Ecological and Environmental Impacts of Large-scale Groundwater Development in the Table Mountain Group (TMG) Aquifer System

Report to the

Water Research Commission

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WRC Report No 1327/1/08
ISBN 978-1-77005-796-8

February 2009

Executive Summary

This study focuses on the ecological role of the Table Mountain Group (TMG) aquifer. It was commissioned in 2002 by the Water Research Commission (WRC) as part of a programme of research on the TMG aquifer. The specific objectives of this research were to:

- Develop predictive tools to assess the impact (or risk) of groundwater abstraction on the environment.
- Improve our understanding of groundwater dependent ecosystems in the TMG and the sensitivity to groundwater level fluctuations.
- Use innovative techniques to determine the impact of groundwater abstraction on the environment.
- Develop indicators to monitor the effect of abstraction on sensitive ecosystems.
- Coupling time series and spatial databases in order to ascertain the impacts of low flows (groundwater and surface water interaction) on the environmental system.
- Improve understanding of the impact of changing low flows on freshwater ecology.

The project was initiated at the same time as a feasibility study funded by the City of Cape Town (CoCT) into the development of the TMG aquifer for bulk water supply. It was agreed that this WRC study should inform the CoCT study in order to minimise the environmental impacts of large-scale groundwater abstraction.

This project was conducted in four phases: 1) Scoping potential links between terrestrial and aquatic ecosystems and the TMG aquifer; 2) Establishing monitoring sites and infrastructure; 3) Collecting monitoring data; 4) Analysing data and reporting. The scoping phase included a workshop with a range of specialists on TMG ecology and hydrology. This phase informed the design of the study and the structure of M.Sc. student projects offered with bursaries as part of this project to several universities. Rivers, estuaries, springs, wetlands and seeps were identified as the ecosystem types that would be most vulnerable to changes in groundwater availability. The most important monitoring parameters were agreed to be surface and groundwater quality and quantity (i.e. flow rate and water level), and vegetation community types and responses to changes in water availability.

The project was exempt from an EIA as no new access routes were planned, no abstraction would take place at the monitoring boreholes, and an Environmental Management Plan (EMP) was enforced during drilling and other site visits. Two study sites were selected to monitor connections between the TMG aquifer and the surface environment. These sites were selected, based on the following criteria: they were hydrogeologically similar to the target sites for the CoCT project and are representative of probable aquifer discharge zones; they are not currently impacted by groundwater abstraction; they support fairly pristine ecosystems; they have some access for drilling rigs; they are reasonably secure. The study sites are Kogelberg, a mountainous reserve area between Betty's Bay and the Bot River estuary, and Purgatory, a mountainous conservancy between the Franschhoek pass and Theewaterskloof dam.

Both sites were equipped by this project for long-term environmental monitoring of surface water, groundwater and local climate. In addition, short-term assessments of the flora and fauna were carried out and could be repeated.

At both sites, weather stations were installed in the valleys. Long-term groundwater monitoring boreholes were drilled with a conventional rig in accessible areas to depths between 40 and 120 m below surface, and with a portable rig in less accessible areas (within 300 m of an established 4 x 4 track) to depths of between 18 and 30 m. In some wetlands, accessible only on foot, piezometers were hand-augered to between 1 and 3 m depth to enable shallow groundwater monitoring. Piezometers were also installed in the streambeds, to house data-loggers monitoring the changing height of surface water. Geophysical resistivity cross-sections were traversed at the sites to characterise the subsurface. The vegetation and geology at the field site were assessed using remotely sensed satellite data and field reconnaissance mapping in the case of the Purgatory site. In addition, wetlands at the Kogelberg site were mapped in the field to determine plant communities associated with different groundwater discharge regimes. Plant water stress measurements were taken at selected Kogelberg wetland sites and plant xylem vessels were assessed for embolism vulnerability. Diatom assessments were carried out in the streams and conventional SASS scores were monitored in different seasonal flow regimes in the streams. Surface water and groundwater chemistry, temperature and water levels were monitored and rainfall was collected at different altitudes in the catchments for stable isotope measurements. Radon radioactivity measurements were taken of groundwater and surface water at the Kogelberg site.

The evidence from the Kogelberg field study indicates that TMG aquifer discharge directly contributes to flow in the Oudebos tributary and cryptic discharge from the mid-slope 'wetland' on a fault. It also indicates that indirect TMG discharge contributes to the valley bottom wetland (via surface water) and to the coastal wetland (via the surficial unconsolidated wetland). All the fynbos species tested showed very high vulnerability to xylem embolism formation, i.e. they were vulnerable to reduced water availability. However, they showed relatively low levels of experienced midday water stress even in terrestrial off-seep settings, particularly the deep rooted Proteas which are known to have root systems up to 10 m deep (within the maximum known depth of soil formation in the TMG terrain). Shallow rooted Restios showed the greatest degree of moisture stress. The Proteaceae appear to be tapping water in the deep soil horizons, the colluvium and weathered TMG.

At the Kogelberg site, the following ecosystems linked to TMG discharge were identified:

- slope wetlands linked to TMG faults and fractures and lithological contacts;
- a coastal wetland linked indirectly to TMG fractures;
- perennial river and riparian zone linked to TMG fractures and lithological structures; and
- terrestrial fynbos and perched high wetlands linked to (non-aquifer) TMG jointing and micro-fractures.

The field study in Purgatory revealed that seeps on the eastern slope of the catchment occur where permeability interfaces (lithological contacts in particular the shale band and Peninsula formation) are transected by the Purgatory fault. These systems constitute a combination of lithologically controlled and fault controlled wetlands where groundwater contribution from the confined Peninsula Aquifer via the fault structure is possible. Seepzones at or just below the Goudini – Cedarberg Shale contact appear to be lithological contact systems and not connected to the confined TMG aquifer. Groundwater discharge into the eastern tributary is clearly evident along the deeply incised gorges. This inflow maintains the perennial character of the eastern tributary. The groundwater contribution most probably originates from the Peninsula Aquifer and discharges along the cross faults. The two wetlands in the non-perennial drainage line of the western tributary show strong seasonality in water level fluctuation. However, it appears that the stream flow in the dry months slightly increases below the second in-stream wetland suggesting some groundwater inflow, contributing to maintaining the ecosystem but not sufficient to create a perennial stream.

At the Purgatory field site, the following groundwater linked ecosystems were identified:

- slope wetlands linked to lithological contact and TMG fracture discharge;
- riparian zone indirectly linked to TMG fault and fracture discharge;
- seasonal and perennial rivers linked to TMG faults and fractures.

The evidence linking these ecosystems to TMG aquifer discharge provides a basis for a more detailed conceptual model of the eco-hydrology of TMG catchments. Aquifer linked hydrotopes can be defined and used to delineate areas of risk and for monitoring linked to specific abstraction sites.

This project has established the following:

- A GIS database and Spatial Decision Support System (SDSS) (Appendix A) to be used in multidisciplinary, hydrogeological projects. The SDSS tool presented in the form of a digital atlas allows spatial analysis of data for catchment managers, researchers and students working with ecosystems and the TMG aquifer. It further is a useful awareness-raising platform about geographic information systems and its capabilities amongst the earth-science community.
- A groundwater-focussed, integrated, hydrological monitoring network for long-term environmental monitoring of TMG flow and ecosystems in ecologically sensitive areas of the two study sites.
- Automated and manual monitoring of components of the eco-hydrological system at two study sites in the Western Cape and relevant field data.
- Recommendations for lines of future research and investigation that will further improve understanding of the spatial and temporal patterns of groundwater discharge to wetlands, seeps and related ecosystems in the TMG.
- An Environmental Monitoring Framework (Appendix B 4) for integrated monitoring of impacts of groundwater abstraction in the TMG, on which current baseline monitoring efforts linked to future large scale abstraction are based.

The key findings of the research carried out on the project can be summarised as follows:

- It is shown that monitoring boreholes can be drilled in ecologically sensitive areas without significant disturbance, using an appropriate EMP and site supervision.
- It is confirmed that it is imperative to collect good quality, hard physical data, such as groundwater level data in correctly sited boreholes and piezometers located at groundwater discharge-linked ecosystems, to monitor the changing availability of groundwater.
- It is shown that Si, DOC and Rn radioactivity are useful tracers of groundwater discharge into the aquatic environment. SiO_2 and DOC are more conservative tracers with respect to changes once discharged, whereas Rn (with a half life of 3.8 days) could be used to indicate points of discharge. Macro-ions did not prove useful tracers in this study.

- Temperature is a useful indicator of groundwater flow and is indicative of the depth of groundwater flow.
- Stable isotopes are useful to distinguish between different plant water sources, although the differences might be more distinct along gradients where the effect of altitude is more significant.
- Aquatic and terrestrial species indicators for groundwater dependency were not evident at the two study sites. Assemblages of plant, invertebrate and diatom communities were very diverse and could not be linked statistically to areas of groundwater discharge.
- The study did not encounter any species (threatened or not threatened) that are solely dependent on groundwater discharge.
- Wood-anatomy-based measures indicate that on and off-seep fynbos plants are highly vulnerable to moisture stress. However, there is no marked difference in the degree of xylem embolism vulnerability shown by on-seep species and their analogues off-seep, showing that the plants are adapted to the currently available moist conditions, i.e. precipitation and mist. The monitoring period covered one slightly wet year (2004/2005) and two dry years (2005/2006 and 2006/2007), compared to long-term average data.
- Deep rooted plants, such as the Proteaceae, did not exhibit moisture stress, while shallow rooted plants, such as Restios, showed some degree of moisture stress during dry periods. The Proteaceae appear to be tapping water in the deep soil horizons, the colluvium and weathered TMG, which is generally found in the top 10-maximum 20 metres below ground. In general most plant species access multiple sources of water, with groundwater as a dominant source during drier periods.
- Remote Sensing can be a useful tool to identify perennial wetland ecosystems and can be utilised for long-term and routine monitoring over a wide area of interest, provided the algorithm is adapted to the study area based on field verification and the spatial scale of the imagery is sufficiently small to detect ecosystems of interest.
- Subsurface flow in TMG mountainous catchments follows multiple geologically controlled flow paths. Groundwater discharge from the TMG aquifers occurs at springs or seepage zones that are usually linked to predictable structural, lithological and topographic hydrogeological settings that can be mapped with high degrees of certainty (Hartnady, pers.comm. 2008)

Groundwater discharge to the surface environment is characteristic of TMG fynbos catchments. These catchments are typically mountainous catchments with orographic rainfall and discharge occurs from multiple flow paths. The relatively high permeability in the system results in a rapid recharge-discharge response in the higher-lying, unsaturated and unconfined parts of the Peninsula and Skurweberg aquifers resulting in seasonal and interflow contribution to springs, wetlands and seeps. Higher storage and the longer flow paths in the lower-lying unconfined and confined parts of this multiple-aquifer system, results in a smoothed recharge response and prolonged, often constant discharge.

Most of the springs, wetlands and seeps studied in the two test sites appear to receive groundwater discharge from the higher-lying flow paths in the upper part of the aquifer. The study did not find individual species or components of the terrestrial ecosystem that are uniquely dependent on groundwater discharge. However, to adhere to the precautionary principle of NEMA, any abstraction from the TMG aquifers should be accompanied by an appropriate monitoring strategy. Useful tools and physico-chemical tracers of groundwater contribution have been identified which will enable test abstraction from the deep TMG to be monitored. Water temperature, dissolved Si, low DOC and radon indicate aquifer flow paths. Above all, the siting and design of abstraction boreholes should be based on a sound conceptual understanding of structural controls on probable flow paths and their discharge points.

The project team believes that long-term aquifer-catchment monitoring should continue at the sites to provide sufficient baseline data and to deepen the knowledge of links between the TMG aquifers and the surface environment. The sites will also serve as control and far-field (distal) monitoring sites if TMG aquifer testing and development proceeds for the City of Cape Town.

Abbreviations

ADEs	Aquifer Dependent Ecosystems
Be/ L	Bequerels per litre
CMA	Catchment Management Agency
CoCT	City of Cape Town
CSIR	Council for Scientific and Industrial Research
DEADP	Department of Environmental Affairs and Development Planning
DEAT	Department of Environment Affairs and Tourism
DOC	Dissolved organic carbon
DWAF	Department of Water Affairs and Forestry
EIA	Environmental Impact Assessment
EMP	Environmental Management Policy
GDEs	Groundwater Dependent Ecosystems
HRM	Hangklip-Riviersonderend Mega-fault
IWRM	Integrated Water Resources Management
mamsl	Metres above mean sea level
MAP	Mean annual precipitation
MAR	Mean annual run-off
mbgl	Metres below ground level
MCM	Mega cubic metres
NBA	National Biodiversity Act
NEMA	National Environmental Management Act
NGA	National Groundwater Archive
NWA	National Water Act
RDM	Resource Directed Measures
RQOs	Resource Quality Objectives
SANBI	South African National Biodiversity Institute
SASS	South African scoring system
SDSS	Spatial Decision Support System
WCNCB	Western Cape Nature Conservation Board
WRC	Water Research Commission

Acknowledgements

- To the WRC, the Department of Water Affairs and the CSIR for the financial support they have given this project.
- To the Department of Environmental Affairs and Development Planning, the Western Cape Nature Conservation board, the Theewaterskloof conservancy, the Kogelberg Biosphere Reserve, the owners of Mountain Rose farm and Stroompie for their cooperation and collaboration on the project.
- To the members of the reference group for their contributions and advice to the project team, in particular:

Dr Shafick Adams	WRC
Dr Kevin Pietersen	(formerly WRC)
Dr Heather Mackay	(formerly WRC)
Mr Mike Smart	Department of Water Affairs and Forestry
Mr Eddy van Wyk	Department of Water Affairs and Forestry
Mr Rodney Bishop	City of Cape Town
Dr Dannie Vermeulen	UFS-Institute for Groundwater Studies
Ms Anet Muir	Department of Water Affairs and Forestry
Dr Johan de Beer	CSIR
Ms Gail Cleaver	Western Cape Nature Conservation Board
Prof Bruce Kelbe	University of Zululand
Mr Mark Johns	Western Cape Nature Conservation Board
Mr William de Lange	Department of Agriculture
Mr Paul Seward	Department of Water Affairs and Forestry

- To the collaborating scientists who have assisted the team in developing their understanding of the role of TMG aquifer discharge in the Cape Floral Kingdom, inter alia, Prof W Bond, Prof J Midgeley, Dr C Hartnady, Mr J Weaver, Ms ER Hay, Mr P Lochner, Prof M Samways, Prof C Boucher.

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Chapter 1:

Introduction and Background

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1. Introduction and Background

1.1 Introduction to this Report

This report presents the final results of a research project funded by the Water Research Commission (WRC). The main report represents a summary of the work whilst more detail and data are given in the appendices, which accompany the report on a CD.

Chapter 1 gives the background to the project and the motivation to research the links between the Table Mountain Group (TMG) aquifer and the surface environment. It introduces other relevant work, including projects funded by the WRC on the TMG and a project funded by the City of Cape Town (CoCT) on evaluating the option of using TMG groundwater for bulk water supply. This chapter also introduces the hydrogeology of the TMG aquifer. We explain the approach that evolved out of the scoping phase of the project and the selection of study sites to test methods to determine ecological groundwater dependency.

Chapter 2 summarises the various methods that were used to assess groundwater discharge and links to the environment. Selected spatial databases have been included in the GIS Atlas (Appendix A), and we give an overview of the data methods and protocols. The methods used to assess remotely sensed data are also given. The focus of the project is the fieldwork carried out at our two study sites, and most of the methods relate to acquiring and analysing this field data.

Chapters 3 and 4 review the results of monitoring at the two study sites: one in the Kogelberg biosphere reserve and one near the Purgatory wetland close to Franschhoek. We describe the hydrogeology and the results that we achieved in our integrated monitoring of the sites and assess which ecosystems appear to be linked to and dependent on discharge from the TMG. All of the field data are included in the appendices.

Chapter 5 reviews which of the field methods we tested gave useful results and should be used in future monitoring of TMG linked ecosystems. We summarise the hydrology and hydrogeology of our catchment sites. We recommend areas for future research that lead on from the work we have completed in this research project.

1.2 Background to the Project

The project, "**Ecological and Environmental Impacts of Large-scale Groundwater Development in the Table Mountain Group (TMG) Aquifer Systems**", forms part of a programme of research funded by the Water Research Commission (WRC) in partnership with Department of Water Affairs and Forestry (DWAF) on "**The hydrogeology of the TMG aquifers**". The programme was created in the light of possible future large-scale groundwater development of the TMG aquifer.

The full WRC TMG research programme has the following specific objectives:

1) Development of an understanding of the occurrence, attributes and dynamics of the TMG aquifer systems.
2) Development of an understanding of the environmental impacts of exploitation from TMG aquifer systems.
3) Integration of groundwater into the broader water management framework.

This project, known as the WRC TMG-Eco project, aims to initiate an assessment of the ecological role of groundwater in the TMG aquifer systems as a first contribution towards the Programme Objective 2 as stated above. Two sister projects have been undertaken by University of the Western Cape on recharge to the TMG (Xu et al., 2007) and flow mechanisms in the TMG (Lin and Xu, 2007; Xu et al., in progress).

The objectives of the WRCTMG-Eco project were as follows:

a) The development of predictive tools to assess the impact (or risk) of groundwater abstraction on the environment.
b) To improve our understanding of groundwater dependent ecosystems (GDEs) in the TMG and the sensitivity to groundwater level fluctuations.
c) The use of innovative techniques to determine the potential impact of groundwater abstraction on the environment.
d) The development of indicators to monitor the effect of abstraction on sensitive ecosystems.
e) Coupling time series and spatial databases in order to ascertain the impacts of low flows (groundwater and surface water interaction) on the environmental system.
f) Improved understanding of the impact of changing low flows on freshwater ecology.
g) Improved understanding of the relationship between surface flow, event discharge from high-lying TMG unconfined aquifers and deep confined-aquifer discharge in maintaining wetlands or seeps.
h) Improved understanding of subsurface TMG discharge in maintaining coastal plain wetlands and vleis.

Furthermore, the project aims to:

- use existing knowledge and develop existing study sites where possible;
- promote capacity building to strengthen the human resources available to monitor and manage possible water-resource developments of the TMG aquifer.

The project was divided into 4 phases: Scoping Phase; Field Work; Data Analysis; Integration and Reporting.

1.3 Rationale

This WRC project is running alongside a feasibility study, funded by the City of Cape Town, the “Table Mountain Group Aquifer Feasibility and Pilot Study” (CCT-TMGA), which is investigating the potential for large-scale water abstraction from the TMG aquifers for supply to Cape Town. This WRC –TMG Eco project was conceived to enable better scientific prediction of impacts of the proposed abstraction by the City of Cape Town from the TMG aquifer on groundwater dependent ecosystems. It began slightly earlier than the CCT-TMGA project and originally had a wider study area than that project, however, the geographical focus of the project has since been narrowed to be coincident with the target areas for exploration on the CCT-TMGA project.

It is the responsibility of the CCT-TMGA project to assess the actual impacts of pilot and full-scale abstraction for bulk water supply. This will be done by the CCT-TMGA project at abstraction monitoring sites, selected in the course of the exploration programme. This WRC project aims to characterize the ecohydrology of selected control sites (i.e. sites not likely to be impacted by abstraction by the CCT-TMGA project) in sub-quaternary catchments that receive groundwater discharge from the CCT-TMGA target aquifer(s), viz. the Peninsula and the Skurweberg aquifers. This project will establish groundwater and ecosystem monitoring at these selected control sites in advance of pilot scale abstraction. The results of this project will inform decision-making by the City as to the sensitivity of the natural environment to abstraction.

1.4 Aquifers and Ecosystems

A recent WRC report provides an introduction to the role that groundwater and aquifers play in the natural environment in South Africa (Colvin et al., 2007). Various habitats linked to aquifers are discussed including terrestrial vegetation, riparian zones, wetlands, aquatic ecosystems, and the coastal zone. Aquifers supply baseflow to perennial rivers to sustain flow during the dry season. In some seasonal or ephemeral rivers, the riverbed might be linked to an alluvial aquifer that supports riparian vegetation and permanent pools. The hydrology of wetlands may be complicated and they may act as recharge and discharge points, and be dependent on surface water flows, ponding rainfall or groundwater, or all at different times during the year.

Colvin et al. (2007) distinguish between groundwater dependent ecosystems (GDEs) and aquifer dependent ecosystems (ADEs). The term groundwater dependent ecosystem (GDE) is difficult to define and means different things in different countries. A broad definition is given by Murray (2006) "*Groundwater-dependent ecosystems (GDEs) are ecosystems that must have access to groundwater to maintain their ecological structure and function*". Scientific definitions of groundwater generally indicate all water in the saturated zone (e.g. DWAF on-line Groundwater Dictionary). Where groundwater is not clearly defined there can be confusion between hydrologists and ecologists. Sub-surface water in the saturated zone includes water stored in aquitards, perched water tables and temporarily saturated deep soil horizons. Groundwater, however, does not include subsurface water in the zone of aeration immediately above the water table, which can range from a few metres to tens of metres.

South African water legislation does not define the term groundwater but defines aquifers as "A geological formation which has structures or textures that hold water or permit appreciable water movement through them." (National Water Act, 1998). *Appreciable water* is usually taken to be enough water to supply a well or borehole.

Most of the current literature refers to GDEs based on an assumption that the groundwater is found in aquifers and can be abstracted. In South Africa, the term **Aquifer Dependent Ecosystem** (ADE) has been defined to avoid confusion about the primary source of water and indicates that these ecosystems are vulnerable to groundwater abstraction. Aquifer dependent ecosystems are ecosystems, which depend on groundwater in, or discharging from, an aquifer (Colvin et al., 2007). They are distinctive because of their connection to the aquifer and would be fundamentally altered in terms of their structure and functions if groundwater was no longer available. This distinction is important because ADEs may be impacted directly by large-scale groundwater abstraction. GDEs may be dependent on sub-surface sources of water at a range of permeability and storage time and spatial scales. ADEs are a subset of these that are dependent on subsurface water stored in strata, which are perennially saturated and are sufficiently permeable and have sufficient storage to be classified as aquifers. They may use other sources of water in addition to groundwater but are critically dependent on groundwater for drier periods or at least part of their life cycle. (See the glossary in Appendix J for a full definition of terms.)

The distinction of ADEs is often not easy in practice as the hydrogeological setting and sources of water in ecosystems are often unclear and change with time. Plants may make use of groundwater being discharged from aquifers, however they may be primarily dependent on soil moisture. There might also be a combination of different plant species within an ecosystem, tapping into different sources of water at different times, making a classification of this ecosystem difficult unless the impacts of abstraction are observed.

Evaluation of the potential impacts of water abstraction from TMG aquifer systems requires an understanding of the nature and extent of dependency of the ecosystems that use groundwater from this system. We need to keep in mind the following:

- demonstration of groundwater use does not necessarily equate to groundwater dependence;
- demonstration of groundwater use in general does not necessarily equate to use of TMG groundwater in particular;
- abstraction of water from the TMG aquifer will not necessarily affect the supply of TMG groundwater to a TMG-dependent ecosystem.

Often the exact nature of a groundwater dependency may only be realised once an ecosystem has been stressed beyond its range of tolerance of change. Groundwater dependence is not limited to the quantity of flows. It can also include dependence on the physical and chemical characteristics of the groundwater. Thus, different parameters may be important in assessing dependency in different ecosystems. For instance, the depth to the water table is likely to be an important hydrogeological parameter controlling the availability of groundwater to the terrestrial plant communities, but salinity gradients and distributions are an important parameter in estuaries.

1.5 Introduction to the Table Mountain Group Aquifer.

1.5.1 Stratigraphy

The Cape Supergroup, and Table Mountain Group (TMG) in particular, underlies and outcrops over a large portion of the Western Cape (see **Figure 1-1**). These faulted and folded sedimentary units form a large geological feature known as the Cape Fold Belt, which also extends into the Eastern and Northern Cape (see **Figure 1-1**). Approximately five to eight kilometres of quartzitic sand, clay and silt was deposited in a shallow marine environment within the Cape Basin between 500 Ma and 290 Ma, forming the Cape Supergroup following burial and lithification. The Cape Supergroup is composed of the Table Mountain, Bokkeveld and Witteberg Groups, although only the TMG will be discussed in detail.

The study area specifically focuses on the fractured quartzite aquifers of the Table Mountain Group, namely the Peninsula Formation and Nardouw Subgroup aquifers, in the vicinity of the Cape Fold Belt syntaxis in the south-eastern Western Cape (see **Figure 1-1**). The structural features of the Cape Fold Belt within the study area, namely NE-SW orientated anticlinal and synclinal fold axes and strike-slip, normal and reverse faulting, are the result of two tectonic events: the Cape Orogeny (~250 Ma) and break up of the Gondwana supercontinent (~180 Ma). These events led to the development of extensive, open folds and large fractures and faults in the brittle, more competent quartzite layers (e.g. Peninsula and Skurweberg Formations), and tighter folding in less competent shale layers (e.g. formations of the Bokkeveld Group).

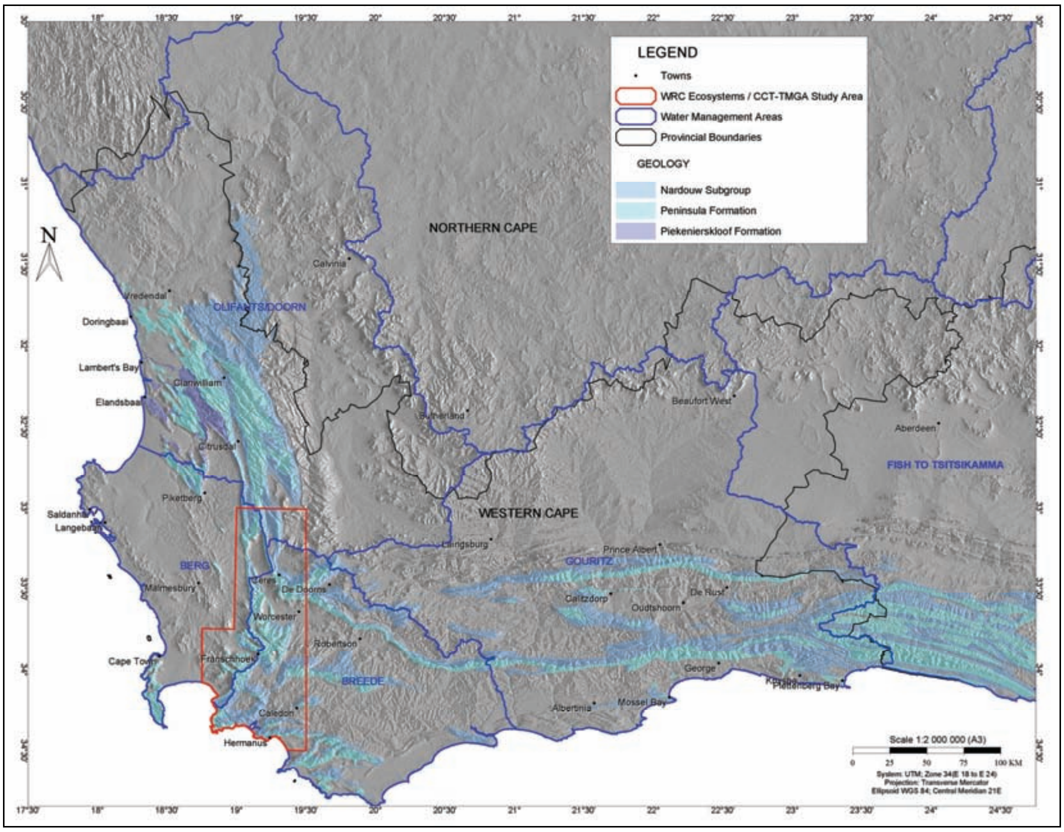

Figure 1-1 Extent of TMG formations and sub-groups in the Western Cape and the study area.

The TMG is subdivided into eight formations (see **Table 1-1**), with four (the Piekenierskloof, Peninsula, Skurweberg and Rietvlei Formations) forming fractured aquifers. The Piekenierskloof and Graafwater Formations are not present within the study area, and are henceforth ignored in this study. Fractured quartzites of the Peninsula Formation, which forms the main aquifer unit within the study area and the entire Cape Fold Belt, unconformably overlie basement rocks of the Malmesbury Group (> 555 Ma) and Cape Granite Suite (555-510 Ma). The Peninsula Formation forms the higher mountainous regions of the study area in the form of exposed anticlines and/or upfaulted blocks, due to the extremely resistant nature of the fractured quartzites.

Table 1-1 Lithostratigraphy[1] (after De Beer, 2002) and hydrostratigraphy[2] (after Hartnady and Hay, 2002) of the TMG (thickness values mostly apply to southwestern outcrops)

Lithostratigraphy			Lithology	Maximum thickness (m)	Hydrostratigraphy		
Group	Subgroup	Formation			Subunit	Unit	Super unit
Table Mountain	Nardouw	Rietvlei	feldspathic sandstone; minor shale at base	280	Rietvlei Subaquifer	Nardouw Aquifer	Table Mountain Superaquifer
					Verlorenvalley Mini-aquitard		
		Skurweberg	thickly bedded quartzitic sandstone	290	Skurweberg Subaquifer		
		Goudini	reddish brown quartzitic sandstone and siltstone	230	Goudini Meso-aquitard	Winterhoek Mega-aquitard	
		Cedarberg	dark grey shale and siltstone	120	Cedarberg Meso-aquitard		
		Pakhuis	diamictite and quartz sandstone	40	Pakhuis Mini-aquitard		
		Peninsula	thickly bedded quartzitic sandstone, finer towards base	1800	Platteklip Subaquifer	Peninsula Aquifer	
					Leeukop Subaquifer		
		Graafwater	siltstone and shale	420	Graafwater Meso-aquitard		
		Piekenierskloof	conglomerate, sandstone and minor shale	900	Piekenierskloof Subaquifer		

The Pakhuis, Cedarberg and Goudini Formations conformably overlie the Peninsula Formation and together constitute the Winterhoek Mega-aquitard, due to their impermeable, tillite-, shale- and siltstone-dominated lithologies. The fractured quartzites of the Skurweberg Formation conformably overlie the Goudini Formation, and form the other main regional aquifer unit. The Rietvlei Formation is fine grained, and has a high feldspathic content and low storativity, and hence is not considered as an exploitable aquifer. The Goudini, Skurweberg and Rietvlei Formations together constitute the Nardouw Subgroup, which topographically forms the lower to middle-relief areas below the mountainous Peninsula Formation ranges.

Younger, more erodable Bokkeveld Group shale and sandstone formations conformably overlie the Nardouw Subgroup, and form synclinal valley infills. A 136 Ma old dolerite dyke swarm termed the False Bay suite intrudes the Cape Supergroup in the vicinity of False Bay and Kogelberg, and may locally affect groundwater flow. Quaternary alluvium unconformably overlies the various Cape Supergroup lithologies, grading from TMG-derived boulders and coarse sands

[1] The sequence in which rock types are layered.
[2] The sequence in which hydrological units (aquifer, aquitard) are layered.

in the upper proximal source areas, to Bokkeveld-derived silts and sands in the more distal reaches.

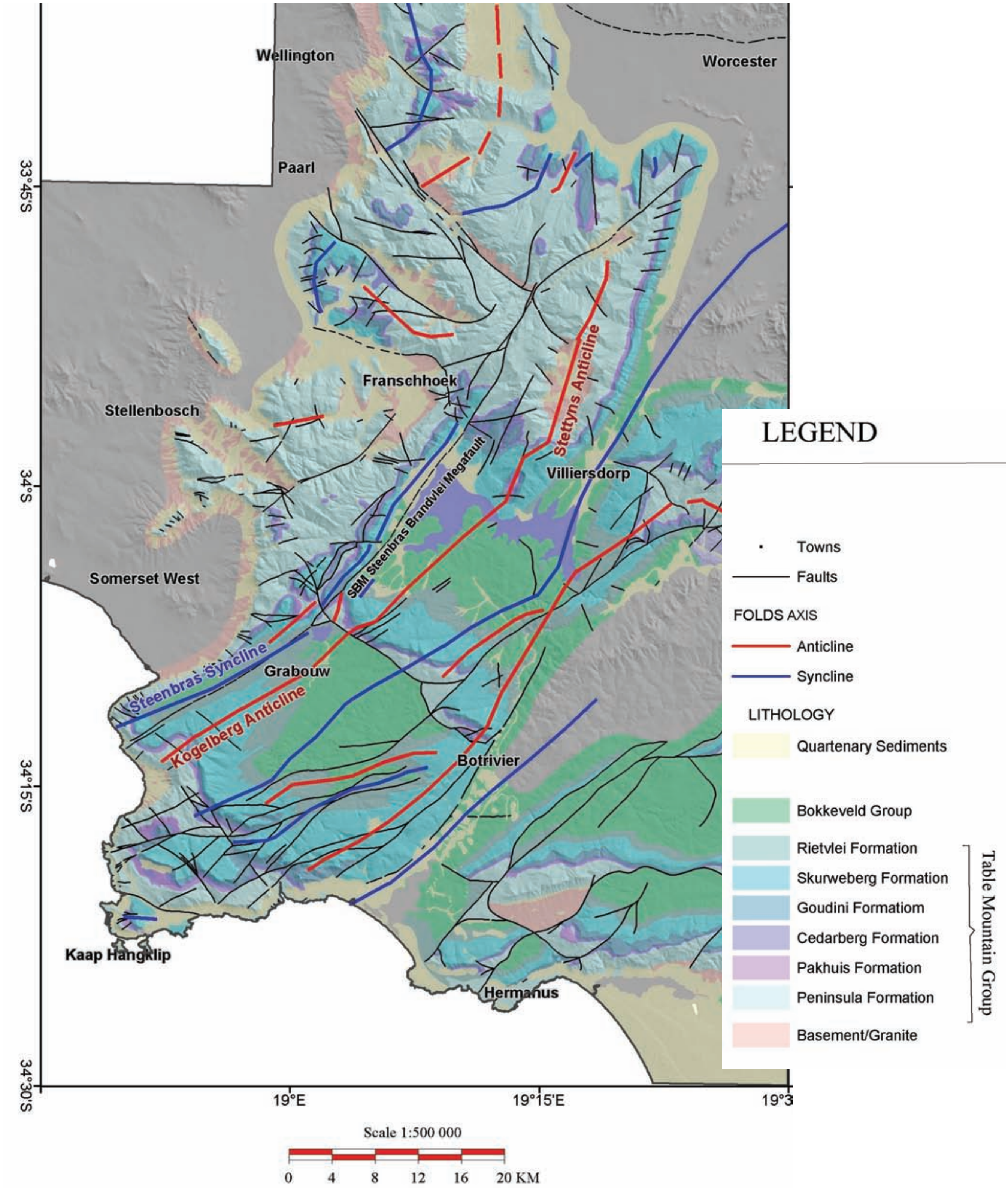

Figure 1-2 Geology of Study Area

1.5.2 Hydrogeology

The lithology and structural characteristics of the Cape Supergroup and TMG in particular control the flow of surface and groundwater in the study area. Main river systems generally flow parallel to the fold axes within the synclinal basins, whereas river tributaries trend parallel to the fracture and fault orientations, orthogonal to the fold axes. Channelled surface water flow from upper mountainous recharge areas via faults and fractures is important, as it realises the potential for surface water – groundwater interaction and localised aquifer recharge when surface water drains aquifer outcrop.

Both recharge and regional flow systems in the Peninsula and Skurweberg aquifers must be defined separately however, simply because of topographic and structural differences. The Peninsula Formation is the topographically dominant unit within the study area forming high continuous mountainous ranges and summit ridges. The Peninsula Aquifer hence receives the greatest amount of precipitation and has the greatest recharge potential, as a result of the strong orographic control on snow and rainfall in the Western Cape. This has been indicated by recharge estimates for the Peninsula Aquifer of up to 50% of mean annual precipitation (MAP) (Weaver et al., 1999). DWAF (2000) estimated the recharge in the Citrusdal area, with a spatially weighted average of 23% MAP. Xu et al. (2007) give recharge estimates for the whole TMG between 0.3% and 12.6%, with an average rate of 30 mm/a. The potential groundwater recharge for the Peninsula Formation aquifer in the study area is estimated to be of the order of 100 million m^3 or more per year (Umvoto, 2001). In contrast, the outcrop and hence recharge areas of the Skurweberg Formation generally underlie lower-range and hillslope areas alongside the higher Peninsula Formation mountain chains, mostly along northern or eastern, rain-shadow slopes (**Figure 1-1**). In comparison to the Peninsula Aquifer, therefore, the Skurweberg Subaquifer receives less precipitation and has a lower recharge potential, as evidenced by recharge estimates of approximately 5% MAP (Kammanassie Mountains; Kotze, 2001).

The Peninsula Aquifer is the thickest and most regionally extensive aquifer, and discharges large amounts of water at perennial and geothermal springs or into the ocean. The exposed, un- to semi-confined portions of the Peninsula Aquifer contribute to river flow mainly as direct surface runoff and interflow, but may also contribute to base flow where crossed by major rivers and mountain headwater streams. Due to the high recharge, and the semi-confined to confined nature of the Peninsula Aquifer around the Winterhoek aquitard contact, springs are generally perennial and are hardly or not at all affected by seasonal changes or groundwater abstraction within the confined portion. In comparison, the generally unconfined parts of the Skurweberg Subaquifer are characterised by low-volume, seasonal springs related to near-surface lithological and structural features, and are more responsive to rainfall events. The Skurweberg Formation also generally outcrops within synclinal basins, and can contribute to riverine baseflow via direct inflow into an overlying channel and through springs around the Winterhoek-Skurweberg aquitard-aquifer contact.

1.5.3 TMG aquifer discharge

The geological setting and geometry of the TMG aquifer requires a three-dimensional conceptual understanding of groundwater flow when evaluating flow paths and groundwater discharge into surface water bodies. The types of interaction with aquatic and terrestrial ecosystems can differ from the examples given above. Groundwater discharge is mostly discrete, locally restricted and directly linked to lineaments such as fractures and faults. Discharge may result in the formation of springs, headwater wetlands, seeps, valley wetlands and contribute to baseflow in rivers.

Groundwater flow paths within the TMG aquifer are commonly at depths of greater than 100 m below surface. The depth and capacity of the system is evidenced by the several perennial hot springs in the region with outflow temperatures of up to 64°C (e.g. Brandvlei). These temperatures are caused by the water being circulated to depths of at least 2000 m below ground level. All of the hot springs are fault controlled with approximately half situated on outcrops of the Peninsula Aquifer (Meyer, 2001). These fractures or fault zones act like conduits, transporting the water over a long distance in a very narrow zone.

An overview of the main TMG specific interactions between groundwater and ecosystems are described below. More background information is given in Appendix B1, the scoping document prepared to workshop TMG ADEs with a multi-disciplinary group of ecological and hydrological specialists.

1.5.3.1 River ecosystems

The groundwater fed river baseflow is mainly contributed by springs in the upper parts of the river system. Streams, rivers and estuaries may be indirectly connected to the TMG aquifers via alluvial aquifers and coastal plain deposits. Alluvium aquifers, which may feed into river or estuarine ecosystems, may receive contributions from high-lying portions of the TMG aquifer via springs and seep zones directly or indirectly after some surface flow. A WRC-funded study in the Kammanassie Mountains demonstrated the environmental importance of TMG aquifers, specifically related to in providing baseflow to the rivers (Cleaver *et al*., 2003).

Several of the rivers in the Fynbos rise in high altitude sponges where the waters are acid and dark in colour. Vegetation in the sponges consists mainly of Restonaceae and Bruniaceae. Generally the rivers are steep, fast flowing mountain streams running through Mountain Fynbos, whilst the lower reaches mainly flow through highly disturbed land, with concomitant effects on water quantity and quality.

One of the adaptions of fynbos vegetation to its harsh environment is the production of secondary plant compounds, which consist mainly of polyphenolics. These are thought to be manufactured by plants as antiherbivore "devices", as the loss of plant tissue to herbivores under harsh conditions is more stressful to a plant than under more mesic conditions. When fynbos litter decays the polyphenolics (or humic substances) are leached out of the dead tissue and into the soil (King *et al.*, 1979). From there they enter the groundwater and finally appear in the surface waters. Owing to the presence of the phenol groups, they behave as weak organic acids. Some classes of these substances are very dark in colour, resulting in waters in the fynbos biome being termed as "black water systems". The impact of fynbos is particularly evident in the case of restio marshes, seasonal wetlands, and acid blackwater lakelets.

Fynbos rivers can be divided into groups; those with clear, white, slightly acid waters such as the Olifants, Berg, Eerste and Breede and those with dark, very acid waters such as the Palmiet and Storms (Harrison and Agnew, 1962; Noble and Hemens ,1978). Generally the white rivers are longer, with clearly defined reaches, while the darker rivers undergo a rapid change from mountain stream to estuary. Most of the rivers change markedly in their physico-chemical character after leaving the mountains, with nutrients, turbidity and pH generally increasing.

1.5.3.2 Wetlands and spring ecosystems

Types of springs have been described by Kotze *et al.* (2001), Meyer (2001), Cleaver *et al.* (2002) and DWAF (2007). TMG springs are essentially controlled by either changes in permeability associated with faults or lithological (aquifer-aquitard) contacts. In the Discussion Document for the present study (WRC, 2003), five spring and groundwater flow-path settings were identified, namely:

1. Citrusdal "CAGE"-Type (fold and lithology controlled)
2. "Brandvlei"-Type (hot-spring fault led)
3. "Wemmershoek"-Type (fault bounded lithology controlled)
4. "Synclinal Aquifer"-Type (fault led)
5. "Voelvlei"-Type (synclinal aquifer and alluvium)

Schematic illustration of setting types 1, 3 and 4 are shown below (**Figure 1-3** to **Figure 1-5**, respectively).

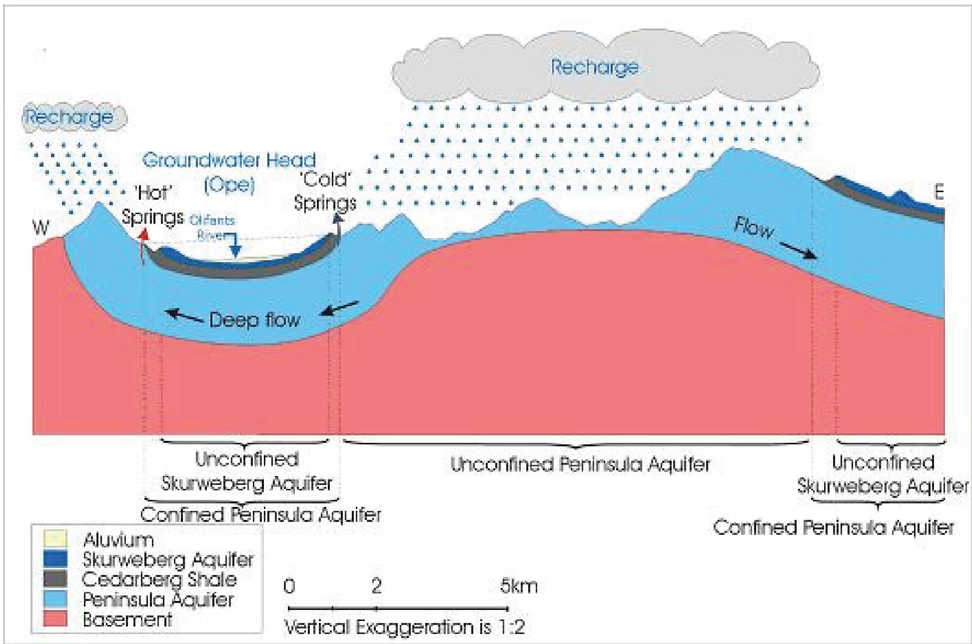

Figure 1-3 Citrusdal "CAGE"-Type (fold and lithology controlled)

Recharge to exposed Peninsula either side of a folded syncline. Cold spring discharge from short flow paths. Hot springs discharge from long, deep flow paths. Flow follows the folded formation and is focussed by faulting (parallel to cross-section).

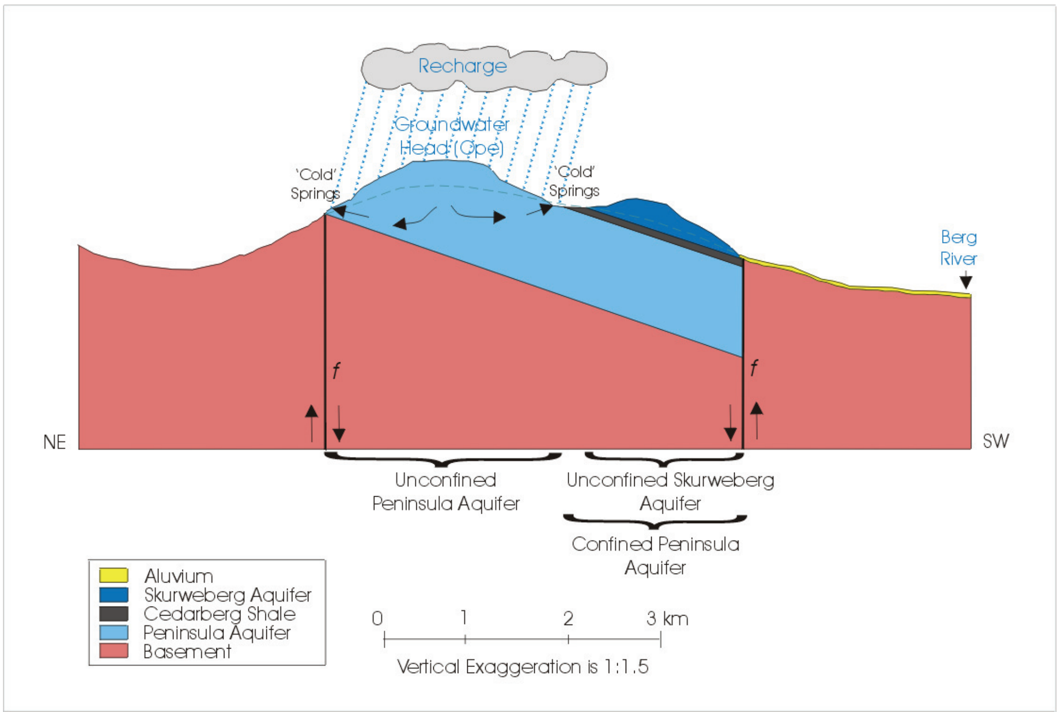

Figure 1-4 "Wemmershoek"–Type (fault bounded)

Faulting throws up impermeable basement. Short local flow paths. Discharge to springs at lithological contacts with impermeable basement and aquitard.

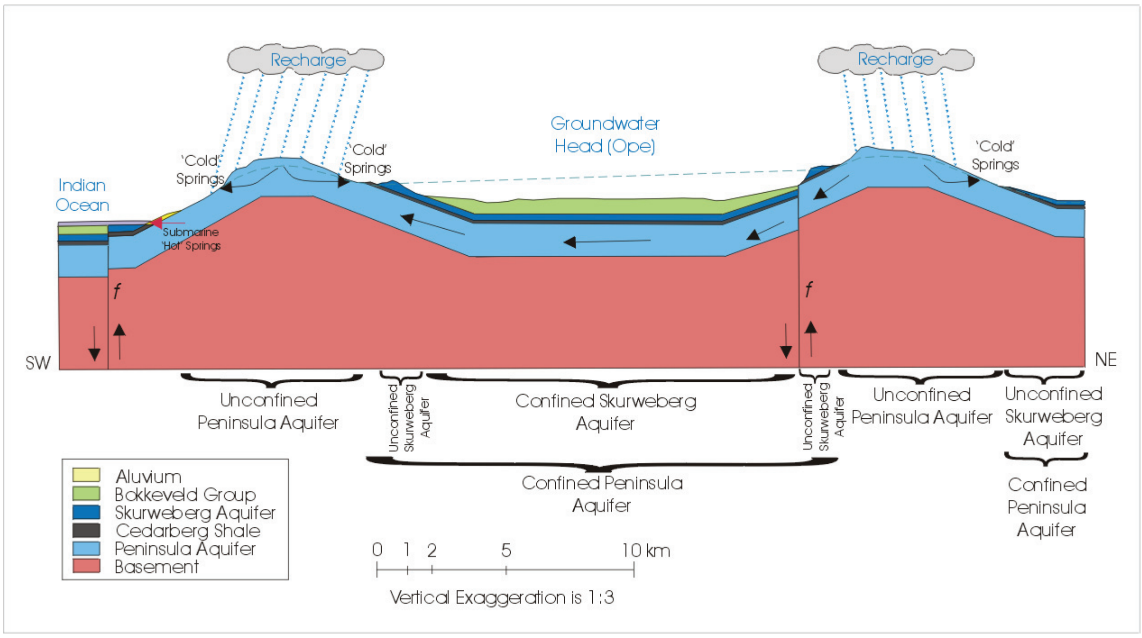

Figure 1-5 "Synclinal Aquifer"-Type (fault led)

Complex interaction of faults and folds. Short and long pathways to hot and cold springs, including coastal and sub-marine springs.

In the Kammanassie Nature Reserve study, three main types of springs were identified (**Figure 1-6**):

Type 1: Shallow seasonal springs and seeps emanating at perched water tables, which can be interpreted as interflow or rejected recharge.

Type 2: Lithologically controlled springs, due to the presence of inter-bedded aquitards, located mainly at the Peninsula - Cedarberg, Goudini – Skurweberg and Nardouw – Bokkeveld contacts.

Type 3: Fault controlled Springs (FCS).

Type 1 springs occur across the Peninsula and Nardouw aquifers, and are not connected to the greater groundwater flow system (Kotze, 2001). The springs seep from a network of fractures within the TMG aquifers directly above localised aquitards and are highly seasonal. According to Kotze (2001) groundwater abstraction from any part of the TMG aquifers should not impact Type 1 springs.

Type 2 and 3 springs are the most significant with regard to the regional water balance (Kotze, 2001). Type 2 refers to those emanating from contacts between Cedarberg shale aquitard and the Peninsula Aquifer, the different strata in the Nardouw group and the Nardouw and Bokkeveld shales, as well as unconformities. The Type 2 springs provide an important portion of the stream run-off in the form of groundwater-fed baseflow. Type 3 is represented by the hot springs. Both types can be impacted by groundwater abstraction provided there is interconnection and the spring occurs within the radius of influence of abstraction.

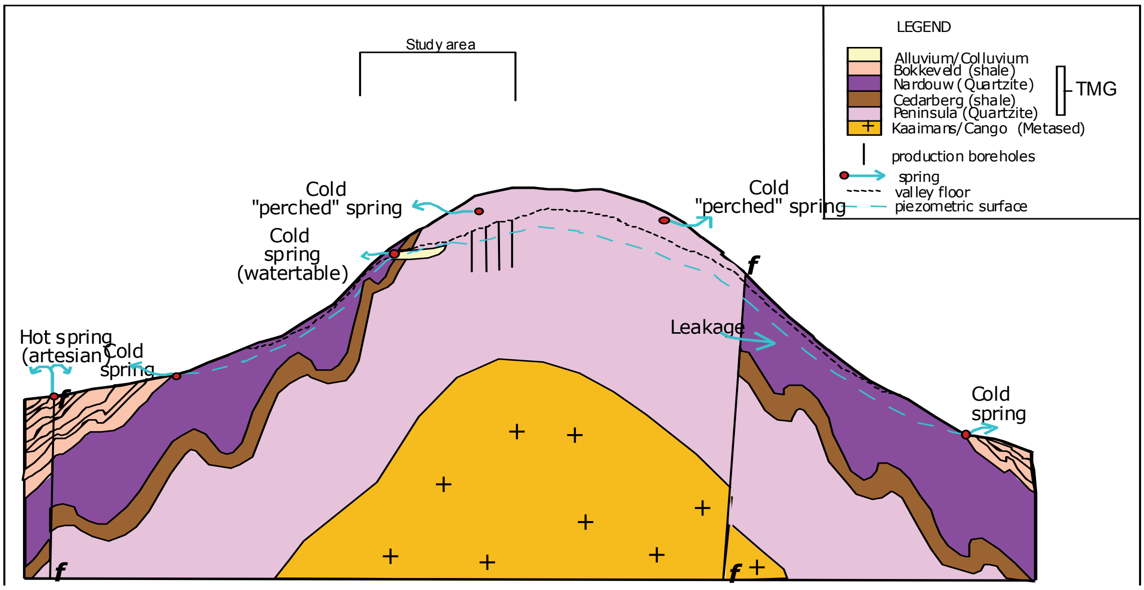

Figure 1-6 Typical spring localities in the Kammanassie area (Cleaver *et al.*, 2003)

Apart from the springs mentioned above, a number of high-lying wetlands occur in the high elevation areas of the TMG. Frequently these are dependent on ponded rainwater in the high rainfall, high-altitude areas and localised, perched water tables. These are not linked to aquifer flow paths.

Wetland communities in fynbos are often distinct from the adjacent communities in their structure and species composition. Many plant species are wetland specialists, including a number of species from the endemic families, notably the Bruniaceae and the Roridulaceae. Riparian fynbos often is characterised by a different species composition from the adjacent dryland communities and may develop into a gallery scrub and woodland comprised of species typical of the forest patches which occur in the sheltered kloofs.

This study examined springs, wetlands and seeps at the study sites. Plant water use as well as the hydrology of these localised systems was investigated to try and understand which were dependent on groundwater discharging from the TMG.

1.5.3.3 Aquifer and cave ecosystems

Subsurface water bodies and caves occur in certain formations within the Cape Supergroup (Mlisa, 2003). These caves are typical of those more usually found in karstic limestone formations and thus the Table Mountain Group is said to have a pseudokarstic character. They are likely to be important in TMG aquifer recharge and discharge patterns, and in particular in the distribution of highland seeps and localised occurrence of groundwater dependent ecosystems. However, in-aquifer and cave ecosystems were not examined at the study sites.

1.5.3.4 Terrestrial ecosystems

The typical vegetation in the high elevation areas, underlain by TMG formations, utilise rain, air moisture and soil moisture as their main water sources. Vegetation depending on groundwater is thought to be fairly localised and can be linked to springs, seep zones and perched wetlands. The results of this project (Chapter 3) throw up some interesting questions about plant water use and water availability in the terrestrial environment.

1.5.3.5 Marine ecosystems

Due to the physical character of the fractured TMG aquifers, discharge of groundwater directly into the sea occurs mostly at discrete points, which could provide small but important ecosystems. There are no known examples of direct groundwater discharge from the TMG into lagoons and estuaries. It is expected that discharge may occur from TMG fault zones into overlying coastal sands or alluvium, and indirectly contribute to the water tables in these primary aquifers. At one of our study sites we assessed a coastal plain wetland and it’s potential dependency on the TMG aquifer.

1.6 Approach to the project

The approach for the project was developed during the scoping phase in consultation with a range of specialists who attended the scoping workshop (Appendix B). The approach focussed on assessing the relationship between TMG aquifer discharge and the natural environment through field studies. In addition, relevant spatial data sets of the TMG area were collated to support the work of this project and the CoCT project. Remote sensing data was also used to develop a broader understanding of vegetation and geological patterns at the sites, beyond the point measurements of the field work.

Two sites were selected which were similar to hydrogeological regimes and discharge areas linked to possible large scale abstraction sites, and representative of the natural environment (section 1.7). The project focussed on two sites to reduce the risk to the project of floods and fire. New field data on the integrated hydrology and ecology of these sites were required in order to understand where groundwater is discharging, what is the relative contribution of groundwater to the ecological water budget and which components of the ecosystem are using TMG groundwater.

The first stage of the field work consisted of identifying potential GDEs within the study sites and developing conceptual models of the underlying hydrogeology and discharge regimes to guide the field sampling and mapping. To improve the understanding the project focussed on abiotic hydrological factors, and on the ecosystems most directly linked to groundwater discharge. The ecosystems this project focuses on are:

1) perennial wetlands directly linked to TMG groundwater discharge sites;
2) perennial rivers directly linked to TMG groundwater discharge sites;
3) seasonal wetlands and rivers directly linked to TMG groundwater discharge sites;
4) riparian vegetation linked to TMG groundwater discharge sites;
5) riverine ecosystems downgradient of TMG groundwater discharge sites.

Some of the key questions that were highlighted at the beginning of this project are listed below and grouped according to scientific disciplines.

Hydrogeological

- Where is groundwater discharging to the surface environment at the site (springs, seeps, cryptic discharge via vegetation, baseflow to rivers)?
- What is the pattern of groundwater discharge at the site over an annual cycle, in terms of timing, quantity and quality?
- What are the controls on groundwater discharge to the site with respect to natural aquifer boundary conditions such as recharge?

Aquatic Ecology

- Which river reaches are associated with groundwater discharge at the site?
- How does groundwater discharge influence the hydrochemistry of aquatic systems throughout one annual cycle?
- How does groundwater discharge contribute to the aquatic ecosystem structure and function?
- Are hyporheic zone processes and faunal assemblages influenced by groundwater discharge?

Wetland Ecology

- What are the composition, structure and function of wetland/ aquatic ecosystems associated with groundwater discharge at the site?
- To what degree are the groundwater associated ecosystems at the site representative of pristine indigenous ecosystems of the region?
- What are the functions of these ecosystems in relation to the broader terrestrial environment of the fynbos biome?
- Which plants and animals are most dependent on groundwater discharge and likely to be most affected by changes in the hydrogeological cycle?

Plant Physiology

- What degrees of water stress are experienced by the key species in these areas?
- What are the different sources of water used by plants at the site with respect to soil moisture, direct rainfall, surface run-off, interflow and groundwater, and how do these vary through an annual cycle?
- Which plants are most dependent on groundwater discharge and likely to be most affected by changes in the hydrogeological cycle?

In order to answer these questions the project focussed on:

1. Characterising the hydrogeology of the study sites and identifying probable discharge features and areas. This was done by reviewing remote sensing data, geophysical measurements of the sub-surface, drilling boreholes and augering shallow monitoring points at probable discharge locations, monitoring water levels and chemistry in ground and surface water.
2. Identifying ecosystems linked to aquifer discharge. This was done by monitoring surface water flows in relation to groundwater levels and rainfall, assessing potential tracers of groundwater discharge, monitoring plant water use, plant water stress at different times of the year and embolism vulnerability, monitoring aquatic invertebrate and diatom assemblages.
3. Understanding the nature of the dependency of the link to groundwater and inferring possible consequences of change in the flow regimes. This was carried out in the interpretation of the field results and the integration of the physical, chemical and biological information derived.

The boreholes that were installed for this project are for monitoring purposes only and groundwater abstraction is not permitted. This project has attempted to assess the role of groundwater in the natural environment and has not examined the consequences of large scale groundwater abstraction and the ecological responses to the change in flow. This may happen in the future as the CoCT begin testing possible abstraction boreholes.

1.7 Study site selection

The criteria for selecting sites for fieldwork in this WRC TMG-Eco project were dependent upon the links with the CCT-TMG project. Since the final abstraction sites for the CCT-TMG project were not decided upon during the course of this project, the fieldwork for the WRC-Eco project focussed on control sites. Control sites were defined as sites that are similar to the hydrogeological and ecological settings of discharge zones linked to the proposed abstraction sites but where abstraction is unlikely to be targeted. It was also accepted that there is a likelihood that the sites chosen as control sites may become a far-field monitoring sites should any of the abstraction sites be chosen on geological features shared by the control site. An example of this is the Kogelberg Area (K1), which could be affected by abstractions in the T6/T7 areas above Grabouw.

The hydrogeological criteria for the control sites were as follows:

- evidence of natural groundwater discharge from the TMG aquifer;
- as little groundwater use as possible in the catchment;
- existing measurement infrastructure (e.g. stream gauges);
- no known plans for bulk-water future groundwater abstraction;
- good access for drilling rigs and security for long term monitoring.

The ecological criteria for the control sites were that each site was:

- ecologically undisturbed, in particular with respect to seep zones, streams and vegetation;
- mirrored, as closely as possible, the conditions at the proposed abstraction sites with respect to geology, hydrogeology, wetlands, perennial streams, altitude, slope and aspect, climate, rainfall, catchment size, vegetation and habitat.

These criteria were used to identify potential control sites in the wider study area on a desktop level, using the GIS database. Six possible control and far-field monitoring sites were short-listed (see **Figure 1-7**). These were:

- Voelvlei (V3)
- Villiersdorp, Silverstream
- Elandskloof, DeVlakte
- Steenbras (H6)
- Theewaterskloof (T8), Purgatory
- Kogelberg (K1).

Final site selection was completed in early 2004. The short-listed control sites/far-field monitoring sites were reviewed, and the sites in the Du Toits River Valley (Theewaterskloof, T8; Purgatory wetlands) and Riviersonderend Mountains (Villiersdorp, Silverstream) were revisited. In the interim, the Riviersonderend Mountains site had been severely burnt in a fire and was deemed not to be suitable for monitoring. As a result Kogelberg and Purgatory were chosen as the final control sites/far-field monitoring sites. Both sites lie on land owned and managed by the Western Cape Nature Conservation Board (WCNCB) which was seen as a considerable benefit for the long-term outcomes of the project, as monitoring is expected to continue beyond the extent of this study. Furthermore, both sites are also in protected areas.

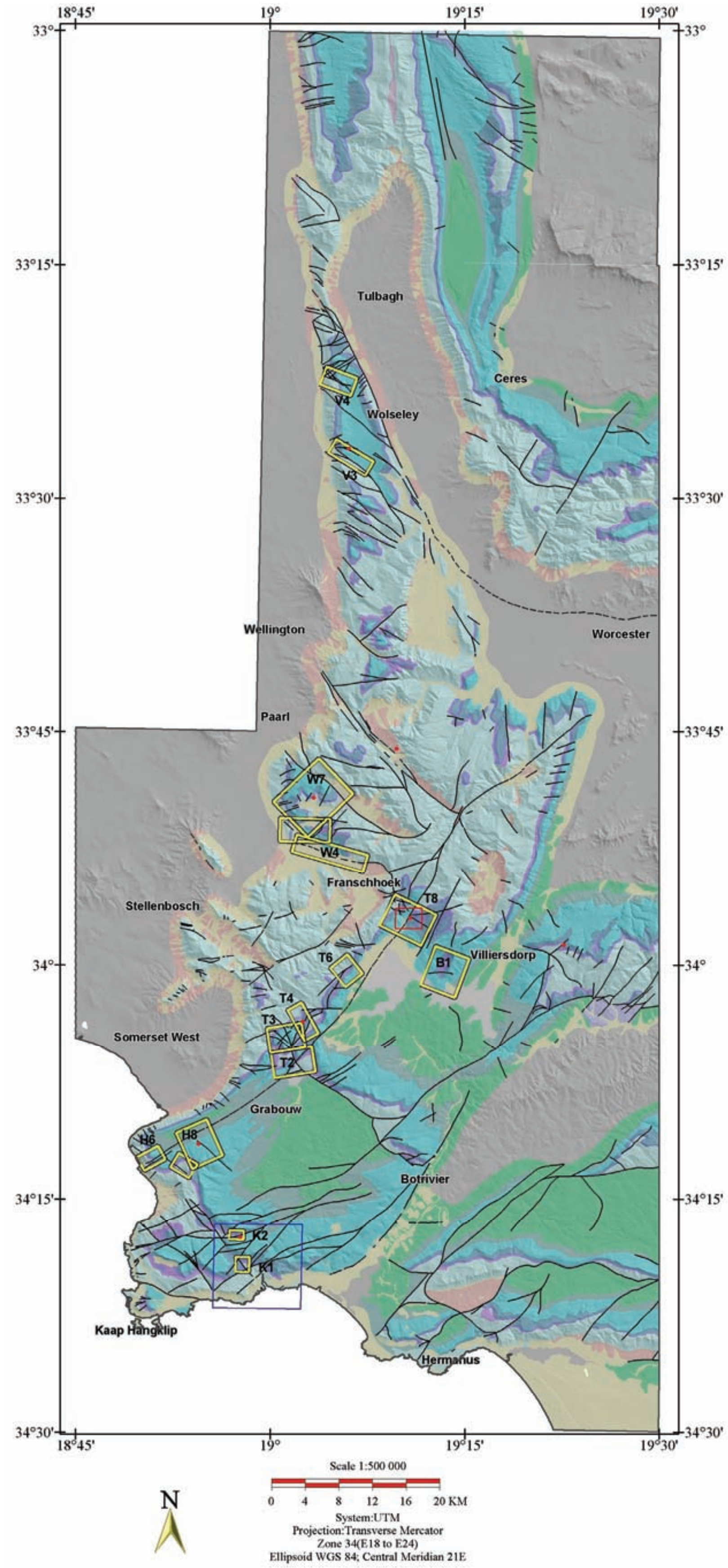

Figure 1-7 Study Site Selection

1.8 Project Environmental Management

One of the key constraints on conducting this project was the ability to install the necessary monitoring infrastructure, especially boreholes, in ecologically sensitive areas. Key stakeholders were concerned that drilling would be destructive to the environment, that the boreholes may be misused in the future for abstraction purposes and that repeated visits to monitoring points would damage the local environment. It was necessary to discuss the environmental management and sensitivity of the project with several stakeholders to ensure that the project did not breach EIA regulations and to develop a comprehensive EMP.

Discussions were held in September 2003 between the project team, the WRC and the provincial Department for Environmental Affairs and Development Planning (DEA&DP) on the planned activities of the project and the requirements for environmental management plans or licensing under the Environmental Impact Assessment (EIA) regulations. The team described the aims of the project, the possible sites and the process to establish monitoring boreholes. Concerns had been raised during the scoping phase that an EIA would be required to establish and pump test monitoring boreholes. It was concluded that:

- The drilling and monitoring activities themselves do not constitute listed activities in terms of the EIA Regulations. However, if the upgrading or construction of an access road is required, this is a listed activity.
- The project team is to proceed with the selection process for the monitoring control sites, taking into consideration the feedback provided by DEADP.
- The WRC team will provide DEADP with a draft EMP for comment and provide the opportunity for a site visit.

As a result of these discussions, the team was able to proceed with selecting environmentally pristine areas for control monitoring as long as vehicular access was restricted to existing roads, strict environmental management was enforced during drilling and sampling and stakeholders were involved in the planning of the monitoring activities.

The full environmental management plan was developed following consultation with SANParks (on a parallel WRC project), WCNCB and DEA&DP. It is included in full in Appendix B. It mainly covers activities associated with the drilling and installation of monitoring boreholes.

Chapter 2:

Methods

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2. METHODS

The first part of this chapter deals with the spatial data collated to support this study and the remote sensing data that was used to identify vegetation linked to the TMG aquifer. The rest of this chapter describes the methods used to acquire new field data. We established integrated monitoring networks at each of the field study sites to examine water flows and use in the catchments. This required drilling boreholes, augering piezometers, securing piezometers in the streams, setting up weather stations and cumulative rainfall samplers at different altitudes in the catchments. Boreholes, the weather stations and piezometers therefore form the fixed network which is designed to continue monitoring after the lifetime of this project. In addition, temporary monitoring methods were used to measure the resistivity of the sub-surface, surface water flow, aquatic invertebrates and diatoms, plant water use and plant communities.

2.1 GIS Database development

A comprehensive GIS database was developed to support the integration of data sets from different disciplines. Additionally, a spatial decision support tool was developed to enhance the communication between the disciplines.

For the development of the GIS database, it was required to undertake several related activities so that the final database would prove useful to researchers and others involved in assessing the impact of groundwater abstraction on GDEs. These were:

- A data audit.
- A requirement analysis.
- Development of a database management protocol.

On completion of these, the database structure was finalised and the relevant data uploaded. The completed GIS Database is attached as Appendix A.

2.1.1 Spatial Decision Support System

The requirements analysis informed the planning and development of the Table Mountain Group Aquifer Spatial Decision Support System (TMGA SDSS), which was developed by Mlisa (2007). The TMGA SDSS was developed using TNTmips v70, Extensible Markup Language (XML) and Spatial Manipulation Language (SML) and can be run on TNTAtlas v70, which is free software.

The user interface for the TMGA SDSS has a two-fold design. The first part of the interface is the front end of the GIS, and is termed the Atlas. The second part of the interface links the user to the GIS data and the spatial analytical tools.

One of the challenges and motivations that supported the building of the TMGA SDSS was to make spatial data available to the project team in a structured manner. The Atlas allows for the data to be presented in a structured way, thereby making it easy for the user to find the data and view it. The Atlas acts as a user interface, as the user is unable to see where the data are actually stored or what its format is. He/she therefore does not need to know how the data are structured in the actual GIS as the data have already been structured and prepared for viewing in a user-friendly way.

Based on the user requirements, four main spatial analytical routines were developed, namely

- Borehole analysis
- Topographic analysis
- Sensitive area analysis
- Image classification.

2.1.2 Database Management Protocol

In a multidisciplinary team, working at different locations with different software, data sharing is critical to integrated problem conceptualisation and solving. The challenges to data sharing include:

- maintaining the data integrity;
- ensuring data quality and access to users of different level of skill, insight and security clearance;
- standardisation in quality, georeferencing and completeness;
- updating and quality control of additional data and meta data sets supplied to the data base;
- variation in presentation style between different disciplines;
- respecting copyright and protecting intellectual property rights

In order to address these challenges, standards and protocols were set for data input and distribution. These are summarised in the Database Management Protocol (see Appendix A.2), which was adopted for this study.

2.2 Remote Sensing methods

The description of the method in this section is taken from J. Engelbrecht (2005) which is given in full in Appendix H. Groundwater-fed wetlands in the area are expected to exhibit significant spectral differences to surrounding vegetation. This is due to the fact that groundwater-fed wetlands are expected to remain water saturated throughout the year, causing the wetland vegetation to remain wetter and greener, even after the dry season. Other natural vegetated areas are expected to experience a certain degree of moisture deficiency, especially after the dry season. Therefore, multi-temporal images (one at the end of the wet season, and one at the end of the dry season) for each year are desirable. The second important aspect, when using optical images, such as Landsat, is to have cloud-free images.

Table 2-1 Image data to be used for wetland change detection

Image Dates	Landsat Sensor	Spatial resolution	Preprocessing level	Other
21 Oct 2001, 18 May 2002, 23 Sep 2002	ETM +	30 m (Bands 1-6) 15 m Panchromatic 30 m Thermal	Level 1G: Geometrically rectified product free from distortions from sensor, satellite and earth	WRS: 175/84 UTM Zone 34, Ref. ellipse: WGS 84

The procedures for the remote sensing analysis adopted in this study include:

- Kauth-Thomas (KT) transformation or tasseled cap Index
- Multispectral vegetation indices
- Change vector analysis

Kauth-Thomas transformation

The Kauth-Thomas (KT) transformation, also known as the tasseled cap transformation, is based on a linear model similar to a principal component analysis (PCA), which considers the spectral variations common to a data set and separates the variability into discrete, non-correlated components. The KT transformation reduces several TM bands into three main components namely:

1. Brightness, which is the weighted sum of all bands and is designed to capture the main trend of variation in soil reflectance,
2. Greenness contrasts the near infrared and visible bands; which is related to the amount of healthy green vegetation present in the scene, and
3. Wetness, the third component, is associated with canopy and soil moisture.

The tasseled cap components are expected to provide a means of discriminating between wetland and non-wetland vegetation classes. Wetland vegetation classes are expected to remain wetter and greener throughout the year in comparison with non-wetland vegetation, especially after the dry season. Two images can then be compared, and change pairs can be computed by differencing images on each of the three tasseled cap components (see section below).

Vegetation indices

Multispectral vegetation indices derived from vegetation reflectance values are known to be valuable in the monitoring of plant growth responses in relation to other measured or predicted climate variables. The most commonly used vegetation indices are based on the rationing strategy, using band ratios of different spectral bands from the same image, in particular the normalized difference vegetation index (NDVI).

Vegetation indices provide quantitative measures of plant biomass or vegetative vigour that can be derived from combinations of spectral bands that can be added, subtracted, multiplied or divided in order to yield a single value that is indicative of the vegetation vigour within a pixel. Higher values would reflect a condition with a high density of healthy vegetation, while lower values would indicate either a lower density of vegetation, or stressed vegetation. The theory is that different plant clusters will have different spectral signatures, so that wetland species can be differentiated from other species in a single image. Variations in the spectral signature for specific species will then provide an indication of stress being experienced, possibly as a result of moisture deficiency.

Change Vector Analysis

Two vegetation index images of different seasons within a year can then be compared in order to determine the change in productivity of the species during an annual cycle. Theoretically, since groundwater seeps remain saturated throughout the year, groundwater dependent species would show a lesser degree of seasonal variation in productivity than other species.

While change vector analysis can be used to detect a variety of changes, this study was only concerned with change related to different degrees of groundwater interaction. In the case of perennial groundwater dependency, a low degree of changes is expected during an annual cycle. The perennial groundwater-dependent ecosystems will remain consistently moisture enriched (low degree of change in wetness component and moisture stress index) and, consequently, consistently productive (low degree of change in productivity index). When these change detection strategies are applied in a monitoring exercise, significant changes experienced in known wetland communities may reveal unnatural fluctuations in groundwater availability to these communities, and the necessary corrective steps can be taken. In the case of non-perennial wetlands, significant changes in moisture stress index and wetness component are expected during the annual cycle. The proximity of these communities to perennial groundwater-dependent communities may be an indication of wetland expansion due to additional water availability from precipitation during the wet period.

2.3 Field Data Collection

2.3.1 Survey of monitoring points

All groundwater monitoring points at the two sites were surveyed in April 2005 by R. Vonk of the CSIR to obtain accurate height measurements. A Leica differential Global Positioning System 1200 was used which has Z accuracy of < 1 cm. The results are given in Appendices D 9 and E 9.

Figure 2-1 The Campell automatic weather station with relative humidity probes, temperature, wind speed and rain gauge.

2.3.2 Climate data collection

Climate data was collected with a Campell automatic weather station at each study site, as shown in Figure 2-1. Each tripod is fitted with a solar panel, a data logger and sensors for wind direction and speed, temperature, relative humidity and a tipping bucket rain gauge. Measurements are recorded on an hourly basis. At Purgatory, the tripod is surrounded by a fence and barbed wire to prevent tampering by baboons. This, however, could not protect it from the fire in the area and minor damage was incurred at that time.

At Kogelberg, the weather station is in the Oudebos valley close to the Reserve offices and can be downloaded by the park manager.

2.3.2.1 Rainfall collectors

In addition to the rain gauge at the weather stations, cumulative rainfall samplers were set up at three different altitudes in each study site to collect samples for isotopic analysis. These cumulative rainfall collectors are constructed by the CSIR from stainless steel with a uPVC sheath. The funnel has a gauze and ping-pong ball 'valve' to prevent solids entering the collector. Silicon oil is added to the collector to prevent evaporation from the sample.

2.3.3 Geophysics

Electrical resistivity traverses were carried out at both field sites to gain a better understanding of the subsurface structures and heterogeneity. Targets included a wetland on valley fault structure, a hillslope wetland at the intersection of lineaments (fractures) in the Peninsula quartzite, and a wetland on the lithological contact between the Cedarberg shale and the Nardouw quartzites.

The Lund imaging system was used, consisting of the SAS1000 resistivity unit, the ES464 switching unit, multi-core cables and electrodes, The Lund imaging system is automated and pre-designed protocols are used to optimise data coverage for specific profiles, e.g. for groundwater flow regimes. Multi-core cables with two-metre electrode spacing were used to improve data coverage and quality at shallow depths. Ten metre spaced electrodes were used on the longer traverses to measure the deeper sub-surface. A full description of the methods, protocols and data quality control procedures are given in Appendix F.

2.3.4 Drilling

The drilling was conducted by JJ Myburgh and Brothers between September 2004 and March 2005, with intermittent breaks. A total of 8 boreholes were drilled with the standard 'down the hole hammer' rig, one borehole with a telescopic ODEX rig and 9 boreholes with the smaller portable rig. The drilling was conducted under continuous supervision, as requested by the WCNCB and the Environmental Monitoring Plan. The on-site geohydrologist acted as the Environmental Control Office in order to comply with the EMP.

The large diameter boreholes were drilled initially at 305 mm diameter in Purgatory and 250 mm at Kogelberg and finished with a diameter of 250 mm and 190 mm respectively. Steel casing was grouted into the upper section in the unsaturated zone, generally for the top 6 to 18 m, so that the boreholes could be closed in the event of artesian water strikes. Below the casing the holes were drilled into the hard formation and uncased. The ODEX rig was used to drill through unconsolidated boulders and sand to bedrock (18mbgl) at the coastal site (Stroompie) near Kogelberg. Steel casing was grouted into place, sealing off the upper unconsolidated formations. The portable rig drilled from 110 mm diameter to 75 mm diameter holes to a maximum depth of 30mbgl. Steel casing was similarly grouted into place in the upper 3 m to 6 m of the boreholes.

The portable rig was specially constructed to enable drilling monitoring boreholes of on slopes and in areas not accessible to a drilling rig. The portable rig was connected to a truck-mounted compressor by a 300 m long umbilical high-pressure hose, so drilling was restricted to within 300 m of an existing track. The rig could be carried and constructed on site by four men. Figure 2-2 shows the portable rig drilling at Kogelberg K7 (right) and the standard rig drilling at K3 (left).

Figure 2-2 Drilling at Kogelberg with the standard ‘down the hole’ hammer rig (left) and the portable rig (right)

The boreholes were flushed following drilling using compressed air to develop the holes for approximately one hour. No drilling muds were used. The boreholes were either fitted with a lockable cap on top of the steel casing and those close to the road at Kogelberg were encased below man-hole covers level with the road.

Boreholes were hand augered at some sites (inaccessible to the drill rigs) to emplace shallow piezometers in wetlands or the riparian zone. The augering was frequently impeded by the presence of boulders. 50 mm ID uPVC casing was installed in these piezometers, typically with 1 m screened at the base and end-caps at the top and bottom.

2.3.5 Groundwater monitoring

Groundwater level monitoring comprised of different measurements at varying time intervals as shown in Table 2-2.

Manual measurements of water level were undertaken seasonally over one annual cycle at all boreholes and piezometers. The measurements were taken from the top of the casing or a marked point on the borehole casing, to ensure measurements are accurate and that consecutive measurements are made from the same point. Water level measurements at each borehole and piezometer are conducted with a dip meter.

Table 2-2 Field data collection activities, periods and frequencies

Discipline	Activity	Time Period	Frequency
Climate	Rainfall	Aug 2004-June 2007	Hourly
	Temperature, etc.	Aug 2004-June 2007	Hourly
Groundwater Monitoring	Water level – manual (piezometers)	Jan 2005-May 2006	Monthly to seasonally
	Water level – continuous (boreholes and piezos)	Mar 2005-July 2007	Bi-Hourly
	Water chemistry (pH, EC)	Jan 2005-May 2006	Seasonally
	Water chemistry (macro ions, Fe, Mn, SiO_2)	Jan 2005-May 2006	Seasonally
	Stable isotopes	August 2004-July 2005	Seasonal
	Rn radioactivity	August 2005 & November 2007	Intermittent
Surface Water Monitoring	Discharge measurements with a flow meter	June 2004-Sept 2005	Minimum of every 6 weeks
	Fixed point flow measurements (Rated section)	Not included – only established in May 2005, and calibrated between May and October 2005.	
	Fixed point water levels measurements (Divers)	July 2005-May 2007	Hourly
	Macro-ion Chemistry	May 2007	Once off
	Isotopes	May 2007	Once off
	Macroinvertebrates	June 2004-May 2005	Three data collections
	Diatoms	June 2004-May 2005	Three data collections
Botanical Monitoring	Plant water stress Plant water use Embolism vulnerability Wetland community mapping	August 2004-July 2005	Seasonal Seasonal Once off Once off

To collect water level data at closer intervals than possible with manual measurements, automatic dataloggers are installed in selected boreholes. Two types of dataloggers were used, *viz*. the Diver from Van Essen Instruments for boreholes with water level below ground and a pressure transducer from STS for the two artesian boreholes.

Diver-type automatic dataloggers were activated with the Logger Data Manager (LDM) computer programme before they are lowered into boreholes and the monitoring frequency set. We used the divers with a maximum operating depth of 5 m below the water surface to ensure reasonable accuracy of < 1 cm. The Diver dataloggers were securely fastened to borehole covers with fishing line (20 kg breaking strength) or steel cable and lowered to the appropriate depth, which is selected at 2 m below the water level to accommodate any rise or fall in water level during the measurement period. To download the data, the Diver is pulled up and out of the borehole, and connected to the laptop via a special adaptor socket. The LDM program then downloads the data onto the computer hard drive. Water level data are presented in the appendices.

Barometric dataloggers were installed in order to correct changes in water pressure with changes in atmospheric pressure. The LDM software allows for automatic compensation of atmospheric pressure to reflect correct water level changes. Baro-divers were installed at Kogelberg and Purgatory, however, problems were experienced with both of these divers and barometric compensation data for 2006/07 is not available.

A special datalogger from STS is mounted in an iron casing on top of the sealed artesian boreholes to measure the artesian pressure within the borehole. The borehole must be sealed properly. To activate the datalogger and download the data a software programme from STS is to be used. No additional correction for atmospheric pressure changes is required.

2.3.6 Surface water flow monitoring

2.3.6.1 Discharge measurements

Discharge was measured using one of two methods:

- McBinny electromagnetic flow meter;
- rated section.

In addition, the flow record from the DWAF gauging weir on the Palmiet River at the head of the estuary was obtained, in order to provide some comparison between the local measurements collected at the Kogelberg site and those for the Palmiet Catchment as a whole.

Discharge measurements using the McBinny electromagnetic flow meter

At each site a point with minimal velocity variation across the section was selected. Standard flow sampling techniques were used at most sites, *viz*.:

- A tape measure was laid at right angles to the direction of flow, forming a single transect across the stream.
- Measurements of flow velocity were recorded using a McBinny electromagnetic flow meter at incremental distances along the flow transect. Each flow measurement was recorded at $6/10^{ths}$ depth (calculated using a top-setting wading rod).
- A depth reading associated with each flow measurement was recorded.
- Discharge was calculated by multiplying distance along the flow transect, by depth and then multiplying the result by the flow velocity, over that distance. The discharge for each incremental distance along the flow transect are then summed to get a total discharge for the site.

Where the discharge at a site was too small to measure with the flow meter, the time taken to fill a 500 ml bottle was recorded, and discharge subsequently calculated.

Discharge measurements were made on roughly a six-week basis starting from July 2004 until September 2005.

Fixed-point flow monitoring (Rated section on Oudebos River)

A stage:discharge relationship was developed for a section across the Oudebos River at the Kogelberg site. To facilitate accurate measurement of water height (stage), three steel pegs (bottom, middle and upper) were placed on the section at different distances away from the right waters edge, with the 'bottom' peg closest to the water and 'upper' furthest. Discharge was calculated by measuring the distance from right waters edge to the closest peg. Discharge was then calculated using the rating curve developed for the section.

The rated section was used during the Event Stage. Readings were collected from discharge measurements were made on roughly a six-week basis starting from July 2004 until September 2005.

2.3.6.2 Fixed point water levels

Diver dataloggers were installed at two points in the Oudebosch River at Kogelberg and at two points at Purgatory. The Divers were encased in L-shaped plastic piezometer screen casing pipes with 7 cm diameter, which were placed in pools in the stream channel with screen sections below the water level. The divers were attached to the top of the plastic pipes using fishing line, and positioned below the low water level in the vertical sections of the pipe.

Figure 2-3 L-shaped piezometer installed in a permanent pool in the Oudebos tributary at Kogelberg to house an automated water level data-logger.

A Diver datalogger measures the absolute value (height) of a water column by measuring water pressure with a built-in pressure sensor (Van Essen Instruments 2003). The value can be related to a reference point, in this instance, the top of the holding pipe. For this reason, the measurements of the surface water level in the holding pipes were taken.

During heavy floods in 2006 one of the stream data loggers at Purgatory and one at Kogelberg were lost.

Note: *The non-uniform nature of the streams and their poor suitability for automatic flow measurements means that the automatic water level data are not useful as a record of absolute discharge. Nonetheless, the data are useful in providing a near-continuous record of relative water fluctuations at each of the monitoring points, which can then be related to precipitation and water level variations.*

2.3.7 Water sampling and analysis

2.3.7.1 Sampling

Groundwater sampling was carried out by members of the project team according to best practice (Weaver *et al.*, 2007). The rest water level was first measured. 50 mm diameter piezometers were bailed (approximately 3 volumes or until they had dried out and recovered) and samples stored in 250 ml plastic bottles filled to the top in a cool bag during transport and in the fridge whilst awaiting analysis. The boreholes were sampled using a submersible pump and were pumped for approximately half an hour. The artesian boreholes were sampled by opening the valve for approximately 20 minutes and allowing a free flow of water. Temperature and EC measurements were made during pumping and bailing to determine when these parameters stabilised, indicating that water stored in the borehole had been removed.

Surface water samples were taken in pools and the river away from the banks in the centre of the water column using the same 250 ml bottles filled to the top.

Isotope analysis

Oxygen and Deuterium

Groundwater and surface water samples for oxygen and deuterium analysis were collected with other chemical samples, following purging by bailing from piezometers and pumping from boreholes. The samples were stored in screw top 250 ml plastic bottles filled to the top, in a cooler bag in the field and then in a fridge. Samples for isotope analysis were decanted into 40 ml vials and couriered overnight to the isotope laboratory at the CSIR, Pretoria, where they were analysed by a mass spectrometer. In addition, water samples from wetlands and plant water samples were collected and analysed at the University of Cape Town (UCT) as described in section 2.3.9.

Table 2-3 Analytical methods used for solute analyses, detection limits and accuracy.

Solute	Method	Detection limit	Accuracy
Potassium as K mg/L	Inductively Couple Plasma Optical Emission Spectrometry (ICP OES)	0.25 mg/L	% Relative Deviation (% R Dev) on 3.75 mg/L is 0.2%
Sodium as Na mg/L	ICP OES	1.25 mg/L	% R Dev on 12.5 mg/L is 1.4%
Calcium as Ca mg/L	ICP OES	0.25 mg/L	% R Dev on 12.5 mg/L is 0.64%
Magnesium as Mg mg/L	ICP OES	0.25 mg/L	% R Dev on 3.75 mg/L is 0.77%
Ammonia as N mg/L	Flow Injection Analysis	0.1 mg/L	1 mg/l for range 5-20 mg/L
Sulphate as SO4 mg/L	Turbidimetric Method	0.5 mg/L	1 mg/l for range 5-50 mg/L
Chloride as Cl mg/L	Automated Ferricyanide Method	1 mg/L	2 mg/l for range 5-50 mg/L
Alkalinity as CaCO3 mg/L	Potentiometric Titration	-	1 mg/l for range 5-50 mg/L
Nitrate plus nitrite as N mg/L	Automated Cadmium Reduction	0.05 mg/L	1 mg/L for range 5-20 mg/L
Iron as Fe mg/L (Total)	ICP OES	0.05 mg/L	% R Dev on 0.50 mg/L is 9.41%
Manganese as Mn mg/L	ICP OES	0.05 mg/L	% R Dev on 0.50 mg/L is 7.2%
Silica as Si mg/L	Automated colorimetric	0.5 mg/L	No data
Dissolved Organic Carbon mg/L	Automated Persulphate-Ultraviolet Oxidation	1 mg/L	1 mg/L for range 10-20 mg/L
Conductivity mS/m (25°C)	Electrometric	0.2 mS/m	2% for the range >1 mS/m
pH (Lab) (25°C)	Potentiometric	-	0.1 pH unit for the range 1-13
Total Dissolved Solids (Calc) mg/L	Calculated		
Hardness as CaCO3 mg/L	Calculated		
Sodium absorption ratio (SAR)	Calculated		

Radon

A group from the Environmental Radioactivity Laboratory (ERL) at iThemba LABS and The University of the Western Cape (UWC), collaborating in a parallel WRC Radon project, collected water samples with members of the project team from selected boreholes at Kogelberg in 2005 and 2007 using the groundwater sampling methods described above.

Two techniques were used to measure Radon in the water samples: high-resolution (~ 2 keV at 1.3 MeV) γ-ray spectroscopy by means of a hyper-pure germanium (HPGe) detector and continuous radon monitoring by means of RAD7 (Durridge) radon detector. The first technique allows one to measure γ-rays emitted in the decay of the natural radionuclides in general and in particular those in the decay of radon progenies ^{214}Pb and ^{214}Bi. The second technique measures α-particles emitted in the decay of ^{218}Po. Samples were measured in the field using the RAD7 technique, within one hour of being sampled. Samples measured using the HPGe technique were measure at iThemba laboratory within 2 days.

2.3.8 Aquatic biology

2.3.8.1 Macroinvertebrates

Macroinvertebrates[1] are commonly used in biological quality assessment (Rosenberg and Resh, 1993; Chessman, 1995) as they tend to have a strong response to prevailing physical conditions. In southern Africa, the South African Scoring System version 5 (SASS5; Chutter, 1998) is the favoured condition assessment method using macroinvertebrates because of its simplicity, cost effectiveness (Dickens and Graham, 2002) and its relevance to local conditions. SASS is routinely used assess water quality and habitat conditions in a stream. In this regard, high 'scores' are allocated to the taxa that are considered to be most sensitive to change in water quality and habitat, and lower scores are allocated to those deemed to be tolerant of such changes. The sum of the scores calculated for taxa found at a site is called the SASS5 score. The SASS score together with the Average Score Per Taxon (ASPT) provide a fairly robust indication of the condition of the study river/stream. Here, the SASS Score and ASPT were used to check for temporal and spatial differences related to:

- location and aspect
- discharge
- chemical character of the water
- links with groundwater (as evaluated through isotopic analysis).

Methods and equipment

South African Scoring System version 5 (SASS5) methodology (Chutter, 1998) was used. A soft 950µm mesh net on a 45 cm square frame on a stout handle was used collecting the specimens at sampling points. Depending on the objectives of the study, samples from different biotopes can be separated or combined (Dickens and Graham, 2002). All the biotopes: Stones; vegetation; and Gravel, Sand and Mud (GSM) present were sampled together, resulting in one sample per sampling point. Stone biotope includes stone in current and stone out of current. Kick sampling was done for 5 min in stone biotopes while holding the net below the water level moving it backward and inward. At each location, *c*. 1 m² of the streambed, and a *c.* 1 m stretch of the marginal and instream vegetation was sampled. In some cases, missed specimens were picked up during sampling procedure. All the collected material was poured into a tray, and the twigs and leaves were removed from the tray to find the macroinvertebrates easier within 15 minutes restricted time per sample. The samples were preserved in 70% ethanol for later identification in the laboratory. Taxa were sorted and identified to Family level with the exception of Baetidae and Hydropsychidae, which were identified to the species level. An identification guide (Gerber and Gabriel, 2002) was used with the aid of stereoscope to identify the specimens. River Health Programme- SASS Score sheets were used to record the data.

Sampling frequency

Samples were collected on roughly a six-week basis starting from July 2004. Nine monitoring points were selected in the two streams in Purgatory catchment (T8) (see chapter 4). Stream A includes monitoring points P2, P3, P4, P5 and P8 whereas stream B includes P9, P10, P11 and P12. In Oudebosch catchment (Kogelberg Nature Reserve), five monitoring points were selected in Oudebosch Stream (see chapter 3), *viz*. O5A, O5B, O6, O7A, and O7B.

[1] Comprised of insect larvae, fresh water crustaceans (e.g. amphipods, crayfish), aquatic annelids (e.g. worms), and zooplankton that are found predominantly in rivers.

2.3.8.2 Diatoms

Diatom collection was undertaken during the surface water discharge flow-sampling trips, and at each flow sampling point. The sampling protocol used is outlined in Harding *et al*. (2004) and summarised below. At each site an area of riffle habitat was preferentially selected, where the epilithon, which consists of the diatom communities that live on the surface of rocks, was sampled. Rocks with an obvious diatom growth (slippery feeling or a brown film covering the substrate) were preferentially selected. If there were no cobbles are present at a site either bedrock or sediment surface scrapings were taken.

On each sampling occasion, between 5 to10 cobbles (depending on their size) were selected. The selected cobbles were scrubbed lightly using a toothbrush and the dislodged material was rinsed into a white plastic tray. Once all of the selected cobbles had been scrubbed, the resulting brown suspension was mixed, and poured into a sample bottle. Samples were preserved by adding *c*. 20 ml of 96% ethanol to each 100 ml of sample. The toothbrush and tray were be rinsed thoroughly between sites to avoid cross-contamination of the samples.

2.3.9 Botanical investigation

The information on the detailed wetland studies has been extracted from Aston, 2007. The full thesis, funded by this project, has been included on the CD that accompanies this report as Appendix Ia and Ib. A summary of the methods is described here. The same applies to the rapid survey of the wetlands of the Oudebos catchment conducted by E. Pienaar and A Johns – the full report is available as Appendix D.8 and only the aspects of the methods are given here. The hydrogeological descriptions of the settings of the detailed wetland study sites are given in more detail because this information is not contained in the M.Sc. thesis.

2.3.9.1 Detailed studies in selected wetlands

The study of wetland plant ecophysiology and water sources was carried out at four wetlands at Kogelberg. The seeps were chosen on the basis of their landscape setting, in particular their altitude and proximity to fault lines which was thought to result in varying levels of dependence on discharge from the TMG aquifer versus use of perched (ponded surface) water and soil in recharge areas.

(a) Water sources

The source of the water in the wetlands was identified using isotopes collected from samples of rainfall, soil water, groundwater and plant xylem water. Rainfall samples were collected in 10 litre samplers located near each seep. The samples were collected four times (every 2.5 months) from 14/09/04 to 05/08/05. The design and construction of the samplers and the handling of the water samples followed the guidelines and procedures given by Weaver (1992, recently updated as Weaver *et al*., 2007). In the Western Cape the amount of rainfall increases strongly with altitude (Wicht *et al*., 1969; Harris *et al*., 1999) and becomes isotopically lighter (Dansgaard, 1964; Midgley and Scott, 1994; Harris *et al*., 1999). The groundwater signature of the different wetland systems was corrected for the altitudinal variation within the catchment believed to be supplying the wetland.

Soil-water was extracted from augured samples which were collected within 2 m of the piezometers before and after the rainfall event at the Valley, Coastal and Perdeberg seeps. Samples were collected in 100mm soil sections from the surface and then at 250 mm intervals down the soil profile up to and including the saturated zone. Water was extracted from the soil samples using a vacuum distillation line with cryogenic collection (Dawson, 1996). The water samples were reduced to H_2 using Coleman *et al*.'s (1982) closed tube reduction method as modified by Harris *et al*. (1999). The data were converted to the SMOW scale. Data are reported in the familiar δ notation, where:

$$\delta = [(R_{sample}/R_{SMOW})-1] \cdot 1000$$

and R=D/H. The average difference between duplicates of CTMP and the mean of the different runs was 0.44‰ which corresponds to a 2σ value of 0.94‰ (n=50).

Groundwater samples were taken from the two deep-fed seeps, the coastal seep and from the perched seep (all at Kogelberg) once the piezometers became available. Samples of groundwater were collected from capped piezometers and water level measurements made throughout the sampling period at the four seeps. Samples were collected after purging three times the volume of water originally in the piezometer using a PVC bailer (Weaver, 1992). Samples were collected in 13.5 ml glass vacutainors (a rubber-stoppered glass vial), which were further sealed with parafilm.

A special sampling device, the ASTON (Ascending Seep Tester of Note) was developed to sample the groundwater as the water table rose inside the piezometer in response to a rainfall event. These devices were installed at the Valley, Coastal and Perdeberg seeps prior to the rainfall event and the sampled water was collected 24 hrs afterwards. The Oudebos seep was not included the event sampling as man power was limited.

(b) Plant vulnerability to water stress

Xylem traits were measured in 11 Fynbos species which were chosen as representative phreato- and non-phreatophytic species. The non-phreatophytes were: *Leucadendron argenteum, Leucadendron xanthoconus, Mimetes cucullatus* and *Erica baccans*. The phreatophytes were: *Leucadendron salicifolium, Mimetes hirtus* and *Erica perspicua.* Four other phreatophytic species were also measured: *Witsenia maura* and *Psoralea pinnata* were thought to be confined to wetter areas while *Osmitopsis asteriscoides* and *Brunia alopecuroides* are more widespread. With the exception of *W. maura* and *E. baccans*, which were collected from Silvermine (34° 04' 36"S, 18° 24' 00") and the slopes above UCT (3° 57' 19"S, 18° 27' 25") respectively, all species were collected from within and nearby the Kogelberg Biosphere Reserve (34° 18' 30"S, 19° 00' 00"). Plant samples were collected in the field, tightly wrapped in cling wrap and transported back to the lab on ice. Vulnerability curves were compiled using the centrifuge technique (Alder *et al*., 1997) with six stems spun per species. The data were then fitted to an exponential sigmoidal equation:

$$PLC = 100 / (1 + \exp(a(\psi - b))),$$

where PLC is the percent loss conductivity from a flushed maximum, ψ = water potential, a and b are two constants and 100 is the asymptote of the function. Coefficient a corresponds to the slope of the vulnerability curve (i.e. the range over which vessels cavitate) and b represents its position on the water potential axis and corresponds to P_{50} (Pammenter and Van der Willigen, 1998). The xylem density of the stems used in the drawing up of vulnerability curves was determined as the dry mass per fresh volume of wood with the pith and bark removed.

(c) Plant water potential and xylem water isotopes

Water potential

Predawn and noon water potentials were measured for plants located on and off seeps at different times in the year. Plant species were selected for water stress monitoring on the basis of their having perceived differences in rooting depths, shallow for Restionaceae and deep for Proteaceae. Plant water stress was measured by determining the xylem pressure potential of plants using a pressure chamber (Model 1000, PMS Instrument Co., Corvallis, Oregon). Samples were sampled predawn (03h00-05h30) as by this time plants have typically recovered from diurnal water stress and have xylem pressure potentials in equilibrium with the water potential of the soil-water to which they have access. Plants are typically at their most stressed by midday (12h00-14h00).

Plant water Isotopes

Stem samples of shallow-rooted Restionaceae and Asteraceae were collected pre-dawn at the end of summer, on the same morning that water stress measurements were taken in March. Samples were immediately sealed in Kimax Tubes using parafilm and were frozen upon return from the laboratory. Water was extracted from the stems while they were still within the Kimax Tubes by vacuum distillation. Values were reported in the familiar δ notation where:

$$\delta = [(Rsample/Rstandard)-1]*1000$$

and R=D/H. The average difference between duplicates of the standard and the mean of the different runs was 0.44 ‰ which corresponds to a 2σ value of 0.94‰ (n=50). Samples were reported relative to V-SMOW. Student t-tests were carried out (*Statistica v.7, Statsoft*) to compare differences in the stable isotope ratio of stem-water between the different species at each of the four sites, between the same species at different sites, and between analogous species on and adjacent to the two seeps.

The depth from which plants are sourcing their water and how this differs before and 24 hours after a rainfall event was determined from samples of stems from species representing a range of rooting depths. The soil at each site was also sampled at depth increments down the soil profile, the water extracted and its δD measured. Rainfall was sampled intensively with a network of rainfall collectors placed to sample the relationship between elevation and rainfall in the seeps' catchments.

2.3.9.2 Wetland botanical mapping in the Oudebos Stream catchment area

The aim of the botanical mapping was (a) to characterise the vegetation of wetlands in the Oudebos valley using simple characteristics or easily identifiable species and (b) to determine whether this can be used as an indicator of the nature of the groundwater source of the wetland: i.e. perched, intermediate (minor faults or lithological contact controlled) or major fault system controlled. The aim was also to compare the results of this survey with the findings of Engelbrecht's M.Sc. study which used remote-sensing to identify wetlands in the Kogelberg area and to determine if they were associated with major fault systems or with lithological contacts. The wetland vegetation was characterized using two different techniques: plots and whole wetland species composition assessments. The plot samples were standardised by using a transect-based method which can accommodate the range in size and shape of the wetlands. Plant cover for individual species in all plots was estimated using a modification (Barkman *et al*., 1964) of the Braun-Blanquet cover-abundance scale. Vegetation representative of the adjacent dryland vegetation was sampled using the same sampling design to obtain equal numbers of plots in both habitats. A multivariate method was used to identify communities using the TWINSPAN programme in *Megatab* 2.0 (Hennekens, 1996) software. Nomenclature of plant taxa follows the checklist of the National Vegetation Database (Mucina *et al*., 2000). The whole wetland survey was done from June to August 2005 and the following data were collected: the approximate size (m), GPS coordinates, botanical species composition and a cover abundance value for each species (see Appendix D.8). Similar data collected by Tim Aston and Amida Johns for the eastern section of the specified area and Platberg was used to avoid repetition and therefore unnecessary trampling of sensitive wetland vegetation. All GPS coordinates were converted and projected by Engelbrecht for use in her remote sensing study.

Chapter 3:

Kogelberg – Detailed Site Data and Discussion

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3. KOGELBERG – DETAILED SITE DATA AND DISCUSSION

The Kogelberg study site includes the Oudebosch catchment of the Kogelberg Biosphere Reserve and Mountain Rose Farm, to the north of the R44 east of Betty's Bay, and a private small holding, Stroompie, to the south of the R44 in this area on the coastal plain. The Kogelberg Nature Reserve forms most of the core of the biosphere reserve, and is known as the "heart of the fynbos" because of the diversity of endemic species and representation of species in the typical fynbos families,.

Multi-disciplinary assessments were made of potentially groundwater dependent habitats at this study site, including: remote sensing analysis, geophysical resistivity surveys, borehole drilling and groundwater monitoring and sampling, surface water flow monitoring and water quality assessments, SASS and diatom surveys of the Oudebos river, climatic monitoring and multi-altitude rainfall sampling, vegetation assessments and wetland community mapping. The results of these assessments therefore cover several scales and attempt to characterise water flows through the catchment in 3 dimensions. Monitoring sites are shown in Figure 3-1.

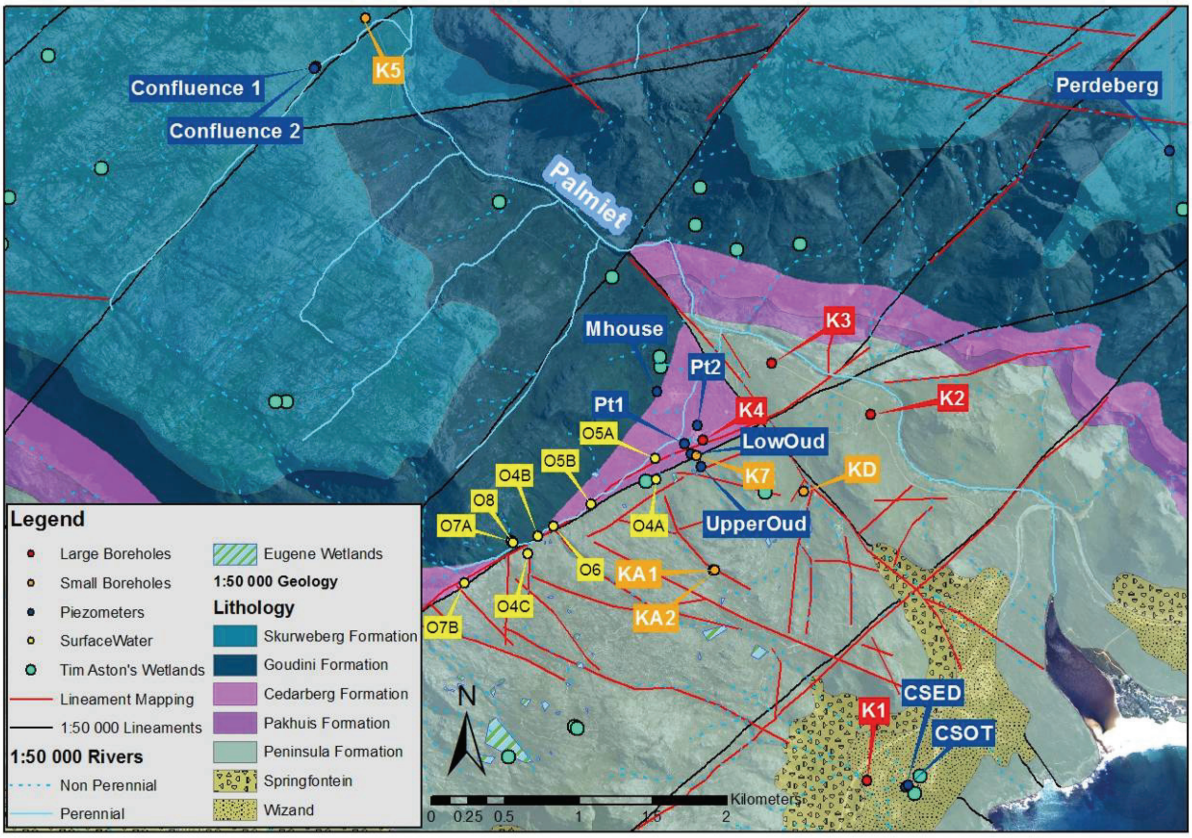

Figure 3-1 Location of monitoring points at Kogelberg study site. K markers are large diameter boreholes; orange K markers are small diameter boreholes; blue markers are piezometers; O are surface water monitoring.

3.1 Topography

The elevation in the study area ranges from 10 mamsl in the wetlands of the coastal plain to the perched wetlands at 500 mamsl on the Perdeberg mountain. The highest peaks in the study area are 909 mamsl at Platberg, which forms the northern flank of the Oudebos valley, and Perdeberg at 571 mamsl on the eastern side of Palmiet River. Mountain Rose farm, the southern flank of the Oudebos valley, reaches a maximum height of 552 mamsl. The Oudebos river flows perennially SW-NE from 340 mamsl at the ridge between the Harold Porter Botanical Gardens, over 3 km to 50 mamsl where it joins the main stem of the Palmiet river. Smaller seasonal streams drain from the Mountain Rose water divide into the Oudebos river and towards the coast.

The boreholes and piezometers in the Reserve were surveyed and range in elevation from 43 mamsl (K2) to 122 mamsl (Confluence 2 piezo) and on Mountain Rose farm at 315 mamsl. The full survey results are given in appendix D9.

3.2 Climate

Rainfall occurs all year round in this area, but with the heaviest events associated with winter cold fronts. Orographic effects dominate the distribution of rainfall with the Mountain Rose and Platberg peaks receiving between 1400 and 1600 mm pa, and Perdeberg receiving 1000 to 1200 mm pa. The modelling of the spatial distribution of MAP suggests a MAP of 600 mm in the Oudebos valley (DWAF, 2007). Longer term climate records from the Steenbras Dam (DWAF station G4E001) indicate that the study period fell within an average to dry period.

3.2.1 Location of monitoring sites

Cumulative rainfall samplers were located at 3 altitudes in the study site to measure whether altitude effects are apparent in precipitation and useful as tracers of different altitude recharge areas. These were located at the WCNCB offices in the Palmiet valley at approximately 50 mamsl, in Mountain Rose farm at 350 mamsl and on the flanks of the Platberg at approximately 600 mamsl. A weather station was also established at the WCNCB offices in the valley.

3.2.2 Measurements on site

Figure 3-2 shows daily maximum and minimum temperature measurements over a period from May 2004 to July 2007. The highest temperatures occur in January, February and March with a maximum shown of 40°C in February 2006. The lowest temperatures occur in June, July and August with the lowest recorded temperature of 0°C recorded in June 2007. Typical seasonal variation of maxima and minima range over 10-15°C, as does diurnal variation.

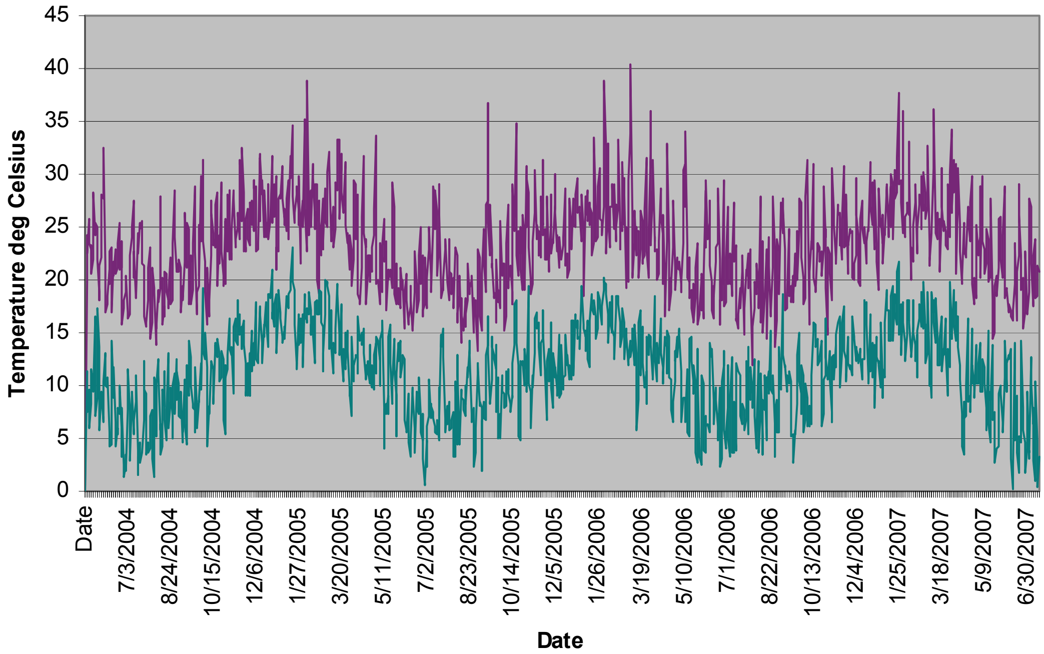

Figure 3-2 Daily maximum (upper line) and minimum temperatures (lower line) at Kogelberg, May 2004 to July 2007.

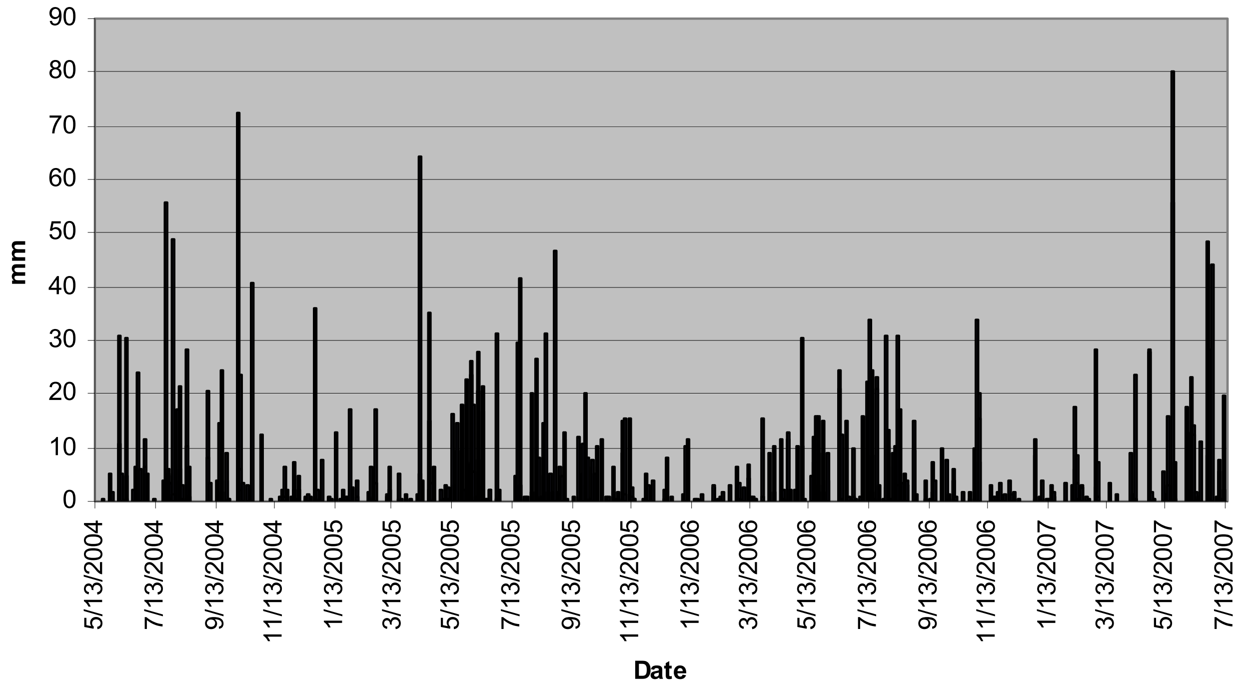

Figure 3-3 Daily rainfall (mm) at Kogelberg from May 2004 from July 2007.

Figure 3-3 above shows the total daily rainfall (mm) in Kogelberg at the offices in the valley. The annual precipitation figures for 2005 and 2006 were 1000 mm and 910 mm respectively. Of the 1158 days recorded, 64% experienced some rainfall: 9% > 10 mm, 4% > 20 mm and 2% > 30 mm. The highest reading of 183 mm was recorded in April 2005 but is not shown on this graph as it is outside the scale of values. The next highest reading is 80 mm in May 2007 and four days have readings > 50 mm: in April, June and October. These observations suggest that the highest daily rainfall typically occurs between May and October. The longest dry periods are for 17 days (July 2005) and 16 days (August 2004),

3.3 Hydrogeology

3.3.1 Geology

This study site contains mega-faults mapped at a 1:250 000 scale and apparent over 10s of kms. Meso-scale (< 1 km) faults, and smaller scale fractures and bedding plane structures occur in both the Skurweberg and Peninsula formations. These two formations have the best aquifer potential of the TMG formations (Table 1-1) and this area is expected to contain regionally driven and locally driven discharge regimes connected to the different scales of structures linked to proximal (Mountain Rose, Platberg) and distal recharge areas (Botrivier).

The Nardouw Subgroup, principally the Skurweberg Formation, occupies a large mountainous area in the northern part of the reserve, around the hinge zone of an open syncline. The main syncline in the mountains north-east of Cape Hangklip is broken by a system of cross-cutting faults, forming part of the Hangklip-Riviersonderend Megafault (HRM) system (TMG-AA, 2004). This Hangklip-Riviersonderend Megafault (HRM) is a significant eastern boundary structure to the southern segments of the Villiersdorp Syncline (TMG-AA, 2004). The HRM is comprised of significant structures of > 10 km length and are targeted by K4 (in the Peninsula) and K5 (in the Skurweberg). The Kogelberg field area is down gradient of multiple potential recharge areas linked to these features and is thought to represent a significant discharge zone to the Palmiet river and its riparian zone (and extended wetlands) and the Oudebosch stream. The HRM and dominant structures are NE to ENE/WSW-striking normal faults. The NE/SW trending faults in the Skurweberg block control the orientation of the easterward flowing perennial tributaries to the Palmiet river. The Palmiet in this part of the reserve follows an antithetic NW-SE fault towards the coast.

Subordinate NW to WNW/ESE fault sets cross-cut both the Skurweberg and Peninsula Formations. These occur in association with springs, tributaries and small wetlands (< 1 ha) in the field area and are thought to represent shallow to moderate length flow paths with low to moderate discharge rates in discrete, structurally controlled zones. Boreholes K2, K3, K7, KA and KD target these structures.

The major fault trends NE-SW in the Oudebos valley. This fault is downthrow to the north, putting the quartzites of the Peninsula Formation on the southern side of the fault against the shales of the Cederberg Formation. The Oudebosch cottages are located on the shale. The light green vegetation defines the aerial extent of the shale and is dominated by *Leucospermum conocarpodendron*. The south-west extension of the fault extends to the Harold Porter Botanical Gardens where it defines Leopards Gorge. This fault extends to the north-east for some 22 kilometres to Botrivier where it merges into the Kleinmond-Botrivier fault, which in turn extends to join the Greyton fault.

Raised beach terraces at 7 to 10 mamsl and 17 to 20 mamsl are found at various places along the False Bay coastline (Theron *et al*., 1992). The coastal Stroompie site is associated with the upper beach terrace. The change in topography from the top to the toe is about 1 to 1.5 m. This relatively abrupt change of elevation is sufficient that the shallow water table of the flat beach terrace daylights at the toe or is very close to surface, thus resulting in a wetland. At the Stroompie site, this wetland is wider than usual and is estimated to vary from 30 to 80 m wide. Elsewhere it is often only 10 to 20 m wide. It is suspected that the Stroompies site is wider than usual due to the influence of a small fault controlled valley inland which generates a greater runoff, resulting in more water draining through the wetland and potentially discharging from the fault in the Peninsula to the overlying sands.

3.3.2 Geophysics

Four profiles were acquired in the Kogelberg Nature Reserve and are shown in full in Appendix G. They were acquired near the cryptic wetland on the north facing Peninsula formation slope near K7. This wetland is thought to be fault controlled. The term ‘cryptic wetland’ is used, as these wetlands do not have a visible saturated soil zone or water table within 30 cm of the surface. It is thought that these lusher stands of vegetation occur in areas where more bioavailable groundwater is present in the deep rooting zone resulting in ‘cryptic’ (not seen) discharge via transpiration.

Resistivity data were acquired both parallel and perpendicular to the orientation of the fault and all profiles show a resistivity contrast associated with the fault. Two of the profiles are shown and discussed here.

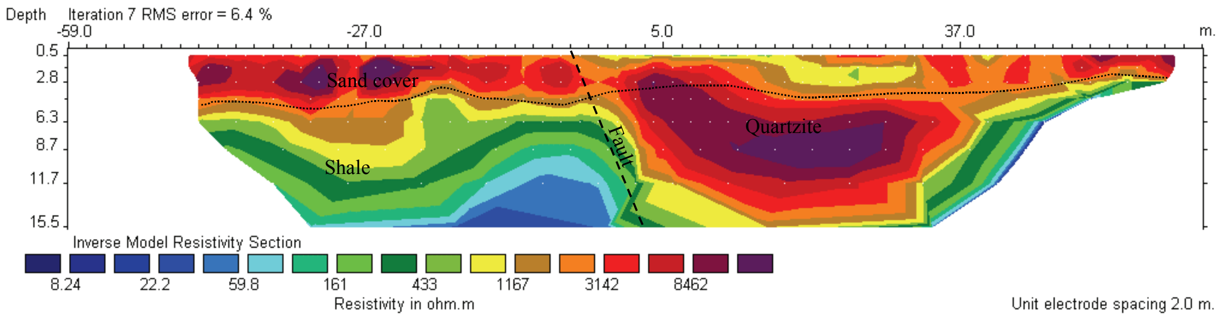

Figure 3-4 Resistivity profile 1 at Kogelberg E-W perpendicular to the fault on the Peninsula north facing slope.

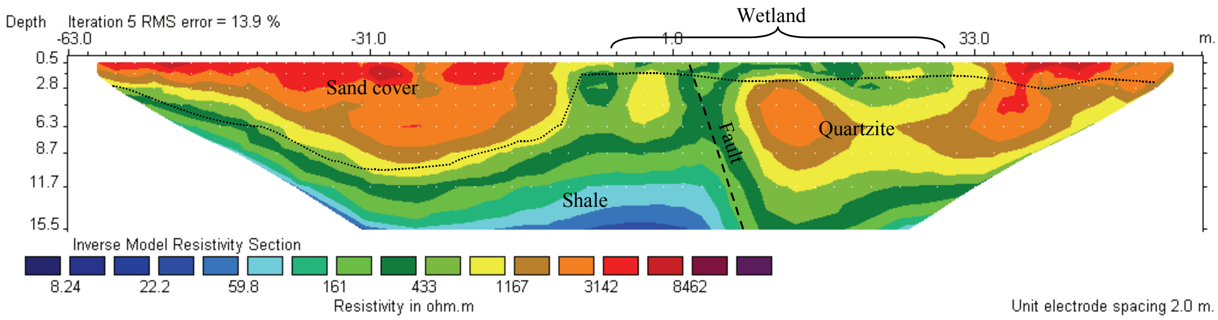

Figure 3-5 Resistivity profile 3 at Kogelberg E-W perpendicular to the fault in the Peninsula north facing slope, crossing the cryptic wetland.

The data for the first profile were acquired at the southern end of the wetland just above where it is crossed by the footpath. This profile is oriented east-west and approximately perpendicular to the fault. The profile does not intersect the wetland. The inverted resistivity profile is shown in Figure 3-4. No elevation data were included, since the slope does not exceed 10° anywhere along the profile. The resistivity data correlate with the expected geological conditions. The area is covered by sand shown as the high resistivity shallow layer. The low resistivity zone at depth may be indicative of shale (less likely increased water content and permeability) whereas the high resistivity zone at depth is indicative of the quartzite. The sharp contact between the two can be delineated as the fault.

The resistivity data for profile 3 were acquired sub-parallel to profile 1 to the north and are shown in Figure 3-5. Whilst the fault is indicated clearly in this profile the resistivity of the downthrown Peninsula shows a lower resistivity of approximately 2000 Ω.m compared to 9000 Ω.m in profile 1 where the wetlands was not present. Drilling in this area (k 7) encountered a water strike in the Peninsula at 8 mbgl, therefore the lower resistivity in profile 3 is caused by saturated permeability in the quartzite which corresponds with the location of the lusher vegetation.

3.3.3 Drilling targets

Drilling targets were limited, within the terms of the Environmental Management Plan (Appendix B), to disturbed or road areas for the large diameter boreholes, and within 300 m of an access road for the small diameter boreholes. Table 3-1 lists the sites shortlisted for drilling with the rationale. Most are sited on probable discharge features in order to monitor groundwater level and quality fluctuations and correlate these to bioavailable water fluctuations in the associated habitat. The locations are shown in Figure 3-1. The drilling was conducted by JJ Myburgh and Brothers with drilling commencing on the 14/10/2004 and finishing on the 08/02/2005, with intermittent breaks. A total of 4 boreholes were drilled with the standard rig, one borehole on the coastal plain with the ODEX rig and 5 boreholes with the portable rig.

3.3.4 Drilling results

The drilling results are given in full in Appendix D 2. A summary of pertinent information is presented below and shown in Table 3-1.

3.3.4.1 Boreholes

K1 – large diameter

Borehole K1, also called the Stroompie borehole after the property on which it was drilled, is located on the coastal terrace reflecting previous sea levels. The presence of boulders in the unconsolidated sediment overlying the bedrock caused delays in the drilling because the percussion drill bit could not penetrate the hard boulders. This resulted in ODEX drilling being used for the top 14 m. The unconsolidated formation was cased off, and from 14 to 65 mbgl the borehole was drilled using the standard rotary method. The borehole intersects the Peninsula formation with an open hole. Moderate water strikes were intersected between 42 and 64 mbgl resulting in a total air lift yield of 4.4 l/s.

K2– large diameter

Borehole K2 is situated in the middle of the road within the Kogelberg Reserve. Limited water was encountered at a depth of 3 m. More water was encountered at a depth of 16 m, and the main water strike was encountered at 33 m below surface. The borehole is cased to 11mbgl and is completed to a depth of 35 m in Peninsula Formation sandstone, and monitors the semi-confined Peninsula Formation aquifer.

K3 – large diameter

Borehole K3 is located on the access road to the Kogelberg Nature reserve targeting a large scale fault in the Peninsula. It is cased to 6 mbgl. It is drilled to 70 mbgl with no significant water strikes and essentially intersects low permeability Peninsula matrix and micro-structures.

K4 – large diameter

K4 is situated within the disturbed site next to the accommodation huts in the Reserve. The lithology of the borehole consists of 24 m of Cedarberg shale overlying Peninsula sandstone. The Cedarberg shale, upon drilling, becomes a fine black powder, and with the addition of water, turns into a clay-like substance. Because of this, the borehole had to be drilled at the wider diameter through the shale, and into the sandstone in order to insert the casing into the top of the underlying sandstone and grout it in place. The main water strike was met at 38 m below surface which resulted in artesian flow. The borehole was drilled to 47 meters in total. A cap needed to be welded onto the borehole in order to prevent the artesian water from flowing out. An artesian flow of 2.1 l/s was recorded with an 80L drum and a stopwatch on the 08/02/2005.

K5 – small diameter

Borehole K5 is situated within the Kogelberg Core Biosphere and as a result, strict site control took place in order to ensure that minimal impact occurred. A water strike was encountered at 3.5 m and the borehole drilled to a depth of 4.3 m. Further drilling could not proceed through the boulders and sand and the borehole was completed at 4 m depth in the surficial talus.

Figure 3-6 The photo on the left shows the KA2 drill site during drilling in misty weather. The photo on the right shows the capped borehole after drilling and the limited footprint of impact from the portable drill rig.

K7 – small diameter

Borehole K7 is situated on a fault in the Peninsula close to the accommodation huts in the Reserve. Hard rock was encountered below 2 mbgl and water strikes at 8 and 12.5 m. The borehole is cased to 4 mbgl and drilled to 16 mbgl.

KA1 & 2 – small diameter

Solid rock was encountered for 0-5 m during drilling and casing was grouted in to 3 m. After 5 m, sand was encountered with a main water strike at 6 m. The sand and the water pressure blocked the hammer and as a result, the borehole could not be drilled further. The borehole was then filled with cement to the surface and left to dry. The following day the borehole was re-drilled through the cement, however the same problem occurred with the running sand blocking the hammer and drilling could not proceed beyond 8 mbgl. The rest water level was 5 mbtoc. The hole was finished off, and the drill rig moved 8 m in order to drill borehole KA2. This borehole did not encounter running sand and was dry during drilling, but with monitoring, the rest water level has been found to be 25 mbtoc. The borehole was drilled to 30 mbgl and is cased to 12 mbgl.

KD – small diameter.

This borehole was drilled in a wetland dominated by Restios in Mountain Rose Farm. Hard rock was encountered at 4 mbgl. 9 m of casing was installed in order to ensure that the problem encountered with borehole KA1 was not repeated. The borehole was dry during drilling, but with subsequent monitoring, the rest water level is situated at 15 mbtoc. The drilling results indicate that this wetland is either perched and not linked to the structure underlying it.

Table 3-1 Summary of drilling information for Kogelberg boreholes

Borehole Number	**Drill method**	Final Depth (m)	Water Strikes (mbgl)	Rest water level (mbtoc)	Airlift yield (l/s) *estimated	Groundwater intersection
K1	Odex and percussion	**65**	**42, 52, 56, 64**	**1.05**	**1.1, 2.6, 3.4, 4.4**	**NW/SE fault in Peninsula Formation underlying coastal sand aquifer**
K2	Percussion	**35**	**3, 16, 33**	**1.66**	**6***	**Large scale NW/SE fault in Peninsula Formation**
K3	Percussion	**72**	**(minor 4)**	**6.83**	**<1**	**Peninsula Formation matrix and micro-structures (or non-water bearing NW-SE structure)**
K4	Percussion	**47**	**38**	**Artesian**	**8***	**Confined NE/SW faulted Peninsula Formation.**
K5	Portable	**4.3**	**3.5**	**1.08**	**2***	**Talus above large scale NE/SW fault in Skurweberg Formation**
K7	Portable	**16**	**8, 12.5**	**7.78**	**3***	**NW/SE faulted Peninsula Formation**
KA1 (MRF1)	Portable	**8**	**6**	**5.04**	**5***	**Recharge zone and NW/SE faulted Peninsula Formation**
KA2 (MRF2)	Portable	**30**	**-**	**25.7**	**<1***	**Recharge zone and Peninsula Formation matrix (or non-water bearing NW-SE structure)**
KD (MRF3)	Portable	**30**	**-**	**19.7**	**<1***	**Peninsula Formation matrix (or non-water bearing NW-SE structure)**

3.3.4.2 Piezometers

Piezometers were hand augered into wetland sites to try and obtain shallow groundwater samples from wetland areas which were inaccessible to either of the drilling rigs. In total 10 piezometers were successfully installed in wetlands in the study area:

- three piezometers were successfully installed in the coastal wetland on the Stroompie site (CSED; CSOT;CSMI);
- two in the valley bottom wetland in the Oudebos valley (Point 1 and 2);
- two on the mid-slope wetland in the Oudebos valley close to the huts (Lower Oudebos and Upper Oudbos);
- one on the top of Perdeberg;
- two on the mid-slope wetland close to the confluence with the Dwars (confluence 1 and 2);
- and one in a wetland close to the spring at the Reserve manager's house (MJHouse).

The shallow sub-surface (to 3 mbgl) of the mid-slope wetlands was generally comprised of coarse sand and boulder talus which was very difficult to auger through. The valley bottom and perched wetlands (i.e. topographically flat wetlands) contained more fines and organic material.

Table 3-2 uPVC 53 mm ID Piezometers installed in the Kogelberg area.

Name	Depth (mbgl)	Rest water level (mbtoc)	Length of screen
Perdeberg	1.85	0.98	22 cm
Confluence 1	1.40	1.31	40 cm
Confluence 2	1.60	1.26	33 cm
M.J house	1.78	0.76	73 cm
POINT 1	3.27	1.72	60 cm
POINT 2	1.50	0.62	38 cm
Lower Oudebosch	1.29	1.10	48 cm
Upper Oudebosch	1.20	0.68	46 cm
CSMI (COAST)	2.30	1.03	76 cm
CSED (COAST)	3.62	1.12	60 cm
CSOT (COAST)	4.42	1.30	32 cm

3.3.4.3 Summary of drilling results

Tables 3-1 and 3-2 summarise the drilling results at this area. A range of hydrogeological targets are intercepted at a (geologically) shallow depths in order to focus on the discharge characteristics of the upper aquifers and aquifer matrix material. Surficial monitoring is enabled by the establishment of piezometers at depths of < 3mbgl in perched, mid-slope and valley bottom wetlands.

3.3.5 Groundwater level data

Water level and temperature data are available for 6 groundwater monitoring points as shown in Figure 3-7 below and summarised in Table 3-3. The relative position of the water levels indicates their position in the catchment. P1 intersects shallow groundwater in the valley bottom wetland, linked to the riparian zone in the Oudebos valley . K1 intersects groundwater in an inferred fault zone in the Peninsula formation underlying unconsolidated coastal sand deposits. K2 intersects a meso-fault in the Peninsula formation and K3 intersects Peninsula formation with low yielding micro-structures or matrix groundwater. K4 intersects the confined Peninsula in a mega-fault zone.

Boreholes 2 and 3 show similar types of responses (borehole 2 intersecting meso and micro-scale fractures in the Peninsula and borehole 3 assumed to be intersecting mainly micro-fractures matrix). Boreholes 1, 2 and 3 all show water level responses to daily rainfalls of 10 mm and above, whereas the artesian borehole (4) only shows responses to daily rainfall greater than 30 mm. This may be because the confined artesian Peninsula is not recharged locally and only widespread significant frontal rainfall events (indicated by >30 mm day^{-1}) have a recharge effect.

Table 3-3 Summary of water table responses in water monitoring points with automated hourly measurements.

BH#	BH depth (mbgl)	Water Strikes (mbgl)	Drilled Rest water level (mbtoc)	Drilled airlift (L/s)	Seasonal amplitude (cm) T°C	Min ppt recharge response (daily mm)	Aquifer/ habitat type
K1	**65**	**42, 52, 56, 64**	**1.05**	**4.4**	**300** **1**	**10**	**NW/SE fault in Peninsula Formation underlying coastal sand aquifer**
K2	**35**	**3, 16, 33**	**1.66**	**6***	**200** **3**	**10**	**NW/SE fault in Peninsula Formation**
K3	**72**	**4**	**6.83**	**<1**	**350** **1**	**10**	**Peninsula Formation matrix and micro-structures (or non-water bearing NW-SE structure)**
K4 Artesian	**47**	**38**	**Artesian**	**8***			**Confined NE/SW faulted Peninsula Formation.**
KD (MRF3)	**30**	**-**	**19.7**	**<1***	**290** **<0.1**	**5**	**Peninsula Formation matrix (or non-water bearing NW-SE structure)**
P1	**3**	**0.5**	**0.3**	**NA**	**60** **3**	**5**	**Valley bottom wetland**
River	**NA**	**NA**	**NA**	**NA**		**5**	**Perennial tributary**

The seasonal amplitude of water level change in all the large diameter boreholes is approximately 300 cm. All respond rapidly to recorded rainfall inputs. K 2, intersecting faults, responds to rainfall in a matter of hours, indicating direct recharge via preferential flow pathways. A smoothed recharge response is seen at both the artesian borehole (K 4) and K 1 at the coast, indicating greater storage linked to these monitoring points. K 1 and K 3 respond over a few days to a recharge event. The TMG water table in K 1 is probably responding to a pressure head propagated from the nearby mountainous exposures. K 3 represents a micro-fracture matrix response which may be delayed for a day or two by lower permeability.

The piezometer P1 and the borehole higher on the mountain at Mountain Rose Farm (MRF3) show smaller responses to a wider range of events and are triggered by rainfalls of > 5 mm day^{-1}. in the valley. P1 is likely to be in hydraulic continuity with surface water via the alluvial aquifer, and will therefore be influenced by river flows. This will reflect inputs from orographic rainfall which will be higher at higher altitudes in the catchment and not recorded at the weather station. P1 shows a seasonal amplitude of 60 cm. During the ‘dry’ season the weekly amplitude is around 20 cm, and during the wetter winter the weekly amplitude is around 30 cm. The pattern of responses in MRF3 differs from the other boreholes and lacks classic recharge steep peaks followed by exponential recession. This may indicate slower recharge mediated by the wetland perched above the water level in this borehole.

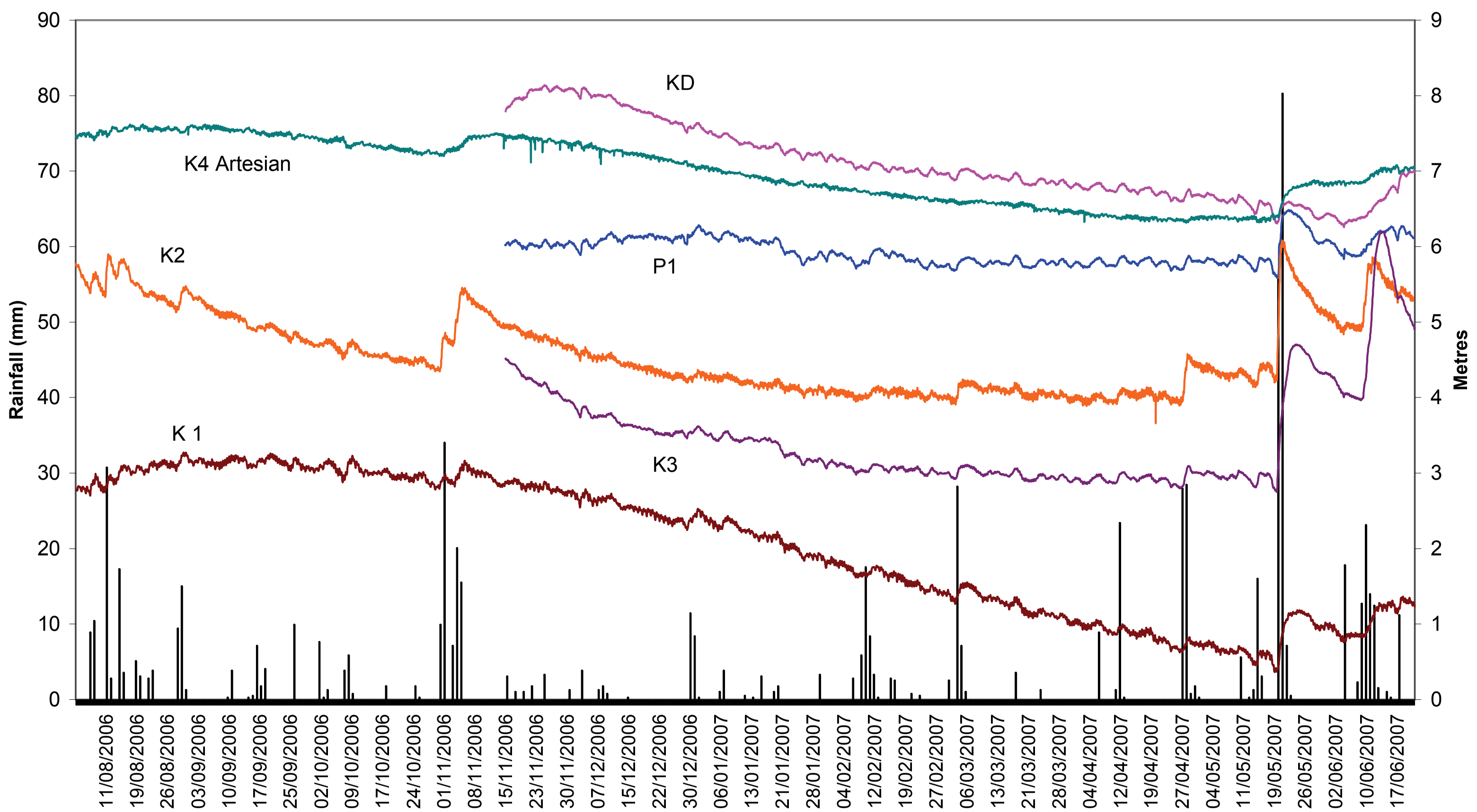

Figure 3-7 Groundwater level data (m) for Kogelberg automated groundwater monitoring points plotted with daily rainfall (mm).

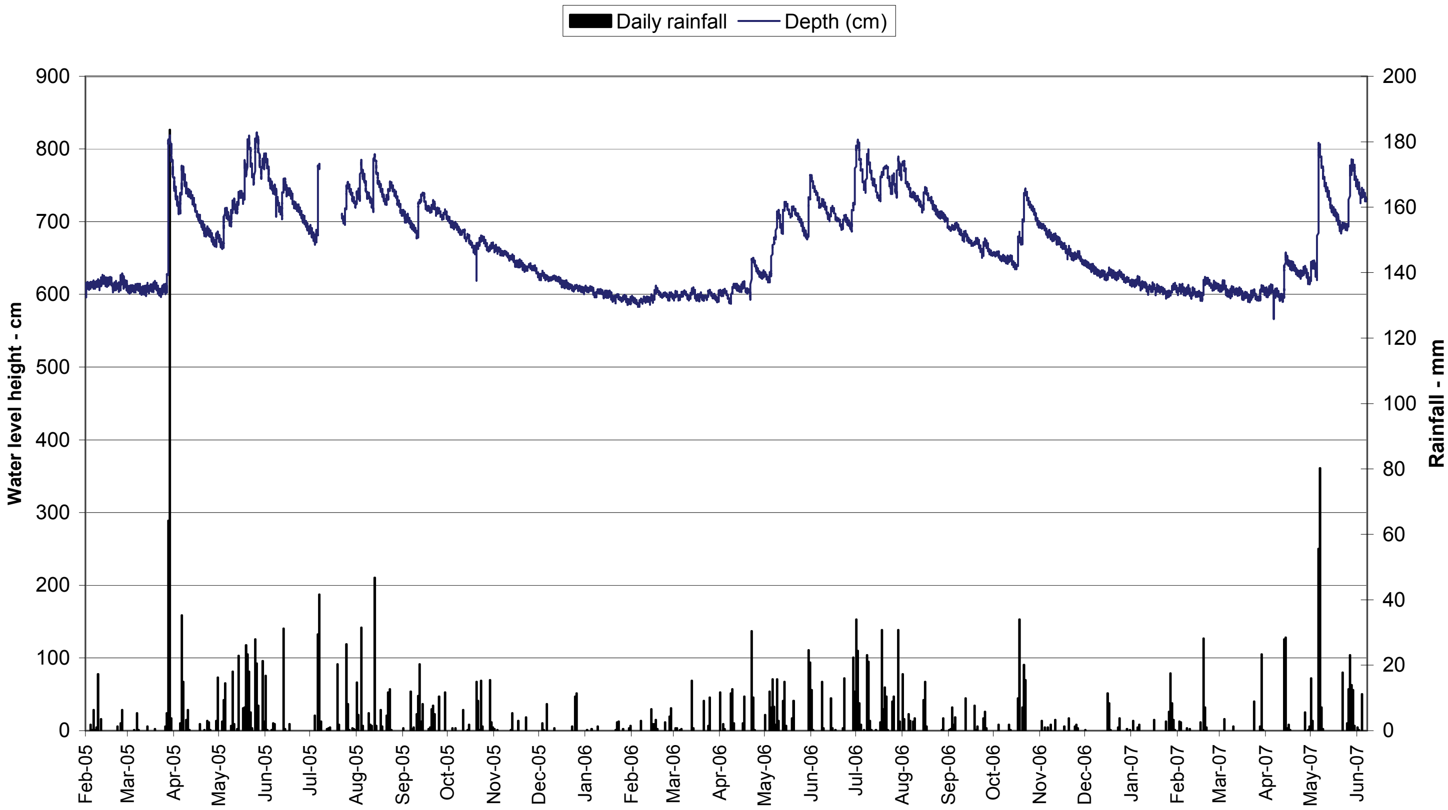

Figure 3-8 K2 water level responses from February 2005 to July 2007 (cm) plotted with daily rainfall (mm) from the Kogelberg weather station

The longest water level record is available for K 2. Figure 3.8 shows this record plotted against daily rainfall. (This includes the one extremely high rain event of 183 mm in one day.) The graph indicates the similar patter over three annual cycles of recharge (May to August), discharge (during recharge and from October to January) and dry season low levels from January to early May. Rapid recession is visible immediately following recharge events, indicating high permeability pathways to discharge zones fed by high water levels (rejected recharge). Prolonged, slower recession of the water level occurs from late winter to mid-summer. During this period the groundwater contribution to the sub-catchment water budget from these meso-scale faults is likely to be the most significant volumetrically as rainfall is typically low. However, during the later summer (dry season) the ecological significance of low levels of discharge may be greatest. For instance, in maintaining lower temperatures, water levels and dissolved Si concentrations in the hyporheic zone, perennial streams, permanent pools and springs.

3.3.5.1 Groundwater temperature

Groundwater temperature measured in the boreholes shows an interesting lag behind the air temperature recorded at the weather station. The seasonal variation in air temperature at the weather station in the valley peaks in February. This is closely mirrored by the temperature in P1, as would be expected. The temperature in K2 peaks in early May, and at K1 and K3 in early June. Similarly, the lowest temperatures are also off-set by approximately 4 months. The largest amplitudes in temperature variation are seen at borehole 2

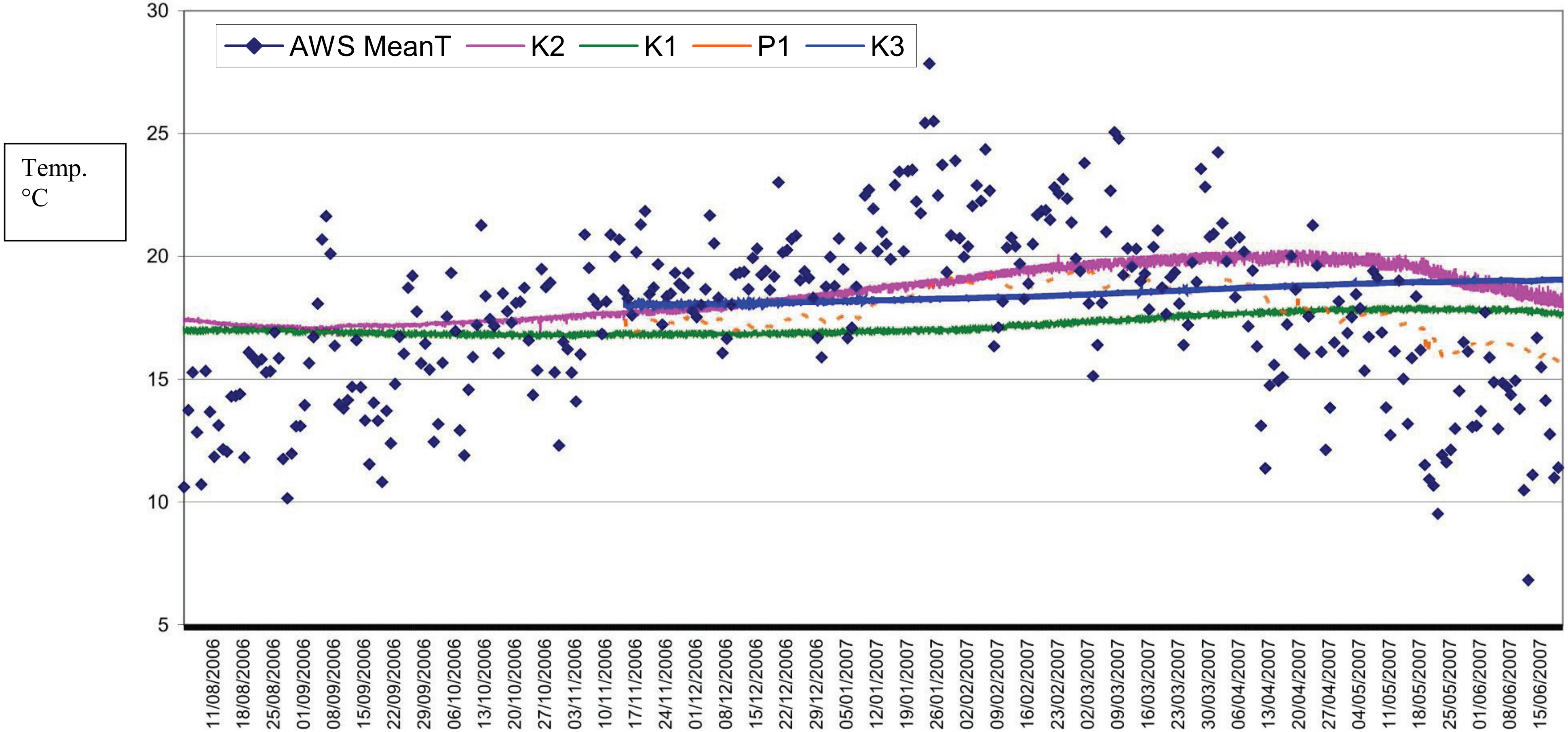

Figure 3-9 Groundwater temperature data and air (AWS) temperature from August 2006 to June 2007 at Kogelberg.

and P1, with 3°C, where as the other boreholes vary by only 1°C. Groundwater temperature generally varies from 16°C to 18°C in the boreholes. It is possible that there is some heat exchange within the borehole, particularly in the low permeability holes with slower through-flow such as MRF3 and K3. Surface water temperature (Figure 3-9) varies from 10°C in winter to nearly 20°C in summer. Temperature measurements may therefore represent a good tracer of groundwater inputs to surface water during periods when there is significant contrast in the end-member (precipitation and interflow-fed surface water Vs aquifer water) values. The greatest difference between K2 (TMG aquifer water) and P1 (mixed surface water and interflow) temperatures occurs in early winter (May) when K2 is 19°C, P1 is 16°C and air temperature is 9°C. Temperature should also be a good tracer of groundwater discharge in the hottest and driest periods (January to March) when surface flows are limited and standing water has a chance to heat up. River reach temperature profiling close to the stream bed (or bedrock) could be used to trace discrete groundwater inflows.

Some of the techniques employed for stream bed tracing of groundwater inflows (Anderson, 2005) would not be applicable in this setting due to the discrete nature of the fracture discharge zones. It is not expected that a consistent gradient would be present in the hyporheic zone due to the discrete nature of discharge via faults and bedding planes, and the poorly sorted nature of boulders and sand within the stream bed.

3.4 Chemistry and Isotopes

3.4.1 Macro-ion chemistry and trace elements.

The macro-ion chemistry of the groundwater samples taken in the study area is typical of that reported for TMG water (Smart and Tredoux, 2001). The full set of analytical results is presented in Appendix D5. The water is predominantly acidic to neutral with a pH of 4 to 7, and has a generally low level of dissolved solutes with a TDS of approximately 50 to 120 mg/L. Changes in EC do not correlate to different sources of water when categorized by their different sources.

The Piper tri-linear plot in Figure 3.9 shows a selection of representative samples which are Na-Cl type. The highest bicarbonate levels are measured in the highest altitude (recharge area) sample from Mountain Rose Farm (MRF2). No flow path hydrochemical evolution is evident in the macro-chemistry and macro-ion solutes are not different for different sources of water. This is probably due to the inert nature of the quartzites.

Iron is present at 1 to 5 mg/L in the large diameter boreholes, and 0.1 to 0.7 mg/L in the shallower groundwater, seep and river samples. Manganese is present at 0.1 to 1.0 mg/L in the large diameter boreholes, but is generally below the detection limit in the other sources. Dissolved organic carbon (DOC) is generally <3 mg/L in the large diameter borehole samples, and between 1 and 20 mg/L in the other sources. DOC is a useful tracer of soil water and water that is sourced from the rooting zone.

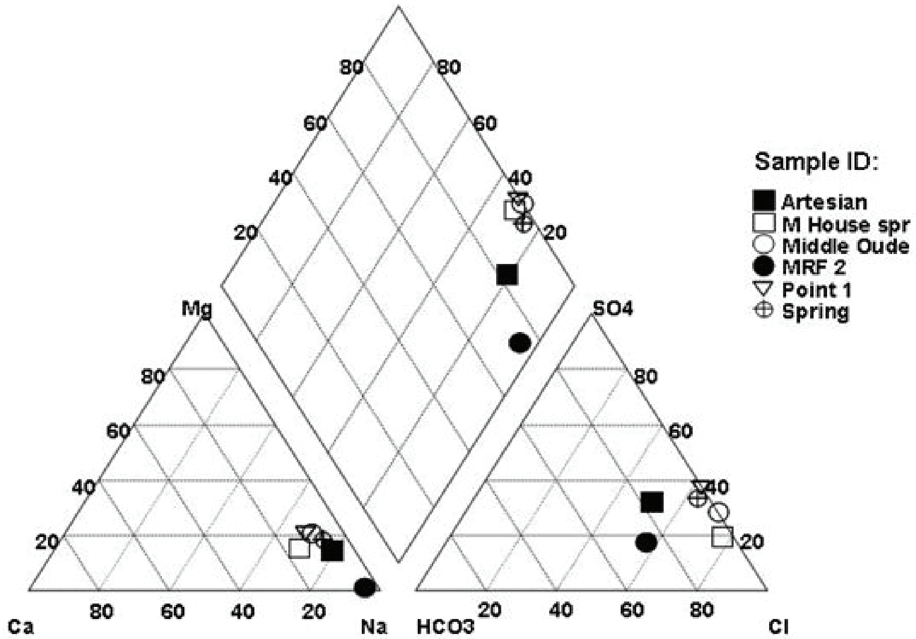

Figure 3-10 Piper trilinear plot showing Na-Cl facies for borehole samples in Kogelberg.

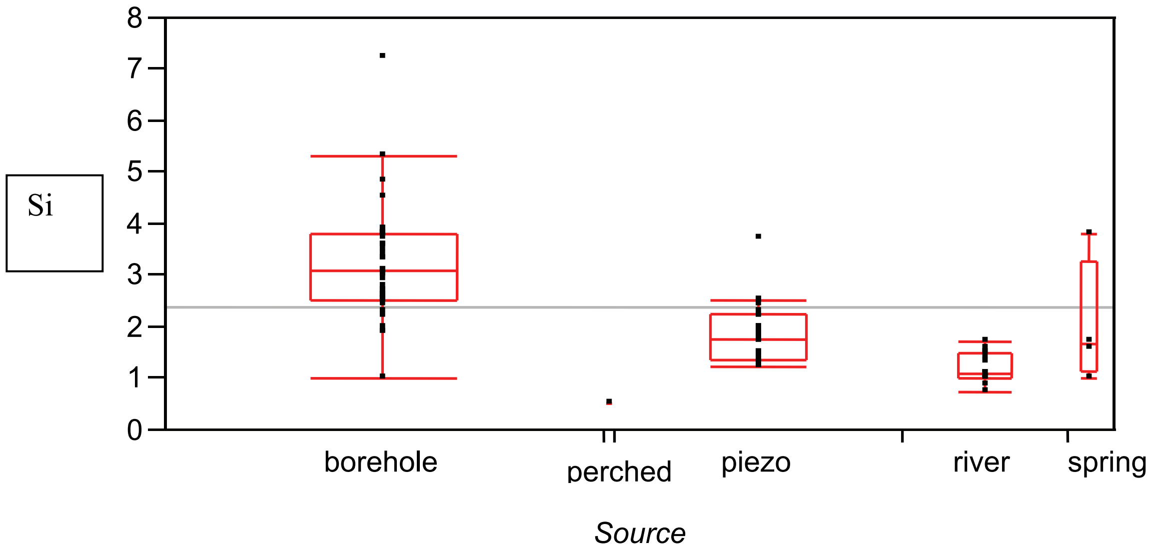

Figure 3-11 Box and whiskers diagram for dissolved Si in samples from different sources in Kogelberg.

Dissolved silica was present in most samples at 0.5 to 6 mg/L. Figure 3-11 above shows the range of values for over 80 samples from different water sources (borehole, spring, piezometer, perched wetland, river). An analysis of variance of the values by different sources shows that there is a statistically significant difference in Si concentrations (with a p value of <0.001). Therefore, Si, particularly in association with DOC and Fe could prove to be a useful conservative tracer of groundwater. Figure 3-12 shows the negative correlation between Si and DOC, which supports the use of Si as an aquifer tracers and DOC as a shallow soil water tracer.

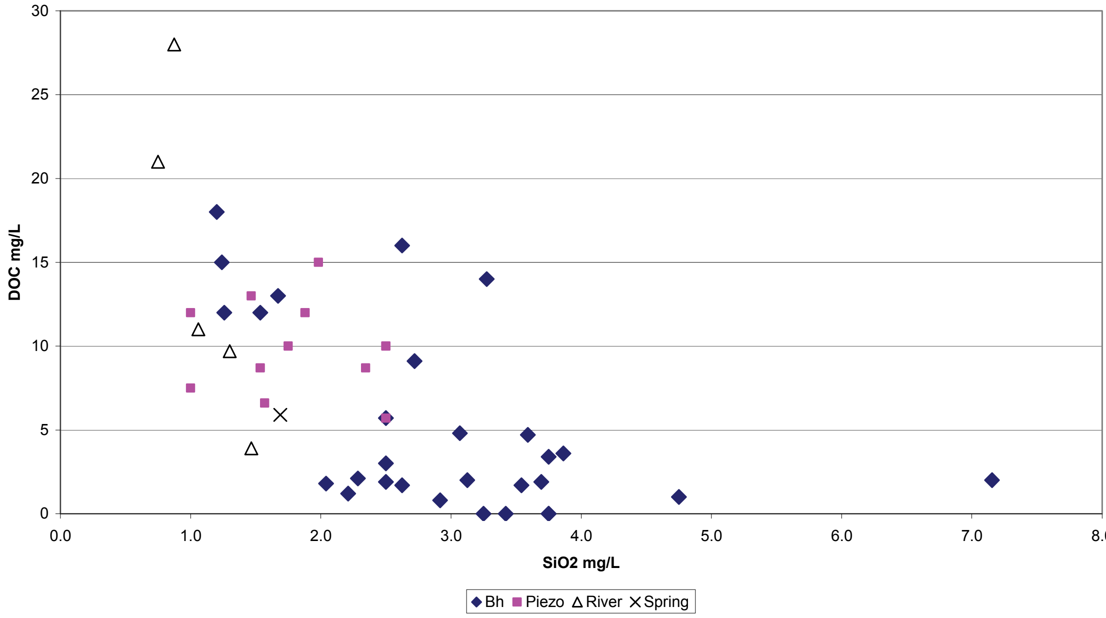

Figure 3-12 Scatter diagram of dissolved DOC vs. Si in samples from different sources in Kogelberg.

3.4.1.1 Stable Isotopes

Oxygen and deuterium isotope analyses are presented in the graph below in relation to the Global Meteoric Water line (GMWL) and the Western Cape Meteoric water line (Diamond and Harris, 1997). Oxygen and deuterium isotopes were sampled from different sources and different altitudes in the catchment to test whether they would be useful tracers of groundwater flow paths. It is possible that altitude effects would significantly fractionate the isotopes in rain falling at different altitudes, so that groundwater recharged at higher altitudes could be differentiated from surface water and soil moisture receiving precipitation inputs at lower altitudes.

Neither O^{18} nor deuterium results showed a significant contrast in the range of values for the different sources ($p=0.13$). They also did not show any correlation of changing values with altitude when sampled at this sub-catchment scale over several rain events. These results indicate that they are not useful tracers of different water flow paths in this catchment. These results are also verified by the botanical studies later in this section. Stable isotopes may be able to add value to understanding the hydrology of the Cape Fold Belt at a coarser scale with broader contrasts in continentality and altitude effects (Cave et al., 2002; Harris and Talma, 2002).

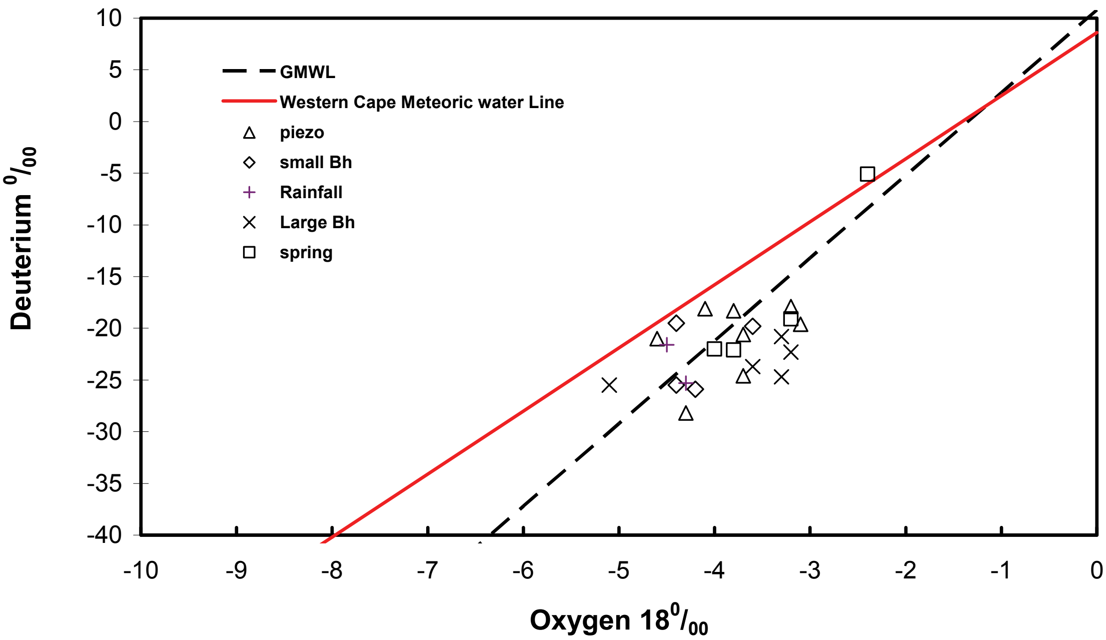

Figure 3-13 Oxygen 18 and Deuterium concentrations (per mille) in water samples from different sources in Kogelberg.

3.4.1.2 Radon sampling

Preliminary radon sampling was carried out at three large diameter boreholes in 2005 to test whether the groundwater had a radon signature. Radon has a short half life of only 3.8 days therefore it could be a useful tracer of aquifer discharge to surface water. A repeat session of sampling and testing was carried out in 2007 to confirm and extend the results, shown in table 3-4.

Table 3-4 Results of Radon measurements in the field (RAD7) and at iThemba laboratory (HPGE) [Bequerels per litre]

Site	HPGE 2005	RAD7 2005	After-rain HPGE 2005	HPGE 2007	RAD7 2007
K2	97	84	81	224	96
K3	-	-	-	-	299
K4	42	41	18	-	47
K1	31	32	28	49	59
K7	-	-	-	-	163
Oudebos spring	-	-	-	ND	ND
Palmiet river	-	-	-	ND	ND
Oudebos river	-	-	-	ND	1

- = Analysis not conducted

ND = Not detected

High measurements of Rn-222 radioactivity were recorded in groundwater samples before and after rain in 2005, the latter with some dilution effects. These results were then confirmed as a groundwater specific source with non-detectable levels in the Palmiet river, which is dammed upstream of the reserve. The very low level recorded in the Oudebos river probably indicates decayed and diluted baseflow. The high result from K3 is interesting as this is a low permeability borehole that yields groundwater that has only been in contact with TMG lithologies within a time period of years. This indicates that the source of the Rn-222 radioactivity is within the TMG and not the result of deep circulation to underlying lithologies. In this area, the Cedarberg shale is present and may represent an important source of Rn. In the USA as granites and marine shales have the highest Rn levels, whereas sands and quartzites are typically low (Brill et al., 1993). The highest levels of Rn-222 radioactivity have been recorded in the TMG aquifer at Uitenhage (Talma, pers.comm. 2007). Here the groundwater is heated and has flowed to significant depths and Rn values of 1407 Bq/L have been recorded. More typical elevated levels of 128 Bq/L have been recorded in Beaufort West in Karoo deposits with uranium ores (Talma, pers.comm. 2007)

These elevated Rn levels indicate that Rn measurements, particularly in the field with the RAD7, could be used to trace aquifer discharge to surface water. Further testing is required of TMG groundwater which is not closely associated with the Cedarberg shale.

3.5 Hydrology

Evaluation of the flows at DWAF gauging weir G4H007 (at the head of the Palmiet Estuary) and G4H030 (at Campanula; Table 3-5) for the period of available overlapping record (1998-2003; G4H030 only started recording in 1998) show a *c.* 90 MCM contribution from the tributaries and other sources to the lower Palmiet River (Figure 3-15). These data are for a relatively short period and did require some patching for missing data. Nonetheless the values obtained agree with those provided by Bruwer (2000) for the main tributaries enter the Palmiet River downstream of Lower Arieskraal Dam:

- Klein Palmiet River (Mean Annual Runoff (MAR) = *c*. 17 million m^3a^{-1});
- Huis River (MAR = *c*. 2 million m^3a^{-1});
- Koos Koster River (MAR minimal), Krom (MAR = *c*. 5 million m^3a^{-1});
- Louws and Dwars Rivers (MAR = *c*. 43 million m^3a^{-1});
- Oudebos (MAR minimal).

Table 3-5 Details of the two DWAF gauging stations on the Palmiet River that were used in the analyses

Station No.	Location	Latitude	Longitude	Catchment area
G4H030	Palmiet River at Monteith (also known as @ Campanula)	34°16'09''	19°01''20'	Not provided.
G4H007	Palmiet River at Farm 562-Welgemoed	34°19'46''	18°59'18''	465 km^2.

Only the Klein Palmiet, the Louws and Dwars River contribute any substantial quantities of water downstream from Lower Arieskraal Dam. The Huis, Koos Koster and Krom tributaries are heavily impacted by abstraction, and water is also abstracted from the Klein Palmiet River. On the other hand, the flow in the Louws and Dwars Rivers is completely natural. These two tributaries, along with the Klein Palmiet, supply the natural hydrological cues in the lower Palmiet River, such as the first annual elevated flows. As such, their continued existence is of vital importance to the continued functioning of the Palmiet River within the Kogelberg.

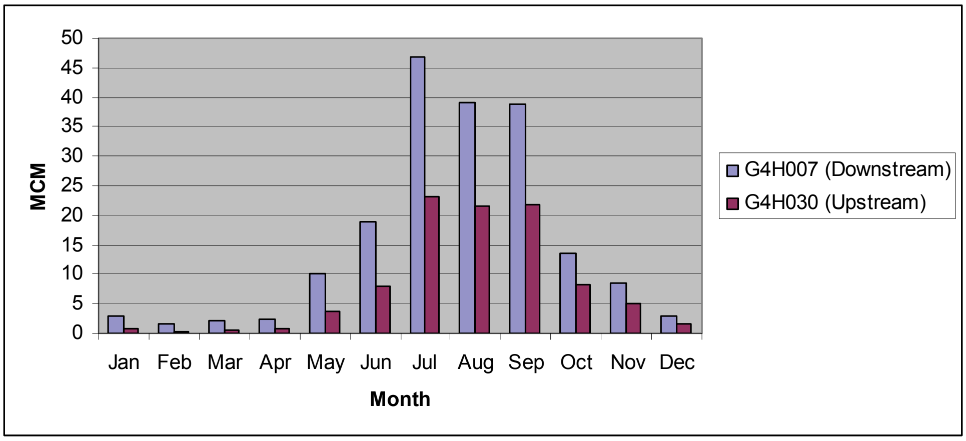

Figure 3-14 Recorded monthly volumes 1998-2003 for the DWAF weir upstream of the Kogelberg (G4H030) and the DWAF weir downstream of the Kogelberg.

Additional detail on the daily contributions (example period 11/98 to 04/99) by the incremental catchment is provided in Figure 3-15

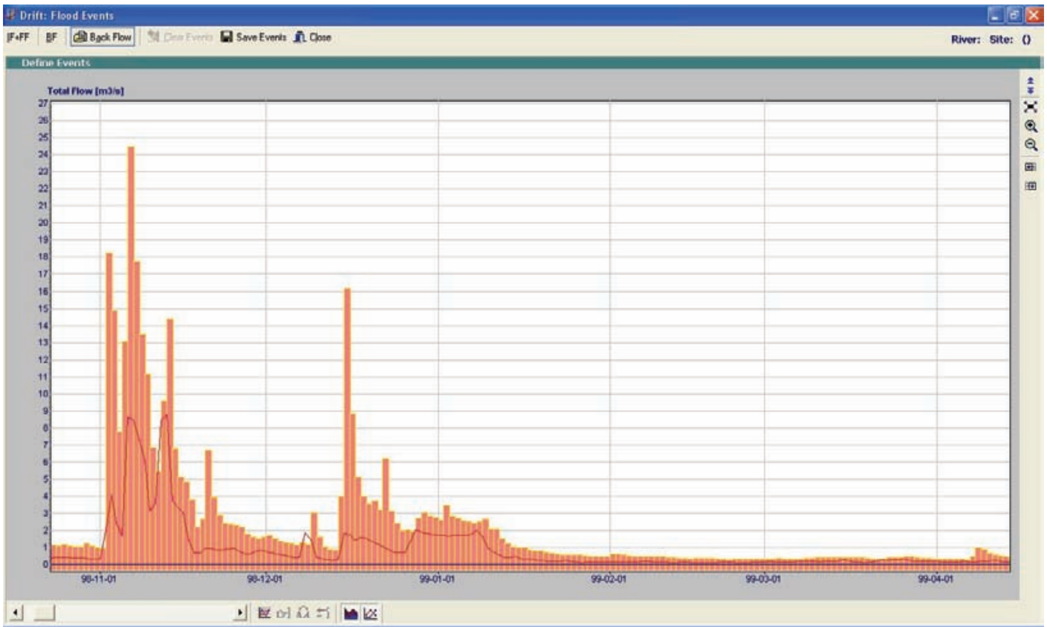

Figure 3-15 A portion of the daily flow hydrographs for G4H007 (pink bars) and G4H030 (red line), indicating contributions to flow (difference between the two) by the incremental catchment.

Interestingly, the percentage contributed by the incremental catchment is higher in late winter (July – September) and early summer (October –November). This pattern is similar (although not identical) to the one shown by the flow measurements in the Oudebos Stream. The reasons for the patterns in contribution are not entirely clear but could be related to one or more of the following:

- rainfall patterns;
- saturation of the lower catchment;

- water abstraction in the upper parts of the catchment, particularly during the growing season in October and November;
- greater contributions by groundwater in the late winter/early summer, once the aquifers have recharged.

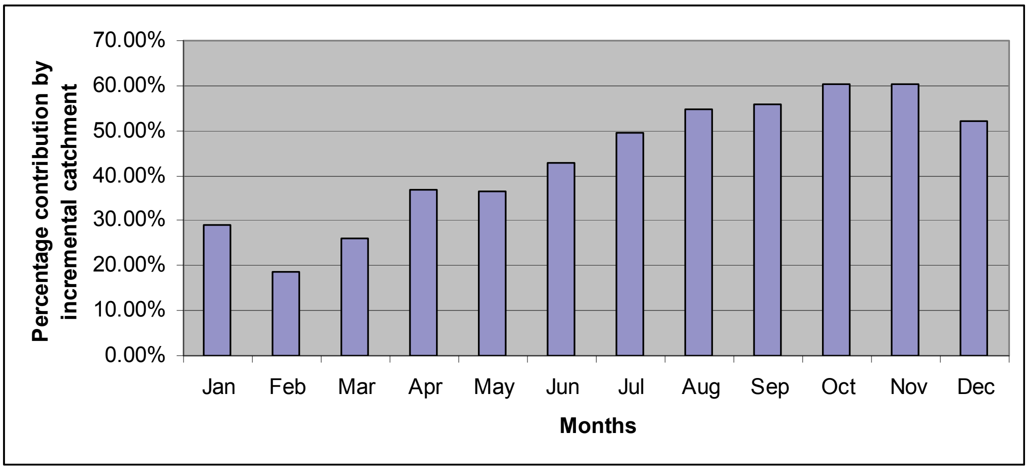

Figure 3-16 Monthly percentage contribution of catchment between G4H030 and G4H007 to flow in the lower Palmiet River.

It is, however, not possible to ascertain with any certainty which, if any, of these are the main reason for the season differences in contributions with the current length of the hydrological record that is available for analysis (i.e., five years). Hydrological data from the Dwars and Louws Rivers (and indeed some of the minor tributaries) could also assist in such an analysis but, other than the few measurements taken in the Oudebos Stream during the study, these are unfortunately not available at this time.

3.5.1 Flow monitoring

The surface water flows in the control sites did not lend themselves readily to cost-effective automated flow monitoring. For this reasons, two kinds of surface water flow points were investigated, namely:

- points at which flow could be measured using a McBinny electromagnetic flow meter;
- possible fixed-point flow monitoring points.

In addition, flow records were obtained from the DWAF gauging weirs on the Palmiet River (No. G4H030 and G4H007), in order to provide some comparison between the local measurements collected and those for the Palmiet Catchment as a whole.

Nine discharge measurement points were selected in the Oudebos catchments for McBinny flow measurements (see appendix D4). Initial sampling points were identified using aerial photographs of the catchment. These points were adjusted during the sampling trips based on their accessibility and the structure of the watercourse. An attempt was made to sample a suite of monitoring points that would provide data for the drainage lines in the catchment, with the focus on those thought to be associated with the TMG Aquifer (faults). This included 4 tributaries and 4 sites on the main watercourse (Oudebosch Stream). In other places, discharge measurements were either complicated or rendered impossible because of multi-channels, dense riparian and instream vegetation and accessibility. The location of the points is given in Appendix D 4 and shown in figure 3-1.

Possible locations and methods for fixed point flow monitoring were assessed and two possible locations were identified. Oudebos 2 was selected and a rated section was installed there in September 2005. This was calibrated between September and November 2005. Oudebos 3 and 4 were selected and Divers installed at each in May 2005.

3.5.2 Flow monitoring results

3.5.2.1 Calibration of rated section

The location of a suitable point along the Oudebos River Valley was crucial to the rated cross-section being used for accurate determination of discharge for an extended period. The site selected is geomorphologically stable and (relatively) free of aquatic and riparian vegetation or resistance elements that would change temporally and influence the relationship between stage (water level) and discharge (flow). The selected point is characterised by flow over bedrock, vegetation along the left bank, and a boulder forming a natural obstruction and downstream control on the water level at low to medium flows. The rating relationship is likely to remain reliable for a range of low and medium flows, although growth of the vegetation colonising the left bank may affect the rating.

Twenty-two measurements of discharge and stage level at the rated cross-section were made over the period May to October 2005. The discharge was calculated using the velocity-area method according to the standards in BS 3680: Part 3A: 1980. Flow velocities were measured using a McBinny electromagnetic flow meter, and stages were measured relative to the reference pegs.

A rating equation was fitted to the observed stage-discharge data, and is given by:

$$Q = 0.0091(z - 787)^{3.45}$$

where

Q is the discharge (l/s); and *Z* is the stage relative to the local datum given in mm.

The value "787" in the equation above represents the residual stage when the river ceases to flow (i.e. zero discharge). It should be noted that this is an estimate (based on a survey of the lowest point over which water flows at the downstream hydraulic control), since the stage of zero discharge has not been directly surveyed for the rated cross-section (the lowest observed discharge is 7l/s).

The rating relationship given by equation 1 is plotted over the discharge range 4 to 140l/s in figure 3-17 below, together with the observed point rating data. The graph shows large scatter in the measured rating data for stages above 1123 mm (i.e., predicted discharge of 47 l/s). This is attributed to measurement inaccuracies and unsteady flow effects. For example, rating data were collected during rainfall events on 21 July, where discharge is measured as varying between 56 and 93 l/s over an hour but corresponding to only a 2 mm change in water level. Discharge computation using the velocity-area method is difficult in this environment due to the lack of appropriate flow gauging sites (uniform cross-channel velocities in a prismatic channel cross-section). Consequently, the average absolute error between the predicted and measured discharges is 25%. Ideally, for a rated cross-section, the maximum absolute error should be less than 10%. There is, however, reasonable correspondence between measured data and the fitted relationship at low flows (7 to 14 l/s). The tabulated calibration table for the Oudebos River Site is provided in Appendix D4 up to a maximum discharge of 80l/s.

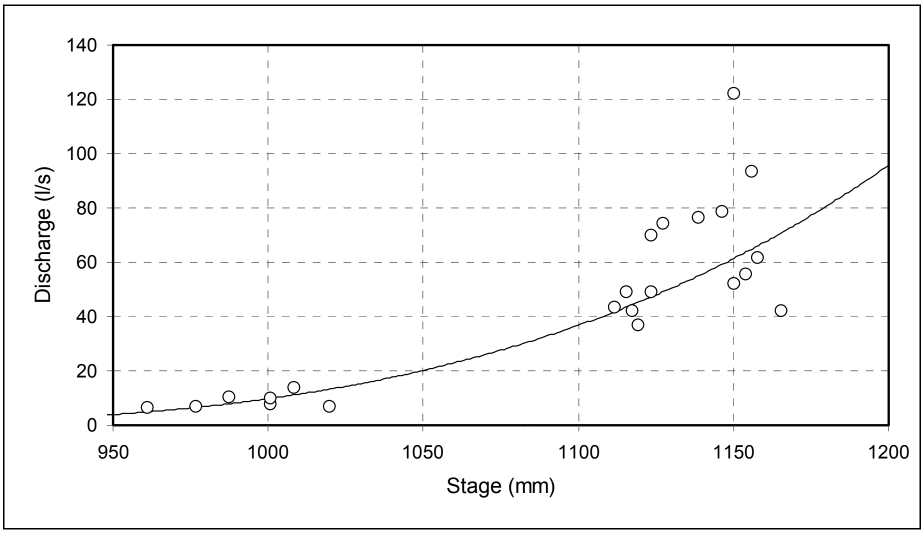

Figure 3-17 Rating relationship for the Oudebos River Site.

Recommendations for application and refinement of the rating

Care must be exercised with application of the rating relationship where changes in flow being monitored are of the same order of magnitude as the potential error inherent in the rating function (or calibration table). The confidence in the calibration is poor at medium to high flows (above 40 l/s), and needs to be refined with further measurements in the range 20 to 40 l/s. Furthermore, the scatter at high flows (40 to 100 l/s) is too high to establish an accurately rated section, and further accurate rating measurements are required with an indication of the unsteadiness of the flow at the time of measurement (since this produces scatter).

3.5.2.2 Routine discharge measurements

Routine discharge measurements were taken in the Oudebos Catchment in August 2004, October 2004, February 2005 and May 2005 (Figure 3-18). It was not possible to collect accurate data in a catchment where discharge varies markedly through the day owing to rain. Patches of clear weather needed to be identified before sampling can be undertaken, and in the winter months several sampling trips has to be abandoned mid-way (e.g., 30th July 2005).

Summer flows in the Oudebos catchment dropped to below levels that could be measured, indicating at best weak perenniality. However, it is noted that whilst flow rates were too low to measure, the river included standing pools along its length, even in the upper reaches in the forest close to the saddle.

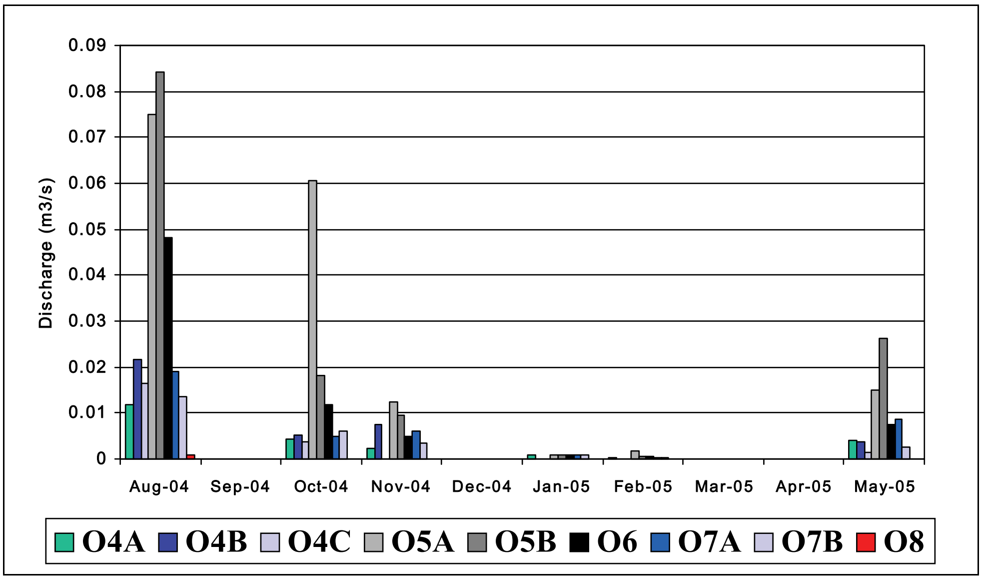

Figure 3-18 Discharge measurements in the Oudebos Catchment (2004/2005)

3.6 Aquatic Biology

3.6.1 Monitoring locations

Macroinvertebrate and diatom sampling took place at a sub-set of the routine discharge measurement locations, namely: O5A; O5B; O6, O7A and O7B shown in figure 3-1.

3.6.2 Results

3.6.2.1 Macroinvertebrates

Macroinvertebrate sampling in the Oudebos Catchment took place in July and November 2004 and May 2005. The composition of the macroinvertebrate communities recorded during each of the sampling occasions is provided in Appendix D 7.

Several factors were found to have a significant impact on macroinvertebrate diversity during the survey period. These include habitat availability, seasonality and flow level during sampling. The changes in abundance of macroinvertebrate taxa were evident during the survey duration.

Habitat availability: Generally, where habitat diversity (biotope) was poor, there was less macroinvertebrate diversity and consequently a lower SASS5 score. The type of substratum present restricts or enhances macroinvertebrates ability to adhere, cling or burrow, deposit eggs, construct cases and affects their ability to escape from predators. In July 2004, location O5B had a relatively low flow and only mud biotope was sampled. Only one individual was recorded for each sampled taxa. The importance of habitat diversity in macroinvertebrate assemblages was evident at that location. There were no stones and aquatic vegetation available for macroinvertebrate taxa and as a result Odonata, Ephemeroptera, and Diptera taxa that are usually associated with these biotopes were absent. Both macroinvertebrate abundance and diversity were influenced by habitat availability. Where habitat diversity was rich (e.g. location O6), higher number of taxa was recorded and hence higher SASS5 score. This location was consisted of moderately fast flow and a variety of biotopes (stones in and out of current, aquatic vegetation and little gravel). Most families that were absent at location with fewer habitats were present where the habitat diversity was greater. The SASS results at indicated that the tributary conditions were good in terms of macroinvertebrates.

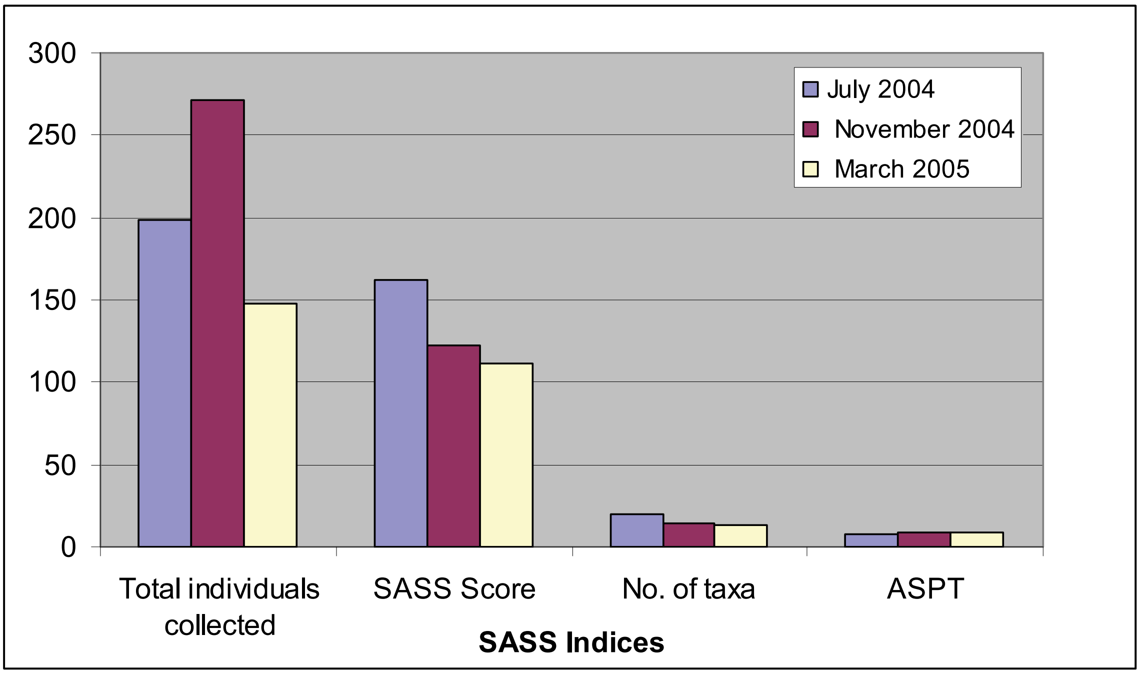

Figure 3-19 Summary Macroinvertebrate assessment (SASS) results recorded from Oudebosch Catchment during 2004 and 2005 survey

Seasonality: The highest SASS5 scores and number of taxa were obtained during winter (July 2004), followed by early summer (November 2004) and late summer (March 2005) respectively (Figure 3-19). There was a clear pattern of response of benthic macroinvertebrate assemblages to a change in the seasons. Certain taxa such as Amphipoda were dominant in all surveys. Average Score Per Taxon (ASPT) did not show any significant difference between seasons. The ASPT Scores ranges from 8.1 in winter to 8.7 during early summer, when most of the macroinvertebrate taxa are active. Interestingly, in the Western Cape higher macroinvertebrate diversity is normally associated with warmer summer months, the results here showed highest diversity in the winter when flows were higher.

Flow conditions: The tributaries in this catchment possess highly variable flows, often independent of seasonality. Although somewhat limited, the results generated here indicate that changes in flow associated with wet and dry seasons were the major influence on macroinvertebrate community structure results, rather than any anthropogenic alterations in water quality.

3.6.2.2 Diatoms

Diatom samples were collected from locations in the Oudebos Catchment on the following dates:

O4 - Sampled 29/07/2004 : Humic stain with fine sediment.
O4b - Sampled 18/08/2004 : Clear water with fine sediment.
O4B - Sampled 18/08/2004 : Stained with medium black sediment.
O4C - Sampled 18/08/2004: Stained /black sediment and gravel.
O5 - Sampled 29/07/2004 : Very little sediment with detritus.
O5B - Sampled 18/08/2004 : Humic color with fine sediment.
O6 - Sampled 18/08/2004 : Clear water with fine sediment.
O7 - Sampled 19/08/2004 : Highly stained with little sediment.
O7B - Sampled 19/08/2004 : Dark-stained/little sediment.
O8 - Sampled 19/08/2004 : Fine black ooze with plant fragments.

The locations of the sampling sites and an inventory of the species that were recorded at each of the sites are presented in Appendix F.

Table 3-6 Assessment of diversity of diatom assemblages at the various locations in the Oudebos Catchment.

Diatom Assemblage	Sequential Comparison Index Values For TMG Sites				
	SCI Index Value (Cairns *et al.,* 1968)				
Oudebos Catchment	O4	O4b	O4B	O4C	O5
	0.47	0.75	0.68	0.84	0.58
	O5B	O6	O7	O7B	O8
	0.72	0.74	0.89	0.79	No count

3.6.3 Summary

Information on macroinvertebrate and the diatom assemblages have been widely used to monitor overall ecosystem condition, and in this regard both sets of data showed the study streams to be in relatively good ecological condition. At this stage, and with the level of detail achieved in this study it is not possible to state for certain that either group would be useful in monitoring groundwater contributions, however it seems unlikely that they will provide a reliable measure of such. This is because, as demonstrated above for the macroinvertebrates, the faunal and floral communities in rivers and streams are a result of a combination of numerous environmental factors, such as geology, water-chemistry, flow-regime and ambient temperature, with the ultimate source of the water in the streams being but one of the mixture of influences acting on them. This makes is difficult, if not impossible, to isolate the influence of groundwater contribution from biotic community data.

3.7 Botanical characterisation

Research in river systems suggests that variability in flow regimes is an important determinant of the kinds of aquatic ecosystems (Gorman and Karr, 1978; Stanford and Ward, 1979; Richter *et al*., 1996). If the same is true of wetland communities on the TMG aquifer, then the species composition or structure of the wetland vegetation communities would differ between aquifer-fed types and wetlands with surface water or rain-fed dominated hydrology. Two different kinds of studies were undertaken to determine whether aquifer linked wetlands differed from other types of wetlands in this catchment:

a) Detailed studies of four representative wetlands with respect to groundwater sources and dynamics, plant water relations, vulnerability to water stress and water sources of plants on and off wetlands (sections 3.7.1-3.7.).

b) A broad scale survey to provide a detailed characterization of the wetlands of the Oudebos River catchment to determine whether wetlands in the three different hydrogeological settings differ in their species composition and structure. This survey included wetlands controlled mainly by surface water accumulation and also by shallow soils, impeded drainage and geomorphological settings (sections 3.7. – 3.7.).

Four sites were chosen for the detailed studies (a) based on their different potential discharge settings. The results of those studies summarized here are taken from Aston (2007) and given in full in Appendix I. The sites are as follows:

- The Oudebos site is located on the lower, north-facing slope of the ridge that defines the southern side of the Oudebos catchment is the site of the geophysical profiles and K7.
- The Coastal Blomhuis site is situated on the Stroompie property on the coastline on the upper raised beach terrace at 17-20 mamsl . It is close to the K1 borehole.
- The Kogelberg Valley site is located on a fault NW trending fault in the upper part of the reserve and is the drill site K5.
- The Perdeberg site seep is situated on a north-facing slope near the crest on the Skurweberg Formation (34°18' 34" S, 19° 00’ 00" E). This is an upland recharge area and is unlikely to be affected by abstraction.

3.7.1 Wetland shallow groundwater level measurements

The sites differed markedly in the amount that their water levels varied throughout the sampling period (Figure 3-20). Shallow groundwater levels in the Perdeberg were the most variable, dropping right down to bedrock in January, February and March, before rising after the first heavy rain in April. The soil zone on top of the mountain does not store sufficient water to maintain a water table throughout the drier summer. The depth to the water table in the Coastal and Oudebos sites varied, by 60 and 40 cm respectively, dropping in the drier summer months. Their soil remained permanently saturated. Water levels at the Valley seep remained essentially unchanged throughout the summer, fluctuating within a range of 6 mm. The other seeps were connected to aquifers that contained sufficient groundwater to sustain the water table throughout the dry summer with the largest “reservoir” being linked to the Valley site. Overall, these findings suggest that the measurement of water levels throughout summer could be a simple, yet effective, way of determining the seasonal fluctuation of water influx into seeps or wetlands and hence, whether they are perched or fed continuously by groundwater from a more regional aquifer.

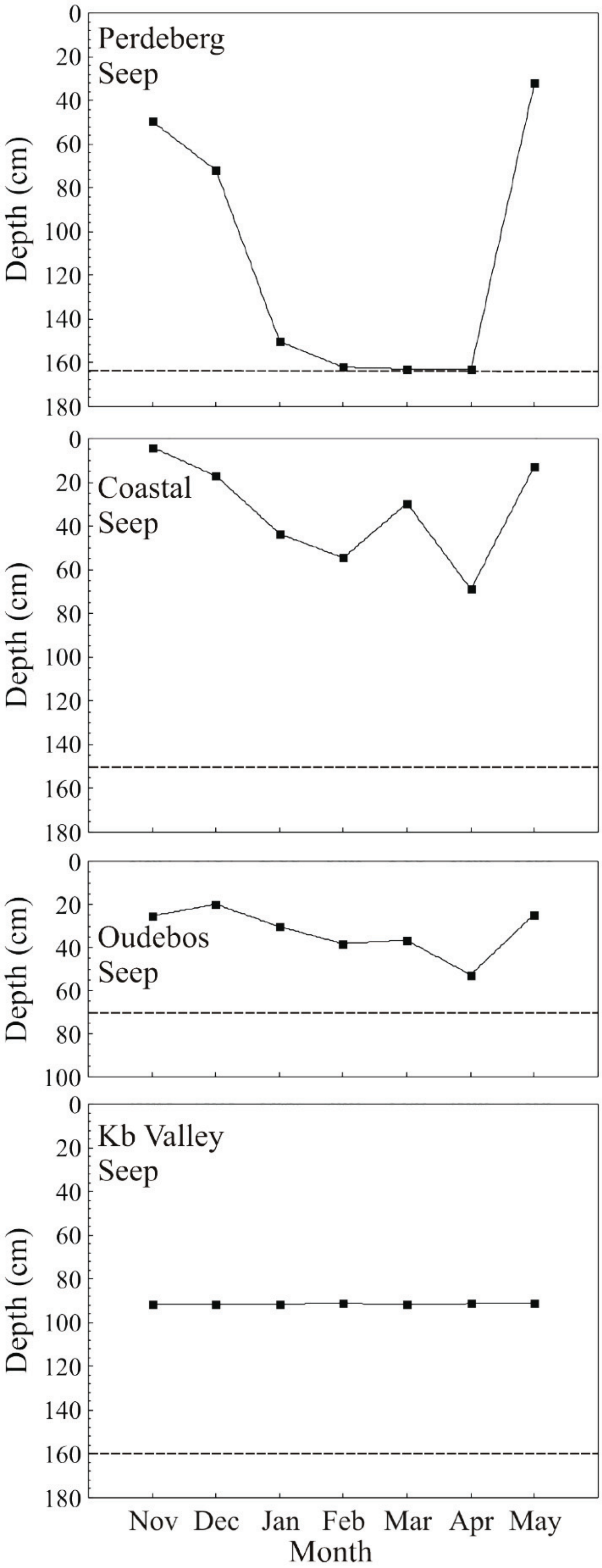

Figure 3-20 Variation in the depth to the water table in piezometers sunk into the four seeps throughout the summer of 2004/05. The dashed line represents the bottom of the piezometer, which was sitting on bedrock (Aston, 2007: appendix I).

The responses to the intensively sampled rainfall event also varied between the study sites. The groundwater levels at the Perdeberg wetland rose by between 60 and 80 mm during the rainfall event. Twenty-four hours later, the water levels had dropped down to just 11 mm above their initial height, although the soil above the initial height was still saturated. The Valley and Coastal seeps had larger surface catchments (1.70 km^2 and 2.51 km^2 respectively) than the Perdeberg wetland (0.06 km^2), and therefore received much larger amounts of rainfall during the rainfall event (an estimated 38,200 kl and 40,800 kl compared to 580 kl) in addition to groundwater discharge. Despite this, the water levels in both the Valley and Coastal seeps rose by less than 20 mm, indicating much greater storage connected to the saturated water body in the rooting zone.

3.7.2 Isotopes in wetland water

Rain, groundwater and saturated zone samples were collected for isotope analysis and fluctuations in the water levels were measured throughout the length of a summer in four wetlands in the Kogelberg. The rainfall in the cumulative rainfall collectors was isotopically the most negative in summer (δD ≈ -9 ‰) and positive in spring (δD ≈ -40 ‰). The shift was probably due to a combination of both amount and air temperature effects. The high proportion of winter rainfall means that its intermediate signature (δD ≈ -31 ‰) will dominate the signature of well-mixed groundwater.

The near-surface soil-water was always isotopically enriched relative to the underlying groundwater. The groundwater in the Valley seep showed the least variation in the isotopic ratio of all the sites with a range of -3.22‰ (Figure 3-21). The stable isotope ratio of groundwater from the Oudebos and Coastal seeps was more variable and appeared to track the seasonal variation in the rain falling within their catchments: being lightest for samples collected in January and February when the rainfall signature was lightest. This indicates significant contribution of local direct recharge to groundwater in the rooting zones at these sites.

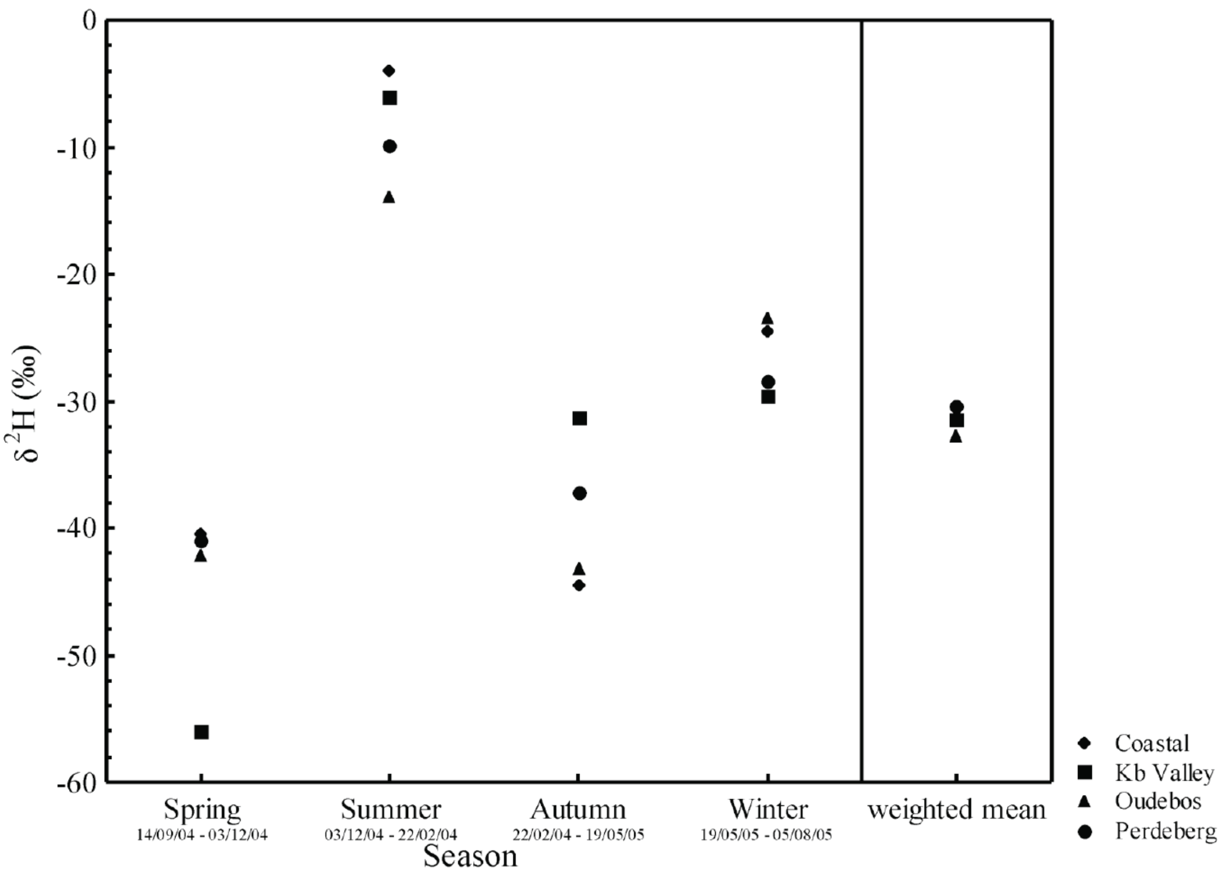

Figure 3-21 The δ2H of rainfall falling into the catchments of the four seeps throughout the sampling period. Values depicted have been corrected for altitudinal effects on both the amount and ratio of stable isotopes. The weighted mean δD values are also depicted.

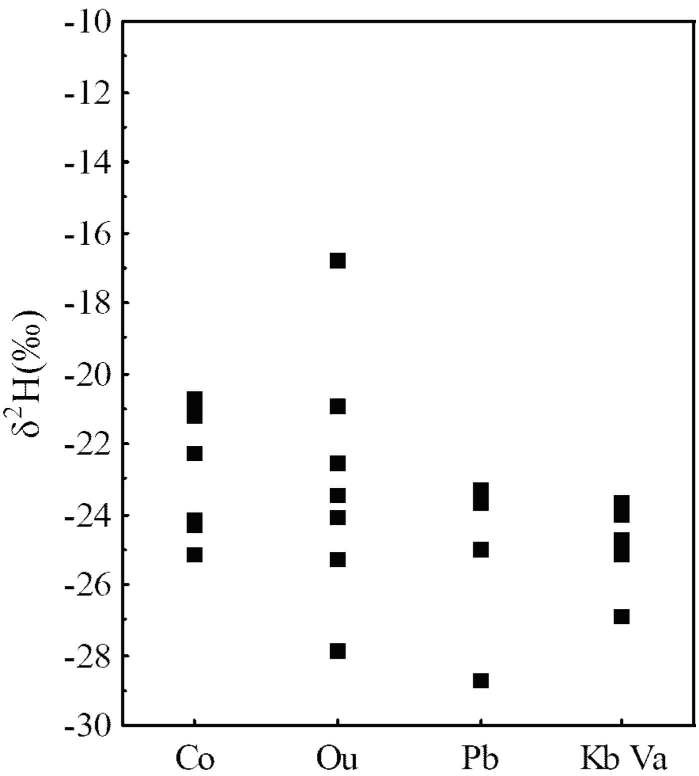

Figure 3-22 Variation in δD (not δ2H) of groundwater samples collected from four seeps in the Kogelberg throughout the sampling period. Co = coastal, Ou = Oudebos, Pb = Perdeberg, Kb Va = Valley.

The seasonal shift in the δD values of groundwater of the Coastal and Oudebos seeps was not as great as that of the rainfall, suggesting that rain that fell earlier in the year was still being discharged. The fact that the δD values of these sites shows greater seasonal variation than the Valley seep, and apparently does track the seasonal pattern of the rainfall signature, suggests that groundwater discharging at these seeps is following shorter flow paths or is not well mixed with groundwater derived from aquifer storage.

These findings suggest that the mixing of groundwater derived from different temporal intervals is more complex than was anticipated and that the use of isotopic tracers should only be carried out with sufficient characterisation of this complexity. A single sampling period is likely to be of little use in identifying aquifer-fed systems. Seasonal sampling may resolve some of these issues for the seeps fed by substantial aquifers but still may not give reliable indication of different water sources.

3.7.3 Plant water relations

November to March was the driest time of the 2004/05 summer in the Kogelberg (Figure 3-23). November and March were the two driest months with totals of 13 mm and 18 mm having fallen respectively. It rained fairly regularly throughout the summer with some wet days (for example the 33.8 mm that fell on 22 December) in the middle of summer. The heavy winter rains started in early April with 141.5 mm of rain falling within six hours on the morning of 11 April.

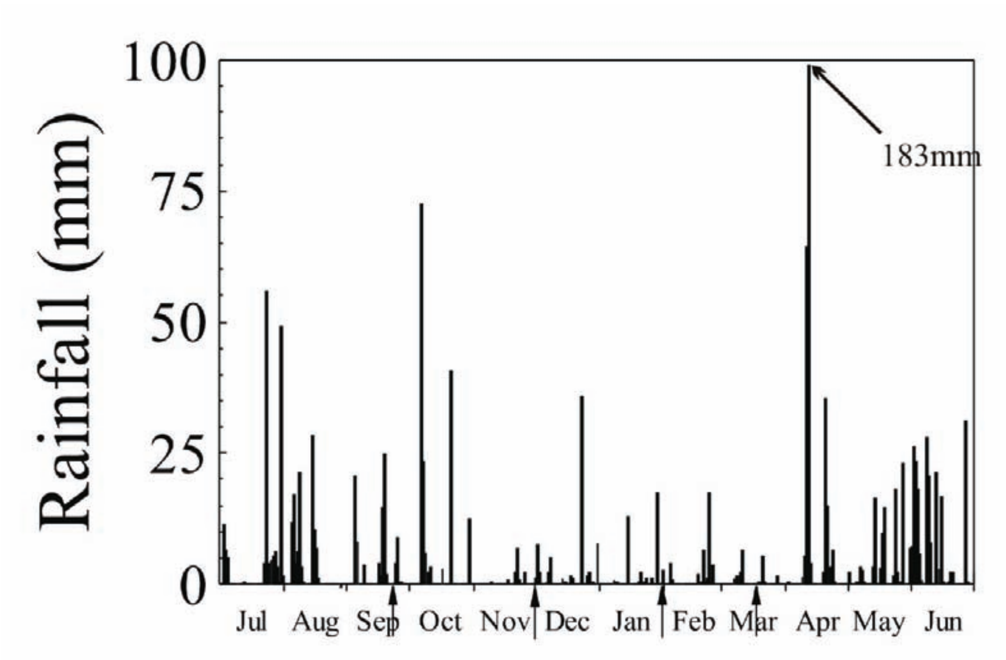

Figure 3-23 The daily amounts of rain that fell at the reserve office, from July 2004 until June 2005. Rainfall on the 11th of April fell off the scale. The arrows on the x-axis indicate the timing of the four sets of plant water stress measurements (Aston, 2007)

Water stress

The results of water stress measurements at Perdeberg and Kogelberg valley wetlands are shown in Figure 3-24. The levels of both pre-dawn and midday water stress of plants on the Perdeberg and Valley seeps did not differ significantly. Off-seep plants experienced similar levels of predawn water stress at both sites but midday water stress was significantly higher at the Valley seep.

There was virtually no seasonal variation in water stress among on-seep plants at the Valley or Perdeberg site except for the Restionaceae at the latter site, which apparently stopped transpiring towards the end of summer. The deeper-rooted Proteaceae species experienced the lowest levels of water stress.

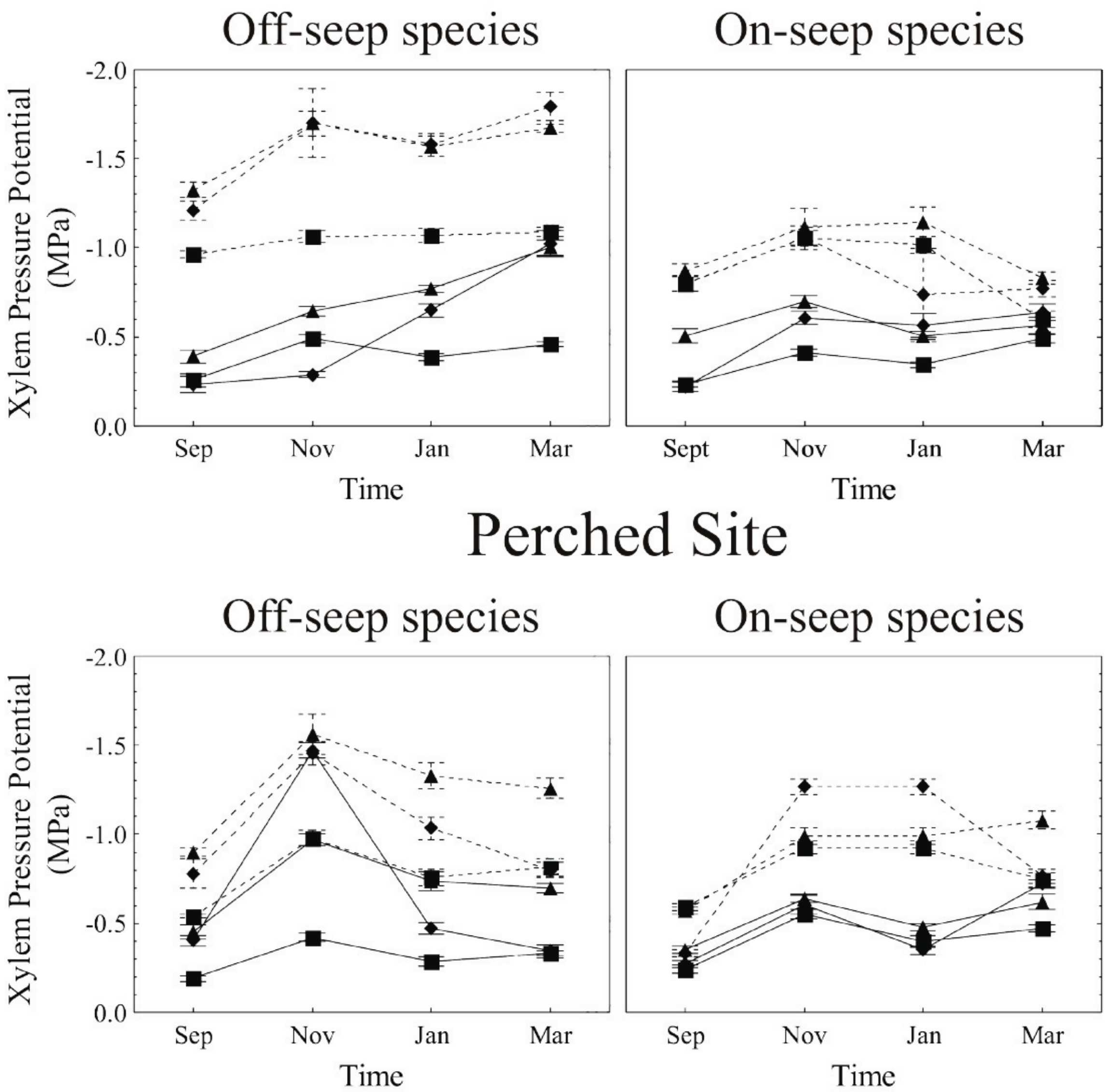

Figure 3-24 Variation in Midday (dashed lines) and pre-dawn (solid lines) xylem water potentials of species living on, and adjacent to, the (Kb) Valley seep and the Perdeberg seep throughout the summer of 2004/05. Means (n = 7) are depicted as well as the SE. Restionaceae are represented by diamonds, Proteaceae by squares and Asteraceous species by triangles.

Surprisingly, Proteaceae adjacent to the Perdeberg seep were significantly less stress stressed than their on-seep analogues. Off-seep Restionaceae and Asteraceae at the Valley seep experienced significantly higher levels of water stress than those at the Perdeberg seep ($P < 0.0001$). Off-seep Restionaceae at the Perdeberg seep were less stressed than their on-seep analogue ($P<0.0001$). The midday water stress of on-seep Proteaceae at the Valley seep was significantly less than that of their off-seep analogues but not at Perdeberg.

The absence of saturated soil water in the rooting zone during the summer at the Perdeberg site did not appear to affect the levels of water stress and off-seep plants experienced less stress than those at the Valley seep. The reason for this appears to be that the upper slopes of the Perdeberg are frequently covered by clouds formed during the strong south-easterly winds which occur in this area. Direct capture of cloud-water from mist formed during south-easterly winds probably is an important source of unsaturated soil of water to plants at this site. Sampling of mist precipitation was attempted but none of the rainfall collectors was able to withstand the powerful winds. The mist capture hypothesis is supported by the fact that off-seep plants at the Perdeberg site experienced their greatest water stress in November which was the month with the longest dry periods. The Kogelberg mountains receive fairly regular rainfall throughout summer. This may account for the low degree of water stress of off-seep plants compared to values reported from studies carried in more arid areas (Miller et al., 1983, 1984; Moll and Summerville, 1985; Jacobsen et al., 2007). For example, the most negative water pressure potential was -1.79 MPa (off-seep *Chondropetalum tectorum* at the Valley site).

The off-seep Proteaceae at the two seeps experienced no increase in water stress throughout the summer, with pre-dawn levels remaining constant at around -0.4 Mpa. The conservative water-use, associated lack of seasonal variation in water stress, and the low level of stress in deep-rooted Proteaceae also was reported by Miller *et al.* (1983, 1984), Richardson and Kruger (1990), and Smith *et al*. (1997). These observations suggest that species of Proteaceae occurring adjacent to the seeps, or further away in dry land situations, must have access to a permanent supply of soil moisture or groundwater throughout the summer (Richardson and Kruger, 1990). At the Kogelberg sites, indications are that the relatively constant and low level of stress is not due to a reduction in transpiration, induced by stomatal closure, because this would be indicated by a significant increase in stress from pre-dawn to midday. The difference between pre-dawn and midday levels of water remained constant at around 1MPa throughout the year. The source of this water is not clear although Richardson and Kruger (1990) noted that even during dry periods, small rainfall events were sufficient to recharge soil moisture in the highly permeable soils, and the same is likely to be true of the Kogelberg sites. It is likely that the water-table in the vicinity of seeps could be sufficiently shallow for deep-rooted Proteaceae to reach it – the depth of root systems is > 3 m (Higgins *et al*., 1987; Smith and Higgins, 1990). However, it is unlikely that there is a water table in sites like the one used by Richardson and Kruger (1990) which was a north-facing slope of about 30° with loamy soils about 0.9 m deep over fractured sandstone. At their study site *Protea nitida* and *P. repens* did experience modest midday water stress in late-summer (max -2 MPa) and leaf transpiration declined during the midday period but still by relatively little. By the late summer, soil water potentials at 0.9 m depth remained below -0.1 MPa (the maximum the potentiometers could measure) for extended periods of time. However, as noted above, root systems of Proteaceae are known to reach depths in excess of 3 m, well beyond the soil depth measured by Richardson and Kruger (1990).

Overall, these observations suggest that even if these Proteaceae are using the groundwater feeding these seeps, they are unlikely to be completely dependent on it as they have extensive root systems and can accommodate greater moisture stress. If abstraction does lower the elevation of the water-table of the groundwater discharging in the seep there may be some die back but the effect is likely to be confined to a limited area upslope of the seep and to more susceptible species such as Restios. The impacts will also be ameliorated in relatively high rainfall areas such as the Kogelberg and plants further away are unlikely to be affected. This is probably not true of shallower-rooted species (e.g. ericoid shrubs) which show more marked seasonal variations (Miller *et al*., 1983, 1984) and may be more severely affected (Cleaver *et al*., 2003). In some situations, the nonproteoid species may also depend on “hydraulic lift” (Richards and Caldwell, 1987; Caldwell and Richards, 1989; Caldwell *et al*., 1998) by the Proteaceae.

The rugged mountain areas typical of the areas being targeted for groundwater abstraction generally lack the extensive, deep, sand deposits typical of sand-plain fynbos in the lowlands. Studies in analogous sand-plain environments Western Australia have found that Proteaceae, and the associated species, are sensitive to the lowering of the water-table, even by relatively small amounts and relatively slowly (Froend *et al*., 1997; Froend and Zencich, 2002; Zencich *et al*., 2002). There are indications that fynbos communities in similar sand-plain environments may be severely affected by lowering of the water table. This seems to be what is happening in the Sandveld where the wetland communities, in particular, have been severely affected by excessive abstraction for agricultural purposes (ref). The occurrence of similar, extensive die-back in montane areas is believed to be unlikely because groundwater discharge is typically highly localised, and extensive and deep sand deposits with shallow water tables are rare.

(iii) Isotopes in stem water

There were no significant differences in the stable isotope ratios of the stem-water of on- or off-seep plants at the Perdeberg and Valley seep at the end of summer, although the ratio for off-seep *Chondropetalum tectorum* was slightly more fractionated than off-seep *Phaenocoma prolifera*. The stem-water of *Chondropetalum tectorum* and *P. prolifera* at the Perdeberg was more enriched than the same species at the Valley seep, but only *P. prolifera* was significantly so (p= 0.0005). At the Valley seep, three *C. tectorum* individuals had a heavy stem-water signature, very similar to that of the preceding rainfall but the stem water of the remaining individuals isotopically indistinguishable from that of *P. prolifera*. Before and after the rainfall event, *R. purpurascens* on the Perdeberg seep had the most isotopically enriched stem-water, and *P. cynaroides* the most depleted. After the rainfall event all three species became isotopically enriched, with none of the plants sampled having stem-water more enriched than that of the antecedent rainfall.

Once again, more shallow rooted species tended to have the most isotopically enriched and most variable stem-water. There was little change in the ratios of stable isotopes of the plants’ stem-water. Before and after the rainfall all of the plants sampled had stem-water enriched relative to the underlying groundwater and even soil-water at as shallow as 300 mm. The Restionaceae became the most stressed at the end of summer, especially off the Valley seep. Their stem-water isotope signatures varied between individuals from values close to the preceding rainfall to values close to the deeper rooted Asteraceae. On-seep plants at the Perdeberg seep had stem water that was isotopically similar to the antecedent rainfall compared with the same species at the Valley seep. Deeper-rooted species tended to have isotopically depleted stem-water, with stem-water from *Protea cynaroides* being closest to groundwater. However, nearly all of the plants sampled had stem-water that was more enriched than soil-water deeper than 300 mm, suggesting that seep species utilize some water from the upper soil layers.

Similar patterns of seasonal variation were found with seasonal shifts between soil and groundwater sources in deep-rooted *Banksia* (Proteaceae) species on a deep sand aquifer in Western Australia (Zencich *et al*., 2002). Changes in the ratio of soil water with depth on the seeps in winter were much less obvious than those reported in other studies (White *et al*., 1985; Ehleringer and Dawson, 1992), which is likely to be as a result of the water table being too close to the surface to allow for the establishment of a large soil-water fractionation gradient. Only the uppermost fraction of the soil was ever significantly fractionated relative to that of the underlying groundwater.

3.7.3.1 Plant vulnerability to water stress

The vulnerability curves of ecologically comparable species were similar, whether or not they were phreatophytic but differed markedly between genera (Figure 3-25). Some species have very steep, short curves (e.g. *Mimetes hirtus* and *Psoralea pinnata*) whereas others have flatter, wider curves (e.g. *Berzelia alopecuroides*) and cavitate less under higher water potentials. At -3 MPa approximately 62% of *B. alopecuroides*' xylem had cavitated whereas *M. hirtus* and *P. pinnata* had experienced total xylem failure i.e. 100% loss of conductance. The wider error bars associated with *W. maura*'s curve are due to its low flow rates which are a result of it being a monocotyledonous species and, thus, having a different wood anatomy. The P_{min} values observed in this study indicated much less water stress than has been reported from the arid end of the fynbos spectrum (e.g. Jacobsen *et al.,* 2007).

Many studies have reported plasticity in vulnerability curves with clones having varying degrees of vulnerability to water stress (Pammenter and van der Willigen, 1998; Harvey and van den Driessche, 1999). The results of this study suggest otherwise. The absolute stress tolerance of a species, as defined by the ability of its xylem to withstand negative pressures, does appear to be 'rigid', i.e. related species had similar shaped curves regardless of whether or not they were phreatophytic. This suggests that selection for changes in fynbos species' vulnerability curves occurs during major taxonomic events, such as the evolution of new genus and is constant within a genus. Alternatively, the relatively small difference between the species studied may be the result of the relatively recent speciation of many fynbos genera which are known for their very high numbers of morphologically and ecologically similar species (Goldblatt, 1978; Cowling and Holmes, 1992; Linder *et al*., 1992; Linder and Hardy, 2004). The recent speciation, combined with the relative constancy of rainfall conditions during the Pleistocene glaciations (Deacon *et al*., 1992), suggests that there may have been little selection, at least in the core of the fynbos region, for differentiation on traits related to water stress.

From the shape of their vulnerability curves it appears that *Mimetes* evolved in wet habitats or during wet periods in the past. Adaptation to drier habitats such as that undergone by the 'vulnerable' *M. cucullatus* must have occurred either by through the development of deeper root systems or at the leaf-level. However, deep root systems are also associated with sprouting after fires (Bond and Midgley, 2003) so it is not clear whether the deep root systems inferred for *M. cucullatus* are associated with its evolution a sprouting habit. In addition, only a phylogenetic analysis can resolve whether or not sprouting is a derived trait (Bond and Midgley, 2003) and no such analysis has yet been done for *Mimetes*.

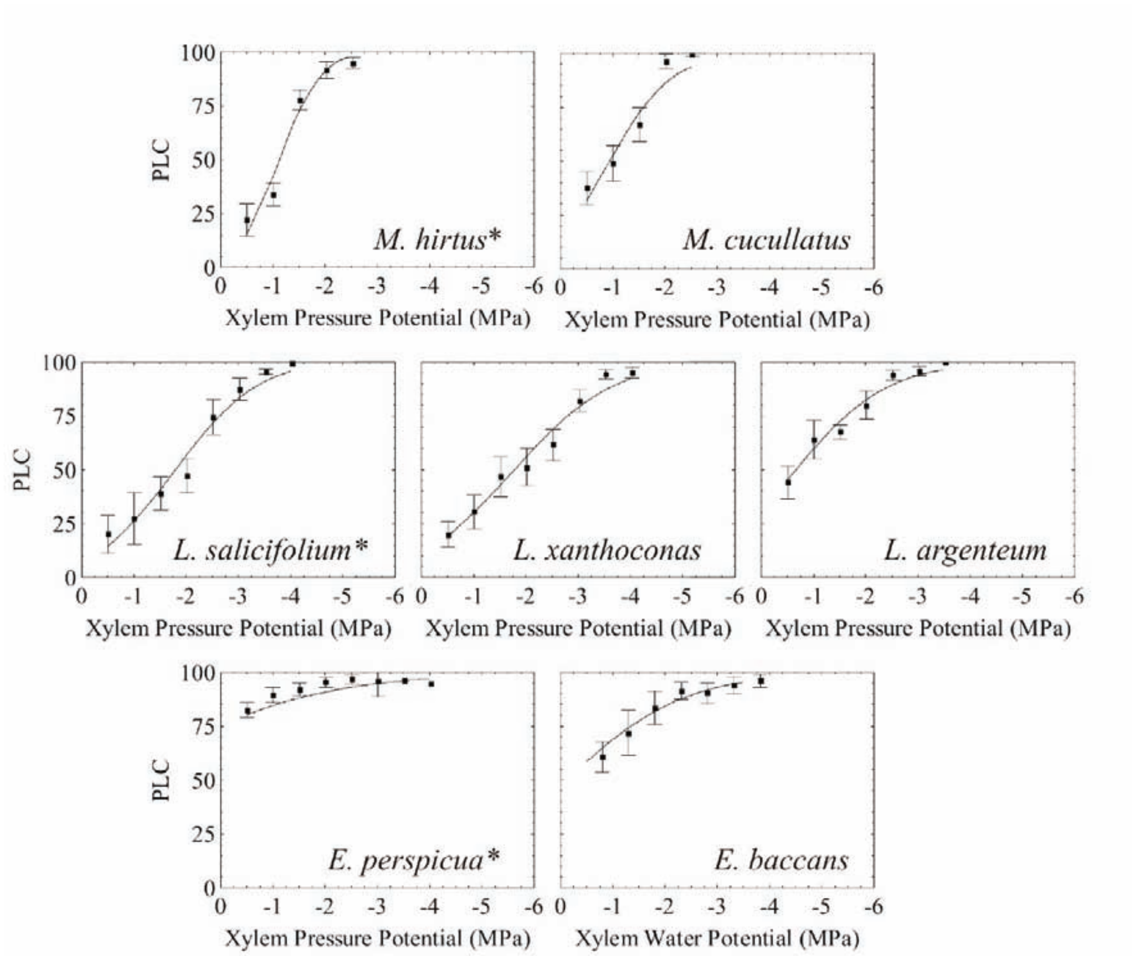

Figure 3-25 Vulnerability curves showing the percentage loss of conductance (PLC) vs. xylem water potential for phreatophytic fynbos species (marked with an asterisk) and analogous non-phreatophytic species (mean ± 1SE, n = 6)

Inter-specific variation in wood anatomy-based drought vulnerability has been found to correlate with species' susceptibility to drought (Froend and Drake, 2006) but the results of this study suggest that their use, in isolation, as a diagnostic tool is somewhat limited. For example, the vulnerability curves of *L. xanthoconus* and *L. salicifolium* are essentially identical despite *L. salicifolium* being a phreatophyte and *L xanthoconus* not. Two of the phreatophytes, *M. hirtus* and *P. pinnata,* have extremely vulnerable xylem, having experienced total xylem failure by -2.5 MPa. The individuals that were sampled were from a permanently wet coastal seep just outside of the Kogelberg. The distribution of these species may be limited to permanently wet areas and warrants further research. Except for *Berzelia alopecuroides*, which is apparently relatively drought tolerant, all the phreatophytic species had experienced total xylem failure by about -3.5 MPa. They will therefore be unable to survive in soils with water potentials that regularly exceed -3.5 MPa. In this study the bedrock in mountain seeps was rarely deeper than 2 m below the surface. Should seep water tables drop as a result of abstraction, the plants on seeps will be unlikely to have access to groundwater - they will not be able to track receding water levels by growing deeper roots unless they can access deeper, water-holding fractures and root growth is sufficiently rapid to track the water table. Plants living on perched seeps, fed by rain falling in their catchments, are able to survive seasonal reductions in access to groundwater. Reductions in access to groundwater on aquifer-fed seeps may, however, be permanent.

The majority of species were sampled from the Kogelberg Biosphere Reserve, the so called 'heart of the Fynbos Kingdom'. The Kogelberg falls at the wetter end of the Fynbos spectrum, with an average of 1540 mm $year^{-1}$ of rain at Oudebos from 1996 to 2006. Nonetheless the apparent drought sensitivity of typical non-phreatophytic species was unexpected and could have serious implications for the sensitivity of fynbos to predicted reductions in precipitation associated with climate change.

Fynbos is comparable to Californian chaparral, the mediterranean-type ecosystem in which plant water relations are the best understood. Very little research has been done on fynbos plant water relations and there is only one study which reported P_{min} values similar to the average for chaparral (-3.78 MPa – based on all the species reported in the literature). This is the one which included species sampled at the edge of the Karoo and reported an average of -3.4 MPa (Jacobsen *et al*., 2007). On average, fynbos species are a great deal more vulnerable – tolerating a maximum of -2.5 MPa. This difference may be due to water stress tolerant Chaparral species receiving more attention than less tolerant species. However, based on the fairly wide range of fynbos species sampled in this study, P_{min} values lower than -2 MPa are rare. The prevalence of presumably drought-sensitive fynbos species may be the product of a relatively stable and high rainfall during the period in which these species evolved (Deacon *et al*., 1992; Linder *et al*., 1992) compared with Chaparral environments (Cowling *et al*., 2005). Coupled with the refuge provided by cooler, wetter, higher altitudes, (and groundwater discharge) these conditions may have allowed drought sensitive species to survive, contributing to the high biodiversity. Their sensitivity to drought may also mean that fynbos could undergo severe, drought-induced, extinction if the climate becomes significantly drier and plant populations cannot migrate rapidly enough. The relatively constancy of winter rainfall regimes in the Cape and western Australia has been hypothesized as an important factor in the evolution of the high proportion of seed regenerating species characteristic of these relatively species rich mediterranean areas (Cowling *et al*., 2005). The reliability of winter recharge and, thus, groundwater discharge may have facilitated the evolution of a generalized wetland flora and may also account for the likely, but as yet untested, richness of the faunal communities, especially invertebrates and river- and pool-dependent amphibians, in these habitats (Minter *et al*., 2004). The Western Cape is recognized as a centre of diversity for Odonata, which require reliably perennial streams (Grant and Samways, 2007), and the same may apply to other invertebrate groups as well (M. Samways personal communication 2007).

3.7.4 Wetlands survey

The study area was defined as the catchment of the Oudebos River from the headwaters to the confluence with the Palmiet River. Boucher (1978) mapped the vegetation of the Kogelberg, including the Oudebos River catchment. Eleven of his communities are found in the Oudebos catchment. The communities range from short, open fynbos with the shrub layer dominated by ericoid shrubs and emergent Proteaceae to tall, forest in kloofs and on a part of the shale band. One of the two main wetland communities mapped by Boucher (1978) occurs in the catchment (Box 1).

The ***Chondropetalum-Berzelia*** **Upper Hygric Fynbos** is found on wetter, steeper southerly slopes at higher altitudes. It is characterized by permanently moist conditions, with the source of the moisture being from seepages, winter rainfall or southeast clouds in summer. Drainage is good and where drainage is impeded, *Chondropetalum-Restio* Marsh communities develop, often resulting in a mosaic between these two communities.

***Chondropetalum-Restio* Tussock Marsh**: This community occurred throughout the entire Oudebosch catchment area wherever a suitably moist seepage area is found, irrespective of aspect or altitude. Dominant species area restioids including: *Restio bifidus, R. ambiguus* and *Nevillea obtusissima* as single species or in combination with *Chondropetalum mucronatum*. *Osmitopsis asteriscoides,* an indicator of a shallow water table, often occurs in this community. *Erica intervallaris* is restricted to this community.

Mixed ericoid and restiod fynbos of the upper mesic slopes: This community has both a drainage line form and a rock outcrop form. In the drainage –line form the shrub layer was often dominated by 2-3 m tall *Brunia albiflora*, although this species also occurred away from drainage lines. From Boucher (1978)

The second major wetland type is the ***Erica-Osmitopsis* seepage marsh and fynbos communities** which are found on the footslopes and the coastal terraces. This community occurs at the Blomhuis site. It occurs on relatively deep sands where the water table is relatively shallow but also is found in areas with shallower, sandy and peaty soils over bedrock, for example around the lakes at Betty's Bay. Its degree of groundwater dependence is not known but it may be high given that it occurs in areas where there rarely is surface water.

Another important community is the ***Berzelia-Leucadendron* Moist Tall Fynbos** which forms the forest margins. It is particularly associated with yellow, plinthic soils and often has significant accumulations of organic material, tending towards bogs. The boggy conditions are often associated with the contact between the shales (Cedarberg Formation) and tillites (Pakhuis Formation) but not always. This community is often associated with saturated soils, usually in gently to moderately sloping areas with very shallow soils over what appears to be massive (unbroken) sandstone bedrock (probably because the slope is determined by the dip of the bedding planes). The ***Podocarpus-Rapanea* Shale forest,** which includes Oudebos forest, is located where it is because it is protected from fire by the narrow valley. The forest tree species are probably not dependent on groundwater although some of the herbs and forest fauna could be.

There is variation in the vegetation structure within these communities which is directly related to moisture availability, even in what are considered dryland vegetation types. The ***Chondropetalum-Berzelia* Upper Hygric Fynbos** often has populations of rare species such as *Orothamnus zeyheri* (Marsh Rose) and *Mimetes hottentoticus* which grow in peaty soils. This ecosystem is unlikely to be linked to groundwater, except for small perched systems. In summer it probably depends mainly on moisture captured from the orographic clouds formed on these ridges by south-easterly winds, especially in late-summer. Its location on steep south-facing slopes undoubtedly reduces water stress as these slopes only get early morning or late evening sun, if any direct sunlight at all.

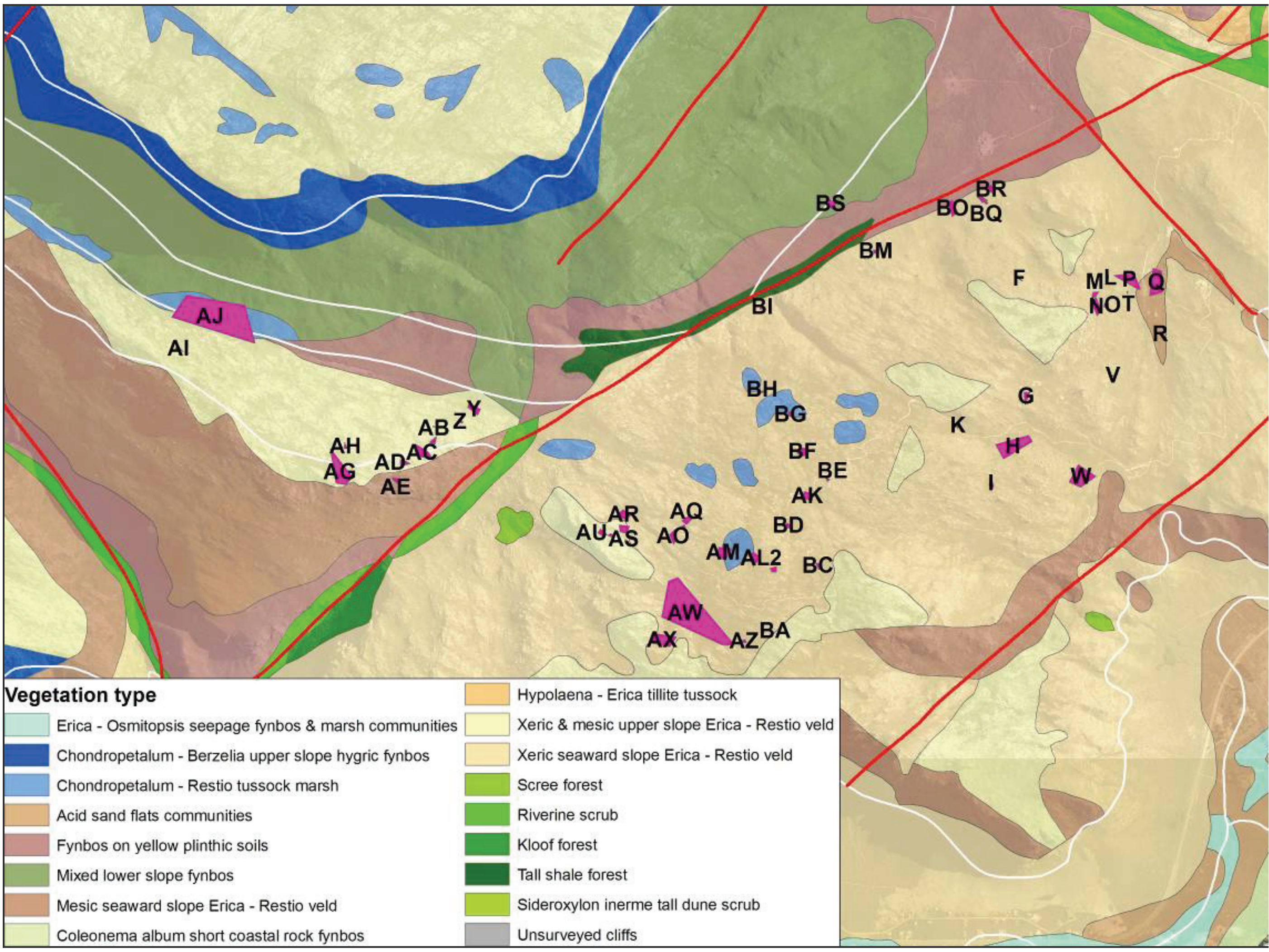

Figure 3-26 Vegetation of the Oudebos area showing the vegetation types mapped by Boucher (1978) overlaid with the wetlands and other vegetation features mapped for this study. Red lines indicate major faults and white lines lithological contacts. The geological formations are shown in Figure 3.3.2a.

3.7.4.1 Plot-based wetlands

Three wetlands in different areas of the catchment were characterized using detailed 1 m^2 sample plots (Figure 3-26):

Area BI: This wetland is situated on the north facing slope of the Oudebos River valley. Visually, the wetland is clearly distinguishable from the surrounding non-wetland vegetation. Both the wetland and the surrounding non-wetland vegetation can be described as open, short restiod shrublands. The transition between wetland and non-wetland vegetation is gradual, explaining the presence of predominantly wetland species in some plots that are classified as non-wetland areas. Linear wetlands on moderate slopes, in particular, are typically wetter at the top where the seep is located than at the bottom, thereby providing some suitable habitat for non-wetland species in the relatively dry parts, further contributing to the occurrence of some predominantly non-wetland species in wetlands.

Area BS: This wetland is situated on the western bank of the Oudebos River, about 150 m from the river and 50 m from the bottom of the western slope of the valley. The wetland is visually very distinct from the surrounding non-wetland vegetation, and can be described as closed tall shrubland. The transition from wetland to non-wetland is sharp.

Area BR: This wetland is situated on the north facing slope of the Oudebos river catchment, approximately 100 m from the Oudebos weekend cottages and was used in the intensive wetland studies. Again, the wetland community is visually very distinct from the surrounding non-wetland vegetation. The wetland consists of medium to tall, open, restioid shrubland, and the non-wetland vegetation of medium, open, restioid shrubland. Few species are shared between the wetland and surrounding non-wetland, notably *Leucadendron xanthoconus* and *Restio similis*.

3.7.4.2 Non-plot-based surveys

The general survey found that the wetlands in the Oudebos River catchment are highly variable, but can be grouped into four main types:

Bruniaceae–*Restio* Type: This type is characterized by the dominance of Bruniaceae and Restionaceae, with *Osmitopsis* species being notably absent. Common species occurring in this type include *Brunia albiflora*, *Chondropetalum mucronatum* and *Restio dispar*. This type was identified by Sieben (2004) as slope seepages which are well drained, highly variable and characterized by an increased presence of Bruniaceae.

***Restio* Type**: Restionaceae such as *Chondropetalum ebracteatum* (male and female), *Restio ambiguus*, *R. dispar* and *R. similes* dominate this type.

***Osmitopsis*-Bruniaceae Type**: This type is characterized by Bruniaceae, *Erica intervallaris*, *Leucadendron microcephalum*, *L. xanthoconus*, *Osmitopsis* sp. and *Restio ambiguus*. The presence of *Osmitopsis* sp. indicates high moisture availability, so that most of the areas identified as this type would belong to Sieben's valley seepages, characterized by high soil water levels and peaty Champagne (Fry, 1987) soils (Sieben, 2004).

***Erica-Restio* Type**: *Erica intervallaris* and *Restio ambiguus*, among others, commonly dominate in this type.

3.7.4.3 Comparison of Boucher's (1978) communities and the present study

Most of the eleven plant communities identified by Boucher (1978) could be identified in the study area. The wetland component of Area BS is floristically and structurally more similar to the ***Berzelia-Leucadendron* Moist Tall Fynbos** community (Boucher, 1978) than to the adjacent dryland community. However, the wetland component of Area BS can clearly be distinguished from both these communities identified by Boucher (1978) by the dominance in the wetland of species such as *Berzelia lanuginosa*, *Cliffortia odorata*, *Erica perspicua*, *Leucadendron salicifolium*, *Osmitopsis asteriscoides*, *Todea barbara* and *Rumohra adiantiformis*. Some parts of the ***Berzelia-Leucadendron* Moist Tall Fynbos** community (Boucher, 1978), where drainage was impeded were also identified (e.g. Area BK). These typically have a relatively high cover of restioids compared to the surrounding vegetation. Wetlands were frequently encountered in the **Mixed ericoid and**

restiod fynbos community of the upper mesic slopes (Boucher, 1978, Area N, Figure 3-26) in the southern section of the study area. This community has two forms as described by Boucher (1978), namely a rock outcrop form and a drainage line form. *Brunia albiflora* frequently dominates moister areas. Groundwater seepage might sustain the rock outcrop community form of this plant community.

Areas AK, AL, AM and AX are representative of the rock outcrop form of this community, while Area AW is representative of the drainage line form of the same community. Many areas were encountered that did not seem to resemble either the drainage line or rock outcrop forms of the above mentioned community, even though the vegetation composition was similar in many cases, but no drainage channel or rock outcrop was present. Wetlands in these areas are probably groundwater dependant. Areas AF, AG and AH are classified as ***Chondropetalum–Berzelia*** **Upper Hygric Fynbos** (Boucher, 1978, Area P, Figure 3-26). Marsh communities form wherever drainage is impeded, resulting in a mosaic between ***Chondropetalum-Restio*** **Marsh** communities and ***Chondropetalum-Berzelia*** **Upper Hygric Fynbos** communities. The area is very wet and probably permanently water saturated, with the source of water being seepage, summer or winter rainfall as noted by Boucher (1978). Many seepages belonging to the ***Chondropetalum-Restio*** **Tussock Marsh** community (Boucher, 1978, Area Q) were located across the entire study area. This community is primarily associated with wet seepage marshes, irrespective of slope and altitude (Boucher, 1978). Several areas including: E, F, J, K, L, M, N and O are representative of this community. Area D is an example of the mixed short ericoid and restiod fynbos community of the upper xeric slopes (Boucher, 1978, Area N). This community, together with the mixed ericoid and restiod fynbos of the xeric slopes (Area J) covers large areas in-between the other types of wetlands, with slight variations occurring due to the local influence of slope, aspect and moisture availability.

3.7.4.4 Remote-sensing-mapped and field mapped wetlands

Most of the wetlands mapped during the course of the study, including those done by Tim Aston, are situated in the Goudini Formation (sandstone), Peninsula Formation (sandstone) and Skurweberg Formation (sandstone), with a few scattered wetlands present in the Pakhuis Formation (tillite). The Peninsula and Skurweberg Formations are the main groundwater bearing lithologies in the TMG (Brown *et al*., 2003). Wetlands were also mapped on the contact between the Pakhuis (TMS) and Peninsula (TMS) Formations, Cederberg (shale) and Pakhuis (TMS) Formations, and Goudini (TMS) and Cederberg (shale) Formations. Wetlands occurring on the contacts between formations are probably indicative of differences in substrate permeability, with water being forced to the surface as a result.

Only 44% of the total area of wetlands identified by means of these field surveys was classified as wetlands using image classification techniques (Engelbrecht, 2005, M.Sc. thesis in Appendix H). Of these, 2.3% were classified as fault and lithological boundary controlled wetlands, 1.2% as fault controlled wetlands, 8.6% as lithological boundary controlled wetlands, 87.6% as general perennial wetlands, and 0.6% as non-perennial wetlands (Engelbrecht, 2005). Aston (personal communication 2005) also mapped wetlands that were classified by Engelbrecht (2005) as fault and lithological boundary controlled wetlands, fault controlled wetlands, lithological boundary controlled wetlands and general perennial wetlands. However, relative importance (extent) of the different wetlands could not be calculated as the wetlands were mapped as individual points and not as polygons.

Large parts of the Oudebos area were classified as perennial wetlands, fault and lithology controlled wetlands, lithology controlled wetlands and fracture-controlled wetlands by Engelbrecht (2005). However, the majority of these areas could not be located during the field survey, with most of the classified perennial and other wetlands being non-wetland vegetation as described by Boucher (1978).

3.7.4.5 Discussion

Wetlands, irrespective of the source of moisture, mostly had very similar plant species composition. Few species were specifically restricted only to wetlands, as also noted by Boucher (1978). Species of the Bruniaceae were the most prominent representatives of the fynbos palaeoendemic families in the wetlands. The most common species are widespread (e.g. *Berzelia lanuginosa*) but two species which also occurred in some of the wetlands, *Brunia albiflora* and *B. stokoei,* have more restricted ranges: Hottentots-Holland to Hermanus and Hottentots-Holland to Kleinmond respectively (Goldblatt and Manning, 2000). Other representatives of palaeoendemic families were *Grubbia rosmarinifolia* (Grubbiaceae), *Roridula gorgonias* (Roridulaceae) and *Retzia capensis* (Stilbaceae). None of these species are confined to wetlands, or particularly to GDEs and *Roridula*, in particular, occurs in a wide range of moist situations. None of these species are considered threatened but some of these wetlands may have *Elegia neesii*, a widespread species which is listed in the South African Red Data List (SANBI, 2007) and is classified as “Least Concern” because it is rare and populations are typically sparse. Under the Provincial Conservation Law (PWC, 2000) the following taxa are listed:

- Endangered Flora under Schedule 3: *Mimetes capitulatus*, *M. hottentoticus*, *M. stokoei* and *Orothamnus zeyheri*
- Protected Flora under Schedule 4: *Retzia capensis*, all species of the Proteaceae, Bruniaceae, Grubbiaceae, Penaceae and Roridulaceae, all species of *Chondropetalum*.

Species from these groups occur in at least some of the wetland areas that were mapped for this study, other wetlands which are considered likely to be GDEs as well as in other wetlands or highly moist situations.

Retzia has an unusual distribution, occurring generally on the upper slopes but occasionally also in lowland wetlands (W Bond personal communication 2003), for example the wetland near the Kleinmond waste-water treatment works (D Le Maitre personal observation 2006). It may have survived in these drier, low altitude situations because of a reliable supply of groundwater and, thus, may be a good indicator, in low altitude wetland settings, of a GDE that is linked to a substantial aquifer. The adult plants appear to be very long-lived, smaller plants are rare and there are no published reports of observations of seedlings in the wild. It is visited and potentially pollinated by sunbirds (Nectarinia violaceae) and sugarbirds (Promerops cafer) (Rebelo, 1987). There are no reported studies of seed production, seed banks or seed germination.

Wetlands occurred for a variety reasons which were not always clearly linked to fractures in the substrate or other geological features. In some cases rocks under shallow soil resulted in water saturated patches of soil which sustained wetland communities similar to those on faults. Slabs of rock on slopes forced groundwater percolating down the slope to the surface, again sustaining a wetland community. Sudden changes in slope often sustained wetland communities, again probably due to the water being forced to the surface. The wetlands were often internally heterogenous, with patches that differed in their species composition and with specific plants dominating different areas of the same wetland. The individual water requirements of species are probably correlated with the patchy distribution of these plants in the wetlands. This was particularly true for linear wetlands occurring on slopes, and has sometimes caused a sudden increase of species being recorded during the data collection, even though the wetland as a unit seems fairly homogenous compared to the surrounding non-wetland vegetation. Most plant species occurring in wetlands also were also present in drainage lines across the landscape, or in areas where normal drainage was slowed down giving water an opportunity to penetrate the soil. Few species were specifically restricted to wetlands. Sieben *et al*. (2004) used soils as a major criterion for the location and delimitation of fens in the Hottentots Holland Mountains. It may be worthwhile to collect and analyse soil samples to determine whether, together with selected environmental parameters, there are relationships between the floristic composition of the wetlands, their soils and environmental parameters. Alternatively, soil or water chemistry may be a more reliable way of identifying the water sources of wetlands in TMG settings like the Kogelberg.

The lack of clear distinctions between on and off-wetland communities, both floristically and in their water stress and vulnerability characteristics indicate that other factors, such as inter-specific competition and tolerance of saturated conditions, are the main factors determining the distribution and species composition of the wide variety of wetlands encountered in the study area. What matters is the amount of water and, to some degree, its reliability, but the nature of the source (e.g. rain or soil water accumulation or groundwater discharge or combinations of these) is relatively unimportant.

3.8 Remote sensing analysis

Figure 3-27 below shows the results of the remote sensing analysis to detect perennially lush areas potentially linked to groundwater discharge. It is unlikely that such extensive perennial wetland communities are indeed present therefore the method resulted in too many false positives. This is an indication that classification threshold values need adjustment. This would however result in diminished classification accuracy.

From the classification accuracy assessment, one could infer that when classifying the wetland communities, there would be a trade-off between errors of omission and errors of commission. The use for which the output of the image classification procedure will be applied would dictate a suitable mid-way between these errors. If the output will be used solely for the monitoring of the changes experienced in known perennial wetland communities, larger errors of commission might be overlooked. However, if the classification procedure is aimed at identifying wetland communities with a high likelihood of groundwater interaction, errors of commission should be kept to a minimum.

The absence of wetlands on the south facing slopes is misleading. Their absence is due to the presence of shadows on the 18 May 2002 image. Since spectral responses of landcover classes cannot be extracted from areas covered by shadows, these areas were masked out of the classification procedure.

Future studies should concentrate on reducing both the errors of omission and the errors of commission in order to produce a system that can be utilized for addressing both problems.

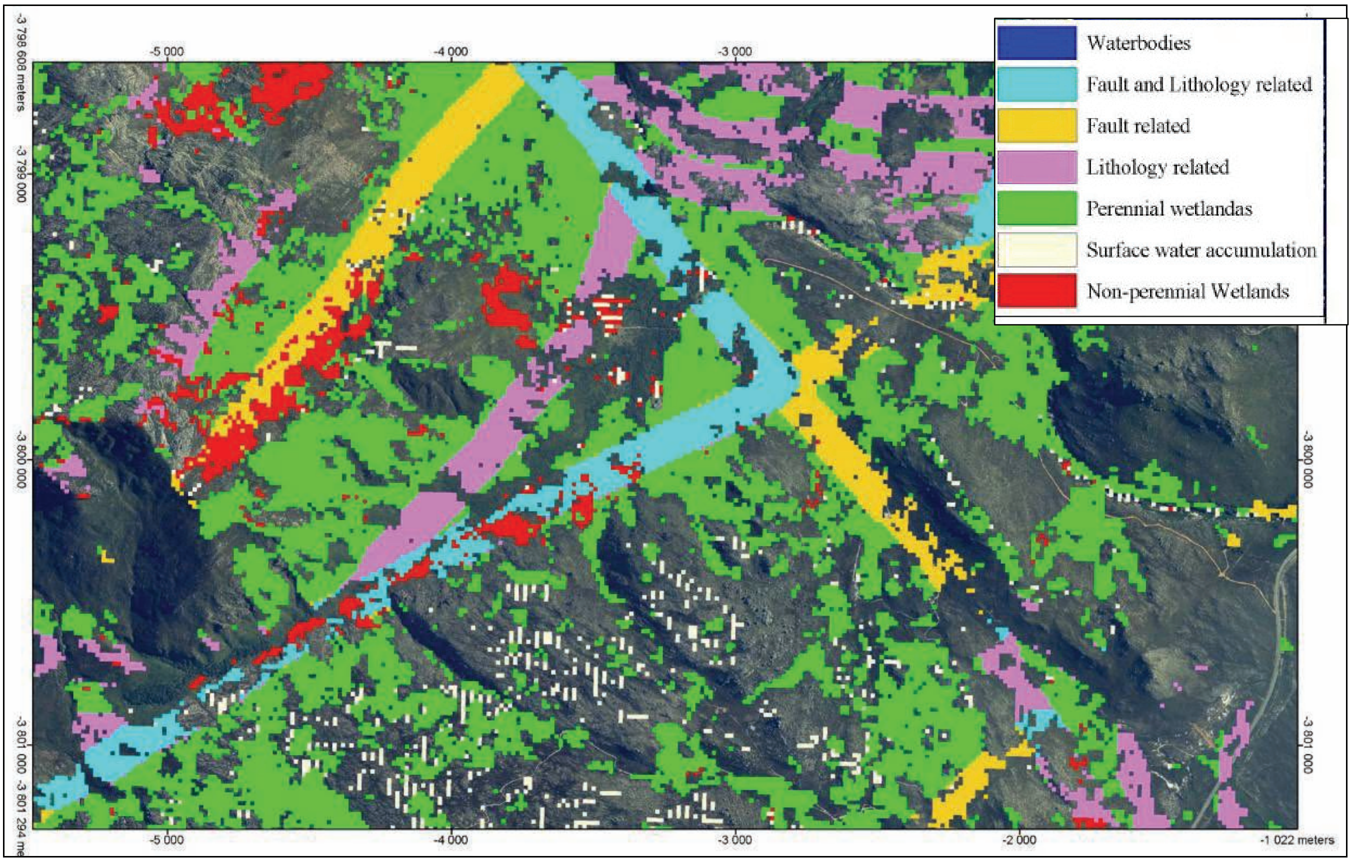

Figure 3-27 Identification of perennial wetlands with remote sensing analysis (see appendix H)

3.9 Summary of field study results and conclusions

The geophysical application showed resistivity contrasts associated with faults, lithological changes and saturation of the quartizites. This method can be used as a non-invasive technique to characterise the sub-surface and extrapolate results from known drilled sites, however, there is a minor trampling impact along the line of the cable as people walk through the fynbos to lay out the electrodes. This method is difficult to apply in summer when surface resistivities are high due to the sand drying out, and in areas with bare rock or thin sand cover.

Recorded annual rainfall at this site (1250 mm for 2004/2005, 985 mm for 2005/2006, and 986 mm for 2006/2007) is higher than rainfall expected in this area, however, records from the DWAF station G4E001 (Steenbras Dam) indicate that the years 2005/2006 and 2006/2007 were slightly below long-term average.

Drilling demonstrated the extreme heterogeneity of this structurally controlled secondary aquifer, with boreholes within less than 10 m of each other having very different water strike depths, permeabilities and RWLs (e.g. MRF1 and MRF 2). Drilling also demonstrated the ubiquitous occurrence of groundwater in the low permeability matrix of micro-structures in the quartzite. Even dry boreholes, such as K3, filled up with seepage water which was undetectable as strikes during drilling, and show a RWL response within a couple of days of local recharge events. Artesian conditions were encountered where the quartzite was confined by the shale in the valley. An upward vertical gradient was seen at the coastal borehole K1, where water strikes in the TMG at 42 to 64 mbgl resulted in a RWL of 1 mbtoc. It is possible therefore that TMG discharge to the unconsolidated coastal sands results in discharge to wetlands and estuaries.

Water level monitoring showed the fairly rapid response of water levels to local rainfall, particularly when daily rainfall exceeded 10 mm. The water level rose by an average of 3 m in the drilled boreholes and 0.5 m in the piezometers. Piezometers linked to potential groundwater discharge features maintained water levels in the summer, typically at less than 1 mbgl. However, the piezometer in the high, rain-fed wetland on Perdeberg dried out in summer.

Temperature, dissolved Si, DOC and Rn radioactivity appear to be useful tracers of groundwater discharge into the aquatic environment. Si and DOC are more conservative, whereas Rn (with a half life of 3.8 days) and temperature could be used to indicate points of discharge. Macro-ions and stable isotopes did not prove useful tracers in this study.

Flow monitoring showed that baseflow to the Oudebos catchment from December to April is minimal. This coincides with the lowest groundwater levels in the TMG boreholes indicating that changes in head due to recharge or discharge are minimal at this time.

The macro-invertebrate and diatom assemblages in the Oudebos catchment confirmed that the stream is in a fairly pristine condition. The macro-invertebrate SASS score was higher in winter and benthic taxa declined during the summer low flows. There is potential to apply SASS techniques over long periods to monitor the impacts of changing groundwater discharge in potentially impacted areas paired with control sites. However, SASS variability is influence by several abiotic and biotic factors and it is difficult to separate out controls with confidence.

All the fynbos species tested showed very high vulnerability to xylem embolism formation, i.e. they were vulnerable to reduced water availability. However, they experienced relatively low levels of midday water stress, particularly the deep rooted Proteaceae, even in terrestrial off-seep settings. Off-seep plants showed slightly more water stress near to the fault controlled slope seep than the off-seep plants close to the perched wetland. Shallow rooted Restionaceae showed the greatest degree of moisture stress. This indicates that water was available to plants in deep soil horizons and potentially in the micro-structures of the TMG matrix.

The evidence from this study indicates that TMG aquifer discharge directly contributes to flow in the Oudebos tributary and cryptic discharge from the mid-slope ‘wetland’ on a meso-fault. It also indicates that indirect TMG discharge contributes to the valley bottom wetland (via surface water) and to the coastal wetland (via the surficial unconsolidated wetland).

Permanently wet habitats fed by the TMG aquifer are likely to have been a feature of fynbos for many millions of years, through different climatic regimes. Aquifer discharge to these unique and localised habitats may have played a significant role in the evolution of the diversity of wetland plant species in fynbos. Perhaps the most unexpected and interesting result was this study’s confirmation that deep-rooted Proteaceae appear to have permanent access to sufficient water, whether from soil moisture (vadose zone), or shallow groundwater. Although there may be situations where Proteaceae may be dependent on groundwater from the TMG aquifer, these situations are believed to be highly localised, at least in montane environments. This is probably not the case in lowland situations, especially in sandplain fynbos. However, many of the other species found on these wetlands may be highly sensitive to reductions in discharges compared with historical levels. Given that these species may have adapted to these low water stress conditions over millennia, the effects of even a limited increase in water stress could be significant. This makes them vulnerable to the effect of climate change.

3.10 Understanding the ecohydrology of TMG catchments

This study has revealed the complexity of water flow through typical TMG landscapes, and the difficulty in measuring ecosystem dependence on any single water source. The sub-surface in these mountainous catchments plays a critical role in storing and releasing precipitation inputs to aquatic and terrestrial ecosystems. However, that storage and release occurs across a continuum of permeability scales determined by the lithology and structural history of the TMG. The relatively inert nature of the TMG quartzites makes it difficult to trace different flow paths and differentiate water sources partitioned through different 'reservoirs' in the natural landscape.

3.10.1 Hydrotopes

Hydrotopes are areas (mapping units) with similar hydrological properties, (Meijerink et al., 1997; Moore et al., 1993; Gurtze et al., 1999) and they have been usefully applied in GIS based catchment studies. Krysanova et al. (2002) define a hydrotope as a set of elementary units in the sub-basin or climate zone, which have the same land use, soil and average groundwater table. Meijerink et al. (1997) take a more biophysical approach and describe a hydrotope as a terrain mapping unit, based on geomorphology and geology, with added hydrological information. Typically they may be delineated to indicate different precipitation, evapotranspiration and soil moisture regimes, derived from surrogate data sets such as land-cover, altitude, aspect, etc. They are analogous to hydrological response units.

Descriptions of hydrotopes need to go beyond basic isohyets and riparian zone distances from active channels, to include the description and quantification of all ecologically relevant components of the hydrologic regime. The sum of all bioavailable sources at a particular scale of ecotope, habitat or biotope is the hydrodiversity of that hydrotope. In some cases it will be relevant to consider hydrodiversity conceptually, and in some cases it will be possible to quantify hydrodiversity in terms of volumes, time scales and water quality.

A hydrotope may then be defined as *a hydrologically homogenous landscape unit with a characteristic spatial and temporal pattern of water provision to ecosystems* (Colvin, in prep). Bioavailable water may be considered in terms of water that is consumed by the biota within an ecosystem and the water that is necessary to maintain the habitat of that ecosystem. The definition and mapping of hydrotopes is a useful tool to integrate conservation planning and water resource and catchment planning at a desktop level and relatively broad scale. However, the local topographic and aquifer settings of the TMG can differ significantly from the regional assumptions and need to be verified with field investigations.

3.10.2 Hydrodiversity

ADEs are distinctive hydrotopes in which groundwater is also bio-available. A holistic ecohydrological characterisation should characterise the full *hydrodiversity* of bio-available water. These may include components of precipitation, surface water, groundwater, soil moisture, and marine water. It is expected that more 'hydrodiverse' hydrotopes will have a greater hydrological resilience to input variations. Different hydrological pathways have different storage and transfer functions and time scales.

The hydrodiversity of a hydrotope gives an indication of the number of different sources (or pathways) of water used by ecosystems at characteristic time scales (Colvin, in prep). Hydrodiversity may be considered in terms of the volumetric ratio of the principal source of water to the ecosystem to the total sources of water (Colvin, in prep).

Hydrodiversity = (total volume of total sources of bioavailable water)/ (volume of principal source of water)

$$HyD = (n_1 + n_2 + \ldots\ldots n_x)/ (n_1)$$

Where a single source of water is available, n1 = nx and HyD = 1 (i.e. low hydrodiversity). Where many sources of water are available the HyD number and the HyD ratio will increase: e.g., (10+9+3+2+1)/10 = HyD = 2.5. Hydrodiversity will vary across the landscape as a result of climate, geology and topography.

In the TMG settings we see a continuum of soil moisture – perched – aquitard – aquifer linked elements and functional groups of ecosystems. It is useful to consider these elements in order to conceptualise those elements that are most at risk to abstraction. Table 5-2 defines a framework of groundwater-fed hydrotopes and aquifer discharge type-settings. It shows which ecological habitats (wetlands, rivers, springs) are linked to these hydrotopes. Aquifers and ADEs may be found linked to all of the discharge settings except the TMG micro-structures.

Figure 3-28 below shows a schematic cross section of the Kogelberg catchment to illustrate some of the flow paths through the landscape in three dimensions. The different discharge linked hydrotopes are numbered from the non-groundwater dependent perched wetland setting (1), to mid-slope meso-fault GDEs (3) and valley bottom mega-fault controlled ADEs (5, 7).

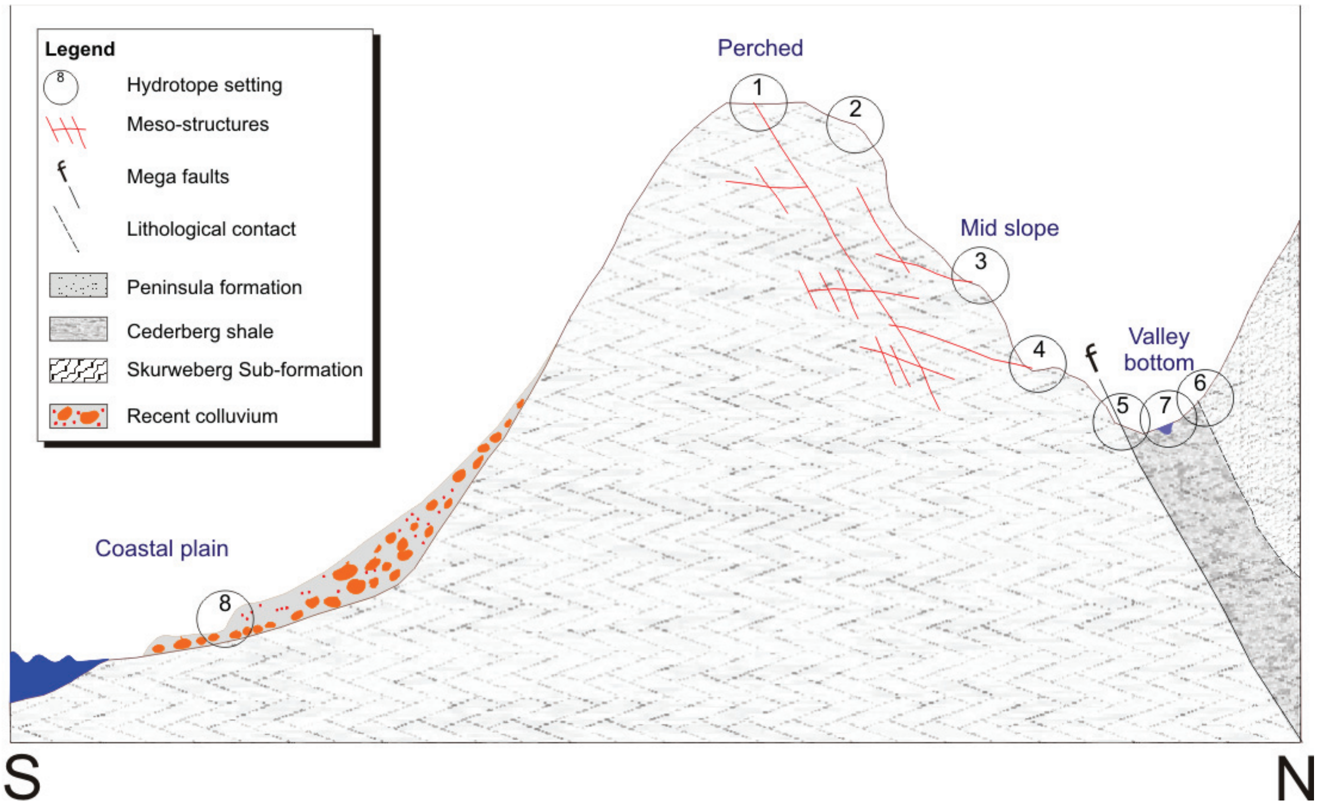

Figure 3-28 Cross-section of the Kogelberg study site illustrating typical hydrotopes in this landscape.1- perched wetland/aquitard; 2- terrestrial dryland/ aquitards; 3 – midslope wetland/ meso-structure; 4 – spring/ meso-structure; 5 – valley bottom wetland/ mega-fault; 7 – perennial river/ mega-fault; 6 – valley bottom wetland/ lithological contact; 8 – coastal wetland.

Hydrotopes can be represented spatially using available data sets. Figure 3-29, below, shows the Kogelberg area classified according to:

- potential groundwater discharge settings lithology (TMG quarzites; colluvium; coastal sands) and structural geology (mega and meso faults);
- landscape position wrt slope (low wetness potential), mountain top (high precipitation potential) and valley bottom (high run-off potential);
- surface water features (perennial and seasonal rivers).

This classification broadly indicates discharge settings and hydrotopes. Further classification to include spatial variation in precipitation could be included.

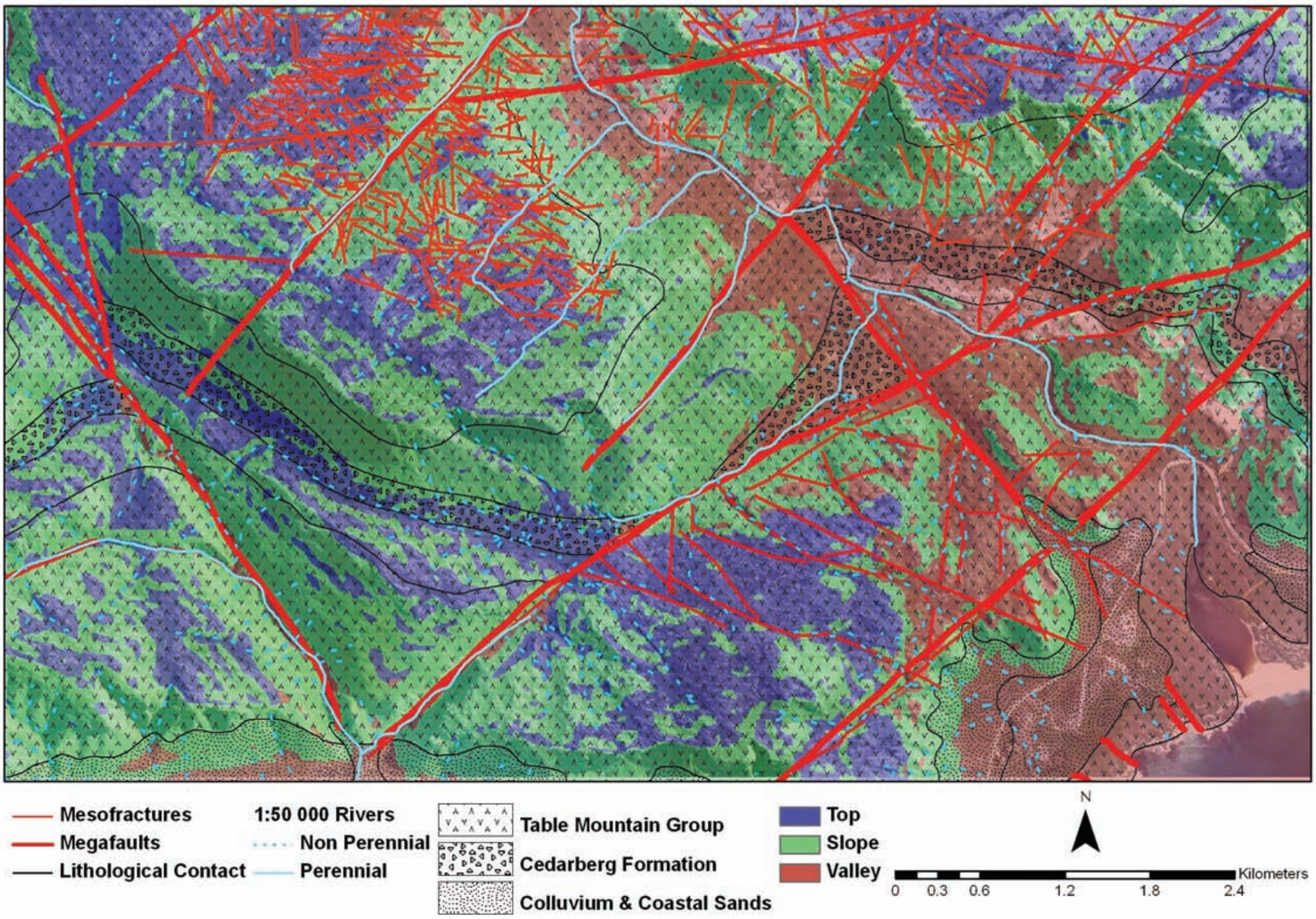

Figure 3-29 Spatial classification of the landscape according to groundwater based hydrotopes at the Kogelberg study site.

Chapter 4:

Purgatory Research Site

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4. PURGATORY RESEARCH SITE

4.1 Location

The Purgatory site is situated on the south side of the Franschhoek pass in the Du Toits River catchment, north of the Main Road R191. The area is centered around a tributary of the Du Toits River, which enters the Purgatory wetland on the northern flank of the Theewaterskloof Dam at "Die Ou Tol" The site falls within the H60B quaternary catchment.

The wider area was identified as a potential exploration target (i.e. Target Site Area T8 in Target Zone T**)** in the CCT TMG Aquifer Feasibility Study (CCT, 2004) with the main hydrogeological exploration objectives being the confined Peninsula Aquifer on both the eastern and western side of the Steenbras-Brandvlei Megafault (SBM), and the un- to semi-confined Skurweberg Aquifer on its downthrown western side.

Access to the Purgatory site is at the old tollhouse camping site. The site has inherent value for monitoring of abstraction further south within the Target Zone T, between the northern (Stettyns) recharge area and possible production wellfields. It also has potential as a far-field monitoring site for abstraction in the Target Zone W (Wemmershoek), through possible hydraulic connections along the NNW/SSE-trending fault in the Du Toits River valley (Franschhoek Pass), linking the SBM to the La Motte Fault.

The site is owned by the Stellenbosch Municipality and is part of the Theewaterskloof Conservancy, which is managed by the Western Cape Nature Conservation Board (WCNCB).

A veld fire occurred on the test site in December 2004, destroying a large area of the vegetation and interrupting the field investigation and research. Subsequently it was decided to focus the research in the study area on groundwater – surface water interaction and to conduct only basic ecological measurements in the study area.

4.2 Site Characterisation

4.2.1 Topography

The site is characterized by the following topographic features:

- Mountain peaks of up to 1000 mamsl on eastern side of sub-catchment, rising to about 1400 mamsl further east
- Two incised gorges emanating from these mountain peaks
- A ridge to the north of the sub-catchment at about 900 mamsl
- Relatively flat area on the western side with low slopes
- Perennial river, fed from the gorges, draining to the south into Purgatory wetland
- Main recharge area to the Peninsula Aquifer north of sub-catchment.

4.2.2 Regional Climatic Characterisation

The Theewaterskloof dam area (H60B and H60C) has a mean annual rainfall (MAP) of approximately 1000 mm (see **Table 4-1**). The higher lying catchment H60A (headwaters of the Riviersonderend) receives more than 1700 mm MAP in average. The difference in mean annual run-off (MAR) between the catchments is also significant, being 1207 mm for the H60A catchment and 564 mm and 386 mm for the H60B and H60C catchments, respectively. The daily average temperatures in the area range between 23°C and 12°C.

Table 4-1 Hydrological Parameters for quaternary catchments adjacent to test site (after DWAF, 2007)

Quaternary catchment	Area	MAP WR90	MAP GRAII	MAP Berg WAAS	MAR WR90	Run-off Efficiency WR90
	km²	*mm*	*mm*	*mm*	*mm*	
H60A	72.64	1895	1723	1695	1207	0.64
H60B	210.00	1127	1094	1161	564	0.50
H60C	216.89	891	879	869	386	0.43
H60D	137.75	652	751	809	184	0.28

Data received from the South African Weather Services (SAWS) for weather stations in the vicinity of the Theewaterskloof dam for the period January 2000 to June 2003 show the seasonal fluctuations of the rainfall pattern with highest rainfall normally between July and September (see **Figure 4-1**). It also indicates the difference in amount of rainfall between low-lying areas (i.e. Villiersdorp) and higher lying areas (i.e. Elandskloof and Welgegund), which is further indicated in the spatial distribution of MAP as shown in **Figure 4-2**.

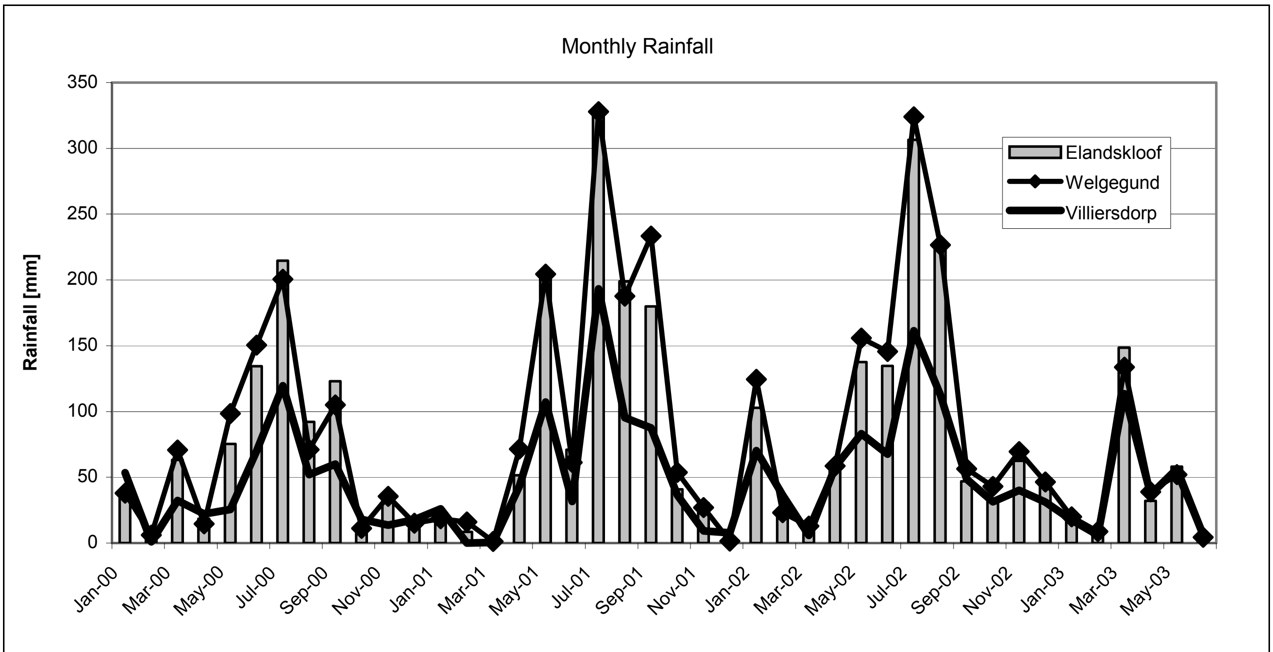


Figure 4-1 Monthly rainfall at weather stations along Theewaterskloof Dam

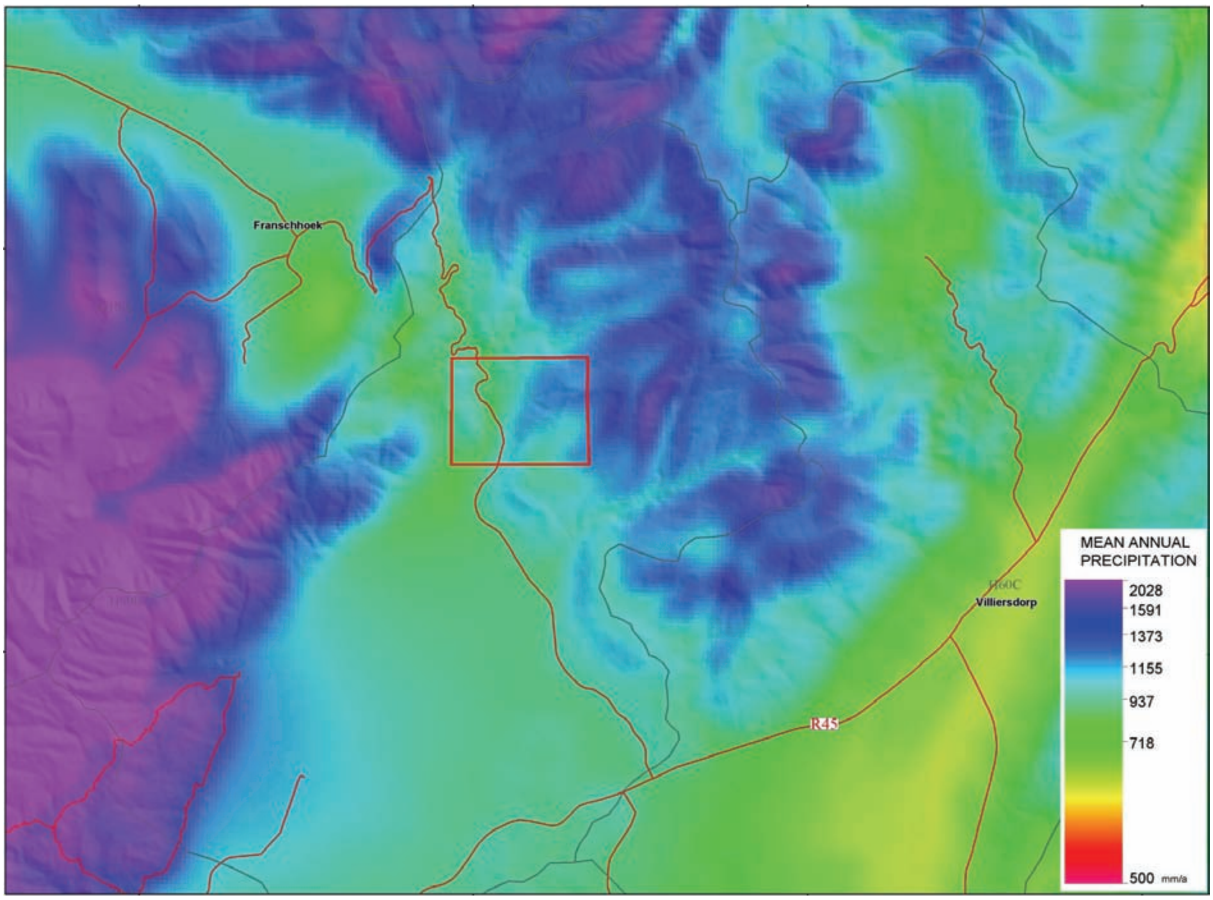


Figure 4-2 Mean Annual Precipitation (after DWAF, 2007)

4.2.3 Regional Hydrology

The stream draining the study catchment comprises two distinct flow courses that combine to create the most downstream perennial tributary of the Du Toit's River, before it enters the Purgatory wetland. The Du Toits River and its tributaries have extremely steep gradients and are deeply incised over most of their reaches, which are typical features of mountain stream zones in the Cape Fold Belt.

The two streams within the study area are very different in their topographic setting and possible flow pattern. While the stream draining the northern part of the catchment area runs down moderate hill slopes, the western stream comes from deeply incised gorges and exhibits steep slopes in head waters. The northern stream is a single channel that is considered seasonal, while the western stream has at least three significant tributaries, some of which are considered perennial.

The DWAF gauging weir, H6H007 (33^{o}56'19'' and 19^{o}10'17'') is situated on the Du Toit's River at the Purgatory Outspan, just upstream of where the study tributaries join the main river (see **Figure 4-5** and **Figure 4-10**). The record for this gauge ends in 1992. However, the general hydrological pattern in the Du Toit's River is evident in **Figure 4-4**. It shows the annual cycle between winter flood and summer low flow, as well as an 8 to 10 year cycle between dry and wet years (most prominent the steady decline from 1975 to 1982).

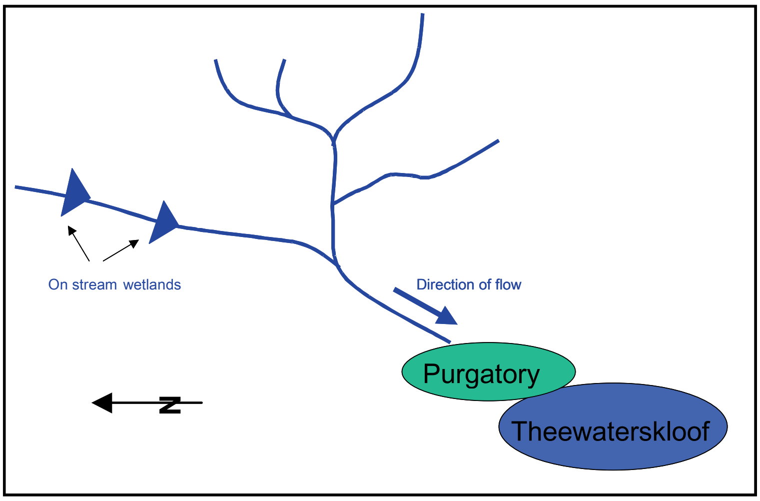
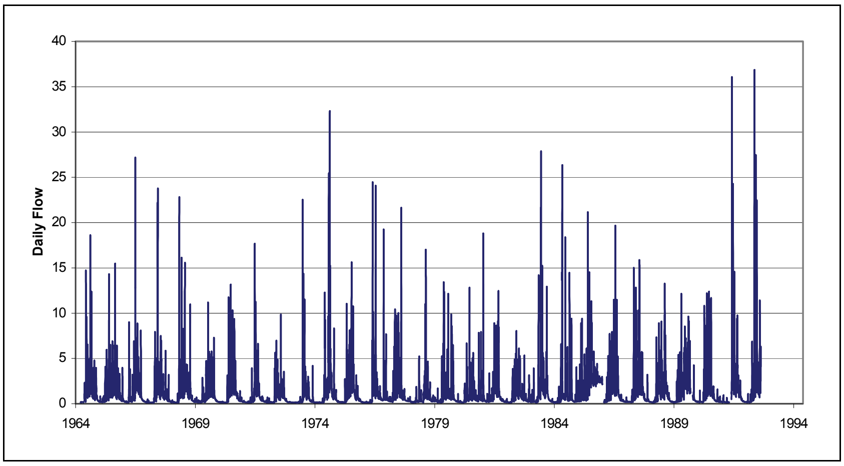


Figure 4-3 Schematic showing the stream network in the Purgatory Catchment. On-stream wetlands are shown as triangles in headwater areas. Purgatory wetland and Theewaterskloof dam as also indicated.

a)



b)

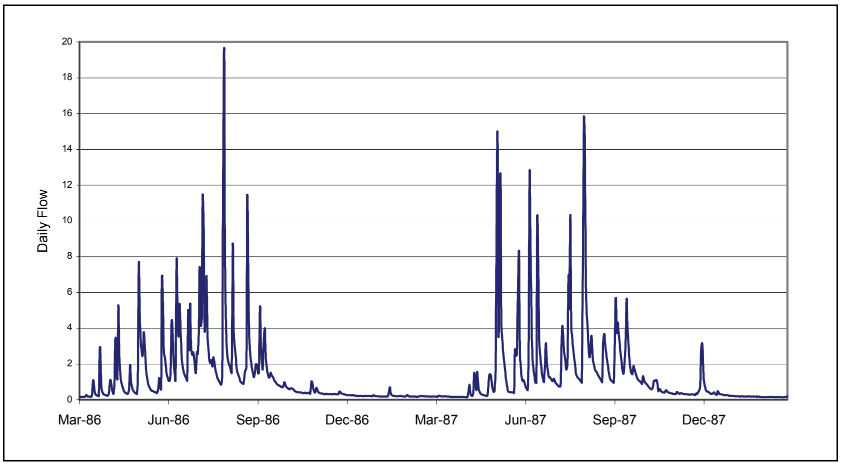


Figure 4-4 Daily Flow Series of Gauge H6H007; a) complete record from 1964 to 1992, b) typical annual records from 1986 to1987. Unit is averaged daily flow in m^3/sec

4.2.4 Geological Characterisation

The preliminary geological characterisation is based on a desktop study of available geological information and detailed field mapping, as required for subsequent borehole siting.

Available geological information

For the available geological information, the reader is referred to the Hydrogeological Report for the TMG Aquifer Feasibility Study and Pilot Project (CCT, 2004), from which the following excerpt is taken. The Peninsula Formation forms the high mountain areas of the Hottentots Holland, Jonkershoek and Groot Drakenstein ranges (see **Figure 4-5**). The Bokkeveld Group underlies the surrounding valley floor. The central fold structure of the T zone is the southwestern extension of the Stettyns Anticline, which may also be a northeastern continuation of the Kogelberg Anticline (see **Figure 1-2**). However, the possible structural connection has an indistinct expression in the Groenlandberge between Grabouw and Theewaterskloof. The other main fold is possibly the northeastern continuation of the Steenbras Syncline, along the locally steeply-dipping transition between the Hottentots-Holland highlands and the western Theewaterskloof lowlands.

The main fault structure crossing Target Zone T between Grabouw and Franschhoek is the Steenbras-Brandvlei Megafault (SBM). The majority of mapped faults in the north-western part of the T Zone strike W/E, with the NE/SW SBM trend appearing as a secondary set. However, this appearance is due to a lack of exposure of the SBM in the western part of Theewaterskloof. The dominant joint systems run N/S and E/W, with a subordinate WNW/ESE set.

Updated geology

First order fold structures in the Franschhoek mountains control the principal N-S drainage axis of the Du Toits River, which is aligned along the shallow S-SW plunging hinge of a broad, open syncline. Similarly, the subsidiary catchment of the study area is elongated along a NE-SW structural grain, defined by an asymmetrical, shallow SE-plunging syncline and a major SW-NE striking fault zone, which affects a significant downthrow to the northwest, resulting in striking duplication of the Cedarberg Shale Formation at two structural levels within the Du Toits valley.

In the vicinity of Die Ou Tol, the fault scarp of this major fault defines the steep southeastern flank of the valley (see **Figure 4-6**). Along the trace of this NE-SW striking master fault (hereafter referred to as the *Purgatory Fault*), the Skurweberg Formation (NW-side) is downthrown against the Peninsula Formation (SE-side). Along the steep mountain front transected by this subvertical fault, a spectacular "pop-up" structure comprising an upthrust fault-bounded wedge of the TMG sequence (Ope-Op-Sc-Sg) is clearly exposed (see **Figure 4-7**). The bounding high-angle faults strike ENE and SE and the enclosed TMG wedge has been extruded upwards and eastwards within an apparent NW-SE compressional framework. Numerous other subsidiary fault and fracture splays are evident within the area and these, together with the master faults, are closely linked to preferred sites of groundwater discharge and focused hydraulic conductivity.

In this area, the main hydrogeological monitoring objectives are the confined Peninsula Aquifer on both the eastern and western side of the SBM, and the un- to semi-confined Skurweberg Aquifer on its downthrown western side.

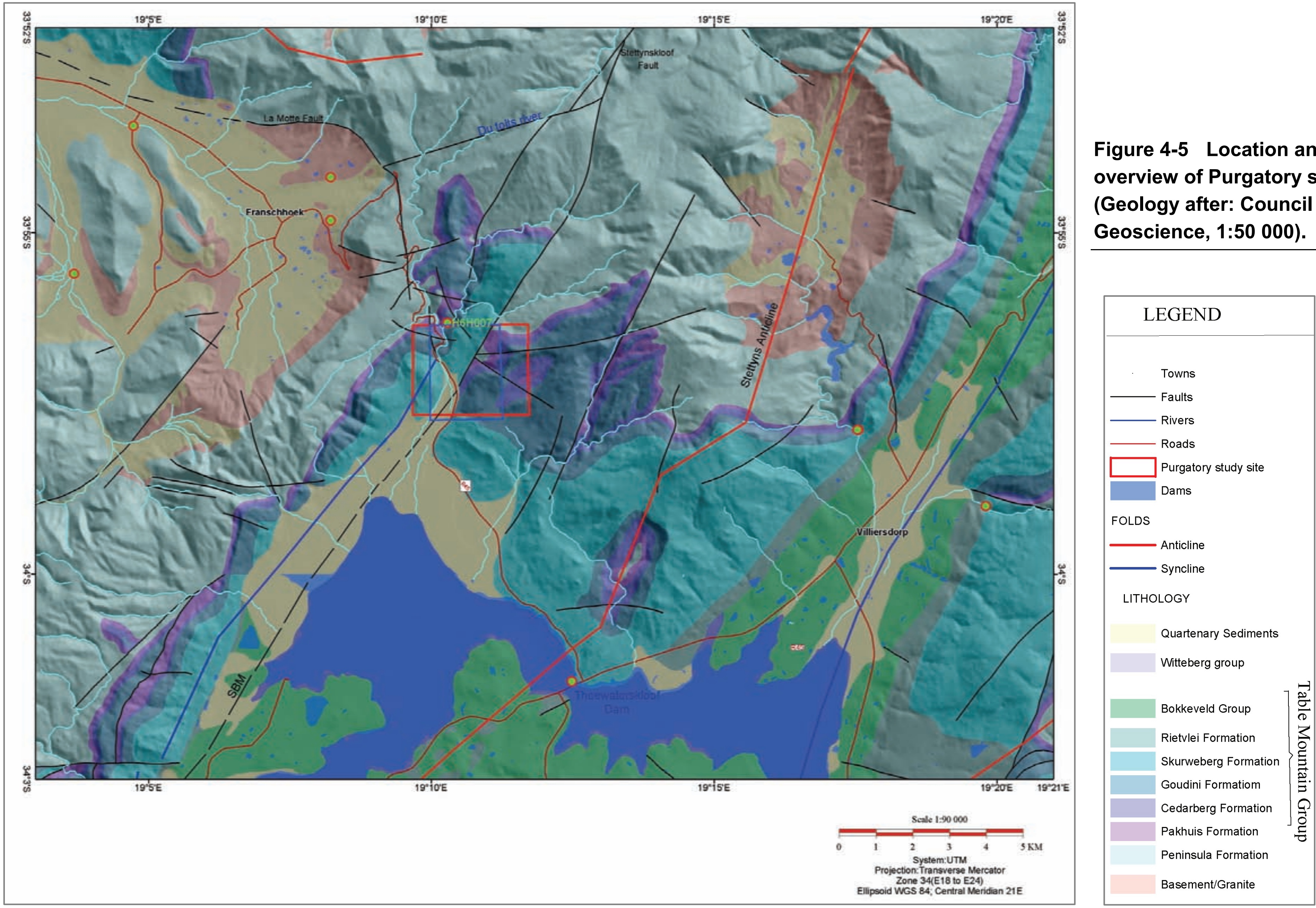


Figure 4-5 Location and geological overview of Purgatory study site (Geology after: Council for Geoscience, 1:50 000).

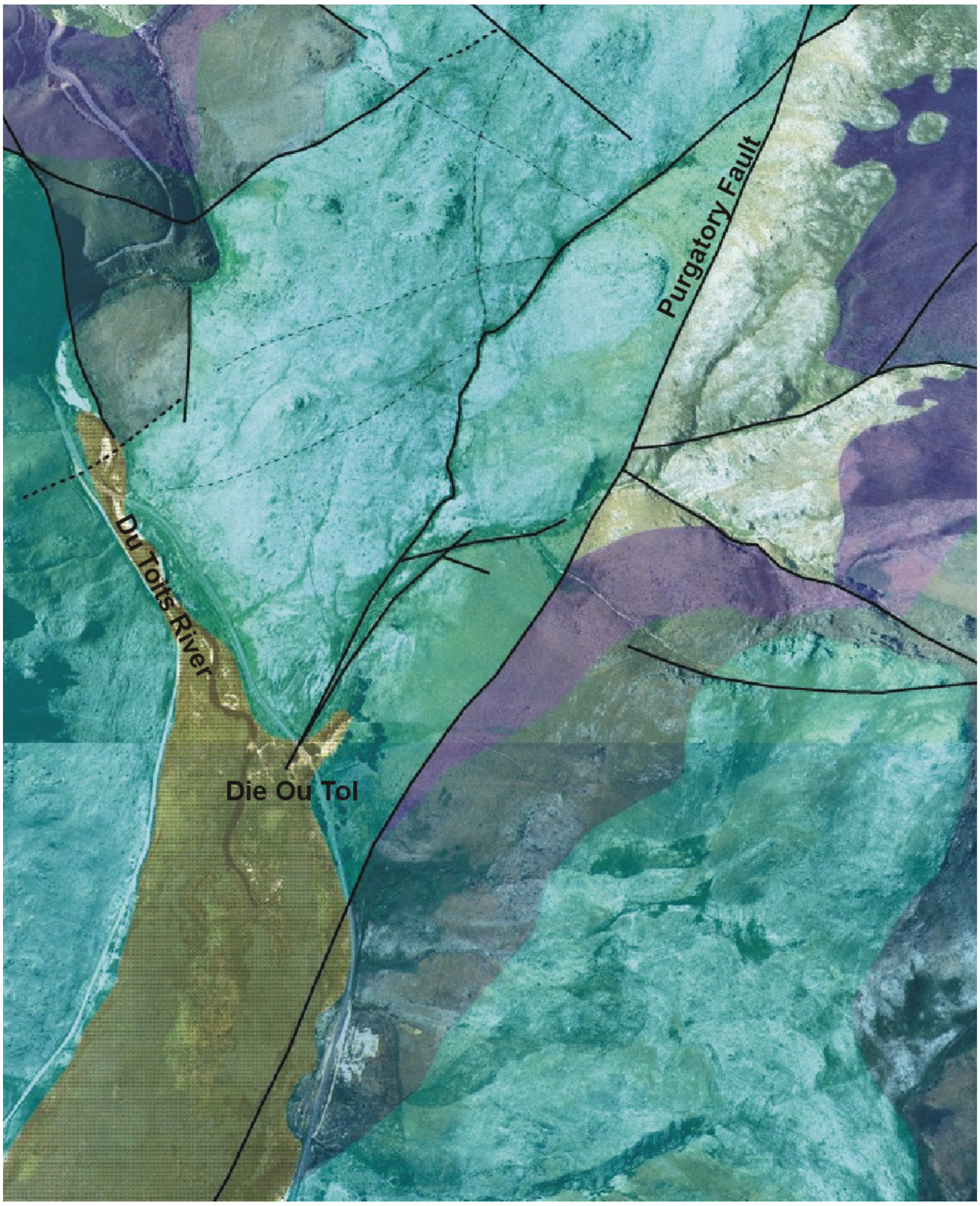


Figure 4-6 Updated Geology and structural features of Study Area; for legend see Figure 4-5.

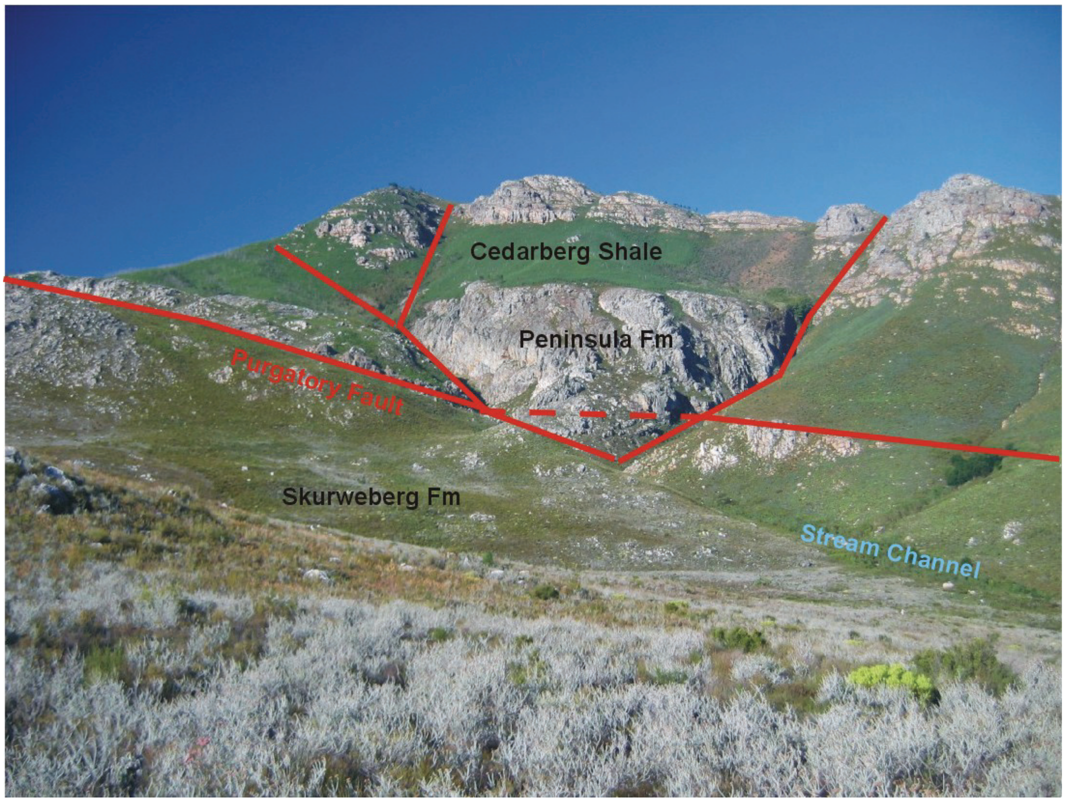


Figure 4-7 View from the western side of catchment towards the mountain peaks and incised gorges, indicating the displacement of the Peninsula Formation along the Purgatory Fault and the cross faults.

4.2.5 Groundwater dependent Ecosystems

The Du Toits River, draining from the Franschhoek Pass into Theewaterskloof Dam, and its tributaries are suspected to contain a high number of endemic and rare plant species, especially in their lower valleys (Purgatory Outspan). However, there are some disturbances related to alien invasion in the wetland areas and along the rivers. It is postulated that the wetlands are associated with groundwater discharge at the major fault lines.

Remote sensing analysis

The same method of remote sensing analysis, as developed for the Kogelberg area (Engelbrecht, 2005) was applied for the Purgatory test site, but only few of the wetlands and seepzones were detected. Apparently, the algorithm and thresholds developed for the Kogelberg area are not applicable in the different topographic and climatic settings of the Purgatory area.

For a comparison, the results of the Change Vector Analysis (CVA) as prepared for the City of Cape Town TMG Aquifer Feasibility Study and Pilot Project (CCT, 2006) are reported and shown in **Figure 4-8**). The results of the CVA were verified in the field in several areas such as Zachariashoek, Nurweberg Forest, Steenbras Dam and Purgatory itself, and therefore considered realistic. The CVA method utilises a slightly different algorithm and variable thresholds to determine groundwater dependent ecosystems.

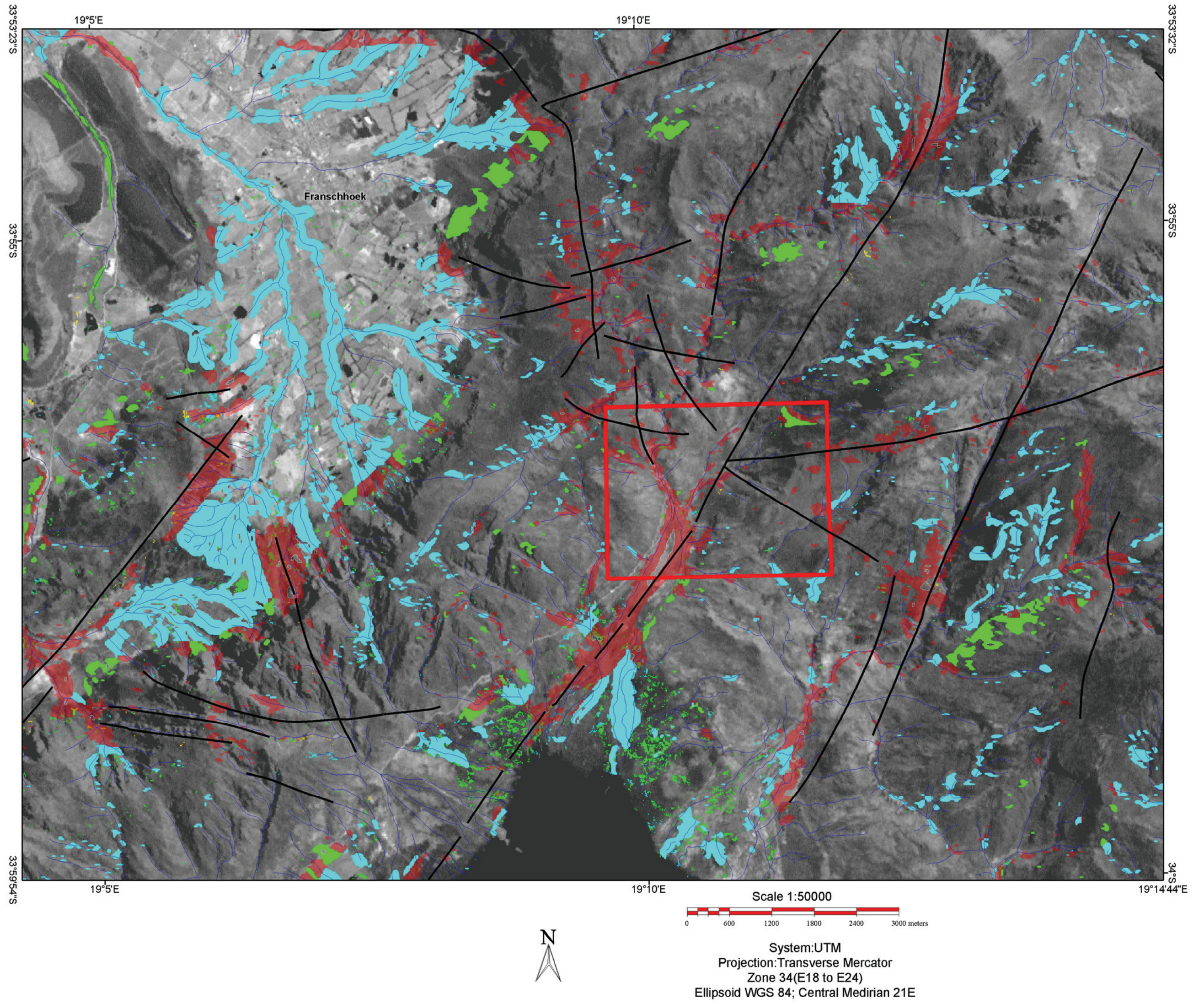
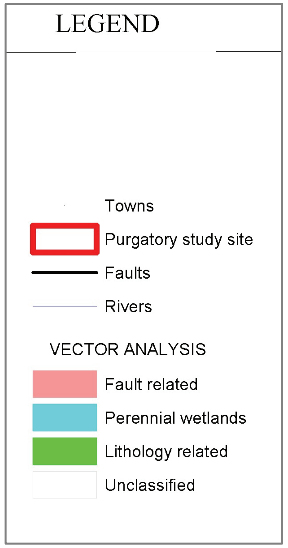


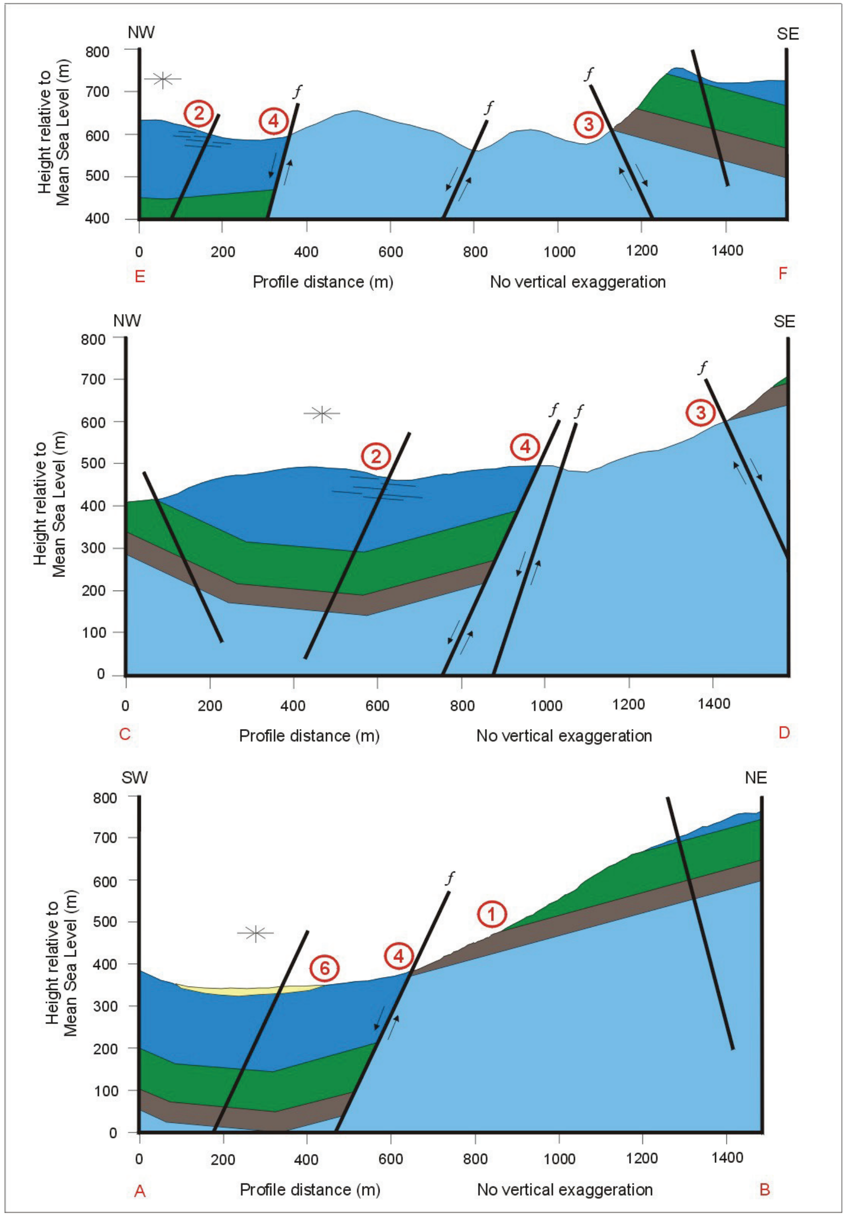
Figure 4-8 Identification of wetlands in Purgatory area from CVA process (after CCT, 2006 and Engelbrecht, 2005)



Geological setting of wetlands

While the major faults clearly influence the channeling of groundwater on a local level, the distribution of wetlands and seep zones in the sub-catchment, reflects a more complex relationship between lithology (aquifer character), topography (aspect & slope) and structure. Wetlands and seeps develop in a variety of settings (see **Figure 4-9**):

1) At or just below the Goudini-Cedarberg Shale contact, where discharge along the Nardouw Aquifer – Cedarberg Shale Aquitard interface results in numerous perched "contact seeps" developed near the top of the typically smooth slopes of the shale band;
2) A non-perennial drainage line closely follows the faulted synclinal fold axis. Wet patches along this surface drainage line commonly coincide with principal fracture / fault intersections, suggesting that these structures are closely connected with deeper groundwater flow and discharge (e.g. proposed monitoring sites 2a & 2b);
3) Significant groundwater seepage occurs along the bounding faults of the extruded wedge of TMG, but only where the Peninsula Aquifer defines the hanging wall. Groundwater seepage is clearly evident along the deeply incised bounding fault planes right up to level of the Cedarberg Shale contact, but never above it, indicating that seepage from the Peninsula Aquifer becomes focused along the enveloping hydrotects. The E-W & NE-SW orientation of the deeply incised "cross-faults" ensures that these gullies receive little sunlight resulting in their progressive downslope transition into predominantly groundwater recharged (high baseflow contribution) perennial streams;
4) Isolated and linked seeps and wetlands are dispersed in a linear chain along the master fault, suggesting that this is a regionally significant hydrotect structure. Localised seeps commonly occur where permeability interfaces (lithological contacts esp. Ope-Sc) are transected by the fault (e.g. proposed groundwater monitoring site 4a, 4b and possibly 4c). Where the fault parallels the Theewaterskloof road in the extreme south of the area, a linear discharge zone is strongly developed which has destabilized the road verge, necessitating restoration work. The possibility that this fault zone links with fault structures in the T6 and T4 exploration areas further southwest, makes it a key structure for far-field monitoring of regional hydraulic connectivity. Analysis of the master-fault kinematics suggests a component of right-lateral strike-slip motion;
5) Linear belts of hydrophile flora are commonly aligned along discordant fractures and fault lines, particularly on steeper slopes with south to southeast aspect;
6) Isolated and elongated seep zones occur at the basal 'break-in-slope' on west-facing valley sides, and presumably reflect topographically controlled discharge (e.g. groundwater monitoring site 6a).



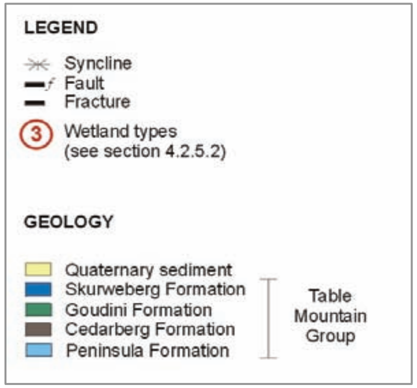
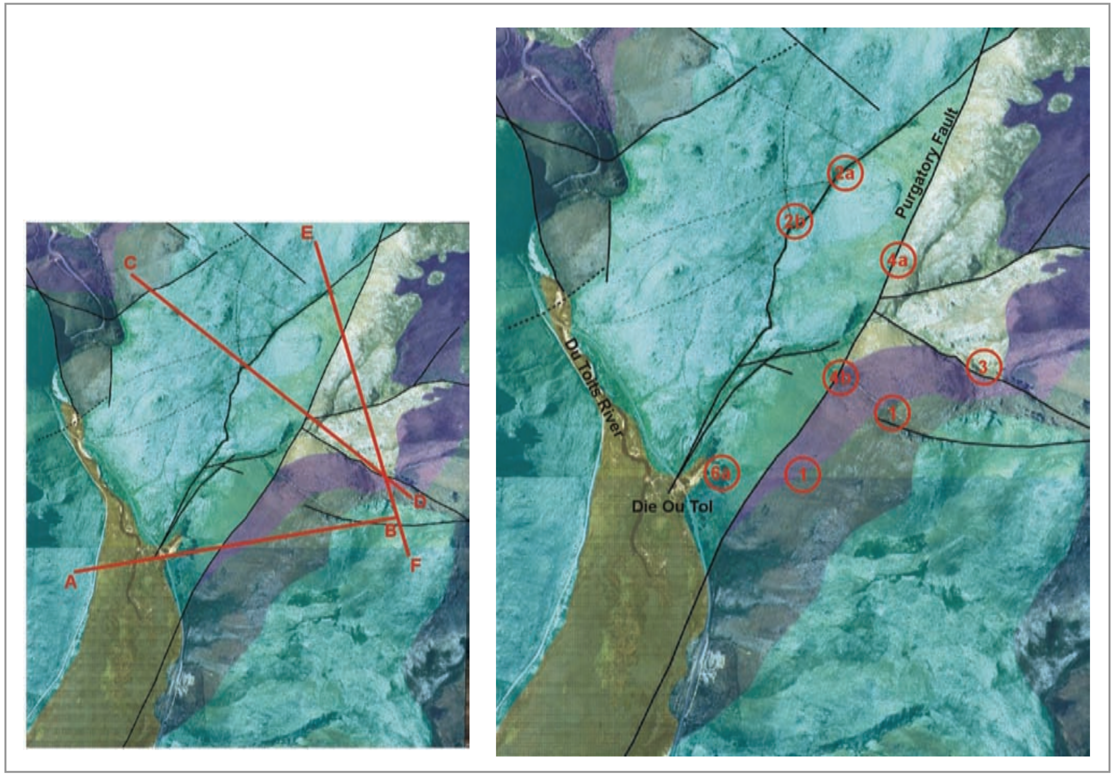


Figure 4-9 Structural setting of springs and wetlands in Purgatory area; numbering of wetlands as per section 4.2.5.2, for geological legend see Figure 4-5



4.3 Location of monitoring sites

Following the approach and methodology for the study, as outlined in Section 1 and 2, a suite of monitoring sites were located and installed within the study catchment. These are, inter alia:

- Weather station
- Boreholes for water levels in shallow and deeper aquifer
- Piezometers for water levels at wetlands
- Streams for surface water flow and aquatic biology monitoring
- Wetlands for vegetation studies.

4.3.1 Weather Station and Rainfall Collectors

Since the existing SAWS stations in the area are too far from the study site and due to the variability in rainfall amount and pattern an automatic weather station was installed in the lower portion of the study catchment. In addition, three rainfall collectors were installed at different elevations within the study catchment to collect rainfall samples and to establish a site-specific rainfall-elevation isotopic ratio.

Table 4-2 Relevant details of the installed rainfall collectors

Rainfall Collector	Latitude	Longitude	Altitude (m)	Comment
Lower RC	33°57'07.3914"S	19°10'28.8908"E	362.719	At entrance of Purgatory site
SRC Top	33°56'47.5769"S	19°10'35.5081"E	422.293	At lower stream wetland
BRC 1	33°56'34.5167"S	19°10'45.5622"E	546.558	On top of ridge

4.3.2 Borehole siting

Hydrogeological criteria for borehole-site selection process conform to the principal objectives of the project and are based on the following premises:

- The targeted aquifer is the Peninsula Formation;
- It is assumed that groundwater from the deeper Peninsula Aquifer discharges in seep zones or wetlands associated with fault structures;
- Within the Purgatory site significant groundwater discharge from the Peninsula Fm appears to be focussed within an extruded fault wedge of the TMG. Borehole monitoring of the Peninsula Aquifer in this fault-bounded compartment is critical to determining the relationship and possible linkages between the deeper fractured rock aquifer, its recharge characteristics and the observed surface discharge;
- Lateral connection between the Purgatory Fault and the fault structures splaying off the SBM in the target areas further south west, is both feasible and likely. Similarly, linkage of the Purgatory Fault and the Stettynskloof Fault to the northeast is possible. Tectonic connection between these fault systems provides potential for deep regional groundwater flow along the SBM, possibly resulting in artesian conditions. Consequently boreholes targeting the Peninsula Aquifer in proximity to the Purgatory Fault provide a potential far-field monitoring site for regional hydro-ecological response to potential abstraction in the Palmiet catchment (G40A);

- Monitoring of the shallow sub-surface water level along river reaches and or adjacent to wetlands is required to determining the groundwater contribution towards these eco-systems and to determining the source aquifer.

Field siting of exploration and monitoring boreholes was performed on 19 October 2004. This followed a desktop appraisal of the most appropriate exploration drilling sites for monitoring the deep hydraulic behaviour and response of the compartmentalised TMG aquifers in the complexly faulted structural setting.

Rationale and targets

Desktop target generation focused on areas where previous field mapping determined surface exposure, or presence at accessible depths of the Peninsula Aquifer. This is restricted to the southeastern footwall of the NW-SE *Purgatory Fault* in this area. Structural situations satisfying these criteria are extremely limited due to the fault bounded nature of the Peninsula Fm. These faults limit its exposure to the northeastern quadrant of the watershed – an area complicated by difficult access. Particular attention therefore has been given to access considerations and potential impacts attendant on using a large drill-rig and compressor unit on the drill-target sites. Access routes into the selected target sites are preferentially routed along 'disturbed' or 'degraded' corridors, and have been validated by field traverses.

Following from the above, four potential borehole target areas were selected in the Purgatory Site. They mostly target the Peninsula Aquifer in wholly unconfined, semi-confined and deeply confined situations. The areas are generally situated adjacent to structures where groundwater discharge was observed at the site. The physiographic situation, hydrogeological context and intended purpose of the four potential areas are listed below:

A: Is situated on the exposed Peninsula Fm within a narrow southeast-dipping wedge of TMG outcropping within the acute juncture zone between the Purgatory Fault and the southernmost cross-fault bounding the 'pop-up wedge i.e. east of the Purgatory Fault and south of the southernmost cross-fault. It is situated on the east bank and in close proximity to, the principal perennial stream discharging from the exposed Peninsula Fm. The purpose of the drilling in this situation is to measure recharge-discharge and water-level fluctuations within the semi-confined Peninsula Aquifer together with the surface stream flow monitoring of the perennial stream.

B: Is situated on exposed Skurweberg Fm on the opposite side of the Purgatory Fault and adjacent to A. Similarly it is situated on the west bank, and in close proximity to, the main perennial stream in the catchment. The purpose of drilling in this position is to measure recharge rates and fluctuating water levels within the unconfined Skurweberg Fm, to compare with a neighbouring borehole in the Peninsula Fm. Contrast between the hydraulic data obtained on either side of the fault will likely allow determination of lateral and sub vertical groundwater exchange between the two aquifers. It is necessary to assess the role of the intervening master fault as a permeability barrier.

C: Is located on the slope overlooking 'die Ou Tol' picnic site as close to a prominent 'contact seep zone' situated below the Goudini contact within the Cedarberg Shales. It coincides with the interpreted position of a NW-SE –striking fault (splay?) identified by remote sensing techniques. The intention is to access the confined Peninsula / Skurweberg Aquifer at depth along the inferred hydraulic pathway paralleling the Purgatory Fault.

D: Is located on the Franschhoek-Villiersdorp road on the eastern margin of the Purgatory wetland. It is coincident with the base of the Goudini Fm and is situated on the inferred E-edge of the Purgatory Fault trace. A prominent eroded area is evident on aerial photographs and this represents a weathered sandstone surface from which soil cover has been stripped by continual seepage and sheet wash. A narrow lay-by within the road reserve presents convenient access to T8d. The intention at this site is to drill from the base of the Goudini Fm, through the Cedarberg shales to intercept the Peninsula Aquifer in a deeply confined situation immediately alongside the Purgatory Fault. It is anticipated that this borehole target site could provide a far-field monitoring station for measuring deep artesian flow and longitudinal hydraulic conductivity along strike of the SBMZ.

Final Borehole Sites

During a discussion meeting with the Theewaters Conservancy Board it became clear that vehicle access to the conservancy is restricted to the already disturbed picnic site. Taking into account the maximum possible distance between the portable drill rig and the truck mounted hydraulic compressor, all borehole sites had to be within a radius of 300 m from the edge of the picnic site. This required re-siting some of the boreholes. The boreholes in the targets C and D could be verified, while A and B were too far from the picnic site and were discarded.

The locations of the final borehole sites are shown on **Figure 4-10**. The **Table 4-3** shows the boreholes sites and rationale behind the selection.

Table 4-3 Final borehole sites and rationale

Borehole Number	Rationale	Possible Drill rig
P1	Deep borehole as close as possible at the fault structure (western side) to establish water level readings in the deeper aquifer (Skurweberg)	Standard
P2	Shallow borehole in the alluvium along the river to check water level changes with respect to river flow	Standard
P3	Deep borehole close to the fault structure (eastern side) to establish water level readings in the Peninsula Aquifer	Standard
P4	Shallow borehole at P3 to check hydraulic connections between upper alluvial and deeper TMG aquifer	Standard
P5	Shallow borehole on western side of river, along newly identified fault structure, to establish water level readings from the underlying aquifer	Portable
P6	As P5, but on other side of fault structure, close to wetland	Portable
P7	Shallow borehole to intersect water level close to possible fault structure	Portable

Piezometers

Due to the access problems for conventional drilling technique, it was not possible to establish deeper groundwater monitoring sites at higher lying wetlands. Therefore, three holes were hand augered at wetlands 2a, 2b and 6a and piezometers installed for water level measurements and water sampling.

4.3.3 Streamflow monitoring points

The surface water flows in the control sites did not lend themselves readily to cost-effective automated flow monitoring. For this reason, two kinds of surface water flow points were investigated, namely:

- points at which flow could be measured using a McBinny electromagnetic flow meter;
- possible fixed-point flow monitoring points.

Ten discharge measurement points were selected in the Purgatory Catchment. Initial sampling points were identified using aerial photographs of the catchment. These points were adjusted during the sampling trips based on their accessibility and the structure of the watercourse. In places, discharge measurements were either complicated or rendered impossible because of multi-channels, dense riparian and instream vegetation and accessibility. An attempt was made to take measurements at a suite of monitoring points that would provide data for the drainage lines in the catchment, with the focus on those thought to be associated with the TMG Aquifer (faults). The location of the points is given in Appendix E 4 and shown in **Figure 4-10**.

Several locations were considered for fixed-point surface water flow monitoring and a full description is given in Appendix E 4. Surface flow points P5 and P11 were selected and Divers installed at each (**Table 4-4**) in April 2005. However, due to the flood in April and May 2005, the installation was washed away and the divers had to be installed again in June 2005, from which time on reliable records exist. The diver in P11 stopped recording in 2006, while the available records of P5 are up to May 2007.

P5 (S 33.94809° E 19.17981°)
This location is on the east tributary 100 m upstream of the *Acacia mearnsii* and *Hakea sericea* infestation in the riparian vegetation, i.e. on the stream after the weather station going upstream, east of an infested tributary. The point consisted of a pool section, with a cobble bed interspersed with sandy/muddy deposits. The riverbanks were relatively steep, with thick riparian vegetation dominated by *Protea* species. The watercourse flowed strong and clean at the time of the site visits during summer and winter months.

P11 (S 33.94712° E 19.18163°)
This sampling location is located on the west tributary a few meters upstream of a deep donga on the right bank, where the walking trail crosses the stream. The site was comprised of a shallow pool section with a mixed cobble/ boulder bed in a small channel. At the time of the site visit, the flow was very low and in places there were only pools (standing water). The cobbles in the riverbed were covered with rooted moss and algae during summer months. The dominant riparian vegetation species was *Leucadendron salignum*. There was discontinuous very low flow during the summer month, at times making it impossible take discharge readings.

Table 4-4 Position of Divers installed in the streams of the Purgatory Catchment

Site Code	River	Coordinates		Date	Diver no.
P5	Tributary of du Toit's	S 33.94809	E 19.17981	April 2005	59892
P11		S 33.94712	E 19.18163	April 2005	59886

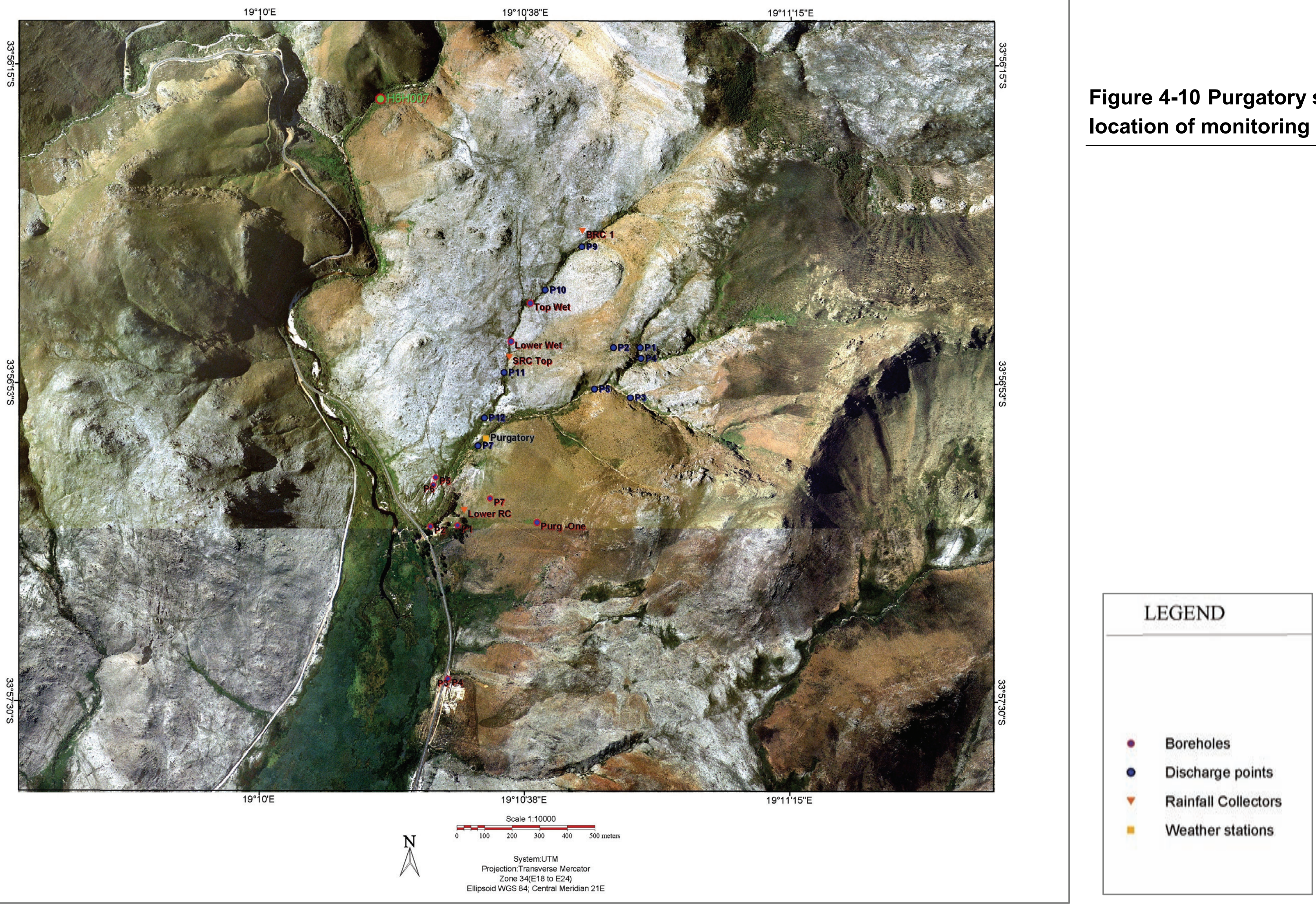


Figure 4-10 Purgatory study site and location of monitoring points

4.4 Field Measurements and Monitoring

4.4.1 Automatic weather station

An automatic weather station was installed within the control site in 2004. It comprises ongoing hourly measurements of rainfall, temperature, radiation, wind speed, wind direction and relative humidity. The records are documented on the attached CD (Appendix E-1). From the monthly data of rainfall, as shown in **Figure 4-11**, the dry season from November 2004 to mid April 2005, as well as the long wet season in the winter 2005 (April to September 2005) is evident. The month with the highest rainfall was August 2006 (306 mm), followed by May 2006 (298 mm), June, July and August 2005 (298 mm, 249 mm and 244 mm, respectively), while the highest daily rainfall occurred on 20 July 2005 (104.1 mm). The total annual rainfall from February 2005 to January 2006 as well as from February 2006 to January 2007 amounts to 1400 mm, which is more than double the MAP for the Theewaterskloof Dam area. The frequency and intensity of rain events is evident from **Figure 4-11** and **Figure 4-12**.

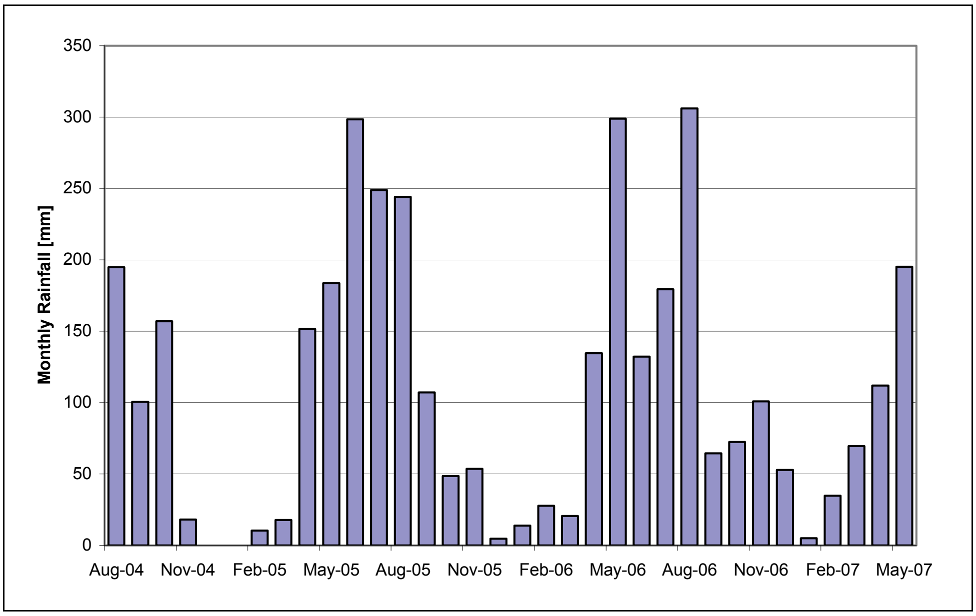


Figure 4-11 Monthly rainfall at Purgatory Study Site

Similarly to the seasonality in rainfall, the cold winter season is indicated in the drop of maximum and minimum temperatures (see **Figure 4-14**). The highest temperature was recorded on 9 December 2004 with 51.9°C. However, this measurement does not reflect natural variation in air temperature, but rather the impact of the veld fire. The actual highest day temperature was measured as 39.7°C, while the lowest temperature was 3.3°C.

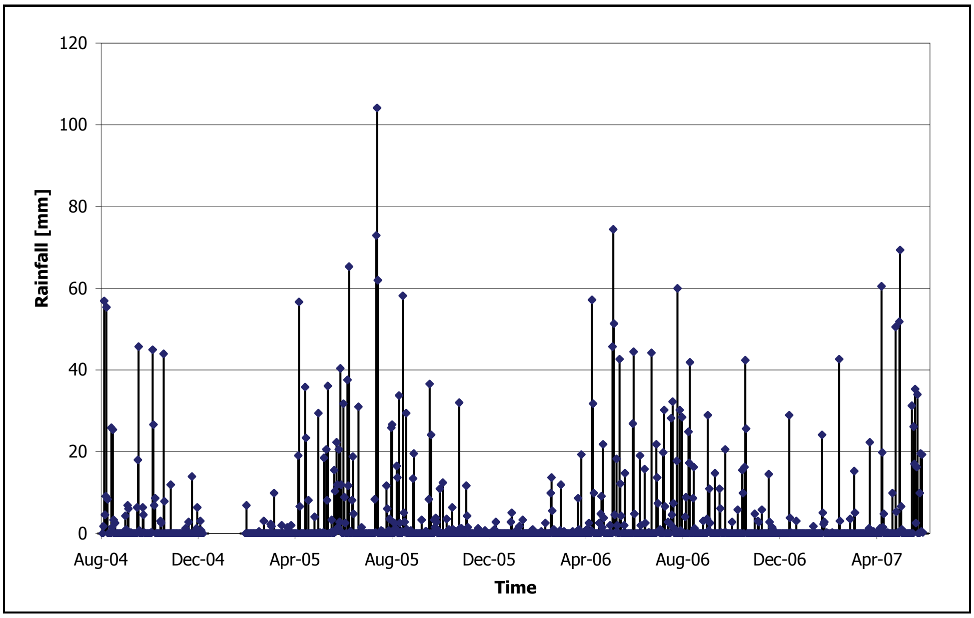


Figure 4-12 Daily rainfall from automatic weather station at Purgatory (data gap in December 2004 due to the veld fire)

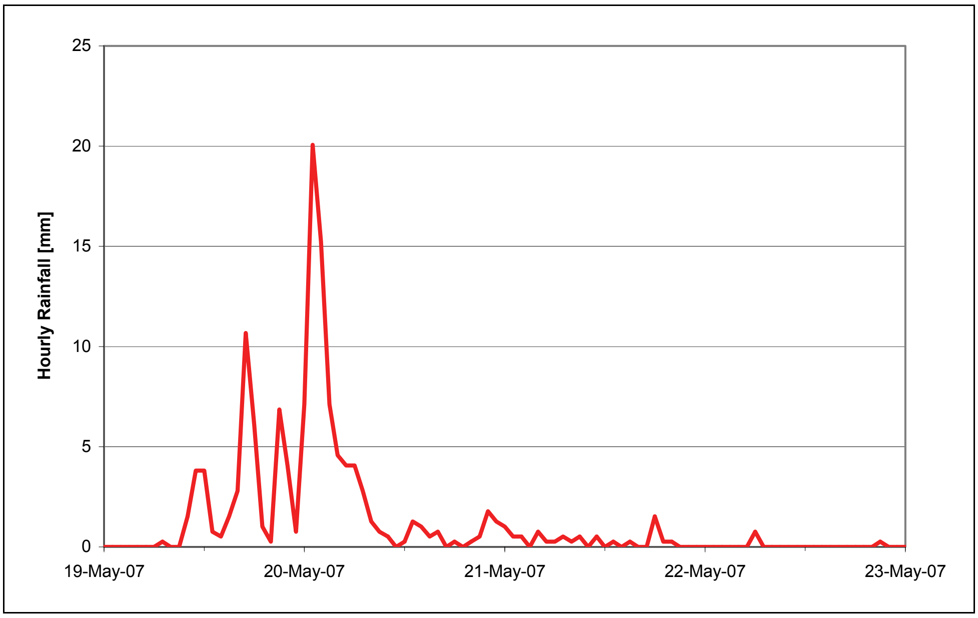


Figure 4-13 Hourly rainfall data of a selected rainfall event (19 to 22 May 2007)

The data for relative humidity shows more the daily variability than seasonal fluctuation. The highest values were mostly recorded during the night and in the early hours, while the lowest humidity was mostly measured in the early afternoon.

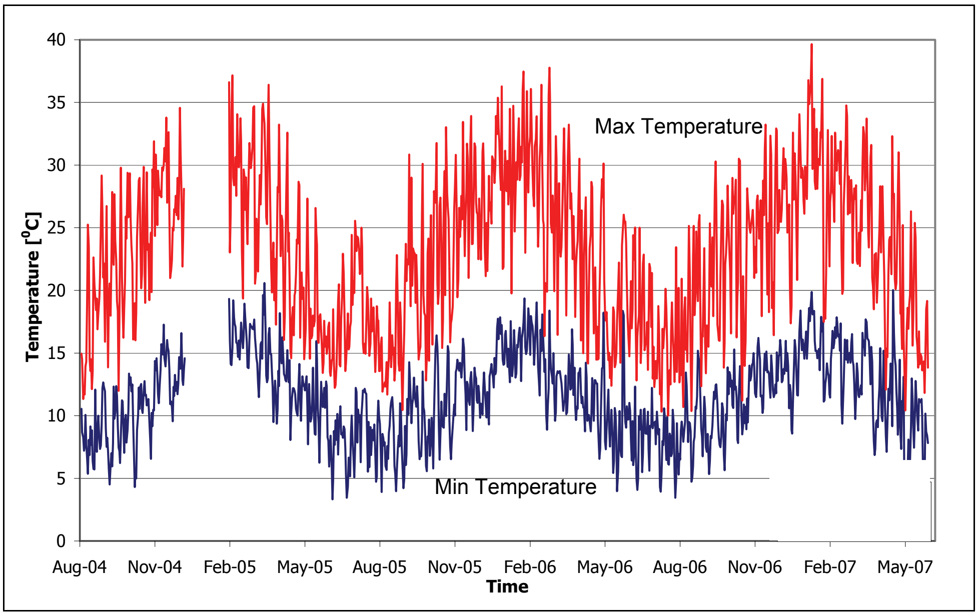


Figure 4-14 Daily minimum and maximum temperatures at Purgatory (data gap due to the veld fire)

4.4.2 Drilling results

A total of 7 boreholes were drilled (**Figure 4-10**). In addition 3 shallow piezometers were installed by hand augering at selected wetlands within the sub-catchment.

Three boreholes (P1, P2 and P3) were drilled using a conventional air-percussion drill rig. The other four boreholes were drilled with a portable air-percussion drill rig due to access problems. Drilling records and borehole logs are documented in Appendix E-2. The drilling operation was conducted under continued supervision, as was requested by WCNCB, the reserve manager for the site. The on site geologist also acted as Environmental Control Officer (ECO) to ensure the compliance with the EMP (Appendix C-2).

The drilling of the shallower boreholes, using the portable drill rig, was interrupted and delayed due to the presence of a group of Xhosa initiates in the close vicinity of the drilling sites. During their presence a veld fire started, which burnt over most of the sub-catchment. Fortunately none of the already installed equipment was destroyed, although the weather station (recording a temperature of 51°C) sustained damage to some instruments including the anometer. The vegetation in much of the catchment was destroyed, making a full botanical characterization impossible.

P1

The P1 borehole was drilled on the eastern side of "Die Ou Tol" picnic area and down gradient of a seepzone. The borehole is located some 130 m west of the major fault. The target was the deeper aquifer on the western side of the fault, while the borehole P3 was sited on the eastern side.

The borehole was drilled to a depth of 110 m. Small water strikes at 39 m, 43 m, 60 m, 70 m, 93 m and 110 m resulted in artesian flow and flowing at a rate of ~ 0.5 l/s. The borehole design allowed for artesian conditions and the borehole was capped and fitted with a tap.

The details of drilling diameter and final construction are given in Table 4-5.

P2

The borehole is located in the west of the “Die Ou Tol” picnic area and east of the riverside in the alluvium. The borehole was drilled to a depth of 18 m with water first intersected at the contact of the unconsolidated alluvial sediments and the weathered sandstone. The static water level was 3.37 m below column.

P3

The P3 borehole was drilled in the road reserve along side the Main Road R191 to a depth of 152 m targeting the Skurweberg Formation at depth east of the major fault. Numerous water strikes were encountered (see attached borehole logs) and the final blow yield was ~ 20 l/s. The static water level was measured 10.08 m below column.

P4

The P4 borehole was drilled a couple of meters from the P3 site to monitor the upper alluvial aquifer. The borehole was drilled to a depth of 30 m with a water strike at 25 m. The final blow yield was 2.5 l/s and with a static water level of 9.17 m below column

P5

The borehole is situated west of the stream flowing through the “Die Ou Tol” picnic area. The borehole targeted the Skurweberg Formation. The borehole was drilled to 18 m and intersected dark brown clay at 10 m and then light grey sandstone. A 2.5 l/s water strike at 15 m resulted in the borehole being artesian.

P6

The P6 borehole was drilled some 15 m south of P5. Both the P5 and P6 boreholes were drilled to 18 m. The P5 borehole was drilled in light grey sandstone and had two water strikes at 10 m and 13 m. The static water level was 1.80 m below column.

P7

This borehole was drilled on the eastern hillside slope of the “Die Ou Tol” picnic area. The P7 borehole was drilled to a depth of 26.4 m and targeted the Skurweberg Formation. Two water strikes were encountered at 19.5 m and 21 m and a static water level of 3.42 m below column was measured. The table below is a summary of the relevant borehole details.

Table 4-5 Relevant details of the newly drilled boreholes

Borehole Number	Final Depth (m)	Start + End diameter (mm)	Water strikes (mbgl)	Blow yield (l/s)	Static Water Level (mbgl)
P1	110	305 / 250	39,43,60,70,93,110	2.5	Artesian
P2	30	305 / 250	-	-	3.37
P3	150	305 / 165	21,50,65,120	20	10.08
P4	30	114 / 75	25.5	2.5	9.17
P5	18	114 / 75	10,13	2.5	Artesian
P6	18	114 / 75	15	2.5	1.80
P7	26.4	114 / 75	19.5, 21	~ 2	3.42

The field measurements during the research study comprised regular and or continuous water level measurements at all boreholes and piezometers as well as sampling and field chemical measurements from boreholes and piezometers.

4.4.3 Groundwater level measurements

Automatic dataloggers Schlumberger (type Diver) for continuous recording of water levels (hydrostatic pressure) were installed in the boreholes P2, P3 and P4 at 26 April 2005. A Baro Diver was installed in the P4 borehole to correct hydrostatic head changes with atmospheric pressure changes. However, the baro diver stopped recording in June 2006. The artesian borehole P1 was sealed and a pressure meter installed. The data are contained in Appendix E-3.

The hydraulic head measurements for these boreholes are shown in **Figure 4-15**, indicating that the artesian borehole P1 has a higher hydraulic head than all others, while the deeper borehole at the road (P3) has a higher hydraulic head than the shallow borehole (P4). The sudden drop of hydraulic head in P1 during March and April 2006 is due to unauthorised use of the water from the artesian borehole for the nearby restroom on the picnic site. The borehole was disconnected and the valve locked so that proper measurements could be taken again.

The hydraulic head in P2, P3 and P4 from June 2006 to May 2007 is recalculated with a constant value of atmospheric pressure, as the baro diver was malfunctioning. This resulted in higher fluctuations and a possible inaccuracy of the actual data of about 20 cm.

The water levels in the other boreholes and the piezometers were measured regularly during monitoring rounds (see **Table 4-6** and **Figure 4-16**).

Table 4-6 Routine water level measurements [m bgl] in the Purgatory Catchment

Site Code	Jan-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Sep-05	Feb-06	Apr-06	May-06
P6	1.80	1.90	1.26	1.17	0.80	0.70	0.60	3.17	3.02	1.38
P7	3.42	3.00	3.65	0.70	0.40	Artesian		3.32	3.26	1.38
Lower Wet		1.12	0.82	1.08	0.82	1.07	0.81		Dry	1.07
Upper Wet			1.16	1.22	1.10	1.18	1.21	1.45	1.66	1.26

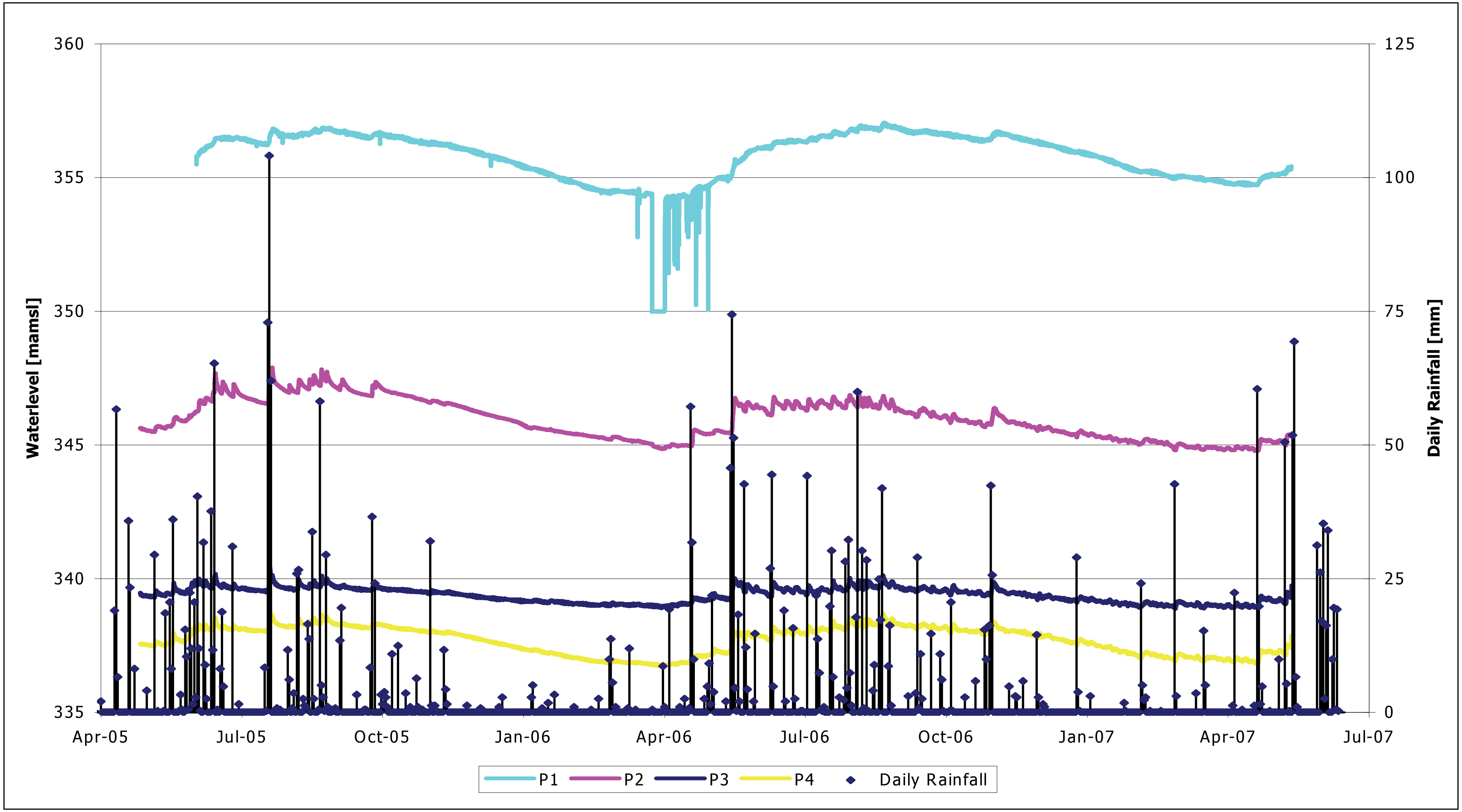


Figure 4-15 Hydrographs of boreholes P1, P2, P3 and P4

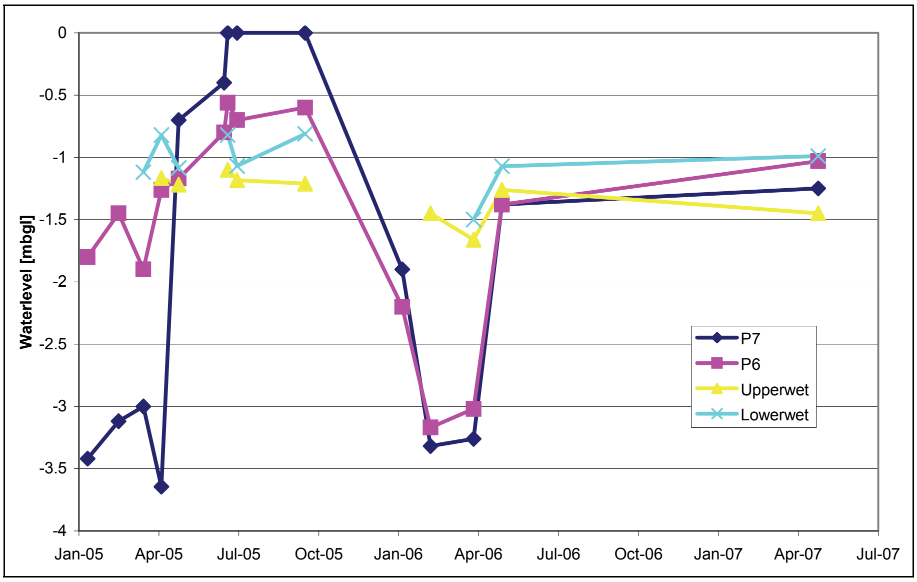


Figure 4-16 Hydrographs of piezometers P6, P7, Lowerwet and Upperwet

A comparison of the water level measurements with the recorded daily rainfall events shows the strong correlation and the nearly immediate response of the water level in most boreholes to rainfall (**Figure 4-17**). The water level in borehole P2 (Alluvium) at the river shows a clear response even to small local rainfall events, while the boreholes at the road respond mainly to rainfall events of more than 20 mm/day.

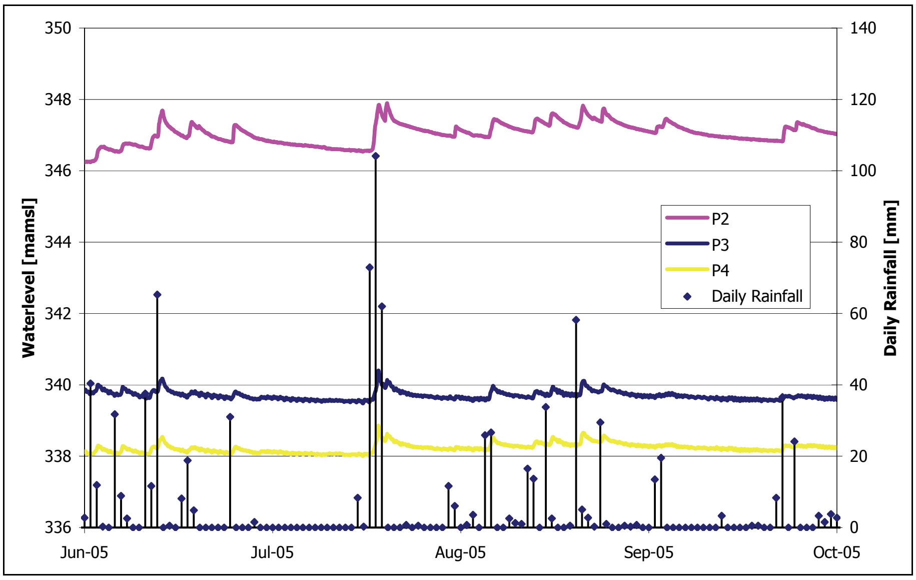


Figure 4-17 Hydrographs and daily rainfall

Summary

The test site is dominated by fractured rock aquifers from the Skurweberg and Peninsula Formations. The Peninsula Aquifer comprises the deeper, confined aquifer that mainly discharges via fault zones into seepzones and directly into the river.

The waterlevel fluctuations in the different aquifers indicate the clear seasonal fluctuations between recharge and discharge cycle. While the water level in the shallow alluvium aquifer and the water level in the seepzones react directly to single rainfall events, the water level in the deeper aquifer does not react to single rainfall event but resembles the general rainfall cycle.

4.4.4 Groundwater temperature measurements

The divers also record the water temperature. As expected, the records show a strong seasonal fluctuation (**Figure 4-18**). However, there is a time lag between the air temperature and the water temperature in the different boreholes evident.

The water temperature in the stream measured at station P5 closely resembles the average air temperature with minimum temperatures below 10°C in July and August and highest temperatures of about 25°C in January and February. The water temperature in the shallow borehole P2 (Alluvium Aquifer) varies between 14°C in August and 19°C in March, showing a time lag in the seasonal fluctuation of about 1 month, indicating a delayed response of the aquifer to temperature changes. The boreholes in the Skurweberg Aquifer (P3 and P4) show a longer time lag of 4 to 5 months and a much smaller variation between 17 and 18.5°C.

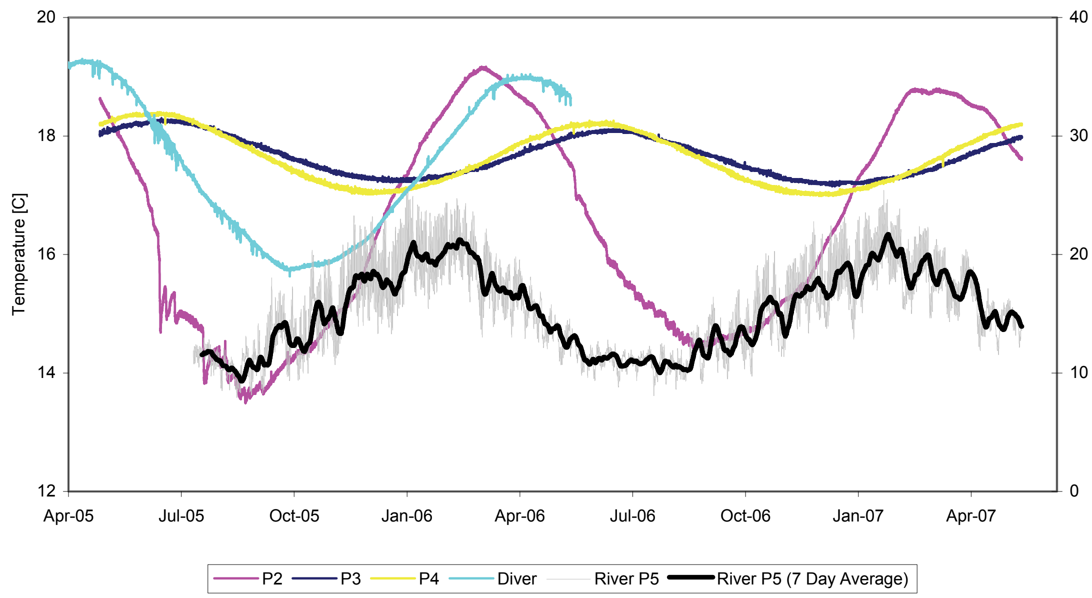


Figure 4-18 Water temperature measurements in boreholes (left axis – P2, P3 and P4) and river (right axis – River P5)

4.4.5 Stream flow measurements

Routine discharge measurements

Routine discharge measurements were taken in the Purgatory Catchment in July 2004, October 2004, December 2004, January 2005 and May 2005 (**Table 4-7** and **Figure 4-19**). It was not possible to make discharge readings in late summer (March/April 2005), as flows were too low to measure. The August sampling trip was abandoned mid-way because of rainfall, which changed the flows in the rivers as they were being measured.

Table 4-7 Routine discharge measurements in the Purgatory Catchment (2004/2005)

Site Code	Jul 2004	Oct 2004	Dec 2004	Jan 2005	March 2005	May 2005
P1	0.001206	0.000594	0	0	Flows too low to measure[1]	0.00283
P2	0.005067	0.005462	0.00317	0.001405		0.00401
P3	0.00287	0.00997	0.00091	0.000369		0.00218
P4	0.002145	0.00477	0.003315	0.001775		0.000472
P5	0.011181	0.01086	0.00454	0.00525		0.0051
P7	0.00122	0.002061	0.00096	0.00062		0.000484
P9	0.00175	0.0000043	0	0		0.0000021
P10	0.002532	0.00145	0.000000125	0.000000112		0.0009498
P11	0.0162	0.006952	0.00078	0.00004		0.00478
P12	0.01312	0.021275	0.00971	0.007101		0.0187

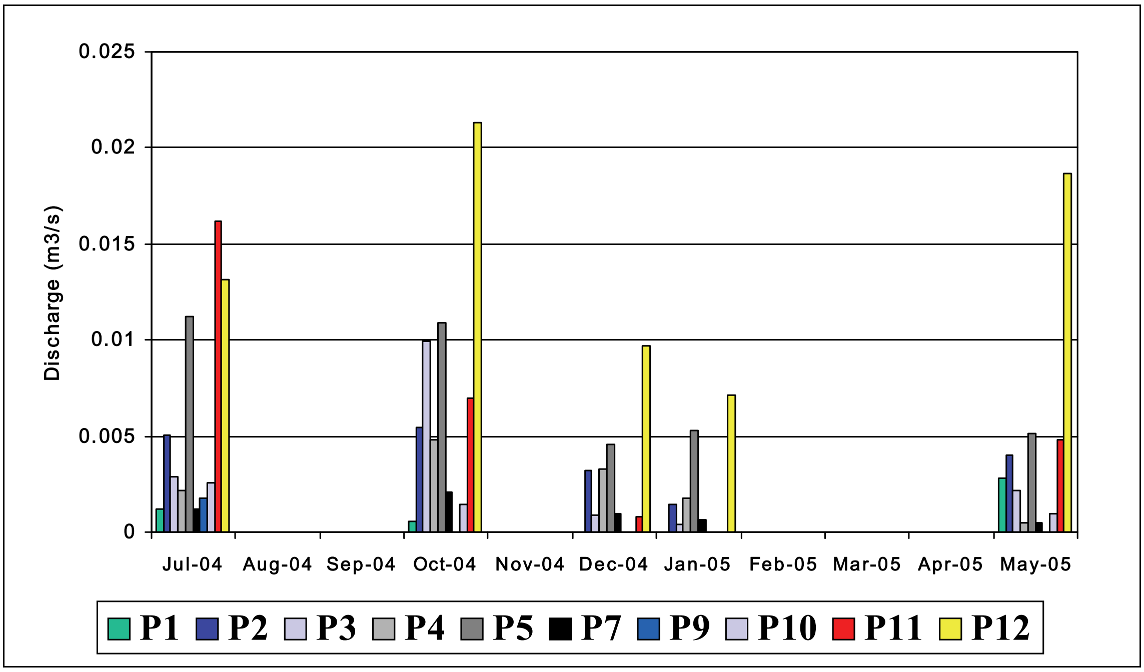


Figure 4-19 Discharge measurements in the Purgatory Catchment (2004/2005)

[1] This does not mean there was no flow, only that it was too small to be measured.

Automated water level measurements

Automated water level measurements were undertaken at the stream stations P5 and P11 (**Figure 4-20**), as described above. No flow measurements were undertaken for the period of water level measurements, so that the water level measurements cannot be calibrated to flow. However, the hydrographs complement and verify the results of the routing discharge measurements.

The strong influence of single rainfall events and the seasonal fluctuation is evident in both hydrographs. P5 remained relatively constant and was flowing throughout the year. The fluctuations in P11 were higher and the water level became very low at the end of summer 2005/2006 (**Figure 4-20**).

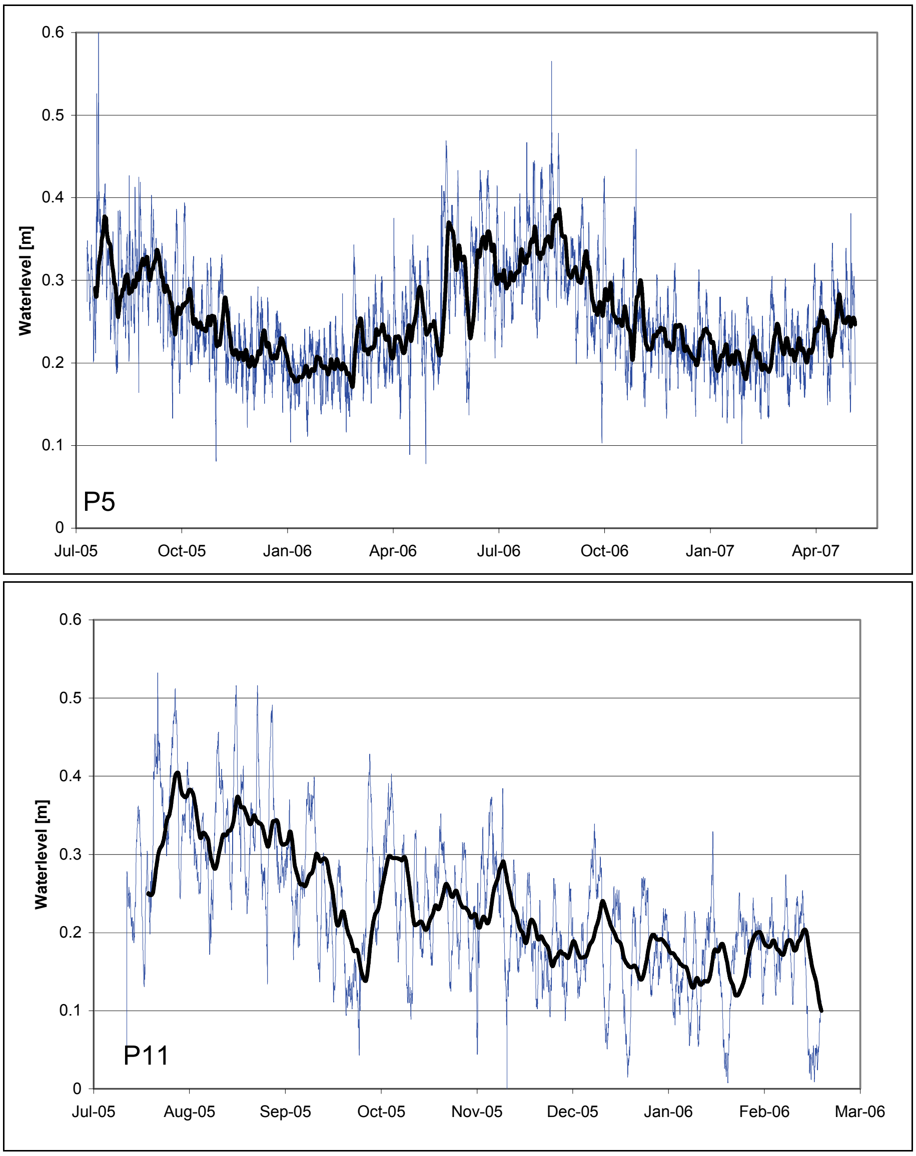


Figure 4-20 Hydrograph from Stream Station P5 [July 2005 – May 2007] and P11 [July 2005 – March 2006] (blue: 1 hourly interval measurements; black: 7-day moving average)

Summary

Despite the relatively small catchment, sampling points on the eastern tributary, e.g. P2, P5, P7, P12, showed fairly strong perenniality. Flow in most of the western tributary was strongly seasonal (P10 and P11). This suggests that, should either of the streams be receiving water from an aquifer, groundwater contribution is most certainly higher for the eastern streams than for the western streams.

4.4.6 Hydrochemistry results

Water samples were taken from the boreholes P1, P2, P3, P4, P5, P6 and P7, the piezometers ‘Lower Wet’ and ‘Upper Wet’, all rainfall collectors and at the stream station P5 for chemical and isotope analysis.

EC and pH field measurements

During the regular monitoring rounds field measurements of electric conductivity [EC] and pH of the groundwater were taken. The records are documented in Appendix E and shown in **Figure 4-21.** There is no clear trend in terms of aquifer specific differences and seasonal influences. The reasons for the strong drop in pH in January 2006 in all boreholes and the stream (River P5) are not clear, but might be related to instrumentation failure.

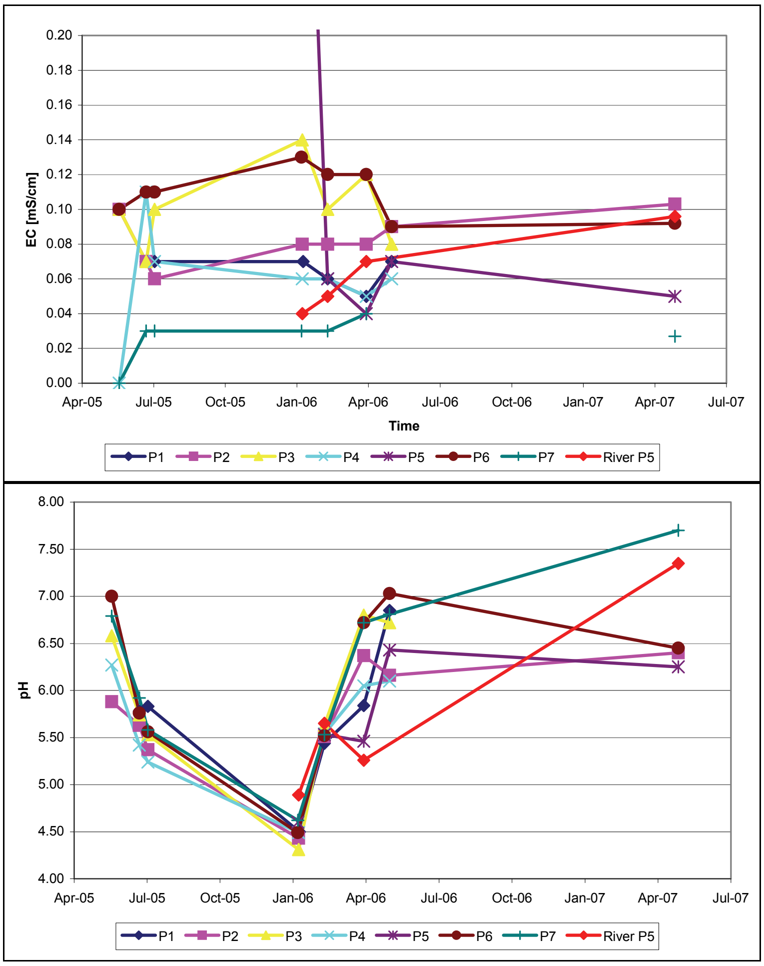


Figure 4-21 Field measurements in boreholes, piezometers and surface water; (a) EC and (b) pH

Groundwater Macro-ions

The groundwater from most boreholes and piezometers is from the Na-Cl type with a very low salt content. The Piper diagram (**Figure 4-22**) shows that the water chemistry of P1 (Peninsula Aquifer) and P7 (shallow seepzone) is very similar, while P5 (artesian Skurweberg) depicts a Na-Alkalinity type.

The EC of the water samples varied between 2 and 12 mS/m, very similar to the field measurements (see above). The Box diagrams in **Figure 4-23** and **Figure 4-24** show that the water quality in P5 appears to differ significantly from the other water samples.

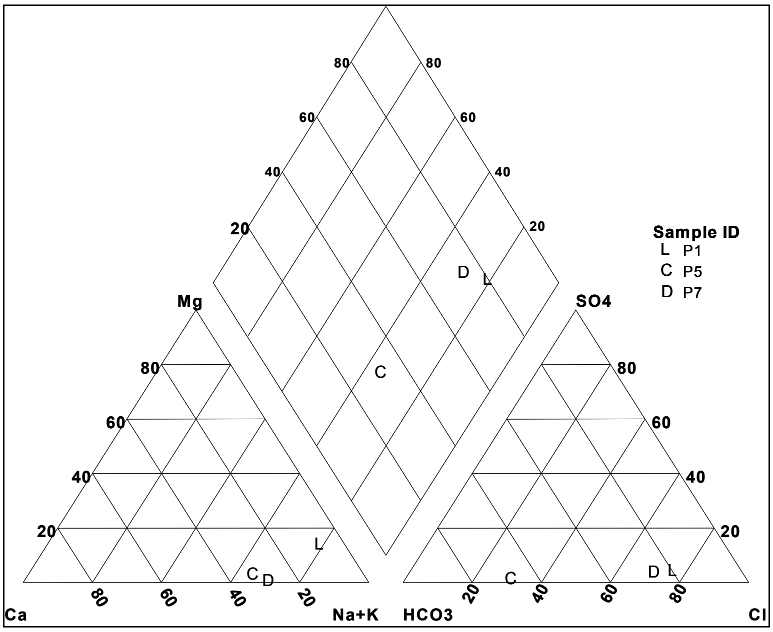


Figure 4-22 Piper Diagram of groundwater samples P1, P5 and P7

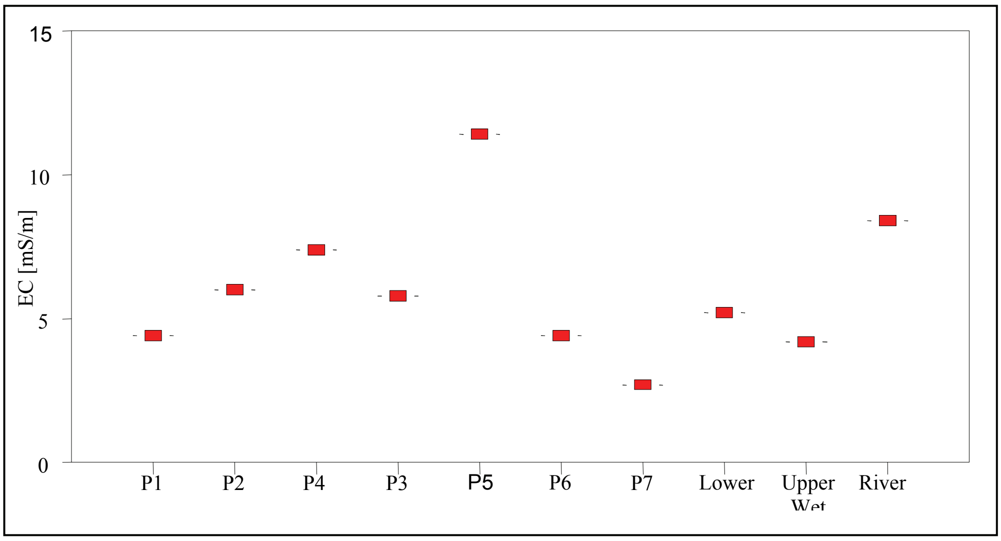


Figure 4-23 Box Diagram of EC measurements on borehole, piezometer and river water samples

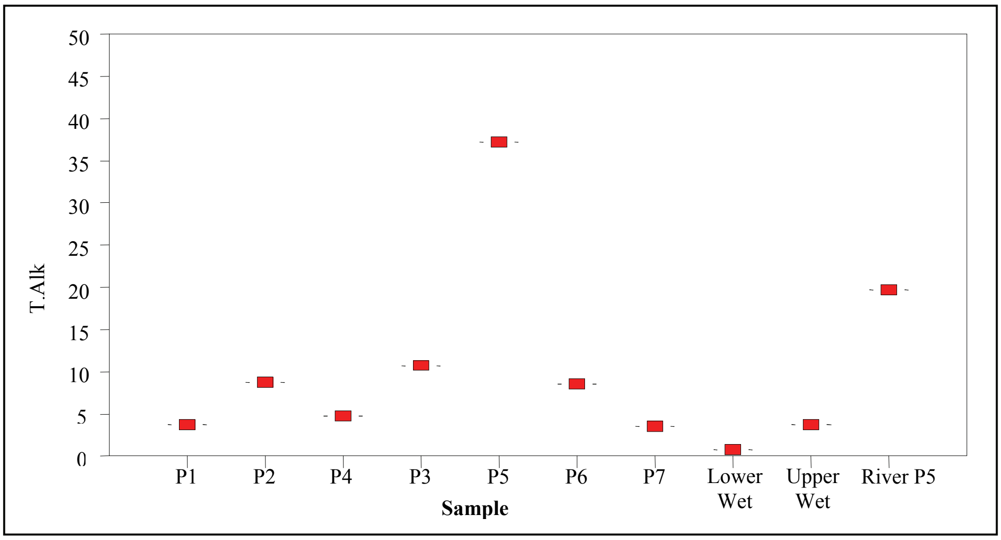


Figure 4-24 Box Diagram of Total Alkalinity of water samples

Surface water Chemistry

There is no significant difference between the surface water chemistry and groundwater chemistry.

Isotope Analysis

The oxygen and hydrogen isotope composition of rainwater varies in a semi-predictable way, depending on source region, climate (temperature, amount of precipitation) and geographic location (altitude, continentality), and thereby provides the basis for "O- and H-isotope hydrology" (e.g. Clark and Fritz, 1997; Harris and Talma, 2002). Samples for analysis of stable isotopes of oxygen (δ18O) and hydrogen (δD) were collected at eight selected localities and submitted to the University of Cape Town. The results are listed in **Table 4-8** and shown graphically in **Figure 4-25**.

Table 4-8 Stable Isotope Analysis

Sample Location	Location Type	δD	δD error	δ18O	δ18O error
LRC	Rainfall	-25.5	0.7	-4.9	0.3
BRC	Rainfall	-25.3	0.1	-4.9	0.5
P1	Groundwater	-26.4	0.4	-4.9	0.2
P2	Groundwater	-20.9	0.6	-2.6	0.2
P5	River Surface Water	-28.6	0.4	-4.8	0.5
Lower wet	Wetland Surface Water	-18.8	0.5	-3.5	0.4
Upper Wet	Wetland Surface Water	-24.6	0.7	-3.7	0.3

It has been recognized for some time that the "Global Meteoric Water Line" (GMWL; **Figure 4-25**), does not fit rainwater results from the Western and Southern Cape, for which a "Cape Meteoric Water Line" (CMWL; **Figure 4-25**) has been defined (Diamond and Harris, 1997). A "Cape Hot Springs Line" (CHSL; **Figure 4-25**) is also recognised from isotope analysis of groundwater samples from widely distributed thermal springs in this region (Diamond, 1997).

The results from the isotope analysis show two distinct clusters (see red triangles in **Figure 4-25**). While the rainfall samples, the deep artesian borehole and the river cluster between the GMWL and CHSL, the Lower Wetland, Upper Wetland and alluvium borehole samples fall clearly outside of the GMWL. This indicates a strong groundwater signal in the river, but very little to no groundwater signal in the wetlands. The deeper groundwater (P1) and the river sample (P5) show only small effect of evaporation, indicating high recharge percentage and high groundwater contribution to the river flow.

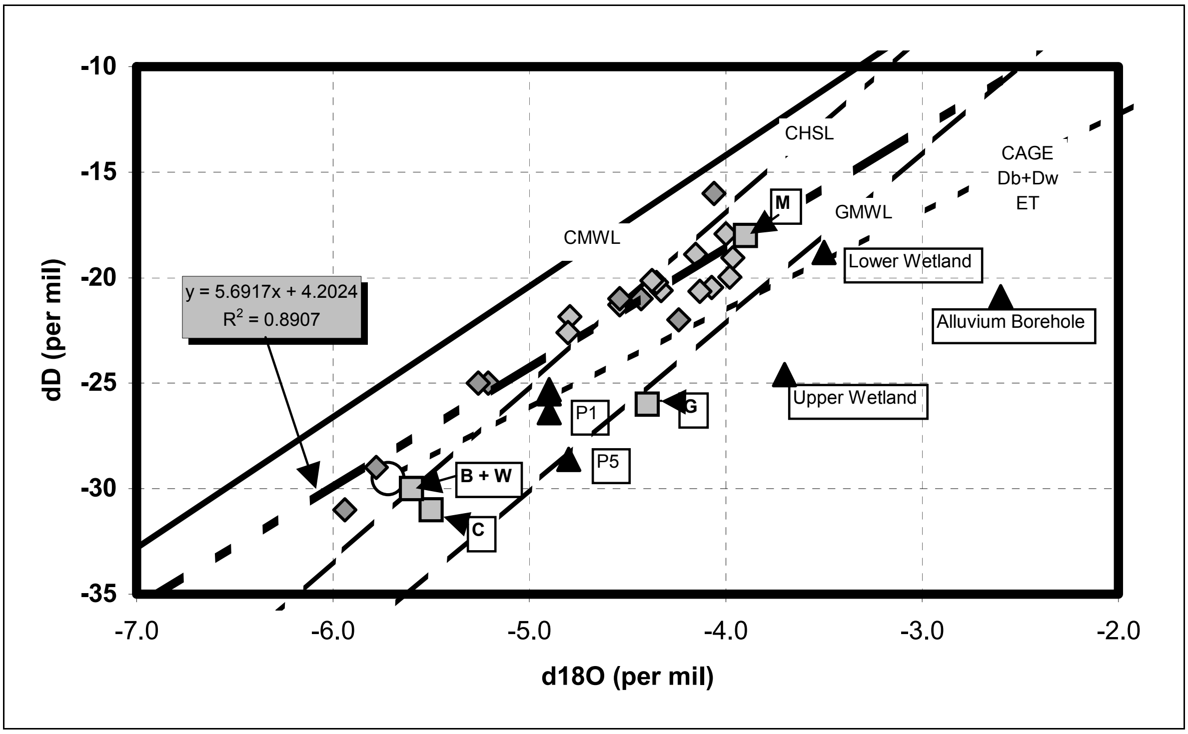


Figure 4-25 Stable isotope results for seven samples from Purgatory (red triangles) in comparison to water samples from the TMGA (diamond symbols; CCT, 2005)

The Cape Meteoric Water Line (CMWL: δD = 6.2*δ18O +10.6; Diamond & Harris, 1997), the Cape Hot Springs Line (CHSL: δD = 8.32*δ18O +16.5; Diamond, 1997) and the Global Meteoric Water Line (GMWL: 8.0*δ18O +10; Craig, 1961) are shown for reference. Also shown is an Evaporation Trend line for Citrusdal Artesian Groundwater Exploration (CAGE) results from Bokkeveld Group (Db)- and Witteberg Group (Dw)-related samples (short-dashed line anchored by circle at lowest value in δ18O range; E.R. Hay, unpublished PhD thesis data). Mean values from thermal springs (triangle symbols) in the study region are provided for Brandvlei (B,) Witzenberg (W), Caledon (C), Goudini (G) and Malmesbury (M), from Diamond and Harris (2000).

4.4.7 Aquatic biology monitoring

Macroinvertebrate and diatom sampling took place at a sub-set of the routine discharge measurement locations. The number of sites sampled on each occasion depended on their being sufficient flow in at each location. In July 2004, five sampling points was sampled in each of the two streams, viz.: Stream A = P1, P2, P3, P4 and P5; and Stream B = P6, P7, P8, P9 and P10. In subsequent trips, however, some of these were not sampled. In December 2004 P3, P8, P11 and P12; in January 2005, P3, P5 and P12 were sampled; and in May 2005, P3, P5, P8 and P11 were sampled.

Macroinvertebrates

Macroinvertebrate sampling in the Purgatory Catchment took place in July and November 2004 and May 2005. The composition of the macroinvertebrate communities recorded during each of the sampling occasions is provided in Appendix E-7.

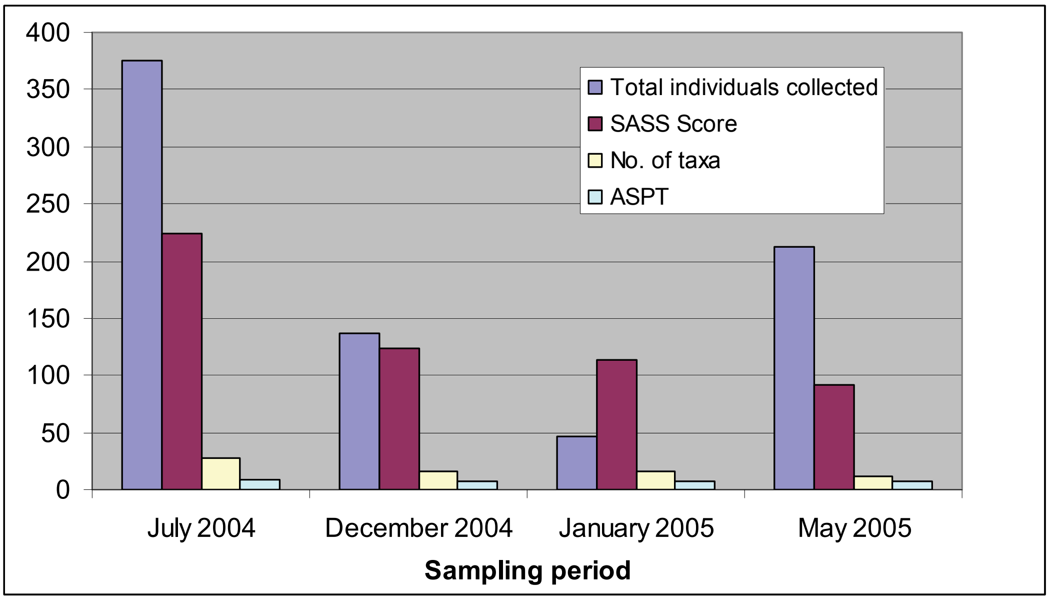


Figure 4-26 Summary Macroinvertebrate assessment (SASS) results recorded from Purgatory Catchment during 2004 and 2005 survey

As was the case for Kogelberg, the factors found to have a significant influence on macroinvertebrate diversity during the survey period were habitat availability, seasonality and flow level during sampling. The changes in abundance of macroinvertebrate taxa were evident during the survey duration.

Habitat availability:

Where habitat diversity (biotope) was poor, generally so was macroinvertebrate diversity. In July 2004, location P10 had only mud biotope sampled in a pond and only five taxa were sampled. However, eight taxa were sampled in a near by location (P11) which was comprised of a variety of biotopes (stones in and out of current, marginal vegetation and little mud). In location P10, there were no stones and marginal vegetation available for macroinvertebrate taxa and as a result; Odonata, Megaloptera and Diptera taxa that are usually associated with these biotopes were absent. Both macroinvertebrate abundance and diversity were influenced by habitat availability. Where habitat diversity was rich (e.g. location P3), higher number of taxa was recorded and hence higher SASS5 score.

Seasonality:

The highest SASS5 score was obtained during winter (July 2004), followed by early summer (December 2004) late summer month (January 2005), respectively (**Figure 4-26**).

The sample from early winter (May 2005) yielded a lower SASS5 score relative to the previous summer samples but certain taxa such as Baetidae, Gomphidae and Simulidae were more abundant compared with late summer samples. This was a clear indication of the shift back to a winter assemblage. The two samples collected during summer months (December 2004 and January 2005) showed much the same taxa. Although it is normally expected that the diversity of invertebrates will be lower during the cold winter months, the results here indicated the reverse, i.e. in these streams diversity was higher in winter.

Flow conditions:

The tributaries in this catchment possess highly variable flows, often independent of seasonality. Changes in flow conditions of a tributary during wet and dry climatic conditions influenced macroinvertebrate results rather than major anthropogenic (man-induced) alterations in water quality. Abundance of certain taxa was found to decrease with a reduced flow (e.g. Hydrosychidae and Elmidae). Most macroinvertebrate taxa were present during high flows in winter rather than during low flows in summer period. Reduced summer flows resulted in very poor water quality (high turbidity) coupled with more standing water. SASS5 score in Purgatory Catchment show an impaired system during very low flows, with SASS5 score in higher flows indicating a fairly good system conditions. These results showed that flow rate was another significant factor in macroinvertebrate community structure within the Purgatory Catchment.

Diatoms

Diatom samples were collected from locations in the Purgatory Catchment on the following dates:

P1 - Sampled 28/07/2004 (16:35) : clear water/fragments of algae.
P2 - Sampled 28/07/2004 (15:50) : clear water with fine sediment.
P3a - Sampled 28/07/2004 (15:10) : Fine ooze with detritus.
P4 - Sampled 28/07/2004 : Fragments of vegetation – mosses.
P5 - Sampled 28/07/2004 (14:20) : Stained fine detritus/sediment.
PO7 - Sampled 28/07/2004 (13:25).
P9 - Sampled 29/07/2004: grey khaki water and black sediment.
P10 - Sampled 29/07/2004: grey-black fine sediment.
P11 - Sampled 29/07/2004 (11:50) : Clear water, fine material.
P12 - Sampled 28/07/2004 (11:50) : Fine organic ooze.

The locations of the sampling sites are given in Appendix E. An inventory of the species that were recorded at each of the sites is presented in Appendix F.

4.5 Summary

The Purgatory test site comprises a number of wetlands, seeps and streams that appear to receive groundwater discharge. The geological setting of these wetlands and seeps are described in Section 4.2.5. The field work and monitoring focussed on wetlands falling under item 2, 3 and 6. Based on the results, the groundwater dependency of these ecosystems and the possible link to the deeper TMG aquifers can be explained as follows:

1) The seepzones at or just below the Goudini – Cedarberg Shale contact were not investigated in detail. However, there is sufficient evidence that they are lithological contact systems and not connected to the deeper TMG aquifer.

2) The two wetlands in the non-perennial drainage line of the western tributary show strong seasonality in water level fluctuation (see **Figure 4-16**). However, it appears that the stream flow in the dry months slightly increases below the second in-stream wetland (see P11, **Figure 4-10** and **Table 4-7**), suggesting some groundwater inflow. The hydrochemical composition also resembles the TMG hydrochemistry. This suggests that these structures are connected with deeper groundwater flow and discharge, contributing to maintaining the ecosystem but not sufficient to create a perennial stream.

3) Groundwater discharge into the eastern tributary is clearly evident along the deeply incised gorges. This inflow maintains the perennial character of the eastern tributary (see P5, **Figure 4-10**). The groundwater contribution most probably originates from the Peninsula Aquifer and discharges along the cross faults. There is no evidence for additional groundwater discharge from the Purgatory fault.

4) The seeps on the eastern slope of the catchment occur where permeability interfaces (lithological contacts esp. Ope-Sc) are transected by the Purgatory fault. These systems constitute a combination of lithologically controlled (see item 1) and fault controlled wetlands (see item 3), where groundwater contribution from deep aquifer flow via the fault structure is possible.

5) The identified linear belts of hydrophile flora were not investigated further as they are clearly morphologically controlled, ephemeral systems and are impacted by alien invasive species.

6) The seep zones at the basal ‘break-in-slope’ on the west-facing valley side show a strong seasonality in water level fluctuation. The water level in P7 became artesian during the winter months, indicating pressure driven subsurface flow. Since the artesian condition did not continue into the summer months, it can be concluded that this is a localised phenomena. The wetland is most probably not connected to the deeper aquifer system. However, the groundwater level remained within the possible rooting depth of the seep plants.

Chapter 5:

Summary and Conclusions

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5. SUMMARY AND CONCLUSIONS

This chapter summarises the findings of this study, namely:

- how the outcomes of this study have addressed the original aims of the project;
- the useful methods to assess TMG aquifer discharge and its contribution to ecosystems;
- a conceptual eco-hydrological framework that enables an understanding of the role of groundwater in the fibs environment;
- important conclusions for future abstraction of groundwater from the TMG aquifer, and
- recommendations for lines of future research.

5.1 Addressing the Project Aims

The overall aim of the project was to improve understanding of the ecological role of the TMG aquifers in order to guide the sustainable development of this water resource for large-scale abstraction. It was envisaged that a parallel project run by the City of Cape Town may have progressed to pilot pumping to test the deep aquifer and this would enable actual impacts to be monitored in potentially sensitive ecosystems. No new large-scale pumping of the TMG has taken place during this project, and therefore the project focussed on tracing the different TMG aquifers' contribution to ecosystems in (relatively) unimpacted conditions and sites. Sites chosen (as described in section 1.7) are similar to those that may be impacted by large-scale abstraction by the CoCT.

The aims of this project (section 1.2), are described below and the outcomes which address them are outlined.

1. *The development of predictive tools to assess the impact (or risk) of groundwater abstraction on the environment.*

   For reasons beyond the control of the project team, test groundwater abstraction did not take place during this project, but several methods were tested which indicate the relative contribution of groundwater discharge to different ecosystems, including terrestrial ecosystems, wetlands, and river ecosystems. Successful tools are summarised in section 5.2.

2. *To improve the understanding of groundwater dependent ecosystems (GDEs) in the TMG and the sensitivity to groundwater level fluctuations*.

   Groundwater level fluctuations near potentially dependent ecosystems and ecosystem responses in terms of plant moisture stress were monitored. Whilst most species on and off seeps were vulnerable to moisture stress, the wetlands or seeps which maintained relatively constant water levels fed by groundwater discharge did not experience water stress during dry periods. Seasonal seeps and off-seep plants experienced only limited moisture stress during dry periods. It has been shown (through tracers and water level measurements) that high altitude seeps are dependent on rain and mist precipitation and their water levels are not maintained within shallow rooting depth.

3. *The use of innovative techniques to determine the impact of groundwater abstraction on the environment*.

Several techniques were applied for the first time in TMG catchments, to trace groundwater contribution to ecosystems:

- Radon has not been used as a tracer of groundwater discharge in this environment before (section 5.2).
- Silica and temperature had been used in groundwater projects to identify TMG related flow paths (e.g., DWAF 2007), and at Kogelberg they were used successfully for the first time to identify groundwater discharge to surface water.
- Groundwater level monitoring has been applied in areas previously believed to be inaccessible to drilling and augering.
- The use of 'piezometers' in boulder-bed tributaries has not been tried before in areas where other means of flow gauging is prohibited.
- Aston (2007) assessed the first data set of xylem embolism vulnerability for fynbos species.
- Vegetation change analysis proved useful in assessing relatively lush areas linked to groundwater bearing features in Purgatory.
- Diatoms were assessed in groundwater fed tributaries but were not found to be useful indicators at this scale (see section 5.5 for further recommendations).

4. *The development of indicators to monitor the effect of abstraction on sensitive ecosystems*.

Following the application and testing of a variety of techniques in combination, it was found that groundwater level monitoring, Rn, dissolved silica, temperature, and VCA mapping linked to groundwater flow mapping were the most useful indicators.

5. *Coupling time series and spatial databases in order to ascertain the impacts of low flows (groundwater and surface water interaction) on the environmental system.*

High resolution multiple groundwater level, surface water level and climate datasets were collected. A preliminary analysis on the recharge and discharge regimes of the multiple flow systems that comprise the TMG was completed, however, more detailed work could be carried out on these and the river hydrographs by a Ph.D. / M.Sc. student.

6. *Improved understanding of the impact of changing low flows on freshwater ecology*.

Since the test sites are located in un-impacted catchments, no changes of low flows were observed. SASS assessments indicated the weak perenniality of the Oudebos and many of the invertebrates could be impacted by a shift to a seasonal system if dry season groundwater-fed baseflow would be significantly reduced. However, the tolerance limits to theses changes would need to be determined, as reduced baseflow is a natural phenomenon during drought periods.

7. *Improved understanding of the relationship between surface flow, event discharge from high-lying TMG unconfined aquifers and deep confined-aquifer discharge in maintaining wetlands or seeps*.

A winter rainfall event was sampled in the wetlands and river at Oudebos. Some samples were lost during the event and for the remainder the isotope tracers being used could not distinguish the different flow path contributions to discharge. Future event responses should focus on Rn, Si and temperature indicators correlated to borehole and river hydrographs.

8. *Improved understanding of subsurface TMG discharge in maintaining coastal plain wetlands and vleis.*

The coastal wetland monitored down gradient of Kogelberg appears to receive a contribution from the TMG aquifer via an underlying groundwater-bearing fault structure. Other footslope vleis may receive contributions from shallow subsurface flow.

5.2 Useful techniques to assess groundwater contribution to the natural environment.

During the course of this project several techniques and methods were tested to identify groundwater contributions to the natural environment, and to understand the ecological dependency on groundwater. Some of these techniques have proved useful and others not.

The identification of biological indicators in aquatic and terrestrial GDE communities was attempted. Plant, diatom or invertebrate indicators of groundwater flow could not be identified at the sub-catchment spatial scales and annual time scales which were assessed. However, there is scope for further work to examine these indicators at coarser time and space scales to assess significant changes linked to differences in groundwater flow regimes between catchments.

Plant water-stress levels clearly picked out the shallow rooted Restionaceae, but overall water stress was low and differed little between wetlands in different hydrogeological settings, particularly among the deep-rooted Proteaceae. Most plant species show a high degree of vulnerability to water stress at relatively low levels, but moist conditions, even off the seeps, kept water stress levels well within those thresholds. The lack of variation in the vulnerability curves of matched species on- and off-wetlands was surprising as was the poor correlation with wood anatomy-based measures of vulnerability. The most reliable and inexpensive method was simply to monitor the seasonal variation in water levels in the wetlands and the responses to rainfall events.

In general, measurement of abiotic parameters directly linked to groundwater flow and storage proved the most useful techniques to trace groundwater flow and discharge. Water levels, water flow and water temperatures are all useful physical parameters and SiO_2 and Rn are useful chemical parameters. Remote-sensing data can give a valuable overview of the surface expression of geological structural controls on groundwater flow. These data are also useful to identify areas of the landscape that remain lush during dry periods. However, the data sets should be of sufficiently fine spatial resolution to identify small-scale seeps associated with groundwater discharge. Interpretation should also take account of the significant orographic precipitation that occurs throughout the year in much of the Cape Fold Belt.

A summary of the degree of success and potential for further application of the techniques tested is given in table 5.1.

Table 5.1 Summary of the efficacy of methods and techniques to assess TMG aquifer discharge and dependency.

Technique	*Scale*	*Indicator*	*Corroborating data*	*Further application*
Remote sensing				
Vegetation Indices / Change Vector Analysis	Catchment	Vegetation lushness, perenniality	Ground- truthed vegetation types and water use.	Refined CVA method can be used to extrapolate results.
Lineament mapping	Catchment	Geological structures	Ground-truthed geology	Delineation of fault orientation and density to indicate groundwater flow paths.
Physical				
Groundwater level monitoring	Wetland	Maintenance of water level in dry season	Rainfall	Can be widely used especially piezometers in wetlands.
Surface water level monitoring	River reach	Groundwater-fed surface flow	Rainfall	Piezometers in pools can measure baseflow
Surface flow	River reach	Groundwater-fed surface flow	Rainfall Rated section	To demonstrate perenniality
Water temperature	Catchment	Groundwater-fed surface flow	Rainfall Water levels	Can be used qualitatively to trace groundwater flow at river reach scale.
Chemical				
Macro-ions in groundwater and surface water	Catchment	Water quality and mixing of end-members	Macro-ions in rainwater (e.g. Cl)	SiO_2 can be used as a groundwater tracer, especially with DOC.
Stable isotopes in soil, groundwater and surface water	Catchment	Mixing of end-members where contrast is evident	Rainfall isotopes	Possible indicator to distinguish between shallow surface or soil water and groundwater; might be more useful where altitude effects are significant. **
Stable isotopes in plant water	Plant	Source of water used by plant if end-members contrast	Isotopic signature of rainfall, groundwater, surface water and shallow vadose zone moisture	Can identify water sources in some settings; may be useful at broader scale where altitude effects are significant; less so at this scale. **
Rn isotopes in surface water and groundwater	River reach	TMG Groundwater tracer	Useful to have SiO_2 and rainfall	Good tracer. Should be tested in other sub-catchments to determine controls on concentrations**
Biological				
Aquatic SASS	River reach	Aquatic macro-fauna diversity	Surface flow regime Groundwater discharge	Should be tested at broader scale in perennial and non-perennial systems.
Diatoms	River reach	Diatom diversity	Surface flow regime	Should be tested at broader scale in perennial and non-perennial systems.
Botanical community mapping	Catchment	Botanical diversity	Rainfall Groundwater discharge features	Should be tested at a broader scale.
Plant water stress	Plant	Access to water	Soil and saturated water levels	May be useful in drier areas**
Xylem Embolism vulnerability	Plant	Access to water	Soil and saturated water levels	May be useful in drier areas**

** Research recommendations given.

5.3 Current understanding of the ecological role of the TMG aquifer

5.3.1 Wetland and Seep Vegetation

The detailed wetland studies and the wetland survey both show that the wetlands are structurally and compositionally very diverse and have both a greater range of types and more internal heterogeneity than was anticipated. They range from tiny patches of 1-2 m^2 to 100s of m^2 and are irregularly distributed. Wetlands with similar species composition seemingly occur within a range of different dryland communities and hydrogeological settings and different wetland types seem to occur in the same hydrogeological settings. High soil moisture levels and rugged terrain result in complex patterns of water flow and soil moisture accumulation and make it difficult to distinguish groundwater-dependent wetlands from shallow (perched) water-flux dependent ones using species assemblages.

The one exception was the ***Berzelia-Leucadendron*** **Moist Tall Fynbos,** where the boggy form was often associated with the contact between the Cedarberg Formation shale and the Pakhuis Formation tillite, and may indicate lithological contact controlled discharge, or simply preferred soil conditions supported by the poor drainage and longer water retention of clays and shales. A similar community was noted along the lower part of the Cedarberg Formation shale band and the contact between the Cedarberg Formation shale band and the Peninsula Formation in the Franschhoek Pass. It was found in the Kogelberg that information on the botanical composition and structure cannot be used to determine whether the wetlands are dependent on groundwater or not.

The lack of variation in the characteristics of matched plant species on- and off-seeps indicates that while plant-based measurements can be used to gauge a plant species' vulnerability and water relations, they do not seem to be a reliable means of identifying and quantifying groundwater dependence.

The research also indicates that the shallow-rooted species (e.g. Restionaceae, Cyperaceae, many herbaceous taxa) in perennial wetlands are likely to be the most vulnerable to changes in groundwater discharge regimes. The ericoid shrubs are likely to be intermediate and the deep-rooted species the least vulnerable. However, it is possible that a decrease in water availability in the medium-term, either due to climate change or therefore to natural and potentially anthropogenic changes in the groundwater discharge, will allow dryland species (e.g. *Leucadendron xanthoconus*) to replace the wetland species (e.g. *L. salicifolium*) – a process termed terrestrialisation.

The loss of ADE-type wetlands could have two additional secondary effects. Wetlands may be a key habitat for a number of specialist pollinators in the adjacent terrestrial ecosystems, notably long-tongued flies (Manning and Goldblatt, 1997; Manning et al., 1999; Johnson and Steiner, 2003). They may also sustain populations of invertebrates (e.g. midges), which are an important food source for fauna in adjacent dryland environments – an interaction termed a food-web subsidy (Nakanu and Marukami, 2001; Power, 2001).

The wetland communities in the Kogelberg are very likely to be functionally similar to ones throughout the high-rainfall parts of the coastal mountain ranges on the sandstones and shale band of the TMG: Winterhoek to Stettyns ranges; Hottentots-Holland to Hermanus, and from the Langeberg through to the Tsitsikamma, including the Riviersonderend and Klein River range. The species composition of the wetlands will differ between the different ranges and within ranges. These differences in species composition are not caused by changes in the environmental controls on these wetlands but because fynbos has inherently high species turnover rates between different areas (e.g. Cape Peninsula versus Kogelberg), – a phenomenon known as high Gamma biodiversity (Cowling et al., 1992). However, it will usually be easy to identify the ecological analogues of the species found in the Kogelberg and they will often belong to the same genera.

These patterns of marked ecological similarities between on- and off-seep communities and species may not hold for the drier northern and inland ranges and the rain shadow areas on the coastal mountains. These areas experience much drier conditions in the summer, and the distinction between perennial wetland and dryland communities could be more marked, although this will be offset by mists, which are plentiful all year round in the highlying northern mountains of the Cape Fold belt. This would apply to both the number of species found only on or off wetlands, the differences in water stress and the vulnerability to water stress between on- and off-wetland plant species. The lower rainfall may result in a higher degree of water stress than is experienced by off-seep species in the Kogelberg study area and/or in species composition that is adapted to prolonged dry conditions. Hence, the response to reductions in groundwater discharge may or may not be more significant.

5.3.2 Groundwater fed rivers and streams.

Distinct groundwater contribution to stream flow is identified along the river reaches, where fault and or fracture traces cross the river. These contribute to the low flow in the river, which supports the riparian vegetation and valley bottom wetland ecosystems further downstream. For example, in Purgatory groundwater discharge into the eastern tributary is evident along the deeply incised gorges. The groundwater contribution originates from the Peninsula Aquifer and discharges at the intersection of the Purgatory Fault and the transecting faults.

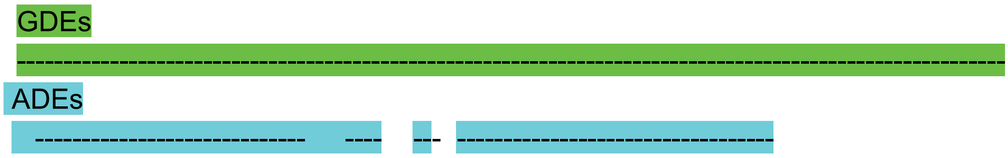
5.3.3 Eco-hydrological Framework for TMG catchments

This study has revealed the complexity of water flow through typical TMG landscapes. The sub-surface in these mountainous catchments plays a critical role in storing and releasing precipitation inputs to aquatic and terrestrial ecosystems. However, storage and release occurs across a continuum of permeability scales determined by the lithology and structural history of the TMG. The relatively inert geochemical nature of the TMG quartzites makes it difficult to trace different flow paths and differentiate water sources partitioned through different ‘reservoirs’ in the natural landscape.

In the TMG settings there is a continuum of elements and functional groups of ecosystems linked to water availability via soil moisture – perched aquifer – aquitard / aquifer contact – regional aquifer. It is useful to consider these elements in order to conceptualise those elements that are most vulnerable to abstraction. The table below provides a generalised framework of groundwater fed hydrotopes and aquifer discharge type-settings. It shows which ecological habitats might be linked to these type-settings as a result of direct or indirect discharge. It must be noted that aquifer geometry characteristics are much more complex than the simple outline described below, and discharge areas may be a combination of one or more factors, e.g., intersecting fault and lithological contacts. ADEs may be found linked to all of the discharge settings except small-scale fractures in the TMG. However, some groundwater discharge in the other settings may be linked to limited storage, which would not qualify as an aquifer.

Table 5-2 Groundwater discharge settings and associated habitats in the TMG

Habitat \ Discharge setting	Alluvium	Recent coastal sediments	Lithological contacts	TMG mega-structures	TMG intermediate structures	TMG micro-structures and matrix
Perched high wetland			■			■
Slope Wetland			■	■	■	
Valley bottom wetland	■	■	■	■	■	
Coastal wetland		■		■	■	
Spring			■	■	■	
Seasonal river	■	■	■		■	
Perennial river	■	■	■	■	■	
Riparian zone	■	■	■	■	■	
Terrestrial fynbos		■				■



The bars below table 5-2 show that ADEs are not associated the habitats 'perched high wetland' and 'terrestrial fynbos' which may access groundwater in aquitards or temporarily saturated horizons.

At the Purgatory field site the following groundwater linked ecosystems were identified:

- slope wetlands linked to lithological contact and TMG fracture discharge;
- riparian zone indirectly linked to TMG fault and fracture discharge;
- seasonal and perennial rivers linked to TMG faults and fractures.

At the Kogelberg site the following ecosystems linked to TMG discharge were identified:

- slope wetlands linked to TMG faults and fractures and lithological contacts;
- a coastal wetland linked indirectly to TMG fractures;
- perennial river and riparian zone linked to TMG fractures and lithological structures; and
- terrestrial fynbos and perched high wetlands linked to (non-aquifer) TMG jointing and micro-fractures.

5.4 Summary of conclusions

This project has established the following:

- A GIS database and Spatial Decision Support System (Appendix A) to be used in multidisciplinary, hydrogeological projects. The SDSS tool presented in the form of a digital atlas allows spatial analysis of data for catchment managers, researchers and students working with ecosystems and the TMG aquifer. It further is a useful awareness-raising platform about geographic information systems and its capabilities amongst the earth-science community.
- A groundwater-focussed, integrated, hydrological monitoring network for long-term environmental monitoring of TMG flow and ecosystems in ecologically sensitive areas of the two study sites.
- Automated and manual monitoring of components of the eco-hydrological system at two study sites in the Western Cape and collate relevant field data.
- Recommendations for lines of future research and investigation that will further improve understanding of the spatial and temporal patterns of groundwater discharge to wetlands, seeps and related ecosystems in the TMG.
- An Environmental Monitoring Framework (Appendix B 4) for integrated monitoring of impacts of groundwater abstraction in the TMG, on which current baseline monitoring efforts linked to future large scale abstraction are based.

The key findings of the research carried out on the project can be summarised as follows:

- It is shown that monitoring boreholes can be drilled in ecologically sensitive areas without significant disturbance, using an appropriate EMP and site supervision.
- It is confirmed that it is imperative to collect good quality, hard physical data, such as groundwater level data in correctly sited boreholes and piezometers located at groundwater discharge-linked ecosystems, to monitor the changing availability of groundwater.
- It is shown that Si, DOC and Rn radioactivity are useful tracers of groundwater discharge into the aquatic environment. SiO_2 and DOC are more conservative tracers with respect to changes once discharged, whereas Rn (with a half life of 3.8 days) could be used to indicate points of discharge. Macro-ions did not prove useful tracers in this study.
- Temperature is a useful indicator of groundwater flow at certain times of the year and may be indicative of the depth of groundwater flow.
- Stable isotopes are useful to distinguish between different plant water sources, although the differences might be more distinct along gradients where the effect of altitude is more significant.
- Aquatic and terrestrial species indicators for groundwater dependency were not evident at the two study sites. Assemblages of plant, invertebrate and diatom communities were very diverse and could not be linked statistically to areas of groundwater discharge at this scale of study.
- The study did not encounter any species (threatened or not threatened), that are solely dependent on groundwater discharge.
- Wood-anatomy based measures indicate that on and off-seep fynbos plants are highly vulnerable to moisture stress. However, there is no marked difference in the degree of xylem embolism vulnerability shown by on-seep species and their analogues off-seep, showing that the plants are adapted to the currently available moist conditions, i.e.

precipitation and mist. The monitoring period covered one slightly wet year (2004/2005) and two dry years (2005/2006 and 2006/2007), compared to long-term average data.

- Deep rooted plants, such as the Proteaceae, do not exhibit moisture stress, while shallow rooted plants, such as Restios, show some degree of moisture stress during dry periods. The Proteaceae appear to be tapping water in the deep soil horizons, the colluvium and weathered TMG which is generally found in the top 10 – maximum 20 metres below ground. In general most plant species access multiple sources of water, with groundwater as a dominant source during drier periods.
- Remote Sensing can be a useful tool to identify perennial wetland ecosystems and can be utilised for long-term and routine monitoring over a wide area of interest, provided the algorithm is adapted to the study area based on field verification and the spatial scale of the imagery is sufficiently small to detect ecosystems of interest.
- Subsurface flow in TMG mountainous catchments follows multiple geologically controlled flow paths that can be mapped. Groundwater discharge from the TMG aquifers occurs at springs or seepage zones that are usually linked to predictable structural, lithological and topographic hydrogeological settings.

5.5 Recommendations for future research

Based on the findings of this study, future research is recommended, as described below, to verify the findings in different hydrogeological and hydroclimatogical settings. Design and recommendation of future research need to take account of realistic 3D aquifer geometry. In addition, the findings of this study should be applied in groundwater exploration and development projects.

- The ecological research found only small differences in moisture stress and water sources between analogous on and off-seep plant species. This is believed to be due to adaptation of the species to the high rainfall and mist patterns in the study area, which resulted in low off-seep moisture stress. Similar studies are useful in drier areas in the Cape Floral Kingdom to establish whether on and off-seep fynbos species are vulnerable to changes in groundwater discharge regimes in different hydroclimatic conditions or whether they are similarly adapted to opportunistic use of water; rain, soil moisture, mist, fog, dew. Similarly, the monitoring at these sites should continue to establish longer-term variability and to monitor the impacts of climate change.

- Radon radioactivity observations were high in the Kogelberg catchment for reasons that are not entirely clear. Whilst these were verified on site with a second set of observations, the wider presence of Rn in the TMG should be tested, as it may be regionally related to deep flow paths linked to radioactive sources within the underlying granitic basement. However, the observation of high values (299 Bq/L) in low-permeability monitoring boreholes may indicate that the source of Rn occurs within the TMG sequence, perhaps in the Cedarberg shales. The levels of Rn should be quantitatively tested in other TMG boreholes at different stratigraphic levels and in a variety of hydrotectonic settings. In addition, regional research is recommended to identify the potential sources of radiogenic Rn in different areas, and to gain insight into the 3D variation of the source lithologies prior to any drilling. This programme would assist in developing the use of Rn as tracer in mixing models for quantification of groundwater contribution.

- Further testing of the physico-chemical indicators identified by this study, Sillica – Temperature – DOC – Radon, should be carried out to determine whether specific discharge sites and mixing volumes could be determined. A wider programme of sampling should be carried out at broader spatial scales to determine the wider applicability of these indicators. Similarly, testing diatoms at a broader spatial scale in conjunction with the chemical indicators outlined above and surface flow hydrographs may identify indicator assemblages. It is noted that the use of broader spatial scale will need to be appropriately defined in terms of the fracture geometry of the TMG aquifers.

- Remote-sensing analysis proved a useful tool. However, it was only possible to test the technique using Landsat imagery, which has a spatial resolution of 30 m. It is recommended to apply the technique for identification of wetlands and for ongoing monitoring at a finer scale using imagery with higher spatial and preferably higher spectral resolution (e.g. SPOT (2.5 m / 10 m), Sumbandila Sat). The results will need to be verified in the field combined with a spring hydrocensus and detailed analysis of structural and drainage fabric.

Significant data, particularly groundwater level data and local climate data, have already been collated as part of this project and are included in full in the appendices. These could be analysed in more detail by students studying groundwater recharge, flow and discharge characteristics in the TMG aquifer and could be used to calibrate numerical models for the study sites.

5.6 Implications for large scale abstraction of the TMG aquifer

Groundwater discharge to the surface environment is characteristic of TMG fynbos catchments. These catchments are typically mountainous catchments with a high proportion of orographic rainfall and discharge occurs from multiple flow paths.

The relatively high permeability of the preferred flow paths in the weathered system results in a rapid recharge-discharge response in the higher-lying, unsaturated and unconfined parts of the Peninsula and Skurweberg aquifers resulting in seasonal and interflow contribution to springs, wetlands and seeps. Higher storage and the longer flow paths in the lower-lying unconfined and confined parts of this multiple-aquifer system, results in a smoothed recharge response and prolonged, often constant discharge. Most of the springs, wetlands and seeps studied in the two test sites appear to receive groundwater discharge from the unsaturated zone, i.e. interflow, and higher-lying flow paths in the upper part of the aquifer. This emphasises the importance of sound understanding of the physical geometry and distinct anisotropy of the aquifer and the relationship between these parameters and the valley and river morphology before designing any research project or selecting sites for detailed evaluation or drawing conclusion based on ecological or morphological setting.

The study did not find species (threatened or unthreatened) or components of the ecosystem that are uniquely dependent on groundwater discharge. However, to adhere to the precautionary principle of NEMA, any abstraction from the TMG aquifers should be accompanied by an appropriate monitoring strategy. Useful tools and physico-chemical tracers of groundwater contribution have been identified which will enable test abstraction from the TMG aquifers to be monitored. Water temperature, dissolved Si, Radon and low DOC indicate aquifer flow paths. In addition to Si, a number of trace elements, not used in this study, have in previous studies (DWAF,

2000) been shown to be most useful in distinguishing the different TMG aquifers as well as indicating possible flowpaths through other lithologies. Above all, the siting and design of abstraction boreholes should be based on a sound conceptual understanding of structural controls on probable flow paths and their discharge points.

Chapter 6:

References

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