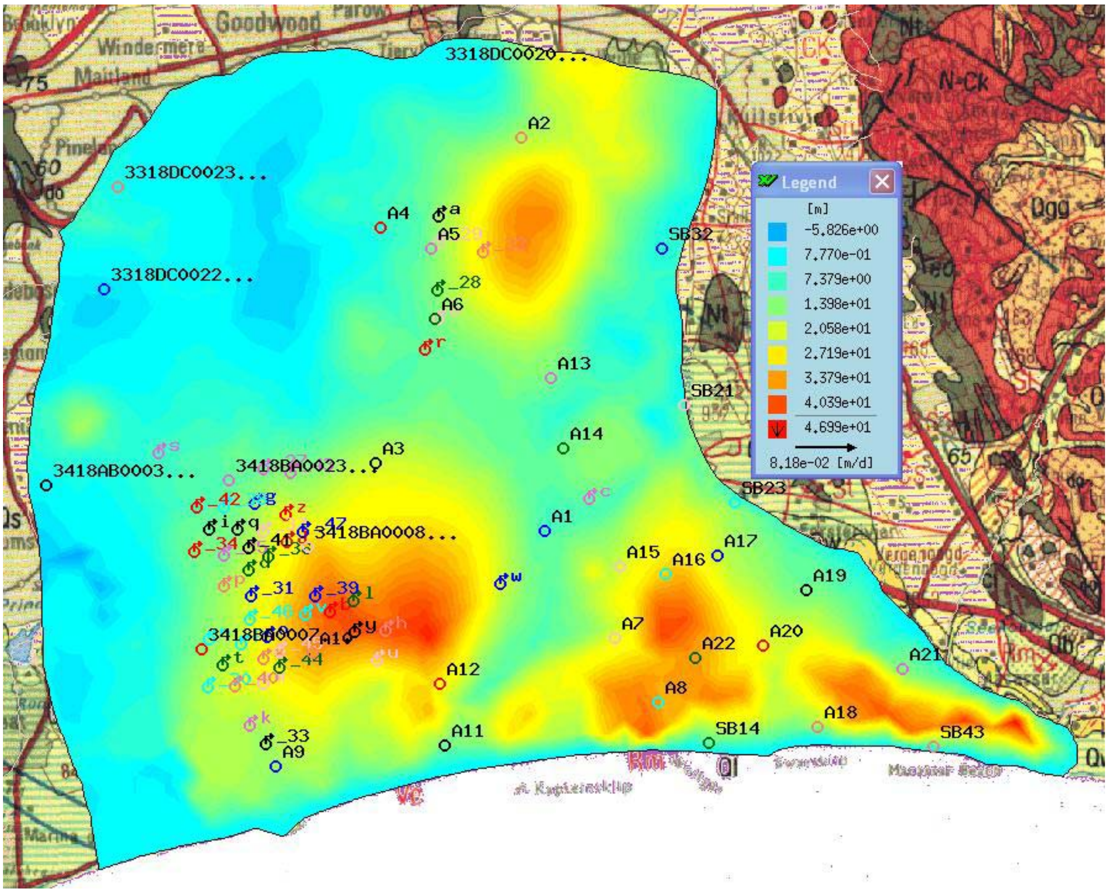


Figure 5-4 Modelled groundwater level compared to ground level, Scenario A

The Figure shows a plot of ground level minus water level (generated by Scenario A). High depth to water is evident beneath the high dunes along the coast, and other topographic highs. The dark blue shows the flooded areas.

Due to model uncertainty 2 additional scenarios were decided upon - the calibrated K of Scenario A was used as a base case. They aimed to improve the fit from the base case. A different recharge distribution (for example lower in the northeast where Scenario A is flooded) was not concluded as an alternate scenario because recharge changes affect the system regionally and caused point data away from the area under question to be affected for the worse. Results are presented for all three scenarios. The scenarios test:

- 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 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.

Scenario A

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

Scenario B

Canalised portions of the rivers in Scenario A are set as a zero transfer rate. Transfer nodes that lie on the edge of the model thus become no-flow boundaries. Those within the model simply have no effect on the simulation. With reference to **Figure 2-11**, the Kuils River, the centre of the Vyekraal River, central parts of the Little and Big Lotus rivers over the Zeekoevlei, the western boundary near Rondevlei, were initially the only functioning transfer boundaries.

The transfer rate at rivers near flooded areas was increased from zero to match that of non-canalised rivers (**Table 5.1**). The flooding in the west of the model indicated that the western boundary, or the transfer nodes around the Rondevlei were not removing enough water. Transfer nodes were added to the entire area of the Vleis on the surface of the model, so as to represent their area accurately (rather than a representation over slices 1 and 2). These changes reduced the flooding from Scenario A significantly and mitigated it in the southwest of the model. The maximum flooding reduced from 5.8 m to 0.5 m (**Table 5.2**). Canalised rivers that remain in the final model as zero transfer rate include the Elsieskraal River and the Big Lotus River (**Figure 5-5** below).

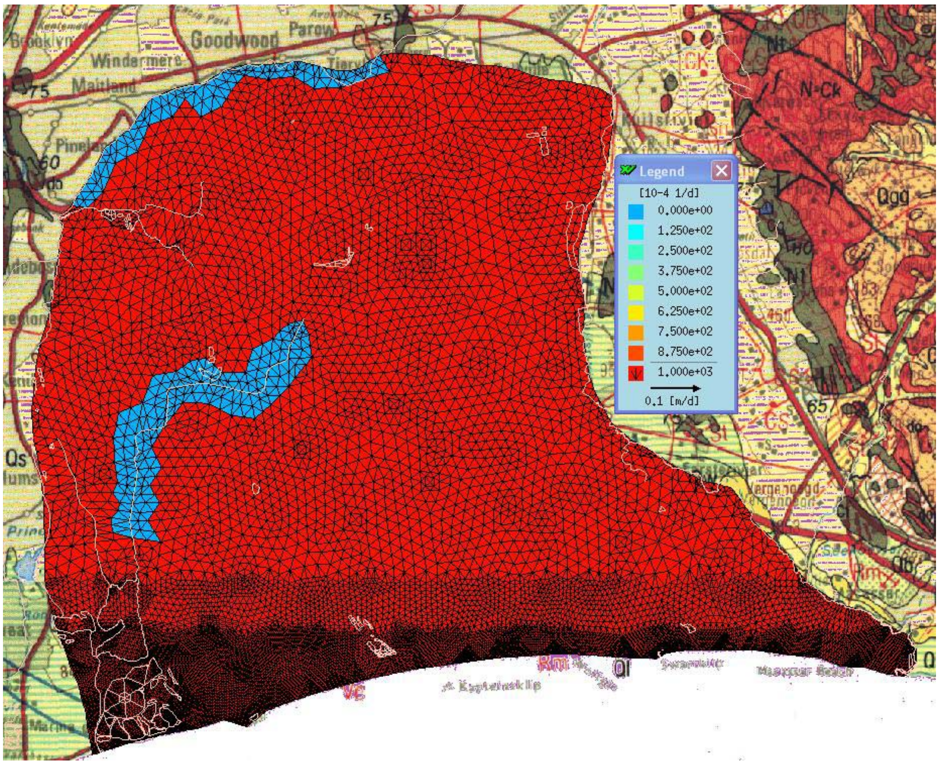


Figure 5-5 Transfer Rate Distribution (shown for Rate IN) Scenario B and C
Red indicates areas in the model where the transfer rate is set at the calibrated value of 0.1 d^{-1}. Blue nodes are those with zero transfer rate, and remain around transfer boundaries of only certain canalised sections of river.

Scenario B achieves the combination of low flooding (0.5 m), point data results that are within the 10% margin, and a mass balance which is realistic with the ocean as the major sink, and the rivers as a whole, acting as sinks to the aquifer.

Scenario C

The calibration data was amended to remove the topographic bias, however some points still appeared to represent highs or domes compared to the regional water table (**Figure 5-1**). Cross sections of the interpolated surface from the calibration data highlighted

- two data points represent groundwater highs compared to the surrounding water table – points 49.6 and 41.4 in the northeast (see **Figure 5-1**). The domes can only exist from local-scale causes such as leakage from sewerage ponds and irrigation ponds.
- the observed levels have a plateau of higher water levels in the northeast where the groundwater gradient is low, with a sharp change in gradient towards the south and west.

Comparison of cross sections in the same position for modelled and observed data show the local highs have not been replicated (**Figure 5-6**). The drop off from the plateau is replicated in the modelled water level results, however the drop off is smoothed. This is also likely to be a scale issue; the regional model smoothes effects which might be due to local features.

The model was run with water levels that pertain to local effects prescribed. Internal prescribed heads should be used to set a known head level, but not to govern a model solution, therefore various prescribed head scenarios were tested. Details of the various settings for the prescribed head models are described in **Table 5-3** below, with results of the key indicators. The relative effect of prescribed head scenarios on the solution is shown in **Table 5-4** below. This shows that when prescribing the water levels which represent local domes, the solution is affected to a large degree: the fluxes from the model to the ocean increases by ~50% as compared to Scenario B. When just the two prescribed heads at the edge of the plateau are set, the largest change is in the increase of flux from the model to rivers, by 15%. These two prescribed heads induce an additional source that represents 10% of the natural model input. The key indicators also suggest a better model fit for the 2 prescribed heads rather than including the groundwater mounds in the northeast. Although the point data is better for 3 or 4 heads, the flooding is significantly worse due to the raised water levels, and the range of the errors increases.

For the above reasons, the model with 2 prescribed heads is considered the best alternative to Scenario A, and is presented as alternative Scenario C in **Table 5-2**. As compared to Scenario B, the point data error is reduced from 6.5 m to 5.2, m however the maximum flooding is increased from 0.5 to 1.6 m. The shape of the groundwater gradient is greatly improved in this Scenario (**Figure 5-7**).

Table 5-2 Results of key indicators for various hydraulic conductivity scenarios, and showing results for final model scenarios

Bold indicates key indicators suggesting a good model run, italics indicate poor model runs.

Scenario	Description	Purpose of model run	Layer 1	Layer 2	Layer 3	Layer 4	Absolute water levels		Calibration point data		Mass Balance (m^3/day)		
							Max WL	Max WL>GL	Absolute error mean	Error range	To Ocean	Model to rivers	Rivers to model
1	Homogeneous, isotropic, Moderate K (10 m/d)	Baseline starting point	10 , 10 , 10	10 , 10 , 10	10 , 10 , 10	10 , 10 , 10	41.1	*8.3*	**6.1**	17.0	*9970*	*10900*	670
2	Homogeneous, isotropic, Low K (1m/d)	Basic test	1 , 1 , 1	1 , 1 , 1	1 , 1 , 1	1 , 1 , 1	*121.8*	*91*	*31.4*	*101.8*	*6420*	*13700*	*135*
3	Homogeneous, isotropic, High K (43 m/d)	Basic test	43 , 43 , 43	43 , 43 , 43	43 , 43 , 43	43 , 43 , 43	38.1	1.8	10.5	20.3	17600	*4730*	*6780*
4	As 3, with higher K basal layer (84 m/d)	Test effect of a high K basal layer	43 , 43 , 43	43 , 43 , 43	43 , 43 , 43	84 , 84 , 84	37.9	**0.9**	*11.0*	*20*	21200	*4600*	*5270*
5	Homogeneous, anisotropic (Kz< Kx and Ky by an order of magnitude)	Test effect of anisotropy	43 . 43 , 4	43 . 43 , 4	43 . 43 , 4	43 . 43 , 4	38.1	1.8	10.5	20.3	17700	**6700**	**3940**
6	As 4, Anisotropic (Kz< Kx and Ky by an order of magnitude)	Combining “best” of scenario 1-4, with anisotropy	43 , 43 , 4	43 , 43 , 4	43 , 43 , 4	84 , 84 , 8	38	**0.9**	*11.0*	*20.1*	21600	4600	5150
7	As 6, with lower K layer 2 (reduced to 10m/d)	Test effect of low K layer 2	43 , 43 , 4	10 , 10 , 1	43 , 43 , 4	84 , 84 , 8	38.3	**1**	*11.0*	*20.1*	20400	4100	4860
8	As 6, with lower K layer 3 (reduced to 10 m/d)	Test effect of low K layer 3	43 , 43 , 4	43 , 43 , 4	10 , 10 , 1	84 , 84 , 8	38.4	**1.1**	*11.0*	*20.1*	19000	3490	4620
9[2]	As 7, with basal layer high in palaeochannel only	Model improvement. Basal high K exists within palaeochannel only.	43 , 43 , 4	10 , 10 , 1	43 , 43 , 4	84 , 84 , 8	38.7	**1.3**	*11.0*	19.7	20400	4700	4590
10	As 8, with basal layer high in palaeochannel only	Model improvement. Basal high K exists within palaeochannel only.	43 , 43 , 4	43 , 43 , 4	10 , 10 , 1	84 , 84 , 8	38.6	**1.1**	9.2	16.4	18000	6470	4310

[2] Scenario 9 onwards tests a heterogeneous K distribution within layer 4. The K was set conditionally based on the elevation of the basement. Positions in layer 4 where the basement is <0 mamsl were assigned the high K shown in the table. Other positions within the layer were assigned the K of the layer above, layer 3.

Scenario	Description	Purpose of model run	Layer 1	Layer 2	Layer 3	Layer 4	Absolute water levels		Calibration point data		Mass Balance (m^3/day)		
							Max WL	**Max WL>GL**	**Absolute error mean**	**Error range**	**To Ocean**	**Model to rivers**	**Rivers to model**
11	As 9, with lower K for the low K layer (1 m/d)	Testing greater difference in K – reduce K at low K layer	43 , 43 , 4	1 , 1 , 0.1	43 , 43 , 4	84 , 84 , 8	39	**1.5**	10.5	19.7	20000	**4100**	**3990**
12	As 10, with lower K for the low K layer (1 m/d)	Testing greater difference in K – reduce K at low K layer	43 , 43 , 4	43 , 43 , 4	1 , 1 , 0.1	84 , 84 , 8	39	1.7	7.8	**14.3**	20100	**4560**	**4030**
13	As 12, with lower (10 m/d) K in the upper layers above the low K layer	Testing greater difference in K – reduce K at low K layer, with an alternative K arrangement	10 , 10 , 1	10 , 10 , 1	1 , 1 , 0.1	84 , 84 , 8	48.7	7.9	**5.1**	*18.3*	15000	7680	2890
14[3]	Similar to 13, with heterogeneous K distribution in layer 3 – to only confine over the positions of higher K.	Test effect of model improvement to a more realistic spatial K distribution in layer 3.	10 , 10 , 1	10 , 10 , 1	1 , 1 , 0.1	84 , 84 , 8	40.9	4.5	**6.5**	14.6	17200	**6400**	**2900**
15	As 12, with heterogeneous K distribution (of model 14) in layer 3.	Test effect of model improvement to a more realistic spatial K distribution in layer 3.	43 , 43 , 4	43 , 43 , 4	1 , 1 , 0.1	84 , 84 , 8	38.1	**1.4**	10.3	19.8	19000	5580	4500
Final model Scenario A	As 14, with lower K for low K layer	Test effect of model improvement to a more realistic spatial K distribution in layer 3.	10 , 10 , 1	10 , 10 , 1	0.1 , 0.1 , 0.01	84 , 84 , 8	43.1	5.8	**6.3**	**13.6**	**16000**	**6610**	**2320**
Final model Scenario B	K as final model Scenario A. Amendments made to the distribution of the transfer rate (Section 5.3.4).	Alternative Scenario	10 , 10 , 1	10 , 10 , 1	0.1 , 0.1 , 0.01	84 , 84 , 8	43.1	**0.5**	**6.5**	**13.5**	**17100**	**7500**	**4180**

[3] Scenario 14 onwards has low K within layer 3 in positions overlying the palaeochannel. The K was set conditionally based on the elevation of the basement. Positions in layer 3 where the basement is <3mamsl were assigned the high K shown in the table. Other positions within the layer were assigned the K of the layer above, layer 2.

Scenario	Description	Purpose of model run	Layer 1	Layer 2	Layer 3	Layer 4	Absolute water levels		Calibration point data		Mass Balance (m^3/day)		
							Max WL	Max WL>GL	Absolute error mean	Error range	To Ocean	Model to rivers	Rivers to model
Final model Scenario C	K as model Scenario A. Amendments made to the distribution of the transfer rate (Section 5.3.4). 2 Prescribed water levels	Alternative Scenario	10 , 10 , 1	10 , 10 , 1	0.1 , 0.1 , 0.01	84 , 84 , 8	42.13	**1.6**	**5.2**	**12.9**	**19200**	**8590**	**3960**

Table 5-3 Results of key indicators for variations on scenario C: Prescribed head scenarios

Scenario	Description	Purpose of model run	Absolute water levels		Calibration point data		Mass Balance (m^3/day)		
			Max water level	Max water level >ground level	Absolute error mean	Error range	To ocean	Model to rivers	Rivers to model
Model **(Scenario B)**	K as scenario A. Amendments made to the distribution of the transfer rate (Section 5.3.4).	Prescribed points reflecting groundwater mounds and those at edge of plateau	43.1	**0.5**	**6.5**	**13.5**	**17100**	**7500**	**4180**
Prescribed Heads Alternative 1	4 prescribed water levels NE: 49.6, 41.4 Centre: 34.4, 30.3	Prescribed 2 points reflecting groundwater mounds and 2 at edge of plateau	49.75	4.8	4.2	17.6	19700	11000	3890
Prescribed Heads Alternative 2	3 prescribed water levels NE: 41.4 Centre: 34.4, 30.3	Prescribed 1 point reflecting groundwater mounds and 2 at edge of plateau	42.81	3.96	4.5	13.6	19600	10000	3900
Prescribed Heads **(Scenario C)**	2 prescribed water levels Centre: 34.4, 30.3	Prescribed 2 points at edge of plateau	42.13	**1.6**	**5.2**	**12.9**	19200	8590	3960

Table 5-4 Comparison of modelled water balance for variations on Scenario C: Prescribed head scenarios

	Flux into Model (m^3/d)			Flux out of Model (m^3/d)			Balance (m^3/d)
	Recharge	Rivers	Internal fixed heads	Rivers	Ocean	Abstraction	
Natural system **Scenario B** ERROR Point 6.9 Range 14	+31 022 88% of the influx to the aquifer	+4 189 12% of the influx to the aquifer	0	-7 495 21% of the total aquifer discharge	-17 172 48% of the total aquifer discharge	-10 794 31% of the total aquifer discharge	-250 Model flux error is 6% of the smallest modelled flux, or 0.4% of the total flux modelled
Prescribed heads Alternative 1 ERROR Point 4.2 Range 18	+31 022 Set	+3 890 decrease of 7%	+6 610 represents 19% of natural influx to model	-11 000 increase of 47%	-19 700 increase of 15%	-10 794 Set	4.5 Model flux error is 0.1% of the smallest modelled flux, or 0.01% of the total flux modelled
Prescribed heads Alternative 2 ERROR Point 4.5 Range 14	+31 022 Set	+3 900 decrease of 7%	+5 460 represents 16% of natural influx to model	-10 000 increase of 33%	-19 600 increase of 14%	-10 794 Set	1.8 Model flux error is 0.05% of the smallest modelled flux, or 0.002% of the total flux modelled
Prescribed heads **Scenario C** ERROR Point 5.2 Range 13	+31 022 Set	+3 960 decrease of 5%	+3 600 represents 10% of natural influx to model	-8 590 increase of 15%	-19 200 increase of 12%	-10 794 Set	0.04 Model flux error is <0.01% of the smallest modelled flux

5.5 RESULTS

5.5.1 The Flow Regime

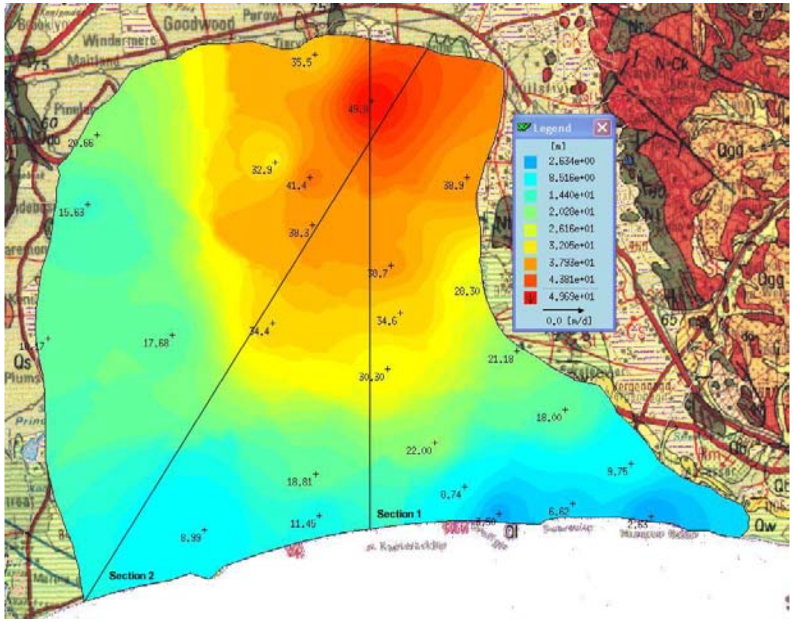
The model results, common to all scenarios, show that the basement topography and the high K basal layer has a big influence on the flow regime. The speed of groundwater flow increases on approach to the transition to the higher K zone within layer 4, and groundwater from the northeast flows towards the south and west, funnelled into the palaeochannel. The effect of the Vyekraal is clear as the groundwater speeds up closer to the transfer nodes. In these steady state simulations the effect of the low K layer is to reduce the speed of groundwater flow within the layer. The average difference in point data between the upper layers and the basal semi-confined layer is 0.2 m (the term semi-confined is used due to the non-complete spatial extent of the low K area). This indicates that even though the difference in hydraulic conductivity is almost 2 orders of magnitude 0.1 m/d to 84 m/d), the effect at the regional scale, over a steady state simulation, is a low degree of confinement.

The resulting modelled groundwater system is shown in the following figures for Scenario A, B and C. Section 1 is drawn from the northeast to the southwest of the model domain and Section 2 is drawn from the north to the south. Each section is shown in the following figures for every Scenario.

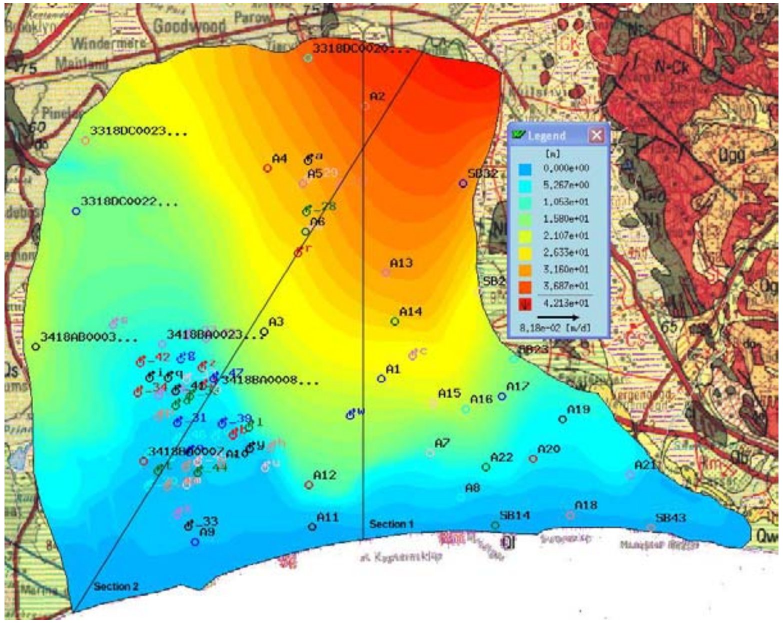
5.5.2 Scenario A results

Figure 5-6 Observed and modelled groundwater surface and cross section of groundwater surface for Scenario A

Observed:

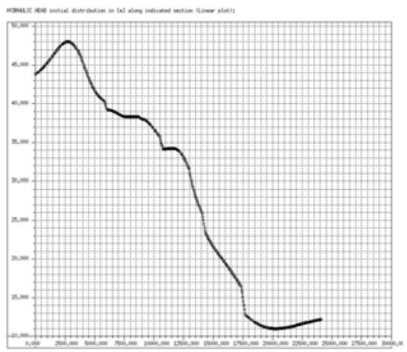


Modelled:

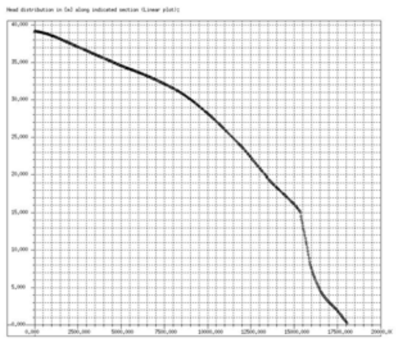


Section 1

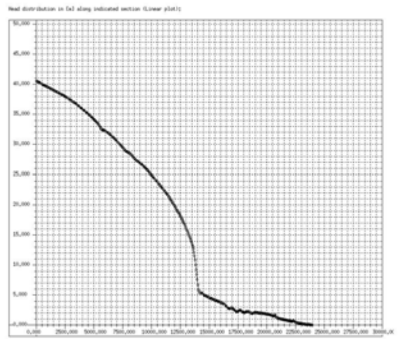
Section 2



Section 1



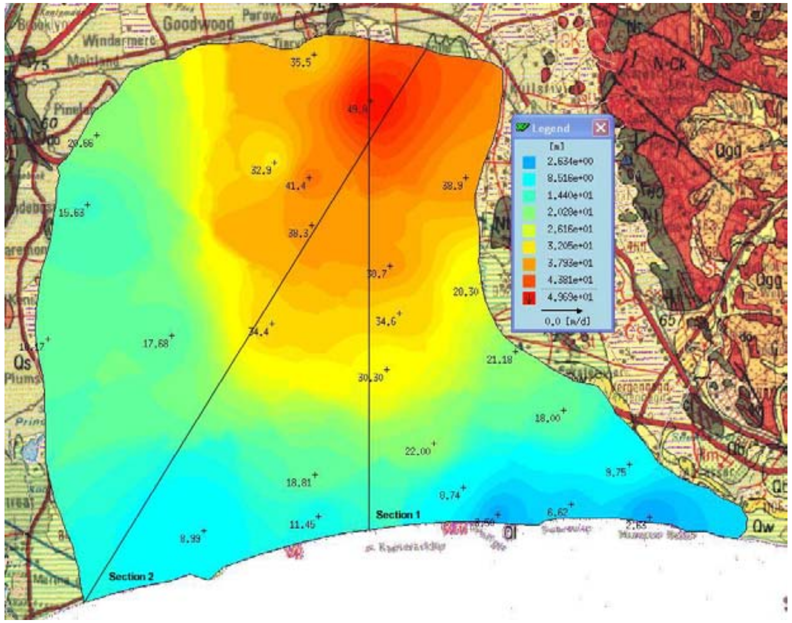
Section 2



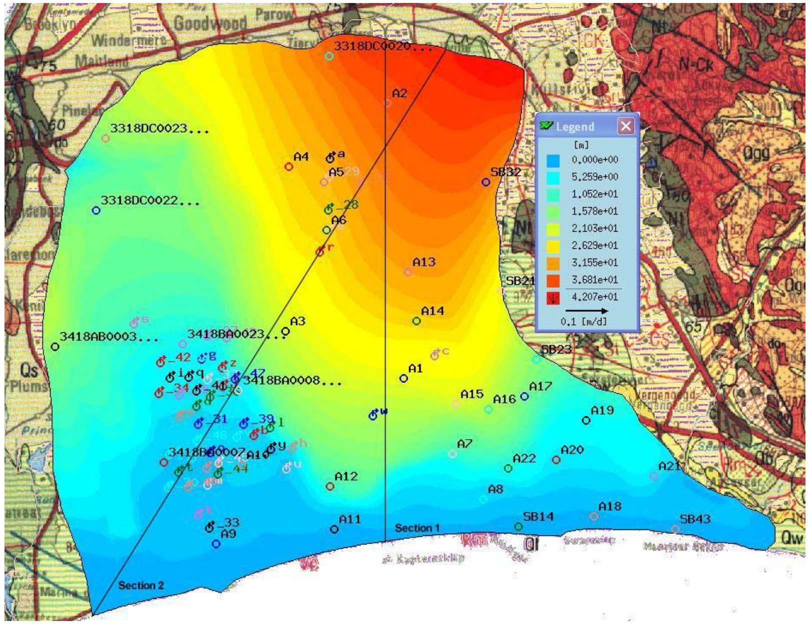
5.5.3 Scenario B results

Figure 5-7 Observed and modelled groundwater surface and cross section of groundwater surface for Scenario B

Observed:

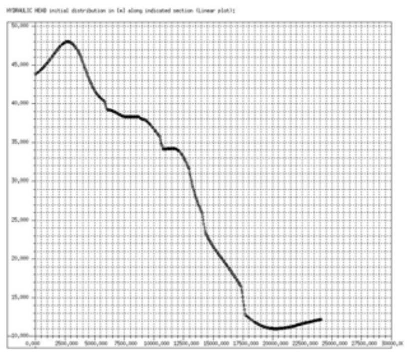


Modelled:

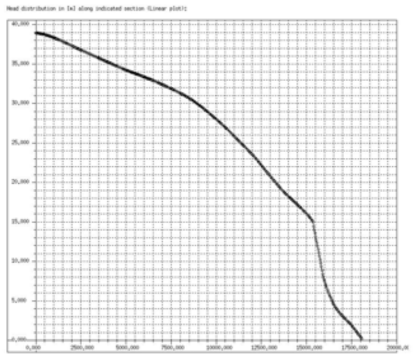


Section 1

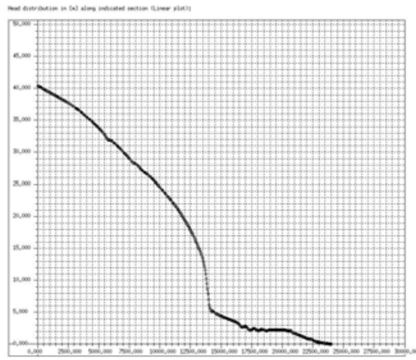
Section 2



Section 1



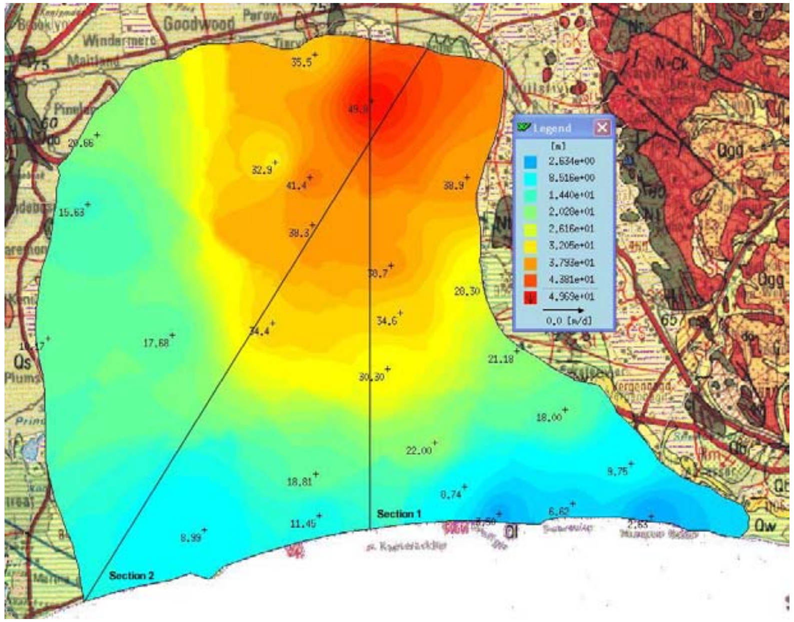
Section 2



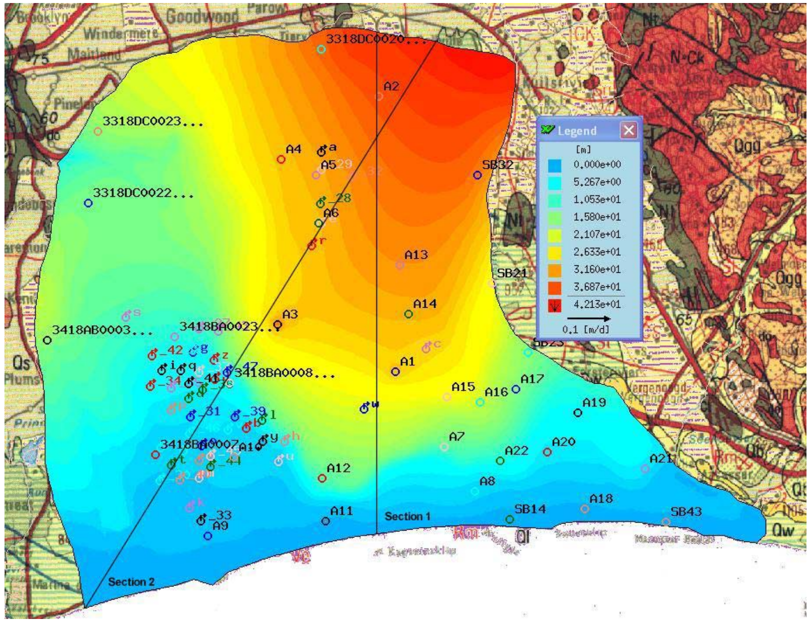
5.5.4 Scenario C results

Figure 5-8 Observed and modelled groundwater surface and cross section of groundwater surface for Scenario C

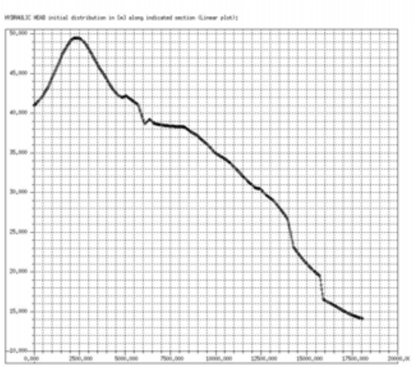
Observed:



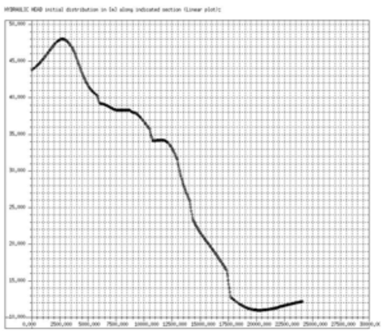
Modelled:



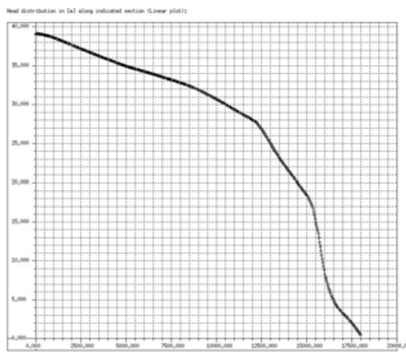
Section 1



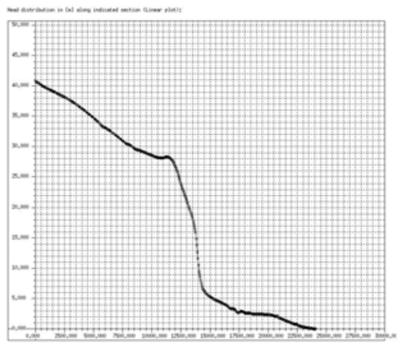
Section 2



Section 1



Section 2



5.5.5 Discussion

The regional groundwater flow is largely unaffected by the prescribed water level points, as the regional water table pattern remains similar, simply raised. At a small scale the effect of the fixed heads as small sources to the aquifer is clear in the contours immediately surrounding the fixed points.

The cross sections presented in **Figure 5-6**, **Figure 5-7** and **Figure 5-8** show that it has been possible to replicate the general features of the observed water level data but that the modelled water level is typically smoothed with respect to the observed water level data especially for Scenarios A and B. Prescribing 2 internal heads improves the accuracy of the cross sectional gradient.

With reference to Section 1, the observed data shows the groundwater mound generated by the high point in the northeast. The general trend without this peak is a water level with one gradient up to a distance of 8 km from the start point in the NE, a steeper gradient from 8 – 14 km, and then a steep drop in water levels until 0 at the coast. This trend is replicated in Scenarios A and B, but the modelled water levels are lower than observed around the change in gradient. The fit between observed and modelled is improved in Scenario C.

Section 2 shows similar trends. The effect of prescribing the heads on the gradients and on the absolute water levels north of the sudden decline in water levels is more significant for this section line. Without the prescribed heads the modelled water level drop off is gradual but with them the water level gradient is closer to the observed data.

The steep drop off in water levels shown in the cross sections is caused by the increase in transmissivity of the aquifer when moving into areas of deeper basement where the aquifer is significantly thicker. **Figure 5-9** shows a profile of the basement topography along Section 2. It does not require a high K in the palaeochnnels to reproduce the drop off. Models with a homogeneous Kx, Ky and Kz also replicated the drop in water levels. The high K in the palaeochannels is required to generate the required dominant flow to the ocean and reduce flooding in the northwest. Models with a lower K in all layers showed a much steeper gradient than observed for measured water levels after the drop off. A very low K generates a mound in water levels below the drop in gradient.

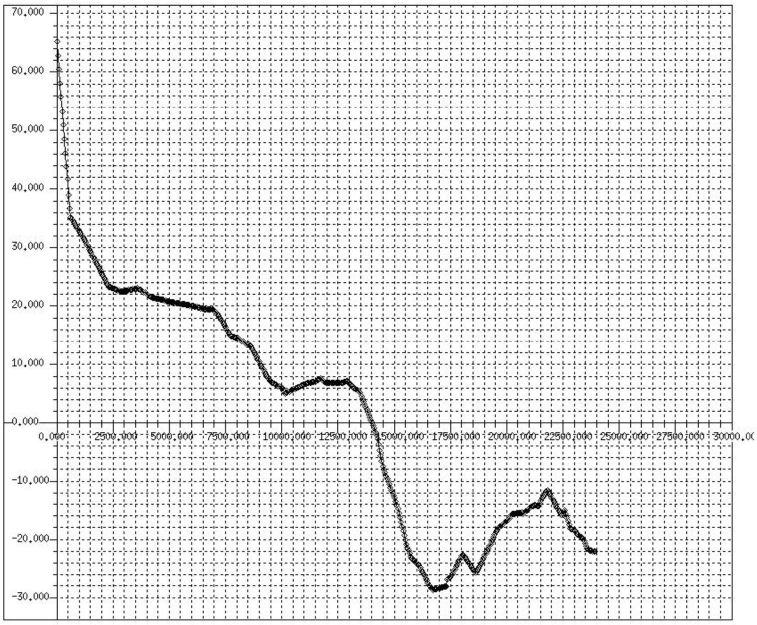


Figure 5-9 Basement topography section 2
(Vertical axis: topography, m, Horizontal axis: distance along section, m.)

5.5.6 Parameter calibration summary

The final model scenarios have a relatively low average point data error, however the range of the point data errors is high. The scatter plot in **Figure 5-10** shows the deviance from the 1:1 line. Typically modelled groundwater levels are lower than observed, however higher than topography in the northwest. A summary of the parameter calibration is shown in **Table 5-5**.

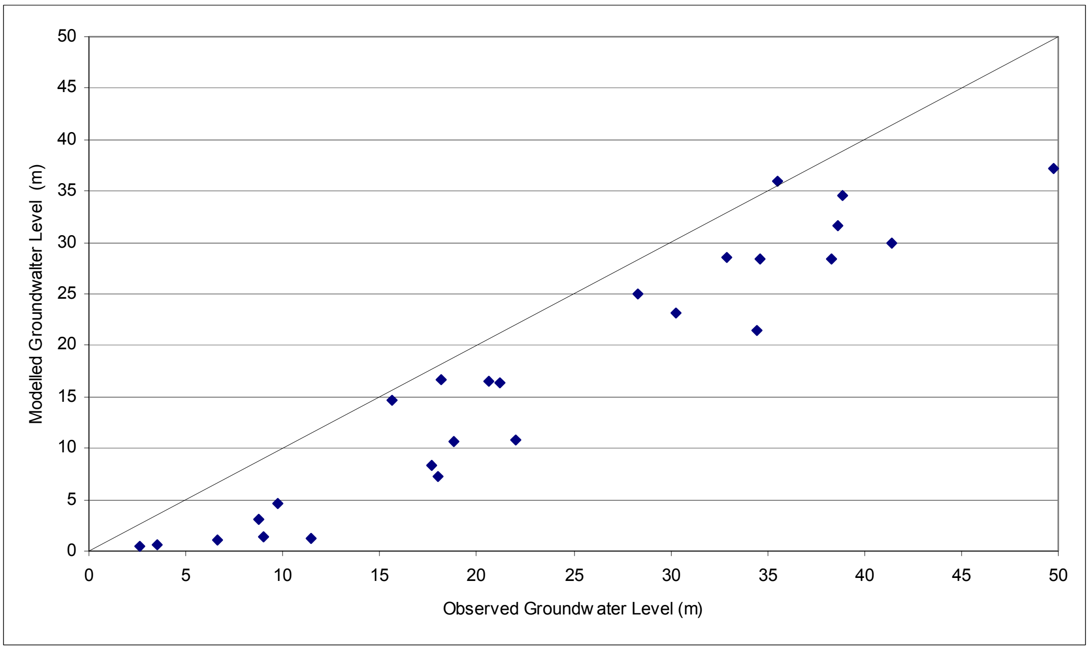


Figure 5-10 Scatter plot of modelled verses observed groundwater levels (shown for Scenario B)

Table 5-5 Summary of Parameter Calibration

Parameter	Initial input	Calibrated value
Aquifer Geometry	3 layered	4 layered
River stages	1-3 m Below real groundwater levels	Average 4.5 m below topography
Transfer rate	1 d^{-1}	*Magnitude*: Rate in = 0.1 d^{-1} Rate out = 1 d^{-1} *Distribution*: Scenario A: Canalised reaches are 0 d^{-1} Scenario B and C: Only certain canalised reached remain at 0 d^{-1}
Hydraulic conductivity	Homogeneous isotropic 10 m/d	Layers 1 and 2 10 m/d, low K layer 3 only in positions over the palaeochannel at 0.1 m/d and a high K basal layer at 84 m/d. Anisotropic with Kz = 0.1 Kx and Kx = Ky

5.6 SURFACE WATER- GROUNDWATER INTERACTIONS

The fluxes of water in the whole model domain are shown in **Table 5-5** above. **Table 5-6** below shows the fluxes to surface water for each of the quaternary catchments, for each model Scenario. The variation in behaviour between catchments and river reaches is high, for example the Kuils River on average gains water from the aquifer, where as the Lotus River and the vleis act as recharge boundaries in the model.

Table 5-6 Modelled Fluxes to Surface Water 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 57% of flux to SW from aquifer	-3783
		B	0	-4094 55% of flux to SW from aquifer	-4090 -
		C	0	-4843 56% of flux to SW from aquifer	-4843
G22D	Lotus, Rondevlei and Zeekoevlei	A	1572 68% of flux from SW to aquifer	-1074 16% of flux to SW from aquifer	+498
		B	+3441 82% of flux from SW across aquifer	-1700 23% of flux to SW from aquifer	+1741 -
		C	+3232 82% of flux from SW across aquifer	-1833 21% of flux to SW from aquifer	+1399
G22E	Kuils	A	+743 32% of flux from SW across aquifer	-1755 27% of flux to SW from aquifer	-1012
		B	+743 18% of flux from SW across aquifer	-1720 23% of flux to SW from aquifer	-977 -
		c	+729 18% of flux from SW across aquifer	-1958 22% of flux to SW from aquifer	-1229

The Surface water-Groundwater fluxes are significantly different between Scenario A and B, which is to be expected due to the differences in the underlying assumption. Comparing Scenario B and C shows that the flow regime is largely unaffected by the prescribed heads in Scenario C; the water level are higher thus the net fluxes to / from surface water are affected (by up to 15% **Table 5-4**) however the proportional contributions from different parts of the model to this flux remains unchanged. The largest difference is noted between Scenario A and B, where there is a 70% difference in the net flux to surface water for G22D.

5.7 THE IMPACT OF CURRENT ABSTRACTION

The wells in the model appear to have a considerable effect on the aquifer. The abstracted volume is a significant proportion of the recharge (35%). The model was used to investigate the effect of the abstraction, by removing all wells and analysing the difference in these results.

The resulting water level without abstraction is shown in **Figure 5-11** below for Scenario B (compare **Figure 5-7**). Regionally, the water levels are not greatly affected. The average difference between groundwater levels at the observation points for this Scenario is 0.9 m. Most points are less than 0.5 m difference, and some only 0.01 m. Those observation points over the palaeochannel where there is the largest cluster of abstractions, show a maximum of 4 m difference between model runs (Scenario B).

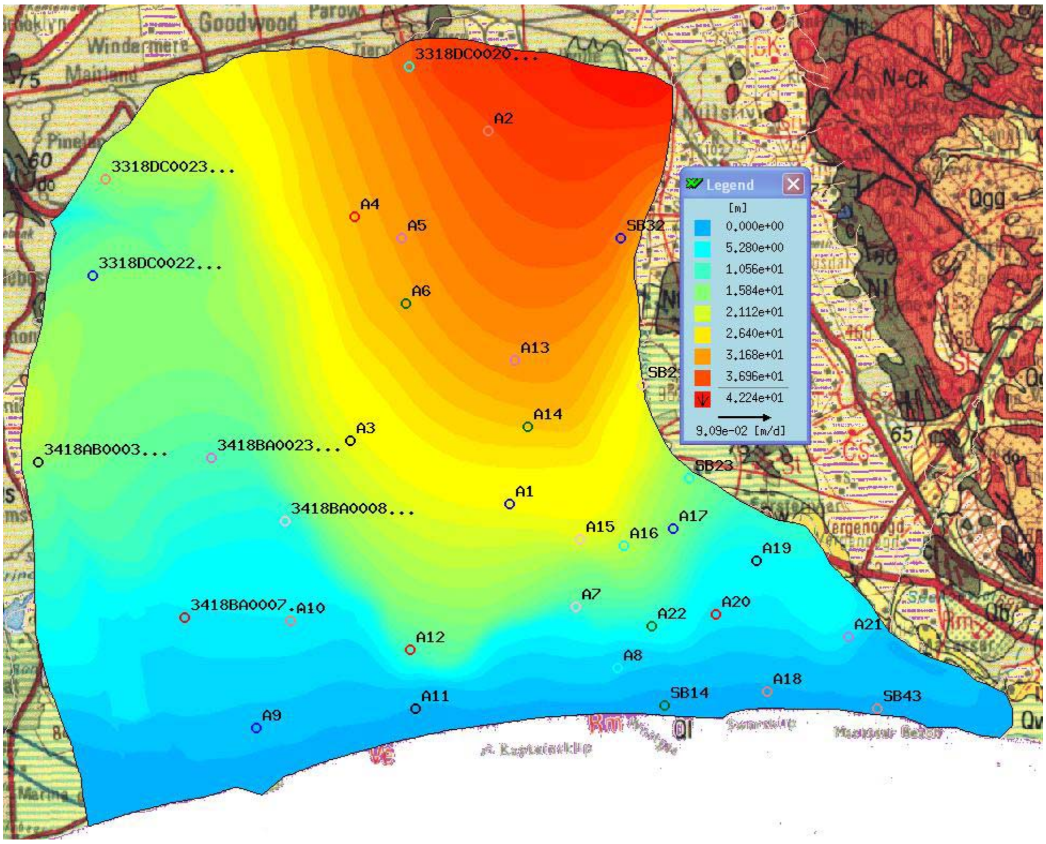


Figure 5-11 Modelled Groundwater Levels for Zero Abstraction: Contours of groundwater head, Layer 1, Scenario B

The affect of the current abstraction on the mass balance is shown in **Table 5-7** below for all scenarios. Abstracting the current ~10 000 m^3/d from the aquifer, reduces the quantity of outflow that would under no abstraction flow to the ocean, by ~30% (similar for all scenarios). The fluxes to the rivers are also reduced. Under a natural system, because the groundwater levels are higher, the outflow to the rivers is higher, by ~24% (similar for all scenarios). The effect within specific catchments is shown in **Table 5-8**. The largest effect is within G22D which is where the most abstraction points are located. The effect of the different assumptions in the model scenarios is clear when analysing the numbers per catchment: within G22D there is a difference of ~200% in net flux to surface water between abstraction and no abstraction models. This increases to ~4000% for Scenario B.

Table 5-7 Mass Balance Fluxes: Zero Abstraction

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 Error (m^3/d)
		Recharge	Rivers	Rivers	Ocean	Abstraction	
A	Abstraction	+31 022	+2 320	-6 610	-16 000	-10 794	-225
	Zero Abstraction	+31 022	+1 735	-8 830	-23 900	0	-1
	Difference caused by abstraction	-	Increase of 33%	Decrease of 25%	Decrease of 33%	-	-
B	Abstraction	+31 022	+4 189	-7 495	-17 172	-10 794	-250
	Zero Abstraction	+31 022	+3 067	-9 897	-24 200	0	-8
	Difference caused by abstraction	-	Increase of 37%	Decrease of 24%	Decrease of 29%	-	-
C	Abstraction	+31 022	+3 960	-8 590	-19 200	-10 794	0
	Zero Abstraction	+31 022	-2 890	-11 000	-26 000	0	0
	Difference caused by abstraction	-	Increase of 37%	Decrease of 22%	Decrease of 26%	-	-

Table 5-8 Fluxes to Surface Water per Quaternary: Zero Abstraction

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

Quaternary Catchment	Rivers	Scenario		Flux into Model (m^3/d)	Flux out of Model (m^3/d)	Net flux to SW
G22C	Elsieskraal and Vyekraal	A	Abstraction	0	-3 780	-3 780
			Zero Abstraction	0	-5 320	-5 320
			Difference	0	Decrease of 29%	Decrease of 29%
		B	Abstraction	0	-4 094	-4 090
			Zero Abstraction	0	-5 682	-5 682
			Difference	0	Decrease of 28%	Decrease of 28%
		C	Abstraction	0	-4 840	-4 840
			Zero Abstraction	0	-6 400	-6 400
			Difference	0	Decrease of 24%	Decrease of 24%
G22D	Lotus, Rondevlei and Zeekoevlei	A	Abstraction	+1 570	-1 070	+500
			Zero Abstraction	+1 000	-1 540	-540
			Difference	Increase of 57%	Decrease of 31%	Decrease of 192%
		B	Abstraction	+3 440	-1 700	+1 740
			Zero Abstraction	+2 328	-2 287	+41
			Difference	Increase of 48%	Decrease of 26%	Decrease of 4146%
		C	Abstraction	+3 230	-1 830	1 400
			Zero Abstraction	+2 170	-2 450	-280
			Difference	Increase of 48%	Decrease of 25%	Decrease of 600%
G22E	Kuils	A	Abstraction	+743	-1 755	-1 012
			Zero Abstraction	+740	-1 970	-1 230

Quaternary Catchment	Rivers	Scenario		Flux into Model (m^3/d)	Flux out of Model (m^3/d)	Net flux to SW
			Difference	Increase of 0.4%	Decrease of 10%	Decrease of 18%
		B	Abstraction	+743	-1 720	-977
			Zero Abstraction	+738	-1 903	-1 165
			Difference	Increase by 0.6%	Decrease by 9%	Decrease by 16%
		C	Abstraction	730	-1 960	-1 230
			Zero Abstraction	730	-2 170	-1 440
			Difference	0	Decrease of 10%	Decrease of 15%

5.8 MODEL CONFIDENCE

This revision of the conceptual model, where certain canalised stretches are active rivers may represent various conceptual possibilities, or a combination of the following:

- The canalised stretches are not impermeable, but cracks and engineered gaps in the concrete channel lining allow connectivity to the aquifer below. However this raises the question of why this would not apply to all canalised rivers. The numerical model did not require the Big Lotus and the Elsieskraal rivers to be permeable.
- Additional non-mapped drainage systems, or storm water systems, may exist in these areas, either draining the aquifer or capturing surface water and rainwater reducing the effective recharge. Gerber (1980) documents that “a considerable but underestimated amount of natural precipitation is intercepted and conveyed to the Vyekraal and Lotus as urban runoff”.

Demographic controls on the aquifer are not replicated in this model, which generally shows the natural groundwater table not accounting for a large number of potential anthropomorphic effects. It is interesting to note that the same model effect was noted by Gerber (1980). His model was calibrated by imposing discharge wells to abstract the excess water in the northwest. However there is no evidence for increased abstraction here, and this model change was not based on any physically real concept.

It is noted that the canals mapped for the Vyekraal River by Ninham Shand (shown in **Figure 2-11**) extend farther east than those mapped by the Chief Directorate Surveys and Mapping (CDSM). The modelled transfer boundaries extend only as far east as those mapped by the CDSM. It is suggested that if the transfer boundaries were extended to the east, this remaining 0.5 m flooding would be mitigated, without a significant effect on the point calibration data in the area. In order to calibrate the model to a greater degree of confidence it would be necessary to obtain data on the surface water features in the northwest, including positions and extent additional of surface drainage features, and typical flow rates. Further calibration in the northwest would also benefit from more point data in the area.

The results show that the basal gravels are significant in discharging large quantities of water to the ocean. This is an alternate interpretation to other workers who did not place significance on the lower layers of the aquifer, and modelled a homogeneous aquifer. Previous workers may not have included the basal gravels because they modelled a smaller area, away from the palaeochannels.

On average the calibrated river stages are 4.5 m below topography. However in the northwest where the modelled groundwater levels were consistently above ground level, river stages were reduced further. This was carried out in order to reduce water levels to the calibration points in the northwest which sit at 1.5 m below topography, and in order to generate the general pattern as shown by the calibration data. The final river stages in the northwest are a maximum of 10 m below topography, and mostly around ~5 m below topography. Although this seems unreasonable, it is potentially a justified model calibration because the lowered stage may actually account for additional flux from a wider river than 1 m. Also the stages are 10 m below the topography at the transfer node. This topography is averaged over a 20 m DEM, and then applied to a node. The transfer boundary node may not be in the exact position of the river, thus the topography may be higher than that at the actual river position.

The calibration process delivered a best result of 0.5 m flooding (Scenario B), which remained in the northwest, with a very similar (ground level – modelled groundwater level) distribution pattern to **Figure 5-4**. The pattern of modelled groundwater flow suggests that groundwater flows out from the northeast to the northwest and cannot escape easily enough.

The steep rise in the interpolated basement surface in the northeast of the area was noted as a possible cause of the "flooding" in the northwest of the model (**Figure 2-7**). It could be possible that the contours remain at around 30-40 mamsl in the Cape Flats aquifer and rise suddenly to 90 mamsl beyond the model boundary. The basement elevation was reduced in the northeast to a maximum of ~30 mamsl, effectively pushing the 30 mamsl contour north to lie along the model boundary. This change in basement elevation reduced the flooding in the northwest only very slightly: from 0.53 to 0.49 m (the test run used Scenario B). The flow regime as a whole (ie the direction of the flow from the northeast) remained the same but the average model error for point data increased slightly to 7.8 m.

The modelled flow regime and this test in which a small area of basement was reduced, indicates that the model solution is highly sensitive to the basement topography.

6. TRANSIENT MODEL

6.1 TRANSIENT MODEL ASSUMPTIONS

In addition to the assumptions that underlie the steady state model, the transient model assumes:

- River stages are constant throughout the year. Therefore the river boundary conditions are the same as for the steady state model. There is no data available to support any other representation of the river stages.
- The specific storativity (Ss) is 10^{-5}
- Recharge is constant within one month. Recharge varies monthly with rainfall.
- Recharge has a homogeneous distribution.
- The BRBS method for recharge calculation also applies to monthly data.
- Rain during the driest 6-month period (October to March inclusive) does not enter the aquifer as recharge. It is lost to evaporation / evapotranspiration. The calibrated steady state recharge value is assumed net effective and processes such as evapotranspiration affect how this recharge is distributed throughout the year.
- All abstractions (whether registered for agriculture or industry) occur during a 7-month dry period of September to March (inclusive). The abstraction boundary conditions described in section 4.8 above are used, however the wells are only pumped in these months and pump rates are adjusted to represent the same total abstraction.

6.2 REQUIRED INPUT DATA

The input data for the transient model is shown in the table below. The data source and whether the parameter is varied in transient modelling or fixed is noted. Input data different to that used in the steady state model (described in chapter 4) is highlighted in bold, and described further below.

Table 6-1 Transient model input Parameters

Model Input Parameter		Source	Type
Topography		20 m DEM	Fixed (same as Steady state)
Bedrock topography		Literature and NGDB	Fixed (same as Steady state)
Layering		Based on geology and numerical requirements	Fixed (same as Steady state)
Current Abstraction		WARMS	Fixed (same as Steady state)
Transfer Rate		Steady State calibrated values	Fixed
River Stages		Steady State calibrated values	Fixed
Hydraulic conductivity		Steady State calibrated values	Fixed
Recharge		BRBS method modified	Fixed for steady state calibration, varied in scenario testing
Storage	**Specific Yield Sy**	1st approx from typical literature values	Transient calibration
	Specific Storativity Ss	Assumption based on literature	Fixed
Porosity		Typical literature values	Dictated by storage, therefore calibrated through storage calibration

6.3 RECHARGE DATA

Monthly rainfall data is generated by re-calculation of modelled mean monthly values, as given by agrohydrology data sets (Schultze et al, 1997), to sum to the annual modelled rainfall (section 2.2c, **Figure 2-2**). Monthly recharge was calculated by applying a modified version of the BRBS method to monthly rainfall data (**Table 6-2**).

The monthly data was averaged over the Cape Flats Aquifer model area, and the recharge calculated from the averaged monthly data, generating a monthly homogeneous recharge. This is due to software limitations that do not easily allow time varying conditions to be applied to a complex heterogeneous property distribution. The effect on the typical variation in water levels is considered negligible.

As with the steady state model, the rainfall peak in the northeast was removed by recalculating the monthly recharge by a factor to ensure the sum of the monthly recharge equated to the steady state recharge used. As with the steady state model, the factor for geology is not applied.

Table 6-2 Monthly Recharge Calculation

Annual rainfall	Monthly rain	Monthly Rain	% applied
0-300 mm	(0-300) / 12	0-25 mm	3
300-600 mm	(300-600) / 12	25-50 mm	6
600-900 mm	(600-900) / 12	50-75 mm	9
900-1200 mm	(900-1200) / 12	75-100 mm	12
1200-1500 mm	(1200-1500) / 12	100-125 mm	15
1500-1800 mm	(1500-1800) / 12	125-15 mm	18
1800-2100 mm	(1800-2100) / 12	150-175 mm	21

The rainfall is low during summer and evapotranspiration is significantly higher. The rainfall in the summer months is assumed to be lost to evapotranspiration. 82% of rainfall occurs within a 6-month period of April – September. It is assumed that only rainfall during this period contributes to recharge. But, the model is calibrated to the steady state recharge which is assumed net effective. The recharge input to the transient model over 1 year must therefore equal that used in the steady state model. The recharge as calculated by the BRBS method occurring in the summer, is summed and spread over the winter months. The rainfall and recharge as calculated from the monthly-modified BRBS method, and the model input recharge is shown in **Figure 6-1** below.

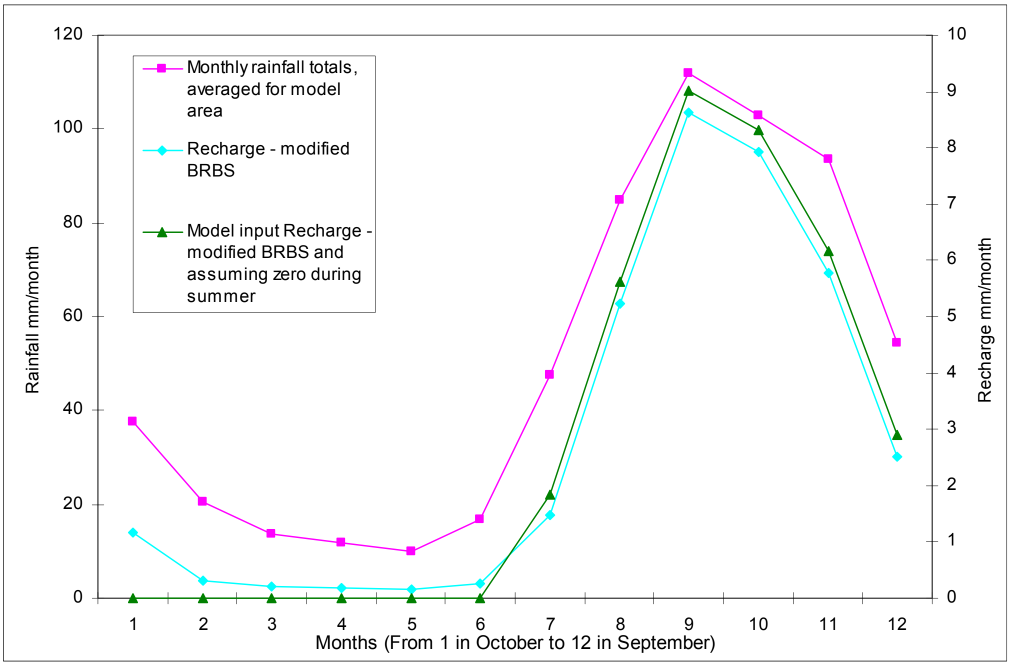


Figure 6-1 Monthly rainfall and recharge

The steady state recharge was significantly lower than estimates provided by other methods (**Table 2-6**). Various recharge values are compared in **Table 6-3** . Values are given as mm for easy comparison. The recharge input to the model here is very low in comparison to other values, hence it is assumed that they are effective recharge values. The transient recharge value accounts fully for water lost to evapotranspiration.

Table 6-3 Comparison of Recharge Values used in the Model with Other Sources

Area	BRBS Method (DWAF 2002)		GRA II Method (DWAF 2006)		GRDM Method (DWAF 2006)		Local Studies: Vandoolaghe (1989)		Local Studies: Gerber (1980)		Modified BRBS method (no 1.5 factor applied)		Model input (Modified BRBS)	
	Mm3	*mm*	*Mm3*	*mm*	*Mm3*	*mm*	*Mm3*	*mm*	*Mm3*	*mm*	*Mm3*	*mm*	*Mm3*	*mm*
G22C	19.62	90.35	14.73	67.84	15.30	70.45	25-58	115 - 267	61.50	283.16	-	-	-	-
G22D	24.37	112.13	22.78	104.79	24.00	110.41	30-71	138 - 327	N/A	N/A	-	-	-	-
G22E	12.00	55.05	10.60	48.63	13.50	61.91	23-53	105 - 243	N/A	N/A	-	-	-	-
G22H	13.90	93.10	9.66	64.68	14.70	98.47	N/A	N/A	N/A	N/A	-	-	-	-
Model	-	-	-	-	-	-	-	-	-	-	12.24	36.6	11.32	33.8

6.4 STORAGE DATA

The storage parameters are the main calibration parameters in transient simulations. Typical values for storage parameters and estimates for the Cape Flats sand aquifer, based on modelling results, are shown in the table below.

Table 6-4 Available Storage values from Cape Flat Aquifer studies and typical literature values

Source	Specific Yield (Sy) [-]	Specific Storativity Ss [m^{-1}]	Method	Applicability
Previous studies				
Shand (1987)	-	0.35-1.16 x10 $^{-5}$ m^{-1}	Transient 2D modelling of pump test results.	Modelling result. Geological scenario applicable to areas outside of palaeochannel at a small scale (a sand aquifer confined by the Langebaan Limestone). Not applicable for regional scale of Cape Flats.
Gerber (1980)	0.05 - 0.12	-	Steady state 2D modelling at regional scale	Potentially over-simplified conceptual model
Vandooleaghe (1989)	1) 0.1 - 0.4 2) 0.02 – 0.05 3) 0.007 – 0.01	-	Modelling result of Timmerman (1987)	Modelling result of Timmerman (1987) Layer 1 Witzand and Langebaan Layer 2 Springfontyn and Vaarswater Layer 3 clayey Vaarswater
Weaver (1994)	0.2	-	A literature-based assumption	Useful as guide only.
Wessels and Greeff (1980)	0.1 – 0.15		Estimated from geology.	Lab drainage tests carried out indicating estimates may be too low.
Typical Literature				
Driscoll (1986)	Total range: 0.005 - 0.3	-		Sand 0.1 - 0.3 Gravel 0.15 - 0.3 Limestone 0.005 – 0.05 Clay 0.01 – 0.1

It is assumed that the specific storage (Ss) is 10-5 or1E-5 and it is not varied. The specific yield (Sy) will be varied in calibration and the values in the table above used as a guide to test the reality of the result.

6.5 CALIBRATION DATA AND STANDARD

A total of 68 of the NGDB boreholes in the total study area (larger than the numerical model area) have monitoring data (i.e. >1 measurement at least). Out of these 22 were selected those which had at least >1 years worth of data. These points are distributed across the area and some are clustered to show the variations within one area. The water level at each borehole was analysed to ensure local pumping effects did not dominate the record and that the record reflected typical annual variation. Five (5) records were discarded in this process leaving a total of 17. Clustered boreholes were grouped generating 7 points with monitoring data. Some of these 7 points are based on one borehole, some on a number of boreholes (**Table 6-4**). The distribution of the 7 points is shown in **Figure 6-2** . There is no available time series data for the northwest of the model area, or for the southeast.

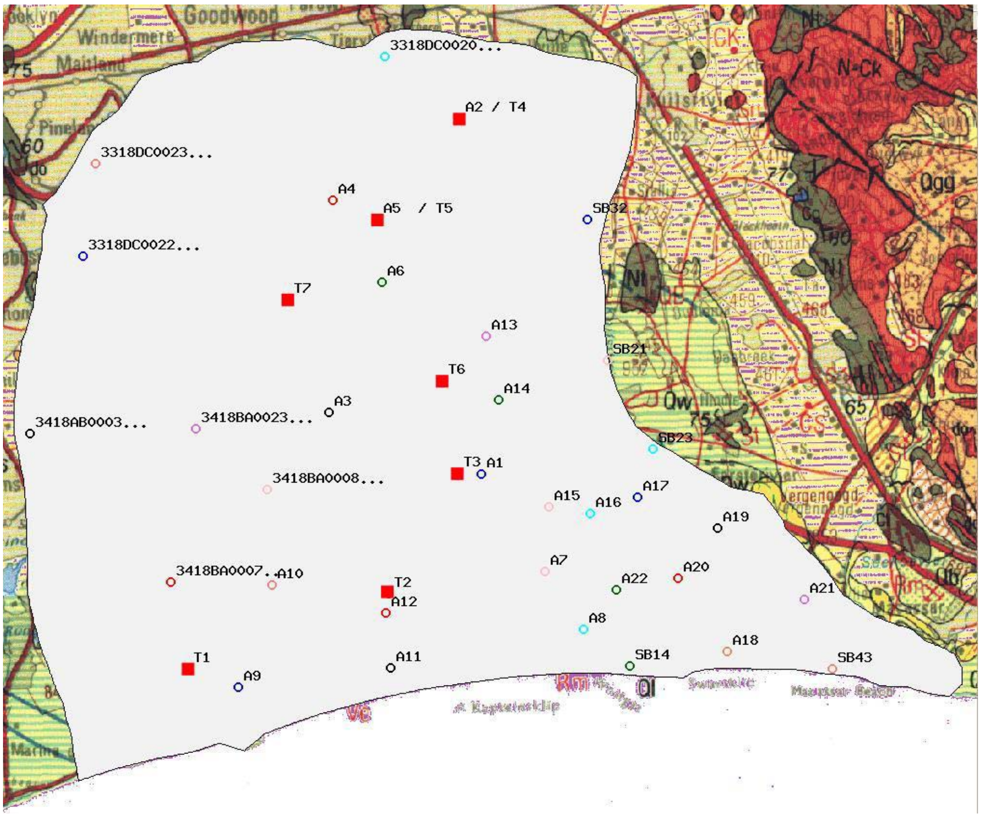


Figure 6-2 Distribution of all observation points.
Transient observation points are labelled T1 to T7 and marked with red squares.

The magnitude of the variations in water level were similar between boreholes but for clustered boreholes the absolute water levels were highly variable (shown for area T1 in **Figure 6-3**). This is likely due to local effects like boreholes situated in topographic lows, not recognised when converting the reported depth to water to mamsl (effects of local topography discussed in section 5.3). The steady state simulation is concerned with absolute water levels. The transient simulation is focussed on generating the observed variations in water level and the variation in water levels at closely positioned boreholes is not important at this scale.

Figure 6-3 indicates water level peaks occurring in September, at the end of the rainy season The observed data is affected by long-term variations in rainfall and irregular years of rainfall, for example at 1825 days; a year of higher rainfall generates a larger recharge pulse which follows a previous year of lower recharge. With the averaged rainfall data used here it is not possible to recreate these features in the observed water level data (which is why the actual year of measurement is not important and all records are reset to number of days since October). Typical 1-year variations are of more relevance to calibration.

The water levels for each borehole record were analysed to manually determine a typical year's variation. Years with an anomalous or abnormally high or low annual variation were discarded, and from the remaining years a mean average annual variation was calculated. This is shown as lines in **Figure 6-3**. For transient observation points that are made up of more than one borehole record, an average was taken from each of the individual borehole averages. This is the average variation at the observations points T1-7.

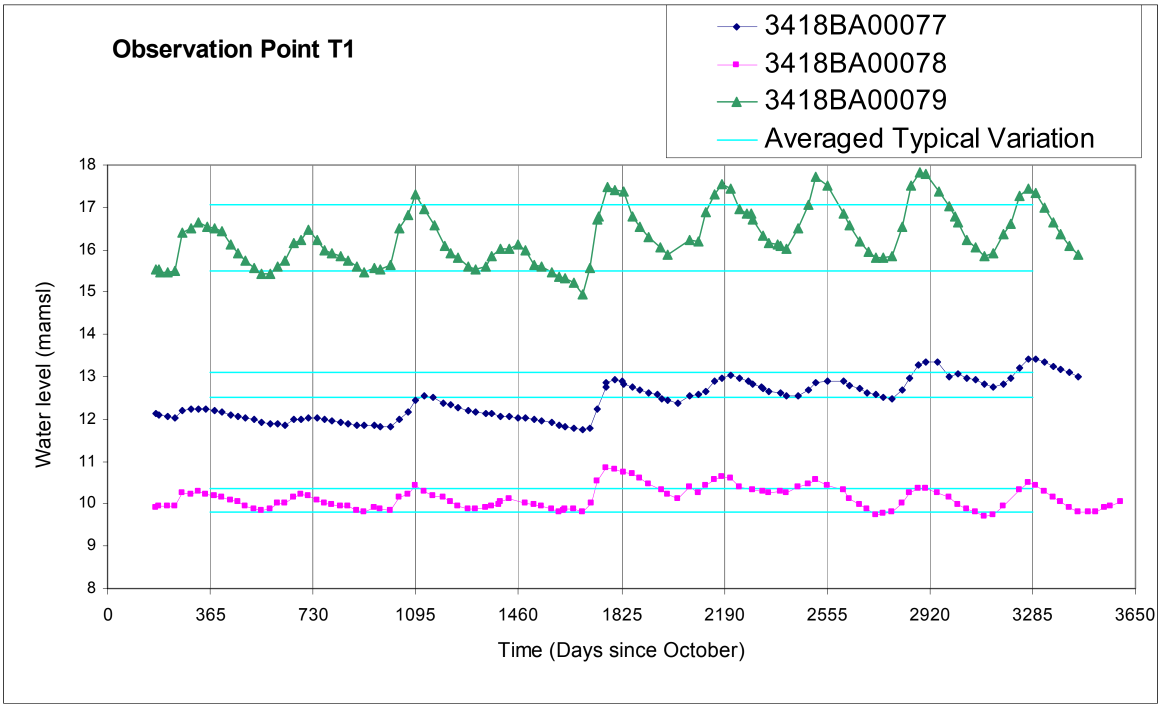


Figure 6-3 Observed Water level variations at observation point T1

The magnitude of the averaged typical annual variation for each record is indicated by the blue bar. An average of the 3 variations is used as the point value for T1.

The typical variation determined for each observation point was also averaged to provide a single typical variation. The typical variation was used as a quantitative indication of the goodness of fit of a model run. The shape of the variations was used as a qualitative guide to the fit of the model run. The date series for the observations data was amended to be from time zero onwards, with time zero representing the start of October.

The observed data shows that typical annual variations average ~0.75 m. A summary of the calibration point data is shown in the table below. There is no noticeable correlation between the typical variations and the position of the boreholes with respect to basement, geology, and proximity to surface water.

Table 6-5 Observed annual water level variations at observation points

[1]*Water level record at the borehole for T3 has only 2 full years of recorded data; therefore it is not possible to select a typical year. In this case an average was taken between the annual variation of the 2 recorded years.*

[2]*Water level records for the 3 boreholes at T4 have only 1 year of recorded data, therefore it is not possible to select a typical year. In this case an average was taken between the boreholes of the single annual variation.*

Calibration point	Number of Boreholes	Maximum annual range (m)	Minimum annual range (m)	Typical annual variation (m)
T1	3	2.55	0.36	0.90
T2	7	1.22	0.65	0.79
T3	1	1.5	0.49	1.00[1]
T4	3	0.56	0.36	0.46[2]
T5	1	1.61	0.31	0.93
T6	1	1.29	0.11	0.47
T7	1	1.11	0.52	0.71
			AVERAGE typical variation	0.75

The error reported for model runs (**Table 6-5**) is the observed typical variation minus the modelled. The calibration standard set was to attain the observed variation to within 80-120% of its value:

- (Modelled variation / Observed typical variation) x 100 =80-100%
- This equates to an averaged modelled annual variation of 0.62 – 0.924.

6.6 MODEL RESULTS

6.6.1 Parameter Calibration: Storage

In the steady state modelling, 3 alternative scenarios were presented. Scenario C is used for the transient modelling, as it is the most numerically stable scenario.

The procedure for the calibration of the storage was to test the model response with the upper and lower bounds of the parameters shown in **Table 6-4** above, and from these results, narrow down the range of possible applicable values. The results of the calibration are shown in **Table 6-6** below (the table is presented in increasing order of Sy, not the order modelled).

Table 6-6 Results for Calibration of Sy

Error refers to (Observed typical variation – modelled), averaged over the 7 points. Range refers to the maximum – minimum error within the 7 points.

Sy	Average 1 yr fluctuation	Error (m)	Range (m)	Modelled variation % of observed
0.01	1.85	-1.10	1.22	265
0.02	0.93	-0.19	0.70	131
0.03	**0.65**	**0.10**	**0.53**	**91**
0.04	0.47	0.28	0.52	65
0.06	0.33	0.42	0.62	46

The range of Specific Yield which generates a match to the observed average typical variation of 0.75 m lies between 0.02 and 0.03 (2-3%), and is closer to 0.03. This is a fairly narrow range of potential values (previous workers have given ranges over orders of magnitude, **Table 6-4**). A value of 3% is concluded and is used in the transient model scenario testing.

The magnitude of the modelled 1-year typical variation varies for each observation point across the model area, shown in **Table 6-7**. The distribution of the modelled variations, as is true for the observation data (mentioned above), does not correlate with areas of high or low basement, positions of steep or shallow changes in basement, areas of higher of lower K, or proximity to surface water or to abstractions. There is a weak correlation between the modelled and observed data points however, as indicated in **Figure 6-4**. The model replicates abstraction and surface waters in a very spatially averaged way and therefore the likely control on the magnitude of seasonal fluctuations is something more intrinsic to the system. For example basement elevation, slope in basement, or more simply the position in the aquifer – i.e. downstream or towards the north where the aquifer is thin and closer to a hydraulic boundary.

Table 6-7 Point results for model run with Sy 0.03

Observation point	Observed annual variation (m)	Modelled annual variation (m)	Error (m)	Modelled variation % of observed
T1	0.90	0.81	0.07	92
T2	0.79	0.60	0.19	76
T3	1.00	0.55	0.45	55
T4	0.46	0.52	-0.06	113
T5	0.93	0.95	-0.02	102
T6	0.47	0.56	-0.09	118
T7	0.71	0.56	0.15	79
Average	0.75	0.65	0.10	91

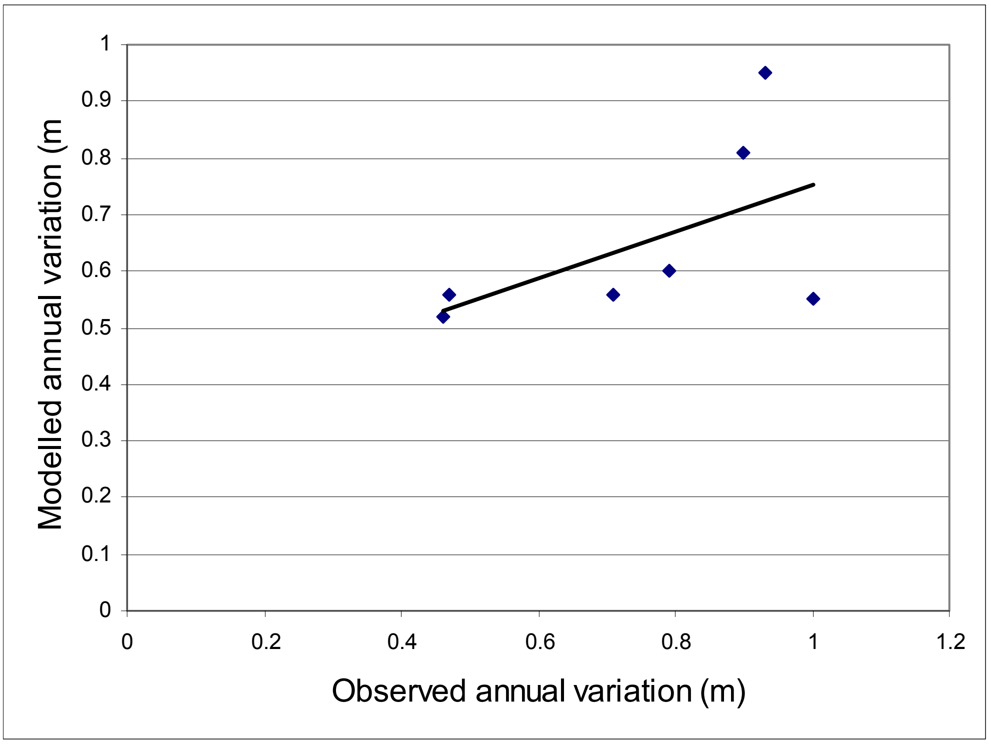


Figure 6-4 Correlation between observed and modelled 1-year water level range (with Sy 0.03)

The modelled Sy is low compared to typical Sy for sands and is closer to that of clay (**Table 6-4** Driscoll, 1986). It is suggested that the modelled Sy is representing an equivalent Sy and is reflecting the effect of the clay layers on the retention of water and the speed of release of water.

6.6.2 Modelled Water Level Variations

Sy affects the magnitude of the variation. The lower the Sy the higher the variation in water levels (clear in **Table 6-6**). The effect is greater at smaller Sy i.e. there is larger difference in the magnitude of the water level variation between model runs with Sy of 0.02 to 0.03, than there is between a Sy of 0.03 to 0.04 (**Figure 6-5**).

The timing of the water level peak, and the steepness of the peak is controlled by the recharge curve. The modelled water levels begin to rise slightly before the observed levels, although the peak is at approximately the same time (**Figure 6-3** and **Figure 6-5**). This suggests that the assumption that a certain linear percentage of the rainfall always enters the aquifer between April and September is an oversimplification. It is possible that the rains that occur in April re-wet the unsaturated zone and are stored here. The aquifer may show a pulsed recharge response where this stored unsaturated zone water forms recharge when additional rains occur to push a pulse of water in front.

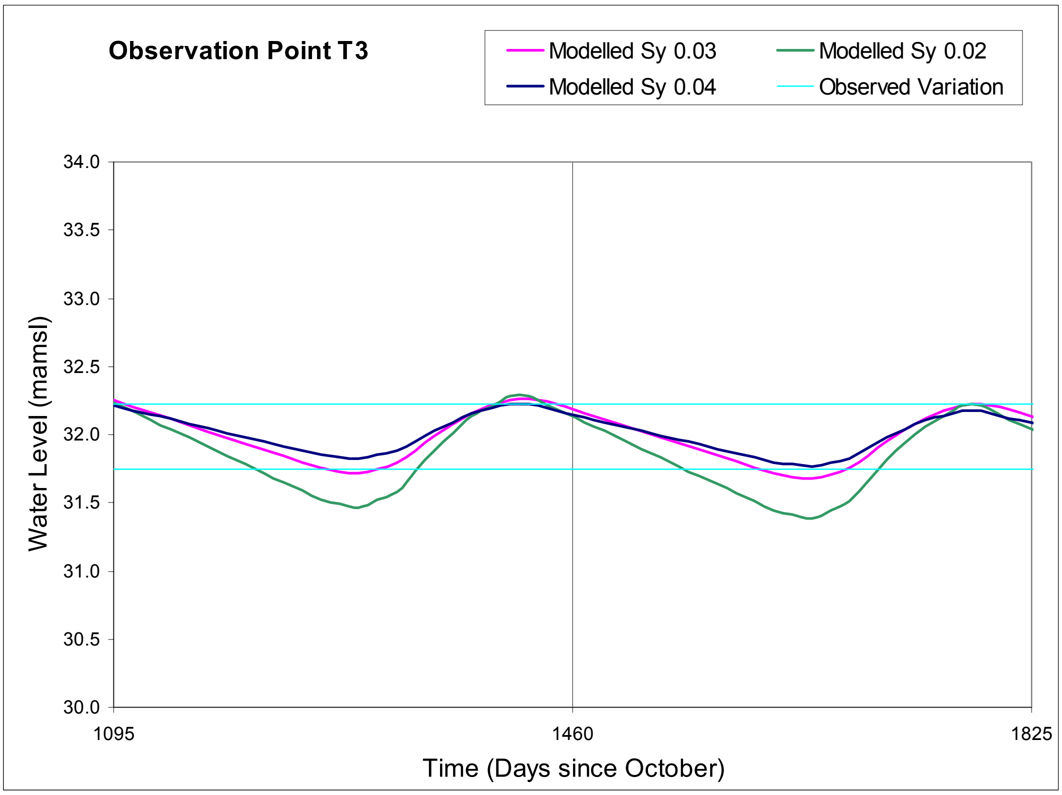


Figure 6-5 Modelled water levels for T3

6.6.3 Mass Balance

The modelled fluxes for monthly periods are shown in **Table 6-8** and **Figure 6-6** below. The winter recharge flux is accommodated by an increase in flux to the ocean and an increase in the net flux to surface water. As water levels rise in response to recharge, the difference between the head in the river and that in the aquifer increases, and so the flux to surface water increases. The balance equates to the sum of the monthly fluxes and reflects the state of the storage in the aquifer (i.e. positive indicates an increase in storage or water levels). During winter (months 7-12) more water enters the aquifer than discharges, generating a positive balance. During the summer months, more water discharges than enters the aquifer. **Table**

6-8 shows that over a year a negative imbalance remains – i.e. water is being lost from the system, at a rate equivalent to 6% of the influx. It may be that the abstraction is causing the system to be in quasi- steady state, with falling water levels until the system re equilibrates with the pumping.

Table 6-8 Monthly fluxes

Month	Month	Influx m³/d			Discharge m³/d			Net GW-SW m³/d	Balance m³/d
		Recharge	Prescribed Heads	SW to GW	Ocean	Abstraction	GW to SW		
1	October	0	3 029	3 882	-20 266	-18 538	-11 494	-7 612	-43 387
2	November	0	3 096	4 222	-18 427	-18 538	-10 603	-6 381	-40 250
3	December	0	3 163	4 461	-17 265	-18 538	-10 010	-5 548	-38 188
4	January	0	3 219	4 642	-16 241	-18 538	-9 547	-4 905	-36 465
5	February	0	3 272	4 803	-15 372	-18 538	-9 156	-4 353	-34 990
6	March	0	3 323	4 958	-14 628	-18 538	-8 824	-3 866	-33 709
7	April	20 557	3 338	4 584	-16 911	0	-8 946	-4 362	2 622
8	May	62 662	3 292	3 996	-19 075	0	-10 018	-6 021	40 858
9	June	100 540	3 178	3 389	-21 732	0	-11 811	-8 421	73 565
10	July	92 757	3 065	3 078	-23 864	0	-13 046	-9 968	61 989
11	August	68 635	2 990	3 042	-24 732	0	-13 363	-10 321	36 572
12	September	32 284	2 993	3 215	-24 458	-18 538	-12 666	-9 451	-17 171
Annual (Mm³/a)		11.32	1.14	1.45	-6.99	-3.89	-3.88	-2.44	-0.86
Total (Mm³/a)		Influx		13.91	Discharge		-14.77	N/A	-0.86
Contribution to total influx / discharge, as percentage		81	8	10	47	26	26	16[2]	6[1]

Positive fluxes are influxes to the aquifer, negative fluxes are aquifer discharges.

[1]*Given as percentage of total influx*

[2]*Given as percentage of total discharge*

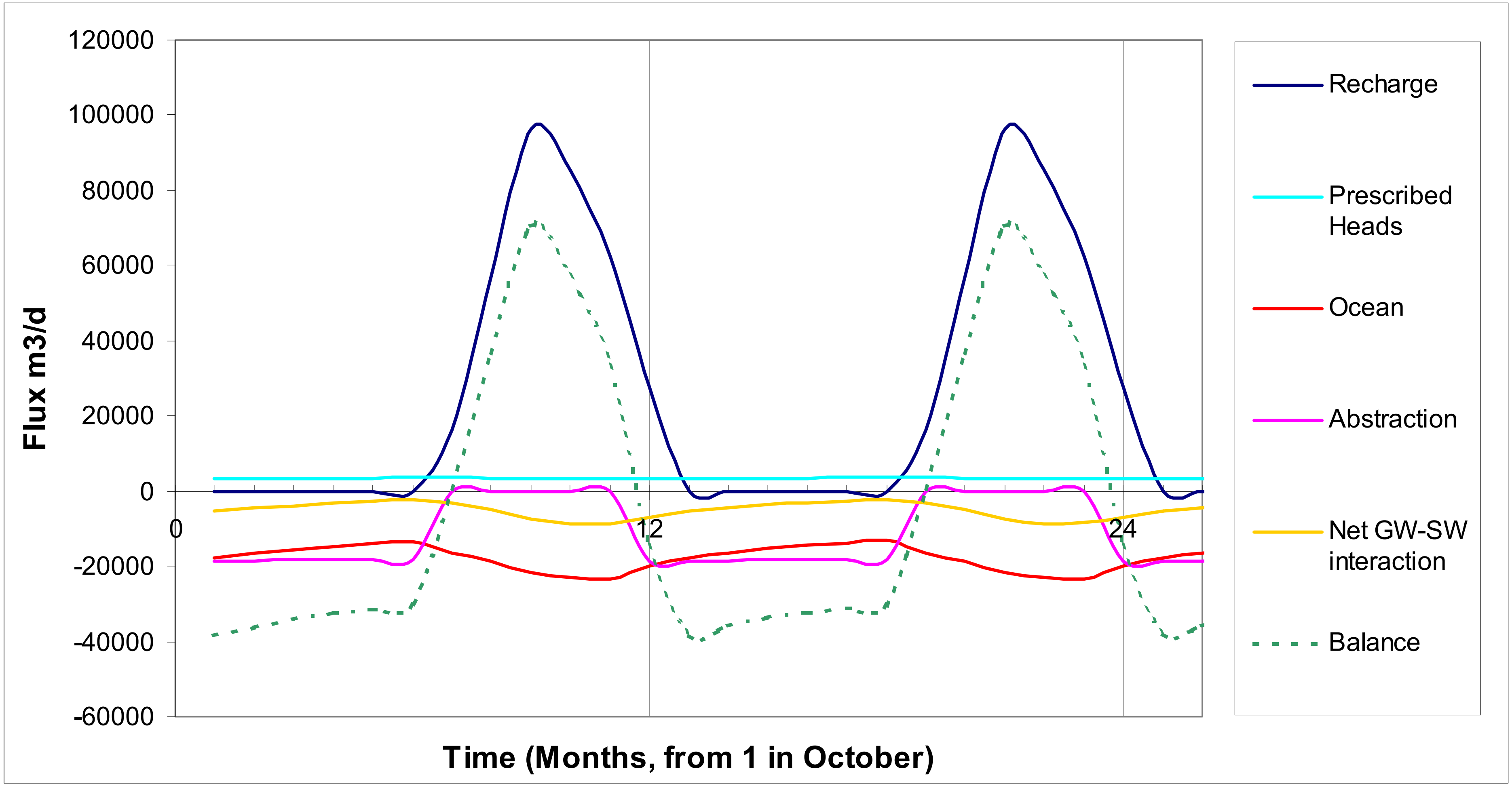


Figure 6-6 Monthly fluxes

Positive fluxes are influxes to the aquifer, negative fluxes are aquifer discharges.

6.6.4 Groundwater-Surface water interaction

Table 6-9 Monthly Groundwater-Surface water fluxes per Quaternary (monthly fluxes given as m^3/d within that month)
(SW indicates surface water)

Month	G22C (Elsieskraal and Vyekraal)			G22D (Lotus, Rondevlei, Zeekoevlei)			G22E (Kuils)		
	Flux into Model	Flux out of Model	Net	Flux into Model	Flux out of Model	Net	Flux into Model	Flux out of Model	Net
October	0	-6 207 54% of flux to SW from aquifer	-6 207	3 261 84% of flux from SW to aquifer	-1 149 14% of flux to SW from aquifer	2111	621 16% of flux to SW from aquifer	-3 793 33% of flux to SW from aquifer	-3 172
November	0	-5 832 55% of flux to SW from aquifer	-5 832	3 546 84% of flux from SW to aquifer	-1 060 12% of flux to SW from aquifer	2486	675 16% of flux to SW from aquifer	-3 499 33% of flux to SW from aquifer	-2 824
December	0	-5 605 56% of flux to SW from aquifer	-5 605	3 792 85% of flux from SW to aquifer	-1 101 12% of flux to SW from aquifer	2691	669 15% of flux to SW from aquifer	-3 303 33% of flux to SW from aquifer	-2 634
January	0	-5 346 56% of flux to SW from aquifer	-5 346	3 945 85% of flux from SW to aquifer	-1 527 11% of flux to SW from aquifer	2418	696 15% of flux to SW from aquifer	-3 150 33% of flux to SW from aquifer	-2 454

Month	G22C (Elsieskraal and Vyekraal)			G22D (Lotus, Rondevlei, Zeekoevlei)			G22E (Kuils)		
	Flux into Model	Flux out of Model	Net	Flux into Model	Flux out of Model	Net	Flux into Model	Flux out of Model	Net
February	0	-5 219 57% of flux to SW from aquifer	-5 219	4 082 85% of flux from SW to aquifer	-1 831 10% of flux to SW from aquifer	2 251	720 15% of flux from SW to aquifer	-3 021 33% of flux to SW from aquifer	-2 301
March	0	-5 030 57% of flux to SW from aquifer	-5 030	4 214 85% of flux from SW to aquifer	-1 853 10% of flux to SW from aquifer	2 361	744 15% of flux from SW to aquifer	-2 912 33% of flux to SW from aquifer	-2 168
April	0	-5 010 56% of flux to SW from aquifer	-5 010	3 805 83% of flux from SW to aquifer	-1 789 11% of flux to SW from aquifer	2 016	779 17% of flux from SW to aquifer	-2 952 33% of flux to SW from aquifer	-2 173
May	0	-5 309 53% of flux to SW from aquifer	-5 309	3 277 82% of flux from SW to aquifer	-1 703 16% of flux to SW from aquifer	1 574	719 18% of flux from SW to aquifer	-3 206 32% of flux to SW from aquifer	-2 486
June	0	-5 905 50% of flux to SW from aquifer	-5 905	2 745 81% of flux from SW to aquifer	-1 653 20% of flux to SW from aquifer	1 092	644 19% of flux from SW to aquifer	-3 543 30% of flux to SW from aquifer	-2 899

Month	G22C (Elsieskraal and Vyekraal)			G22D (Lotus, Rondevlei, Zeekoevlei)			G22E (Kuils)		
	Flux into Model	Flux out of Model	Net	Flux into Model	Flux out of Model	Net	Flux into Model	Flux out of Model	Net
July	0	-6 392 49% of flux to SW from aquifer	-6 392	2 493 81% of flux from SW to aquifer	-1 565 21% of flux to SW from aquifer	928	585 19% of flux from SW to aquifer	-3 914 30% of flux to SW from aquifer	-3 329
August	0	-6 682 50% of flux to SW from aquifer	-6 682	2 464 81% of flux from SW to aquifer	-1 604 20% of flux to SW from aquifer	861	578 19% of flux from SW to aquifer	-4 143 31% of flux to SW from aquifer	-3 565
September	0	-6 587 52% of flux to SW from aquifer	-6 587	2 669 83% of flux from SW to aquifer	-1 393 17% of flux to SW from aquifer	1275	547 17% of flux from SW to aquifer	-4 053 32% of flux to SW from aquifer	-3 507
Annual Total within catchment (Mm^3/d)	<0.001 <0.1%	-2.07 54% of flux out of model to SW over whole aquifer	N/A	1.21 83% of flux into model to SW over whole aquifer	0.55 14% of flux out of model to SW over whole aquifer	N/A	0.24 17% of flux into model to SW over whole aquifer	1.24 32% of flux out of model to SW over whole aquifer	N/A

Modelled fluxes of groundwater-surface water interaction vary monthly in response to recharge (**Figure 6-6** above). The contribution to the total model groundwater-surface water flux per month, from each quaternary remains fairly constant through the year, indicating that although the water levels fluctuate over the year, the major flow paths and directions do not change (**Table 6-9**). As in the steady state model, the majority of the influx from surface water to groundwater for the modelled area occurs in G22D where the Zeekoevlei and Rondevlei act as recharge to the aquifer. The rivers in G22C act as a sink to the aquifer throughout the year, and represent ~50% of the total, the remainder coming mainly from G22E (Kuils River).

The data of **Table 6-9** is displayed graphically in **Figure 6-7**.

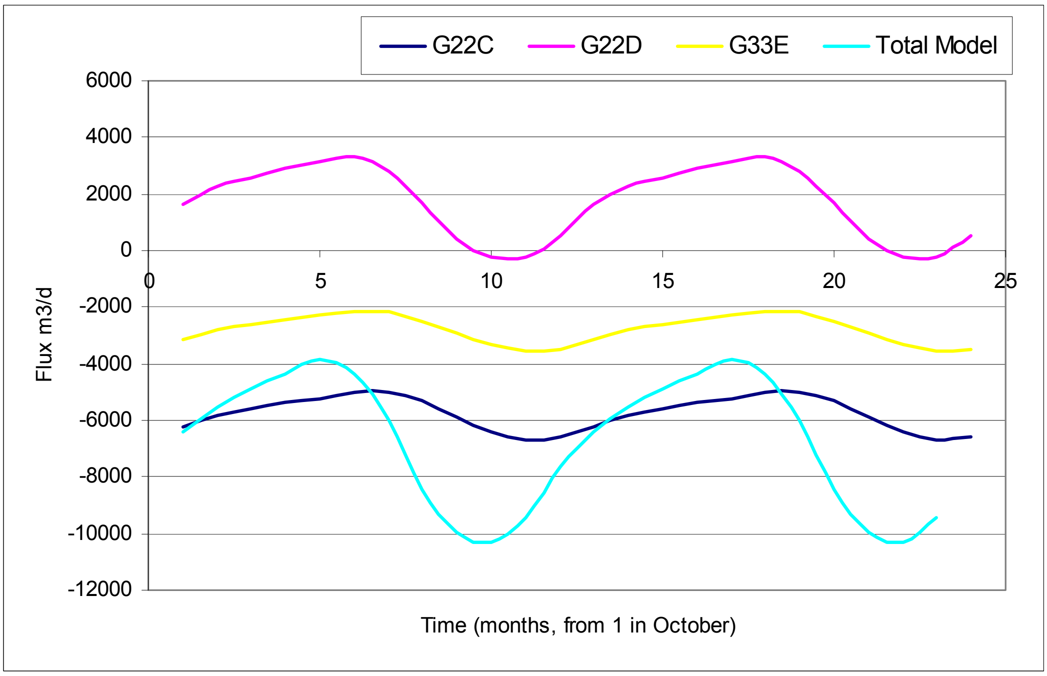


Figure 6-7 Net Groundwater-surface water Flux per Quaternary

7. SCENARIO TESTING

7.1 SCENARIO 1: SENSITIVITY TO RAINFALL

The rainfall dependency of aspects of the model can be tested through variation of the recharge. Rainfall data from a rainfall station in the east of the Cape Flats near the Kuils River (section 2.2) shows that the maximum variation from a mean annual rainfall is approximately 20%. The model was run with 20% higher recharge than that used in the standard case. Other parameters in the model remained constant (abstraction, hydraulic conductivity). With an increased recharge the annual variation in water levels increases.

The mass balance for the increased recharge test is shown in **Table 7-1** below. The increased recharge is accommodated by an increase in the discharge to the ocean (an increase of 11%) and to surface water (17% increase). The fluxes from surface water and from the prescribed heads both depend on the water level surface, and therefore decrease with increased recharge.

The balance (representing the storage) has increased from –0.86 for the standard situation (**Table 6-8**) to a positive 0.33. This indicates a switching from a system where more water is discharged than recharges, to one with a positive balance, i.e. an increase in storage. Some (~60%) of the additional 2.26 Mm^3/a goes into increased discharge; the rest is contributed to storage in the aquifer.

Table 7-1 Sensitivity of Mass Balance to Recharge

Month	Month	Influx m^3/d			Discharge m^3/d			Net GW-SW m^3/d	Balance m^3/d
		Recharge	Prescribed Heads	SW to GW	Ocean		GW to SW		
1	October	0	2 687	3 571	-22 637	-18 538	-13 444	-9 873	-48 361
2	November	0	2 768	3 935	-20 502	-18 538	-12 336	-8 401	-44 672
3	December	0	2 840	4 190	-19 037	-18 538	-11 594	-7 404	-42 139
4	January	0	2 913	4 389	-17 976	-18 538	-11 021	-6 632	-40 232
5	February	0	2 977	4 543	-16 994	-18 538	-10 551	-6 009	-38 564
6	March	0	3 036	4 704	-16 141	-18 538	-10 145	-5 441	-37 083
7	April	24 668	3 054	4 330	-18 359	0	-10 331	-6 001	3 362
8	May	75 195	2 994	3 687	-20 780	0	-11 690	-8 003	49 405
9	June	120 648	2 849	3 015	-23 960	0	-13 943	-10 928	88 609
10	July	111 308	2 703	2 692	-26 536	0	-15 539	-12 846	74 628
11	August	82 362	2 613	2 643	-27 631	0	-15 942	-13 299	44 045
12	September	38 741	2 606	2 860	-27 183	-18 538	-15 078	-12 218	1 946
	Annual (Mm^3/a)	13.59	1.02	1.34	-7.73	-3.89	-4.55	-3.21	0.33
		Influx			Discharge				
	Total (Mm^3/a)			15.95			-16.17		-0.23
	Contribution to total influx / discharge, as percentage	85	6	8	48	24	28	20[2]	1[1]
Effect of Increased recharge									
	Annual Fluxes	20% increase	10% decrease	8% decrease	11% increase	No Change	17% increase	32% increase	N/A
		Influx			Discharge				
	Total Fluxes			15% increase			10% increase	N/A	N/A

7.2 SCENARIO 2: UTILISATION OF THE CAPE FLATS AQUIFER FOR AUGMENTATION TO CAPE TOWN

7.2.1 SCENARIO 2.1 Wellfield based on Gerber (1980) – centre south

Vandoolaeghe (1989) documents a pilot abstraction scheme in the south central area, based on an area shown to be high transmissivity in Gerber's model (1980). There were other scientific and economic advantages to the choice of the area in this position. The wellfield was designed to produce 10 000 Ml/annum (10 Mm^3/annum), with 27 boreholes pumping at 12 l/s each. Fraser et al (2001) proposed a wellfield in the same area but suggested a total yield of 18 Mm^3/amun.

A hypothetical wellfield was entered into the model, in the same area (between the Weltevreden and Swartklip roads, see **Figure 2-1**), and between 4 000-1 500 m inland, shown in **Figure 7-1** below.

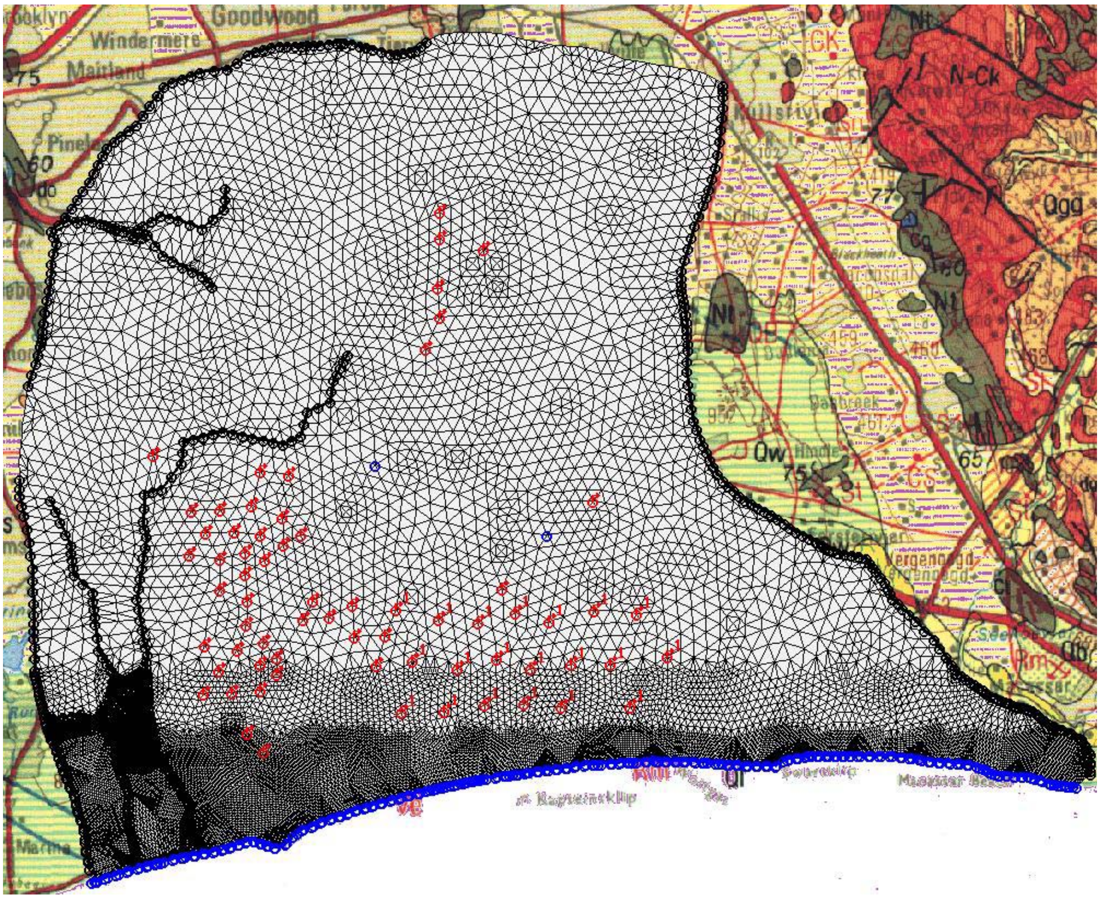


Figure 7-1 Wellfield position; figure shows boundary conditions for model run. Red circles indicate wells; those labelled with a 1 are the wellfield.

The aquifer was tested with a total yield as Fraser et al (2001) suggest, and also with a reduced rate. The pumping was simulated as continuous, which is realistic for a water supply scenario. The current abstraction is modelled in the transient model to only pump during dry months because most of the water is for agriculture. The effects of the wellfields are documented in **Table 7-2**. A total abstraction of 18 Mm^3/annum is clearly in excess of the safe yield of the aquifer. It is higher than the recharge, and the model mass balance showed influx from the constant head boundary at the coast, indicating that the cone of depression extends to the coast and direct seawater intrusion was a high risk. The pumping generated drawdowns < 0 mamsl indicating seawater intrusion is also likely through upconing.

Based on a recharge of 10.4 Mm^3/a and existing abstraction at 3.9 Mm^3/a, a conservative yield of 3.7 Mm^3/a was tested.

Table 7-2 Details of wellfields simulated in centre south of area

Scenario ID	Wellfield total abstraction	Wellfield details	Effects
Scenario 2.1 Rate 1	18 Mm^3/annum Based on Vandoolaeghe (1989) and Fraser et al (2001)	20 wells, each pumping at 2 566 m^3/d (30 l/s)	Cone of depression extends to coastline, direct seawater intrusion likely. Water levels drawn down to < 0 mamsl causing upconing of seawater and intrusion into wells
Scenario 2.1 Rate 2	3.7 Mm^3/annum	20 wells, each pumping at 500 m^3/d (6 l/s)	Cone of depression does not extend to coastline, low risk of direct seawater intrusion. Water levels drawn down to < 0 mamsl causing upconing of seawater and intrusion into wells

Seawater intrusion was also a likely risk with a reduced rate of 3.7 Mm^3/annum. The position of the wellfield around the Weltevreden and Swartklip roads is outside of the main palaeochannel, in areas where the aquifer is not particularly thick (**Figure 2-7**). The pump rates entered in the reduced rate wellfield are similar to those in the agricultural wells in the Phillipi farms / palaeochannel area. In the hypothetical wellfield the rates cause significant drawdown, due to their position. There is no palaeochannel upstream of the wellfield. The hydraulic conductivity in areas of lower basement elevation is high and facilitates low drawdown distributed over a larger area. For the hypothetical wellfield, the area of high hydraulic conductivity is much smaller and doesn't extend upstream, therefore the wellfield sources water against an effective barrier in hydraulic conductivity.

The advantages of a wellfield in this area include being away from Philippi farms area, and so less interaction or effect on already existing boreholes. However hydraulically it is clearly an unfavourable position.

7.2.2 SCENARIO 2.2 Well field in Palaeochannel

A hypothetical wellfield was entered focussed on the palaeochannel. The current abstraction on the Cape Flats is clustered in the palaeochannel, in its southern end (see **Figure 3-4**). The wellfield was entered to the north of the current abstraction (see **Figure 7-2**). As with Scenario 2.1 the wellfield was simulated to pump continually.

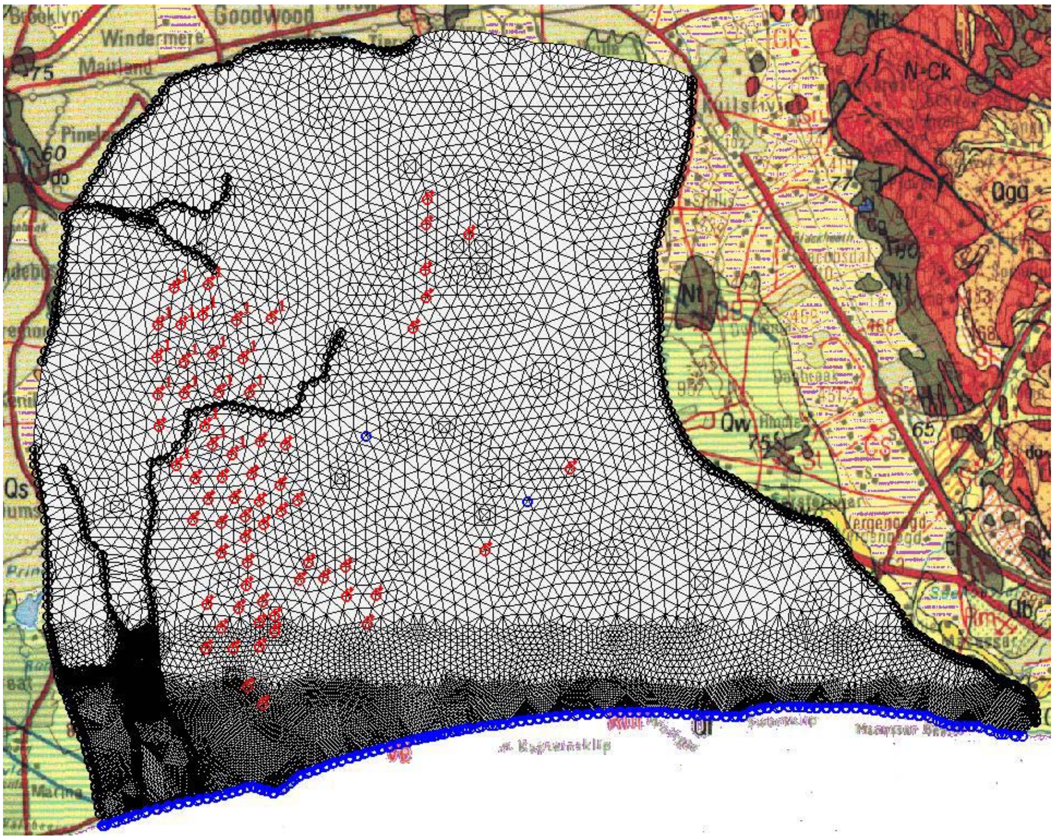


Figure 7-2 Wellfield position; figure shows boundary conditions for model run. Wells are indicated by red circles, those labelled with a 1 are the wellfield.

Two possibilities for the total abstraction were tested (**Table 7-3**).

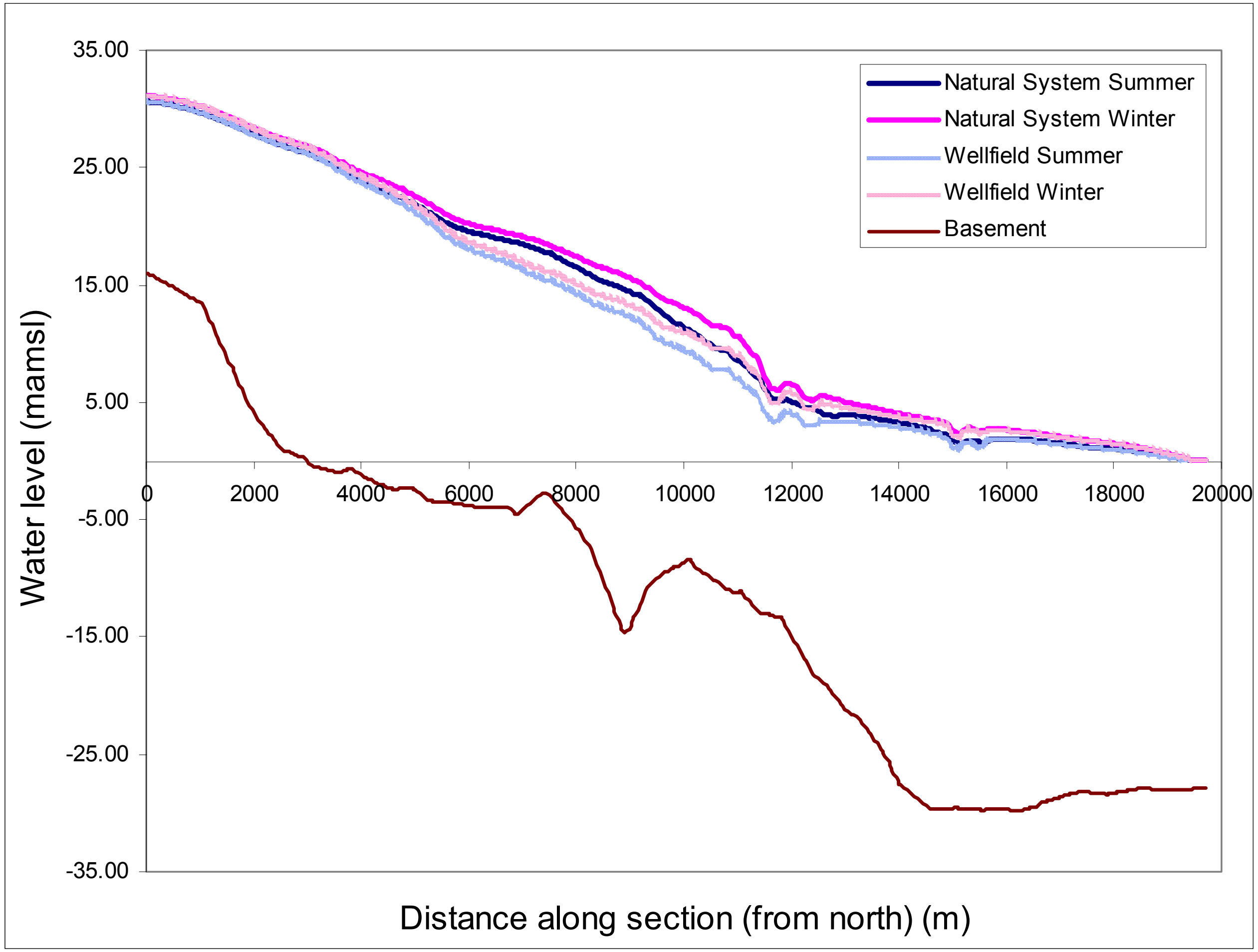
Table 7-3 Details of wellfields simulated in palaeochannel

Scenario ID	Wellfield total abstraction	Wellfield details	Effects
Scenario 2.2 Rate 1	3.7 Mm^3/annum	20 wells, each pumping at 500 m^3/d (6 l/s)	Water levels reduced significantly south of the wellfield, to the extent that certain irrigation wells in the south of the palaeochannel induce drawdowns to water level < 0 mamsl.
Scenario 2.2 Rate 2	2.0 Mm^3/annum	19 wells each pumping at 275 m^3/d (3 l/s)	Described below, see **Figure 7-3**

The high hydraulic conductivity in the palaeochannel induces a very shallow gradient in water levels, which increases slowly away from the coast. The abstraction of 3.7 Mm^3/annum reduces the regional water table such that the wells in the south of the palaeochannel cause drawdowns to below 0 mamsl, generating the possibility for upconing causing seawater intrusion.

Abstracting 2 Mm^3/annum does not have this effect. The effect on the water levels is shown in **Figure 7-3.** The wellfield reduced the water table by an average of 1.5 m over the palaeochannel.

The effect on the mass balance of the system is shown in **Table 7-4**. The increased abstraction reduces the net flux to surface water by ~37%. The hypothetical wellfield was sited with consideration of the palaeochannel and basement elevation. The impact on surface water could be reduced by optimising the abstractions and electing positions which are further from surface water features, yet still within the palaeochannel. The mass balance show that 40% of the required water for the wellfield is taken from storage, the rest coming from reducing discharge.



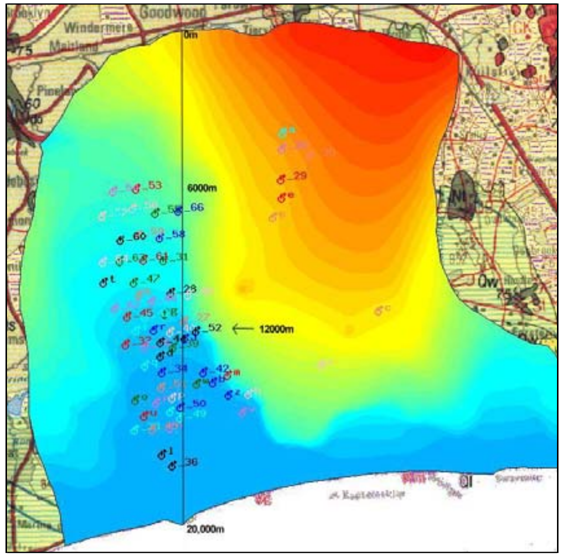


Figure 7-3 Effect on water levels of palaeochannel wellfield abstracting 2 Mm^3/annum

The dips in the water level surface around 12 and 15 km are generated where the cross section passes clustered abstractions. The inset shows the position of the cross section, with markers for the length along section.

Table 7-4 Mass Balance for Palaeochannel Wellfield

		Influx			Discharge			Net Ground Water-Surface Water	Balance
		Recharge	Prescribed Heads	SW to GW	Ocean	Abstraction	GW to SW		
Standard state	Annual Fluxes (Mm^3/a)	11.32	1.14	1.45	-6.99	-3.89	-3.88	-2.44	-0.86
	Total Fluxes (Mm^3/a)	Influx		13.91	Discharge		-14.77	N/A	-0.86
	Contribution to total influx / discharge, as percentage	81	8	10	47	26	26	16[2]	6[1]
Wellfield model	Annual Fluxes (Mm^3/a)	11.31	1.14	1.55	-6.70	-5.72	-3.19	-1.64	-1.61
	Total Fluxes (Mm^3/a)	Influx		14.01	Discharge		-15.62	N/A	-1.61
	Contribution to total influx / discharge, as percentage	81	8	11	43	37	20	10[2]	11[1]
Effect of wellfield	Annual Fluxes (Mm^3/a)	No change	No change	7% increase	4% decrease	47% increase	18% decrease	33% decrease	N/A
	Total Fluxes (Mm^3/a)	Influx		<1% increase	Discharge		6% increase	N/A	N/A

7.3 SCENARIO 3 FLOOD MANAGEMENT

The steady state simulation showed that on average water levels are above ground level in certain areas, mostly in the north (**Figure 5-4**). The transient simulation shows that the "flooding" in these areas is present throughout the year, and the distribution of modelled groundwater compared to ground level is similar to that in **Figure 5-4**.

The modelled "flooded" areas are not necessarily the same areas that flood in reality because the real system is governed by infrastructure and run off drains that are not modelled. For this reason the flood scenario is not centred on specific areas of known flooding. The aim of the scenario was to determine and demonstrate whether pumping in areas where modelled water levels rise above ground level, can reduce the water levels enough during summer that the regional water table during winter is reduced. The hypothetical wells are spread around areas of flooding and avoiding basement highs, concentrating on positions within the palaeochannel (**Figure 7-4**).

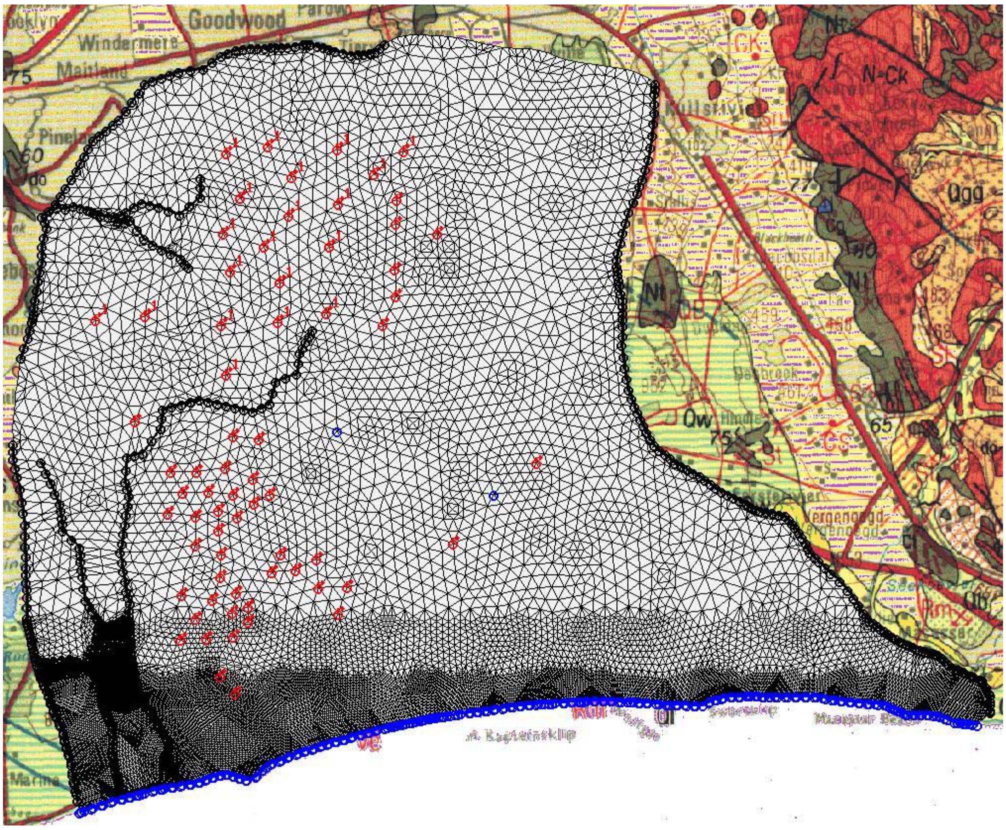


Figure 7-4 Flooding scenario well positions; figure shows boundary conditions for model run. Red circles indicate wells, those labelled with a 1 are the hypothetical wells centred on model-flooded areas.

The hypothetical wells were set to pump in summer months only. This is based on a scenario in which the additional pumping would be of similar use to that existing already in the Cape Flats – i.e. for agricultural irrigation or for watering of sports fields, which occurs in summer months. The boreholes are therefore not clustered which is typical of a wellfield; they are spread out representing scattered users. The details of the wells are shown in **Table 7-5** below.

Table 7-5 Details of the hypothetical wells entered to mitigate flooding

Additional wells total abstraction	Well details	Effects
1.8 Mm^3/annum Based on Wellfield Scenario 2.2 Rate 2.	20 wells, each pumping at 500 m^3/d, pumping during summer months only	Described below, see **Figure 7-5**

The effect on the water table of the targeted pumping is illustrated in **Figure 7-5**. This shows the water levels at point T7, an observation point that is within the area of flood targeted wells. The water level variation at T7 for Wellfield Scenario 2.2 (Rate 2) is also included in the plot for comparison. The plot shows that pumping only in summer causes an increase in the seasonal variation in water levels. The presence of the wellfield in the north can reduce the averaged regional water table. The seasonal fluctuation is not affected because the pumping is constant; hence there is no allowance for recovery from pumping.

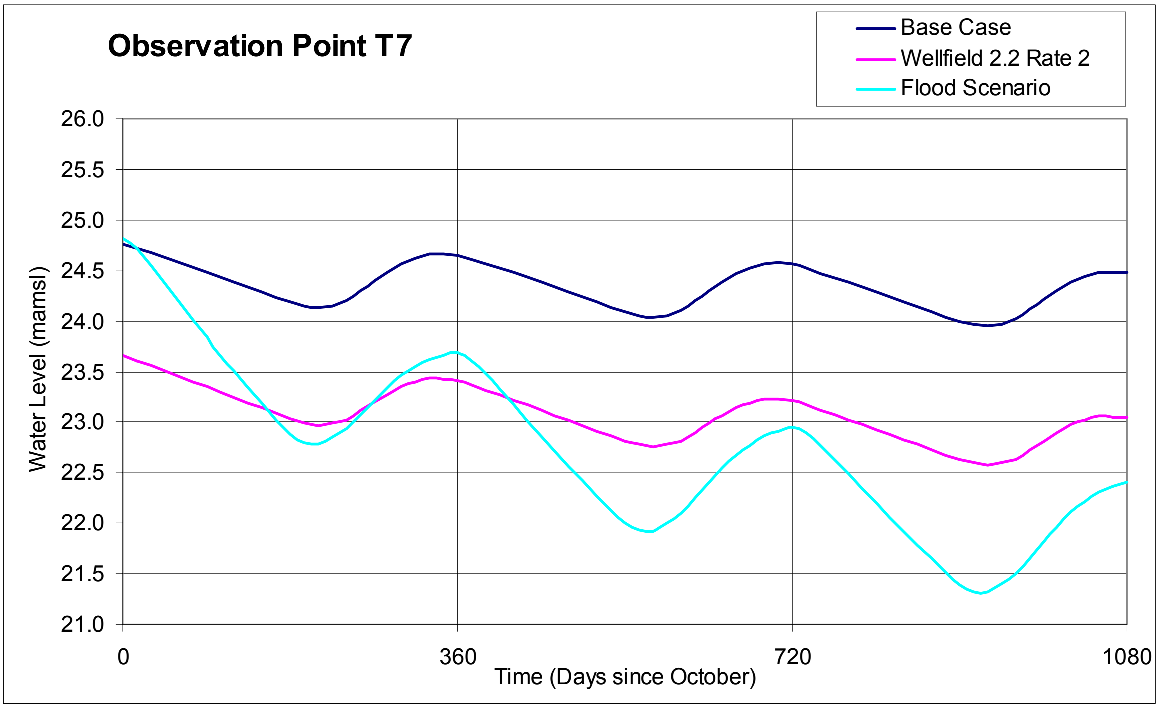


Figure 7-5 Water levels at observation point T7. The flood scenario was run following a base case simulation; hence the drop in water levels from base case is shown. For the wellfield scenario the stabilised lower water level is shown.

The flood scenario wells have caused the water levels to continually decline at T7. The recovery period during the winter is not long enough for water levels to stabilise. This may be due to the proximity of the observation point to a well. The flood scenario wells are not optimised with respect to number of wells, pump rates etc. If the pump rate was reduced and spread between more wells, this continuing decline may not occur. The plot shows that summer pumping can indeed draw water tables down enough to allow the winter rise to be less than without the pumping. This shows it is likely there is an optimal arrangement of flood-targeted wells that can generate a stable lower water table in winter.

Because the same amount of water is abstracted in the flood-targeted wells and in Wellfield 2.2 Rate 2, the effect of the flood targeted additional wells on the annual mass balance over the whole model is similar. The seasonal pumping will cause higher seasonal differences in the surface-groundwater fluxes. The position of the flood scenario wells are not optimised with respect to surface water, therefore the mass balance is not relevant as an indication of the effect.

7.4 YIELD ESTIMATION

The steady state calibrated recharge is 11.3 Mm^3/annum. With reference to **Table 6-3,** the steady state recharge is very low compared to other estimates, therefore it is concluded that the steady state recharge is a calibrated effective recharge, representing water which enters the aquifer, so already accounted for evapotranspiration. Calculating the rainfall that this effective recahrge equates to, and comparing it to the actual rainfall across the model area could give an indication of the actual measure of water lost to evapotranspiration.

Using the modelled recharge, the total available yield is:

Total yield = Recharge 11.3 Mm^3/annum – current abstraction 3.9 Mm^3/annum = 7.4 Mm^3/annum.

The wellfield scenarios show that the best position for abstraction is within the high hydraulic conductivity sediments of the palaeochannel. Outside of this the drawdown is large and the risk of seawater intrusion through upconing is high. However the high K in the palaeochannel means that the effect of pumping is distributed further. The wellfield scenarios suggest the best place for any additional abstraction is in the north of the palaeochannel. The suggested estimated sustainable yield, which does not cause negative effects on seawater intrusion, is 2.0 Mm^3/annum

The saturated volume of an aquifer and the travel time through the aquifer has implications on the management of its resource. In order to determine the total saturated volume of an aquifer knowledge about the porosity is required. The transient model calibrates the specific yield which is a good proxy for the porosity. In a dominantly sand aquifer the retention is assumed to be low. It is assumed that the specific yield equates to the porosity (Hiscock, 2005).

The saturated volume of the aquifer (for the base case) is given in **Table 7-6** below, also showing the monthly variation in volume. An average residence time can be estimated by dividing the saturated volume by the recharge, and suggests a timing of ~13 years. This gives the time taken to fill the aquifer, essentially the same as the time taken for water to pass through the aquifer. This time is also the management time of the aquifer. Any management plan must be sustainable over a 13-year cycle.

Table 7-6 Model Saturated Volume and Average Residence Time

Time (month from October)	Saturated Volume Mm^3
1	135.56
2	134.67
3	133.82
4	133.00
5	132.22
6	131.47
7	131.59
8	132.54
9	134.32
10	135.76
11	136.61
12	136.16
Average	133.98
Average Residence time	12.7 years

7.5 SCENARIO 4 POLLULTION

Industrial areas, as based on the landuse mapped by Landsat (**Figure 2-16**), were considered as potential sources of pollution to the aquifer. In addition to these areas, known sites of sewage disposal works and treatment works were also considered. These include sewage disposal works at:

- Athlone, just south of the N2 between the suburbs of Hazendal and Bridgetown;
- the northeast of the model area west of the R300 near the Pentech train station;

and a waste disposal site on the Swartklip road. The sewage site south of the Zeekoevlei was not included due to its proximity to the coast. In the regional model flow from the area is immediately to the coast. The sewage sites just north of the model boundary in the southeast, around the intersection of the N2 and the R310 are also not included. The Kuils River on average gains from the modelled aquifer. Therefore flow is towards the boundary and any potential contamination simulated close to the boundary would flow towards it. The model suggests that potential contamination from these sites north of the Kuils River, would enter the Kuils River.

The potential threat to the aquifer from these sites was analysed through particle tracking. **Figure 7-6** below shows the path lines for particles from the above-mentioned areas, with symbols showing the time taken along the path.

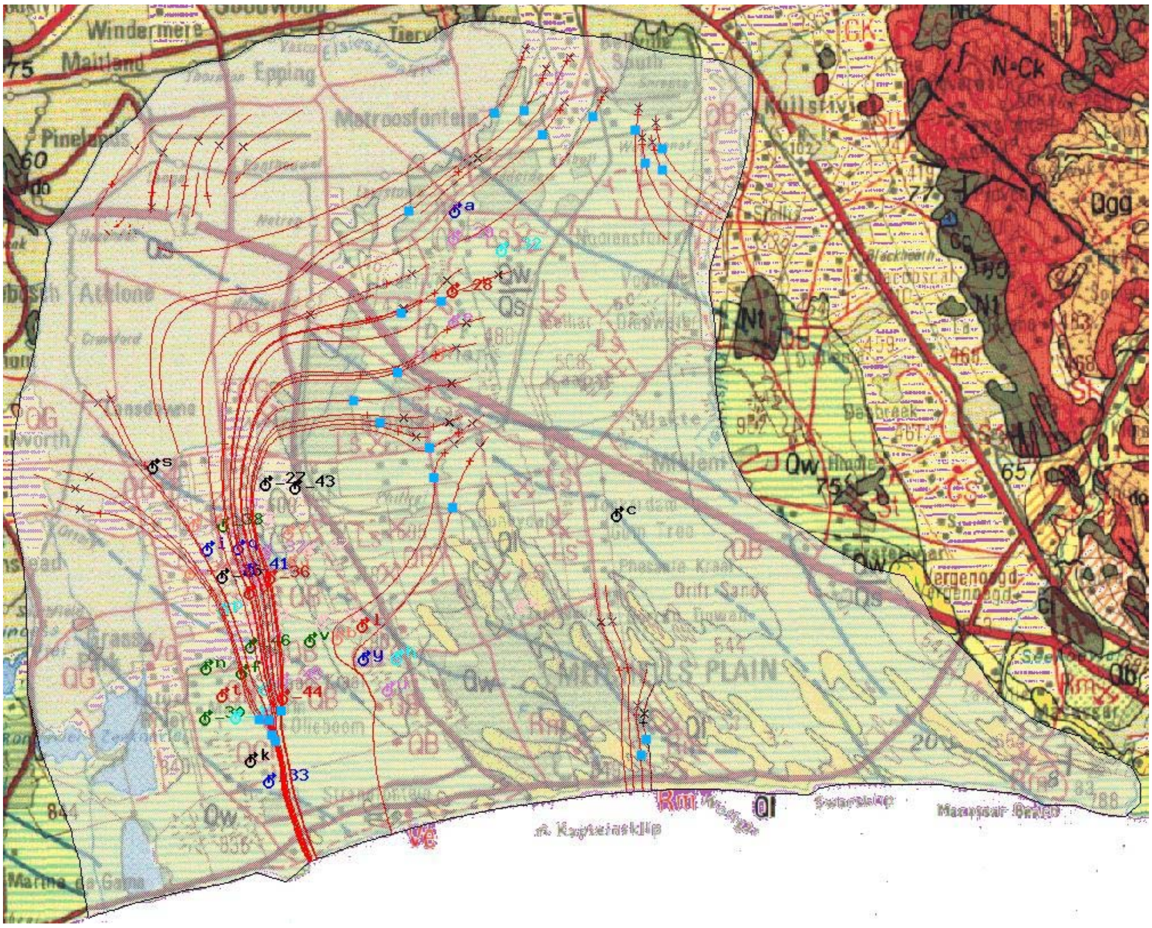


Figure 7-6 Path lines for particles from potential pollution sources.
The plot shows the surface projection of the 3D path of particles. x indicates position after 5 years, + indicates position after 10 years, ■ indicates position after 20 years.

the path lines highlight the dominant flow directions; a sink zone in northwest at Vyekraal; a sink zone at eastern boundary at Kuils River and a dominating flow path into the palaeochannel and to the south.

The Vyekraal River is the sink zone for groundwater beneath the industrial sites in the northeast, and in the northwest. The Kuils River is the sink for groundwater from the sewage disposal works in the northeast of the model area (west of the R300 near the Pentech train station). The palaeochannel and wells in the palaeochannel and centre of the model area are sinks for groundwater from beneath the industrial sites in the centre of the model, around the N2 near the airport. Groundwater from beneath the waste disposal site and the industrial site on the Swartklip road flows south to False Bay.

Each of these sink zones is a potential receptor to pollution from these sites. However the actual risk of pollution is considered low because of the high travel times. Travel times from the northeast of the model to the sinks of the Vyekraal River or the palaeochannel are greater than 20 years (the ■ indicates position after 20 years). Travel times from the northwest of the model to the sink of the Vyekraal River are 10-20 years. Groundwater moves much faster within the palaeochannel, as shown by path lines that start outside of the palaeochannel and reach a short distance after 10 years, then enter the palaeochannel and travel much further between 10-20 years (e.g. path lines starting in the centre west of the model).

The majority of the path lines show that the time to reach receptors is > 20 years. Over this timescale the pollution threat from sewage works is likely to be mitigated through natural attenuation and microbial action. A pollution source of Non Aqueous Phase Liquids (NALPs) from industrial sites would however pose a contamination issue, as attenuation times are longer. The residence time suggested in section 7.4 is shorter than this travel time to receptors because it is a spatial average.

8. CONCLUSIONS AND RECCOMENDATIONS

8.1 SUMMARY OF INTERPRETATIONS

The main features of the conceptual model developed here detail a heterogeneous aquifer, which at the largest scale is unconfined and at the local scale is a heterogeneous multi-layered aquifer with confining beds (calcrete and clay beds), confined units, and an unconfined sand at the surface. The aquifer is underlain by an impermeable boundary. Recharge occurs to the aquifer through rainfall. The aquifer discharges to the ocean and to surface water features. The major flow direction is from high ground in the northeast of the area towards the south and southwest, and exploits the palaeochannel in the west of the area. The rivers that traverse the unconfined aquifer are in hydraulic connection to the aquifer and therefore act as recharge or discharge boundaries. Where canalisation occurs this hydraulic connection is reduced and it is assumed there is no connectivity between surface and groundwater.

The conceptual model was translated to a numerical model and the finite element groundwater software package Feflow was used to numerically model the aquifer. Rivers were used as transfer boundaries at the landward borders of the model, and the ocean was used as a constant head boundary in the south of the model. The calibration has achieved modelled groundwater levels that, on average, match the observation data to within 10% of the total head drop over the model. The modelled groundwater table across much of the central parts of the model is significantly lower than the calibration points, by up to 13 m. In the north western area the modelled groundwater table is above surface. Despite these particular areas of difference the model error is within acceptable limits for a regional scale model.

The numerical model shows the best fit to observed data was achieved with a 4-layered model geometry. The basal unit that fills palaeochannels, has a high hydraulic conductivity of 84 m/d. The high conductivity is overlain by a low one of 0.1 m/d. Remaining areas of the modelled aquifer have a conductivity of 10 m/d. The vertical hydraulic conductivity is an order of magnitude lower than horizontal. 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 Mm^3/annum is available, from the northern palaeochannel areas.

In the following section shortfalls and uncertainties in the model are discussed. Recommendations to improve model reliability in the future are made.

Recommendations fall under the broad purposes of:

1. Testing of the impact of different conceptual models and boundary conditions in a numerical model;
2. Numerical model sensitivity and further scenario testing;
3. Data collection in areas of greatest difference between model and inferred water table.

8.2 CONCEPTUAL MODEL AND NUMERICAL MODEL BOUNDARY AMENDMENTS

The modelled groundwater flow directions, the shape of the model boundary, and pattern of "flooding" against the northwest model boundary (which exist in the steady state and transient model) suggests that the flooding is potentially a boundary effect. Groundwater flows radially from the northeast to the south and west, and it is possible that not enough water is removed at the northwestern boundary.

An alternate conceptual model was discussed in Section 3 under which deep groundwater in the northwest flowed out to Table Bay in the northwest (**Figure 3-2**). It is possible that the transfer boundary used is not removing enough water. In the model this boundary exists at the surface only (over the upper 1m of the model) and deep groundwater beneath must exit through the surface in order to flow to the northwest. If in reality large-scale groundwater flow to the northwest occurs, this isn't adequately represented by the transfer boundary. Certain model set-ups could test this reality, by assigning flux boundaries beneath the transfer boundary to allow deep groundwater to also move too the northwest. However to place confidence in the model result the model would need more data from the northwest of the area – groundwater levels for calibration and basement elevation data.

> <u>*Summary Recommendation 1:*</u> *Test reality of the conceptual model by investigating whether significant groundwater flow occurs to the northwest and discharging to Table Bay. This requires additional water-level data in the northwest of the Cape Flats in order to interpret directions of groundwater flow. The possibility of significant groundwater flow to the northwest was discounted due to evidence of a basement high, or at very least a basement constriction (see basement topography map presented by Gerber (1980). Additional basement data would be required in the northwest, from borehole logs and geophysical investigation.*

8.3 HYDRAULIC NATURE OF THE AQUIFER

Various model runs were conducted in order to determine whether the aquifer is best represented as confined or unconfined. Setting the basal layer (layer 4) in the model as confined or unconfined in terms of how the layer is treated mathematically, generates identical results. This simply suggests that layer 4 remains saturated during the simulation. The calibrated hydraulic conductivities suggest that the basal layer is high hydrauliuc conductivity and overlain by a low hydrauliuc conductivity, however these are equivalent hydraulic conductivities and it is possible that the solution is not unique. Using the confined or unconfined settings in the model may generate a difference when the model is run in transient settings.

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.

> Summary Recommendation 2: Do pu*mp 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.*

8.4 WATER LEVEL SURFACE

It is stated above that additional point data and more reliable point data (i.e. with coordinates and borehole elevation certain) is required to test the conceptual model that groundwater flows out to the northwest of the model area. The observed water level surface even when corrected for topographic bias, indicates groundwater mounds exist. Whether these are from unresolved topographic bias or indicate real effects also requires additional and reliable water level information. With a larger data set the points that are affected by local features such as local pumping or abstraction, can be more confidently removed from the data set and a smooth water table, applicable at the regional scale can be generated.

> *Summary Recommendation 3: Hydrocensus data collected across the Cape Flats area: water levels and borehole use, accurate X,Y and Z coordinates.*

8.5 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.

> *Summary Recommendation 4: Additional data is sourced or collected in fieldwork on the river geometries, typical bed sediments, and most importantly the river stages*.

8.6 OPTIMISATION OF SCENARIOS FOR INCREASED ABSTRACTION

The scenarios presented for abstraction suggest that there is 2 Mm^3/annum additional water available, from the northern palaeochannel areas. Refining the model based on additional calibration data (previous recommendation) would improve reliability of this conclusion. A regional scale model such as this one, or an improved version of, could be used as a basis for construction of smaller scale models centred on the palaeochannel. These would be required for optimisation of the position of additional abstractions, with respect to yield and also proximity to surface water, other existing users.

Summary Recommendation 5: 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.

8.7 SCENARIOS FOR EVAPOTRANSPIRATION

The model presented here has not explicitly quantified loss of water to evapotranspiration, only assumed an effective recharge. Quantification of water lost to evapotranspiration requires data on the water usage by alien vegetation (not yet available), and mapping of the extent of alien vegetation. From this data an alternative recharge distribution could be generated and tested in the model.

Summary Recommendation 6: Data on alien vegetation water usage and aerial extent is required in order to explicitly quantify evapotranspiration.

8.8 SUMMARY OF RECOMMENDATIONS

Table 8-1 Summary of recommendations

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 Borehole logs 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; Downhole geophysics; Estimates of porosity to refine model layers; Field estimates for different layers.	Pump test conducted in the central palaeochannel; Layer specific monitoring

Purpose	**Aspect**	**Information required**	**Source of information**
Improve confidence in numerical model	Test reliability of numerical model boundary conditions and uniqueness of model solution for surface water-groundwater interactions; 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 surface water-ground water interaction numbers	Field measurements of actual river widths; River stage data

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