OPTIMIZED MONITORING OF GROUNDWATER – SURFACE WATER – ATMOSPHERIC PARAMETERS FOR ENHANCED DECISION-MAKING AT A LOCAL SCALE

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND

Advances have been made in recent years in developing networks and databases for monitoring water systems in South Africa, in particular groundwater and atmospheric variables, with the ultimate aim of facilitating integrated water resources management at a catchment scale. However, these monitoring systems need to be consolidated and integrated amongst various components of catchment systems: groundwater, surface water, soil and vadose zone (unsaturated zone, including surface-groundwater interactions) and atmospheric monitoring (including rainfall and evapotranspiration). Each of these components requires the development of a monitoring framework that would allow collection and management of purposeful and relevant data to address the main problems identified in current water research and practice. Many institutions and government departments manage monitoring databases for various components of the environment separately. The management of individual databases for surface water, groundwater, weather monitoring, etc. functions potentially well, however there is need to link these databases in order to optimize data collection, standardize methodologies, exchange data and, in general, add value to the data. It was proposed that an Integrated Catchment Monitoring (ICM) framework be produced in order to facilitate the integration of different components of catchment monitoring systems.

As water managers are usually not experts in all disciplines (geohydrology, hydrology, soil science, meteorology), there was need to provide a product that would direct the user in finding the appropriate guideline, database, methodology or information. The key question in the development of the ICM framework was: “What does a catchment manager need?” The product would be used to indicate the minimum monitoring requirements (e.g. type of variables, space and time frequency, etc.), essential information and sources of information in order to obtain a meaningful amount of data for a specific monitoring objective. The main target institutions were seen to be Catchment Management Agency (CMA) or similar boards.

OBJECTIVES AND AIMS

The main objective of this project was the development of an integrated framework for optimized monitoring of water resources that will account for the different components of catchment systems and their interactions. In order to achieve the objectives stipulated in the project proposal, specialists for each component of the environment (groundwater, surface water, soil and vadose zone, atmosphere) were included in the research team. The specific aims were as follows:

AIM 1

To understand the institutional and legal interactions of different agencies responsible for various monitoring programs.

AIM 2

To develop guidelines for monitoring best practices applicable to South(ern) African conditions, for the different components of catchment systems (groundwater, surface water, soil and vadose zone, atmosphere).

AIM 3

To develop a framework for integrated monitoring of the different fluxes so that they are consistently measured in time and space.

INTEGRATED CATCHMENT MONITORING FRAMEWORK (ICM MIND MAP)

At stakeholder and research team workshops that took place during the course of this project, it was suggested that the ICM framework takes the form of a mind map. An ICM mind map was therefore developed to include:

1) Essential information with guidelines and recommendations on the procedure to design and implement an ideal monitoring programme, including optimization procedures for individual components of the environment.
2) Matrixes (monitoring objectives vs. type of monitoring variables, spatial and time frequency) including guidelines and recommendations on the ideal monitoring network.

The ICM mind map is a user-friendly tool where water managers are able to find and access any information and guidelines for monitoring any of the components of the environment (groundwater, surface water, soil and vadose zone, atmosphere, river health) related to water in catchments. For this purpose, a freely downloadable mind mapping software, called FreeMind v. 0.9.0, was used.

Each component of the environment includes the following items:

1 ***Objectives of monitoring*** and applications;
2 ***Users of monitoring***;
3 Available ***databases***, roles and responsibilities in monitoring;
4 Type of ***monitoring variables***;
5 Selection of monitoring sites, ***space and time frequency of monitoring***;
6 ***Methodologies in monitoring***: sampling, analytical procedures, data capture, handling, presentation of results and quality assurance, and inventory of hardware and accredited laboratories countrywide.

Each of these items includes hyperlinks that are used to connect directly to:

- Deliverables of this project (Word files with newly developed guidelines on monitoring) and/or
- Existing guideline documents (generally .pdf files downloaded from web sites) and/or
- Web sites (e.g. database of South African Weather Services for atmospheric monitoring)

A matrix includes a summary of monitoring objectives vs. type of variables, spatial and time frequency for the different components of catchment systems. The ICM programme can be easily expanded and updated by including any additional information.

During the development of the ICM mind map, knowledge was gained and suggestions were made on the interactions between institutions responsible for monitoring and custodians of databases, as well as on sustainable strategies for future monitoring and handling of data. The lessons learned can be summarized as follows:

1 Data and databases should be kept separately for different environmental components and handled by specialists in the particular discipline.
2 The modalities of data exchanges between institutions that monitor and manage

databases were discussed.

3 Recommendations on collation of existing weather data from research projects, farmers, schools, etc.
4 Recommendations on collation of existing soil data from universities, municipalities, consulting firms and accredited laboratories.
5 The ideal and most appropriate operational scale for management and monitoring of natural resources, in particular water, is the catchment scale. It is likely to have 10 to 20 quaternary catchments managed by Catchment Management Agencies (CMAs) within Water Management Areas (WMAs).
6 Interactions between water governance levels and three different scales of data collection with a common database were proposed, namely:
    - ❖ The local most dense network of data should be handled by local government with the objective of day-to-day water supply to users.
    - ❖ A medium density network of data should be handled by Regional Offices of the Department of Water Affairs (DWA) and/or Catchment Management Agencies (CMAs) with the objective of catchment management.
    - ❖ The national lowest density network of data should be handled by DWA Head Office for assessment, management and planning purposes.
7 Typical minimum input data requirements for hydrological and groundwater models were summarized.
8 Considerations on financial and practical feasibility of monitoring were made.

EXAMPLE OF APPLICATION, DEMO/PILOT STUDY SITE

The Sandspruit catchment in the Berg River basin was selected as the demo/pilot study site. The main motivation for choosing the Sandspruit catchment was the existence of ***long-term hydrological data*** (almost 30 years) at DWA station No. G1H043, the existence of ***boreholes included in DWA's National Groundwater Archive*** (NGA), the catchment served as ***study site to another Water Research Commission project*** (K5/1503) on dryland salinity, and ***logistics***. The primary objectives of the monitoring programme in the Sandspruit catchment were to quantify the water balance and the refinement of the conceptual model for this catchment.

Sandspruit is a seasonal tributary of the Berg River (quaternary catchment G10J) and it flows predominantly between May and November. The Sandspruit catchment is approximately 152 km^2 in size. Before undertaking a monitoring programme in any region of interest, an initial desk study and review of existing data are pre-requisites. The following baseline data were therefore collected:

- ***Topography***. The elevation ranges between 40 and 900 mamsl, with an average slope of 0.013.
- ***Climate***. Mediterranean, semi-arid area that receives approximately 350 mm a^{-1}, less than the average rainfall of the Berg River basin.
- ***Geology***. The geology is dominated by Table Mountain Group (TMG) sandstone in the high elevation areas and Malmesbury shale in the mid- to low elevation parts.
- ***Hydrology***. Historic water flow and quality were obtained for DWA station No. G1H043 (1980-2009).
- ***Hydrogeology***. Aquifer characteristics, groundwater level and flow characteristics were described using mainly historic data from the National Groundwater Archive.
- ***Soils and land use***. Soils are generally poorly developed, shallow on hard or weathering rock. Soil drainage is somewhat impeded by the low hydraulic conductivity of the semi-weathered Malmesbury shale. Land use is predominantly for the production of wheat, pasture, grapes, lupins and canola. Soil erosion is minimized through the use of man-made anti erosion contours.

Collection of baseline data served the purpose of assessing what data were available and what monitoring gaps existed for a comprehensive description of the Sandspruit catchment. In particular, the following monitoring gaps were identified:

1. Atmospheric monitoring. No weather station or known rain gauge was found within the Sandspruit watershed.
2. Surface water monitoring. Long records of water flow and chemistry data were available from DWA station No. G1H043. However, no monitoring of sub-catchments was taking place.
3. Groundwater monitoring. The information from the NGA was used. However, it was deemed necessary to drill more boreholes for a comprehensive monitoring programme in the Sandspruit catchment due to borehole data being erratic and inconsistent in space and time. Borehole logs were not found.
4. Soil and vadose zone monitoring. No continuous record of soil and vadose zone was taking place. It was therefore suggested to monitor the interflow component through the installation of piezometers at the interface between the soil cover and the Malmesbury shale, where temporary perched water tables may occur especially during the rainy winter season.

Following a recognizance trip undertaken in November 2008, three broad sections of the Sandspruit catchment were identified based on the geological environments:

1. Sandstone/Malmesbury shale geology in the upper reaches
2. Undulated Malmesbury shale in the mid-reaches
3. Malmesbury shale with alluvial sandy soils in the lower reaches.

It was therefore decided to investigate each of these sections in detail, and use them as a basis for an expanded monitoring programme that included:

- ***Weather monitoring***. Establishment of three rain and temperature stations within the catchment.
- ***Hydrometry***.
    - *Surface water flow and quality*. A feasibility investigation was carried out for monitoring surface water in sub-catchments. This idea was eventually abandoned because of an environmental impact assessment and extensive maintenance was required for the establishment and operation of weirs or similar water flow monitoring structures.
    - *Groundwater flow and quality*. Drilling and monitoring 24 boreholes along four cross-sectional transects.
- ***Vadose zone profiling***. Water content, electrical conductivity (EC) and Cl analyses were done on disturbed sediment samples collected during borehole drilling.
- ***Geophysical study***. Resistivity tomography measurements were done along three cross-sectional transects in the catchment.
- ***Isotope studies***. ^{18}O and ^{2}H were sampled in groundwater and surface water, and analyzed.

Data gathered during this investigation allowed for the annual water balance to be quantified and a conceptual flow model to be refined for the Sandspruit catchment. The catchment receives 473 mm a^{-1} precipitation on average. Streamflow at the catchment outlet (DWA station No. G1H043) was measured to be approximately 30 mm a^{-1}. Evapotranspiration makes up the remainder of the water balance (443 mm a^{-1}), assuming there are no other losses of water, e.g. regional groundwater losses. Soil water and groundwater storage are negligible components of the water balance in the long run.

Data collected in the pilot study site at Sandspruit were applied for hydrological modelling with J2000. J2000 is a distributed parameter hydrological modelling system that simulates hydrological processes, the water balance, runoff and its concentration time as well as the components of the hydrograph. An extensive calibration exercise was performed for data collected in 2009 at Sandspruit, by changing values of each of these inputs within a justifiable range and at certain intervals, until optimal efficiencies of model performance (statistical indicators) were achieved. The statistical indicators were calculated by comparison of simulated and observed runoff (at DWA station No. G1H043). Particular focus was given to the transfer coefficients used to characterize the contributions to streamflow via overland flow, interflow and baseflow. The main purpose of the model calibration exercise was therefore to accurately quantify the different contributions to streamflow. A sensitivity analysis was carried out to investigate how important it is to collect weather data, in particular rainfall, within the catchment, and whether weather stations located outside the catchment can provide extrapolated data that would result in a sufficient accuracy of runoff simulation. The accuracy of the simulation was poorer when only weather stations outside the Sandspruit catchment were used.

The following benefits were drawn from the expanded monitoring programme in the Sandspruit catchment:

- All additional equipment and monitoring facilitated a better understanding and conceptualization of the system. As a result, the conceptual model of the system was refined.
- A correct conceptual model is the basis for a scientifically sound description of the system and numerical modelling. Data collected in the expanded monitoring programme were used to generate inputs for the J2000 hydrological model.
- Quantification of the water balance.
- Weather stations installed within the watershed showed a gradient in rainfall (decreasing) and air temperature (increasing) from the upper reaches downwards.
- Drilling and installation of boreholes gave the opportunity to start a long-term, continuous monitoring programme.
- An invaluable set of sediment samples was collected during the borehole drilling campaign, analyzed and stored for further use.
- Groundwater potentiometric and quality maps were updated and refined.
- Interflow is the dominant component of the hydrograph (94%), followed by overland flow (5%), based on the interpretation of data from borehole logs, resistivity tomography imagery, time series of surface water flow, borehole water levels and isotope analyses. The contribution of baseflow to streamflow is negligible (1%). The values were estimated with hydrological modelling for year 2009.
- Groundwater recharge is about 29 mm a^{-1}, less than historic estimates.
- It is of utmost importance that an adequate network of spatial monitoring of climatic variables is established, particularly rainfall.
- Data were collected that can allow evaluation of errors and uncertainties.

OVERALL CONCLUSIONS AND RECOMMENDATIONS

This research project provided new insight into the importance of establishing and maintaining sound water monitoring programmes in our catchments. The importance of monitoring the whole water cycle was particularly highlighted. This includes integration of all environmental compartments, namely groundwater, surface water, unsaturated zone and atmospheric measurements.

The aims of the project were achieved through the development of an integrated catchment management (ICM) mind map. The ICM mind map is meant to answer the key question: “What does a catchment manager need?” The ICM mind map provides guidelines on the minimum monitoring requirements (e.g. type of variables, space and time frequency, etc.) in order to obtain a meaningful amount of data for a specific monitoring objective. The main target users are Catchment Management Agencies (CMAs), but also government departments, private practitioners and water users, as well as research institutions.

The integrated monitoring guidelines were applied to a demo/pilot study site in the Sandspruit catchment (quaternary catchment G10J). It was highlighted that there is a consequential cause and effect relationship between geology, climate, soil and land use. The expanded monitoring programme resulted in a better understanding of the natural system, and in the development of an improved conceptual model and quantification of the water balance fluxes. The combination of monitoring data and modelling proved to be a powerful tool in the quantitative description of the system.

The products and knowledge gained through this project fit into the broader programme of development of supporting tools to Catchment Management Agencies and other similar water management boards. The ICM mind map can be easily expanded to update guidelines and to include more guidelines as they get developed (e.g. guidelines on soil erosion and sediment monitoring, microbiological monitoring, etc.). Similarly, monitoring programmes should be seen as dynamic, they can be updated, expanded and reduced as necessary. On-going refinement is possible through feedback loops between monitoring programmes and hydrological modelling. It is envisaged that the knowledge gained from this investigation could potentially be applied to other catchments, in particular in semi-arid areas.

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LIST OF ABBREVIATIONS

ACRU - Agricultural Catchment Research Unit
AGIS - Agricultural Geo-referenced Information System
ARC - Agricultural Research Council
AVE - Absolute volume error
Cl_{gw} - Chloride concentration in groundwater (mg L^{-1})
Cl_P - Chloride concentration in rain water (mg L^{-1})
CMA - Catchment Management Agency
CSIR - Council for Scientific and Industrial Research
DM - Malansdam farm
DoH - Department of Health
DWA - Department of Water Affairs
DWAF - Department of Water Affairs and Forestry
e1- Modified Nash-Sutcliff efficiency (differences are not squared but their absolute values are applied)
e2 - Nash-Sutcliff efficiency with power 2 (classic form)
EC - Electrical conductivity (mS m^{-1})
EPA - Environmental Protection Agency
FAII - Fish Assemblage Integrity Index
FAO - Food and Agricultural Organization
GI - Geomorphological Index
GIS - Geographical Information System
GMWL - Global Meteoric Water Line
Grad - Slope of the regression line
HRU - Hydrological Response Unit
ICM - Integrated Catchment Management
IDW - Inverse Distance Weighting
IHAS - Invertebrate Habitat Assessment System
IHI - Index of Habitat Integrity
ioa1 - Modified index of agreement according to Willmott (differences are not squared)
ioa2 - Index of agreement according to Willmott
ISCW - Institute for Soil, Climate and Water
ISO - International Organization for Standardization
IWRM - Integrated Water Resource Management
Log(e1) - Modified Nash-Sutcliff efficiency (the logarithm of the values is taken; differences are not squared but their absolute values are applied)
Log(e2) - Modified Nash-Sutcliff efficiency (the logarithm of the values is taken)
LWML - Local Meteoric Water Line
MMS - Modular Modelling System
NEMA - National Environmental Management Act
NGA - National Groundwater Archive
NGO - Non-Governmental Organization
OK - Oranjeskraal farm
OKR - Oudekraal farm
P - Annual precipitation (mm a^{-1})
PRMS - Precipitation-Runoff Modular System
r^2 - Coefficient of determination
RD1 - Fast direct runoff-overland flow
RD2 - Slow direct runoff-interflow within the soil zone
RDM - Resource Directed Measures
RG1 - Fast base runoff-interflow from permeable weathering zones
RG2 - Slow base runoff-baseflow from joint aquifer or homogeneous loose rock aquifer

RHP - River Health Programme
RMSE - Root mean square error
RQO - Resource Quality Objectives
R_T - Groundwater recharge (mm a^{-1})
RVI - Riparian Vegetation Index
SADC - Southern African Development Community
SANAS - South African National Accreditation System
SASS5 - The South African Scoring Index version 5 for invertebrates
SAWS - South African Weather Services
TDS - Total Dissolved Solids (mg L^{-1})
TMG - Table Mountain Group
UNEP - United Nations Environmental Programme
USDA - United States Department of Agriculture
USGS - United States Geological Survey
UV - Uitvlug farm
WHO - World Health Organization
WMA - Water Management Agency
WMO - World Meteorological Organization
wr^2 - Coefficient of determination, weighted for the slope of the regression line
WRC - Water Research Commission
WUA - Water Users Association
ZB - Zwavelberg farm

1 INTRODUCTION AND OBJECTIVES

1.1 Background and motivation for study

Advances have been made in recent years in South Africa in developing networks and databases for monitoring water systems, in particular groundwater and atmospheric variables, with the ultimate aim of facilitating integrated water resources management at a catchment scale. This resulted in the compilation of two documents relevant to the DANIDA programme of the Department of Water Affairs (DWA), the one related to groundwater quality management strategies and the other to groundwater monitoring and integrated monitoring networks (DWAF-DANCED, 2007a and b). These documents include an initial monitoring framework aimed at supporting collection and management of water resources information, and integrating three monitoring levels (national, catchment and local monitoring levels and databases) in the context of the three core strategies for water quality management listed in the National Water Act of 1998 (resource directed measures, source directed controls and remediation). This monitoring framework needs now to be expanded, consolidated and integrated amongst various components of catchment systems. These components can be broadly classified into:

- Groundwater
- Surface water
- Soil and vadose zone (unsaturated zone, including surface-groundwater interactions)
- Atmospheric (including rainfall and evapotranspiration)

Each of these components required the development of a monitoring framework that would allow collection and management of purposeful and relevant data to be used to address the main problems identified in current groundwater research and practice, namely groundwater protection, recharge and groundwater-surface water interactions. The data also needed to be reliable by making use of state-of-the-art monitoring technologies, easy to handle and compatible with models. Data collection and management is currently done by different government departments, institutions, firms, etc. for each component of the catchment system and, often, within each component. Given the interactions between these components, it was essential to develop a framework for coordination of data collection, management and exchange amongst the different stakeholders (e.g. defining roles and responsibilities for data collection and management).

In addition, monitoring is often limited in time (e.g. during individual research projects), space (e.g. areas of ecological sensitivity or hotspots) or type (e.g. specific contaminants) and this needs to be expanded in order to assist management of water resources at catchment level. Different land uses were also an important variable to account for in the monitoring framework (Usher et al., 2004). Land use and associated sources of pollution determine the intensity and type of monitoring to be done. Real time data collection with sensors is favoured, but it is expensive, hence the need for optimizing the use and quality of data collection. Appropriate scales and frequencies of data collection and management had to be defined in order to facilitate the integration of the different components of catchment systems. Optimization of monitoring networks had to account for both spatial and temporal variations through the application of geostatistical analyses, as well as logistical and financial feasibility.

One of the main envisaged outputs of this project was a monitoring framework that would highlight institutional arrangements, allow consistency in data collection and management, standardization of methodologies, and facilitate handling, planning and budgeting for data collection and management, as well as integration of different components of catchment systems through, for example, the use of models for which specific data sets are required. The monitoring network would be used both for research needs and operational requirements in management of water resources. It would facilitate the interpretation and analyses of monitored data. In practical terms, the main target institutions for implementation and operation of monitoring systems are Catchment Management Agencies (CMAs). As water managers are usually not experts in all disciplines (geohydrology, hydrology, soil science, meteorology), there was need to provide a product that would direct the user in finding the appropriate guideline, database, methodology or information. The product would be used to indicate the minimum monitoring requirements (e.g. type of variables, space and time frequency, etc.) in order to obtain a meaningful amount of data for a specific monitoring objective.

1.2 Project objectives

The main aim of this project was the development of an integrated framework for optimized monitoring of water resources that will account for the different components of catchment systems and their interactions.

The specific objectives were:

1. To understand the institutional and legal interactions of different agencies responsible for various monitoring programs.
2. To develop guidelines for monitoring best practices applicable to South(ern) African conditions, for the different components of catchment systems (groundwater, surface water, soil and vadose zone, atmosphere).
3. To develop a framework for integrated monitoring of the different fluxes so that they are consistently measured in time and space.

1.3 Project structure

The project was run under the leadership of CSIR, Natural Resources and Environment, and with the participation of the University of Stellenbosch, the University of KwaZulu-Natal and GEOSS.

In order to achieve the objectives stipulated in the project proposal, specialists for each component of the environment (groundwater, surface water, soil and vadose zone, atmosphere) were included in the research team. At the Initial Workshop held on 15 September 2008 at CSIR, Stellenbosch (see Deliverable 1 of this project), the research team decided on the structure and responsibilities, based on the expertise in the different environmental components. The research team was therefore structured as in Table 1. Microbiological water properties were not specifically discussed because this was not within the scope of the project, although their importance is recognized.

TABLE 1 STRUCTURE AND RESPONSIBILITIES OF THE RESEARCH TEAM	
Research team member	**Responsibility**
R. Rose replaced by J. Conrad (GEOSS)	Groundwater physical component
M. Bekele (University of KwaZulu-Natal)	Groundwater quality and isotopes
W. de Clercq (University of Stellenbosch)	Surface water physical component
S. Israel (CSIR, Stellenbosch)	Surface water quality
C. Petersen (CSIR, Stellenbosch)	River health component
N. Jovanovic (CSIR, Stellenbosch)	Soil and vadose (unsaturated) zone
W. de Clercq (University of Stellenbosch)	Atmospheric component

Five deliverables of the project were structured to include information for each component of the environment (groundwater, surface water, soil and vadose zone, atmosphere) (Table 2). The contributions of the research team (according to responsibilities in Table 1) were collated by the project manager at CSIR. The remaining deliverables of the project required contribution from the entire research team in various forms (Table 2).

TABLE 2 LIST OF DELIVERABLES COMPILED PER COMPONENT OF THE ENVIRONMENT AND THROUGH OVERALL CONTRIBUTIONS BY THE RESEARCH TEAM		
Deliverable No.	**Deliverable title**	**Research team contribution**
1	Initial workshop	Participation
2	Report on definition of objectives of monitoring programmes and users of data	Per environmental component
3	Definition of roles and responsibilities in data collection, capture, storage and management	Per environmental component
4	Guidelines on type of monitoring at specific sites	Per environmental component
5	Report on the demo/pilot study site 1	All (as applicable)
6	Progress report 1	All (as applicable)
7	Interim workshop 1: Integrated monitoring framework	Participation
8	Guidelines for selection of monitoring sites, scale and frequency of data collection	Per environmental component
9	Development of guidelines for methodologies	Per environmental component
10	Report on the demo/pilot study site 2	All (as applicable)
11	Interim workshop 2: Integrated monitoring framework	Participation
12	Report on integrated monitoring framework	All
13	Final project report	All
14	Progress report 2	All (as applicable)
15	Progress report on field investigation at pilot study site (addendum)	CSIR

2 INTEGRATED CATCHMENT MONITORING FRAMEWORK (ICM MIND MAP)

2.1 Introduction and underlying philosophy

Hydrological monitoring can be done for different purposes, for example for natural/reference conditions, regulatory, early warning and surveillance, etc. (DWAF, 2004a). DWAF (2004a) also recommended the following steps to be followed in a hydrocensus:

1) State the problem
2) Identify inputs
3) Define the boundaries of the study area
4) Develop action plan
5) Collect field data
6) Collation, manipulation and analysis of data

Some common principles to monitoring different catchment components are (DWAF, 2004a):

- Monitoring purpose must be clearly defined.
- Data collected should be relevant to decision-making.
- Monitoring should be physically and financially feasible.
- Data collected should be compatible with models.
- Monitoring should make use of state-of-the-art technologies.
- Monitoring programmes should be updated periodically.
- Monitoring activities should be prioritized to provide the most critical information.
- Cooperation and coordination with monitoring of other catchment components needs to be promoted.
- Monitoring should make use of data and infrastructure that already exist.
- The monitoring network design should include a rough cost-benefit analysis, for example greater capital expenditure initially on the installation of automated equipment could be more cost-effective in the long run, as well as supply more data.

During the course of this project, it became evident that many institutions and government departments manage monitoring databases according to these principles, but separately for various components of the environment. The management of individual databases for surface water, groundwater, weather data, etc. functions potentially well, however there is need to integrate these databases in order to optimize data collection, standardize methodologies, exchange data and, in general, add value to the data. Integration of data and/or metadata is also required. It also became evident that, from the water management perspective, the catchment is the most appropriate operational scale for management and monitoring of natural resources, in particular water. It was proposed that an integrated catchment monitoring (ICM) framework be produced in order to fulfil these requirements.

A step-by-step programme for designing a groundwater monitoring system already existed and it was given in the DANIDA document on integrated water resource management published by the Department of Water Affairs and Forestry (DWAF, 2004a). This is summarized in Appendix A. The question was what would be of more value and how it would be possible to integrate guidelines and other material for the different environmental components. Therefore, the ICM framework would highlight institutional arrangements for data collection and management, ensure that there is consistency amongst monitoring systems and databases (e.g. frequency and type of measurements), and consistency between monitoring networks and modelling requirements.

Two stakeholder interim workshops took place during the course of the project in order to identify the purpose and content of the ICM framework. At the first workshop that took place on 15 May 2009 (Deliverable 7), it was decided that no new database software or interface development will take place in this project because the management of current databases and software by the custodians is on-going. It was decided that focus should be given rather on strengthening the interactions between custodians of data and on developing a framework to facilitate the integration of information between the different databases.

The key question in the development of an ICM framework was: “What does a catchment manager need?” The product should be a document telling practitioners what is available or what data they should be collecting (e.g. frequency and compatibility), and be usable by Catchment Management Agencies (CMAs). The product should not aim at solving issues, but rather helping the process, with roles and responsibilities in monitoring to be highlighted. It is unlikely that a water manager possesses expertise in monitoring all environmental components. However, a tool was required that would direct the water manager to the right, essential information and sources of information. It was suggested that the integrated monitoring framework takes the form of a mind map.

The second workshop took place on 20-21 May 2010 (Deliverable 11) and its purpose was to finalize the contents of the ICM mind map. The ICM mind map accounts for the different components of catchment systems and their interactions, so that the different fluxes can be measured consistently in time and space, where applicable. It was initially suggested that the ICM mind map be structured in such a way that the user selects criteria in order to obtain a recommended level of monitoring. The suggested criteria in hierarchical order were: uses of monitoring networks, geographical location, scale, sensitivity of location and financial feasibility. The suggestion was to assign a score to each of these criteria based on qualitative categories (e.g. low, medium and high intensity of monitoring). It was, however, realized that these criteria are not consistent with each other and that the calculation of a combined score for the criteria would not easily define the level of monitoring required (e.g. What do the boundaries between low, medium and high intensity of monitoring imply? What would a combined score imply?). In addition, some of the criteria would be overarching to others. For example, a national scale would in any case imply low spatial intensity of monitoring, or a sensitive receiving environment would in any case require high intensity monitoring regardless of other criteria. A subjective tendency of using low intensity of monitoring for all cases may be realized in order to save on costs. During the stakeholder workshops, it became evident that lack of funds is the most common constraint. For these reasons and following extensive discussion, it was decided that the following actions be taken in the development of the ICM mind map:

1) Inclusion of essential information with guidelines and recommendations on the procedure to design and implement an ideal monitoring programme, including optimization procedures for individual components of the environment.
2) Development of matrixes (monitoring objectives vs. type of monitoring variables, spatial and time frequency) including guidelines and recommendations on the ideal monitoring network.

2.2 Development of the ICM mind map

The ultimate product of this research project was the development of an Integrated Catchment Monitoring (ICM) framework. The ICM framework was conceptualized as a mind map, a user-friendly tool where water managers are able to find and access any information and guidelines for monitoring any of the components of the environment (groundwater, surface water, soil and vadose zone, atmosphere, river health) related to water in catchments. Some of the criteria used to develop the ICM mind map were that guidelines should be practical, user-friendly and accessible. For this purpose, a freely downloadable mind mapping software, called FreeMind v. 0.9.0, was used.

The ICM mind map is supplied on CD with all accompanying database files in the folder "/Files/". The FreeMind Windows Installer is also supplied to be able to run the programme. The programme is accessed by double-clicking on the file ICM mind map.mm or the icon:

Note: The database files must be in the root path /Files/ in the folder where the ICM mind map.mm file is located.

The screen in Figure 1 will appear. The primary branches of the ICM mind map are:

- Groundwater Monitoring
- Hydrological Monitoring
- Atmospheric Monitoring
- Soil and Vadose Zone
- River Health
- Matrix of monitoring objectives vs. space and time frequency of monitoring variables
- Modelling input data requirements

Secondary branches can be accessed from the primary branches, and so on. A sketch of the full tree of the ICM mind map, compiled in FreeMind, is shown in Figure 2. Each component of the environment includes the following items (Figure 2):

- ***Objectives of monitoring*** and applications;
- ***Users of monitoring***;
- Available ***databases***, roles and responsibilities in monitoring;
- Type of ***monitoring variables***;
- Selection of monitoring sites, ***space and time frequency of monitoring***;
- ***Methodologies in monitoring***: sampling, analytical procedures, data capture, handling, presentation of results and quality assurance, and inventory of hardware and accredited laboratories countrywide.

Each of these items includes hyperlinks (Figure 2). The hyperlinks are used to connect directly to:

- Deliverables of this project (Word files with newly developed guidelines on monitoring) and/or
- Existing guideline documents (generally .pdf files downloaded from web sites) and/or
- Web sites (e.g. database of South African Weather Services for atmospheric monitoring)

Additional hyperlinks are given for the Groundwater Monitoring component to the following .pdf documents:

- A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa (DWAF, 2006).
- Artificial Recharge Strategy (DWAF, 2007a).
- Guidelines for Groundwater Management – Volume 2: Implementation (DWAF, 2004a).
- Borehole drilling standards (Minimum Standards and Guidelines for Groundwater Resource Development for the Community Water Supply and Sanitation Programme; DWAF, 1997).
- Standard Descriptors for Geosites (DWAF, 2004b).

- Borehole Logging v. 1.0 Excel-based software developed by H. Jia (University of Fort Hare) and Y. Xu (University of the Western Cape).

The ICM mind map makes provision for data exchange, actions and interactions between custodians in data collection, capture, storage and management, through the inclusion of specific functions (Figure 2):

- Interactions (e.g. monitoring of water flow and quality concurrently). Comments to this function can be seen in the bottom space (text editor) of the programme.
- Data exchange (e.g. how to exchange rainfall records between South African Weather Services and other institutions?)
- Action points (e.g. how to collect monitored data from private bodies and collate them into a central database?)

The matrix can be accessed by double-clicking on “Matrix”, and it is an Excel file (Figure 3). It includes a summary of monitoring objectives vs. type of variable, spatial and time frequency for the different components of catchment systems. Each spreadsheet represents a component (groundwater, surface water, river health, soil and vadose zone, and atmospheric measurements). Comments are added to cells of the matrix to provide explanation on its usage. Modelling input data requirements include a summary of typical minimum requirements for input data in hydrological and groundwater models.

Note: The ICM programme can be easily expanded and updated by including just any additional information.

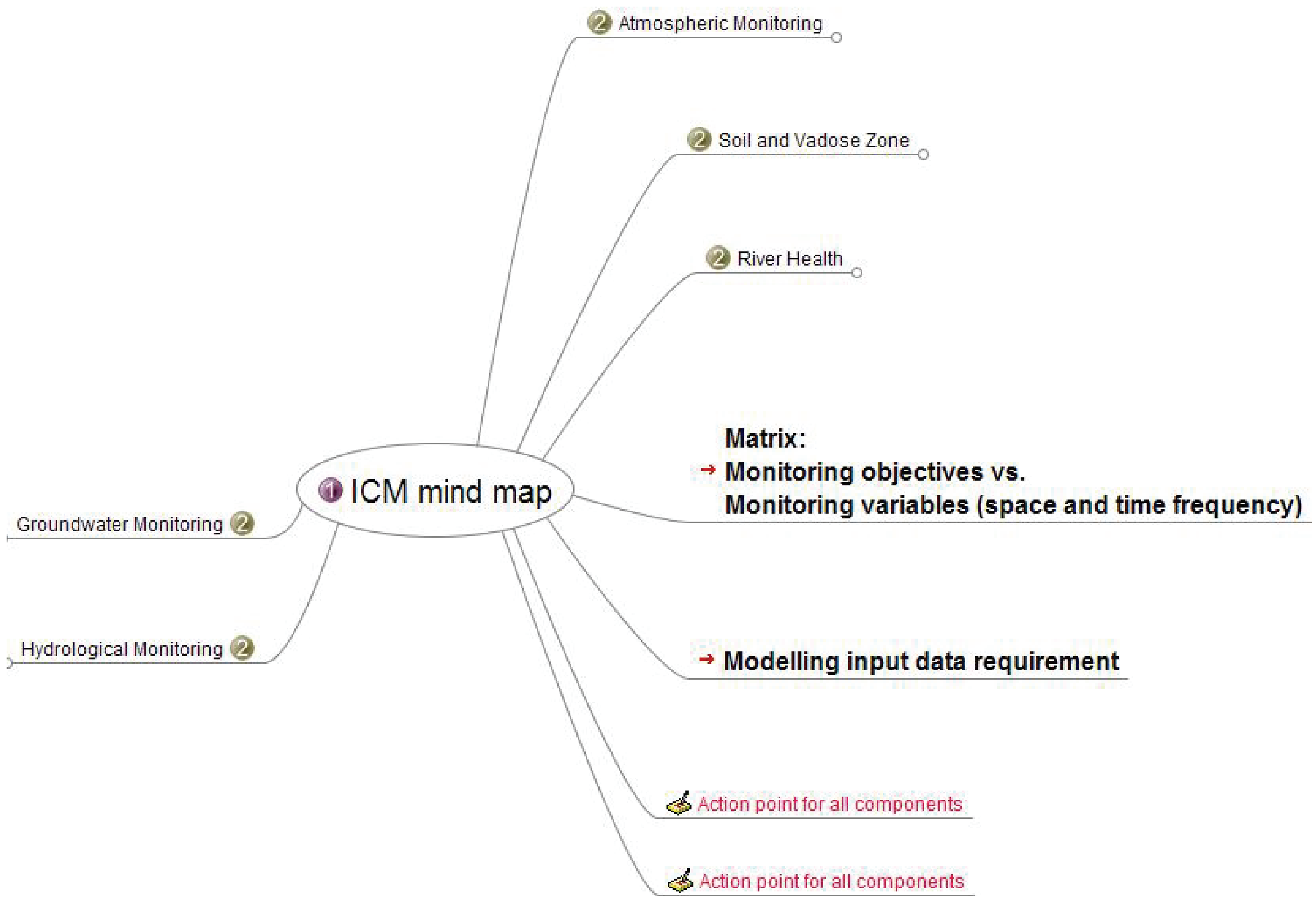


Figure 1
Screen printout if the ICM mind map when the programme is started

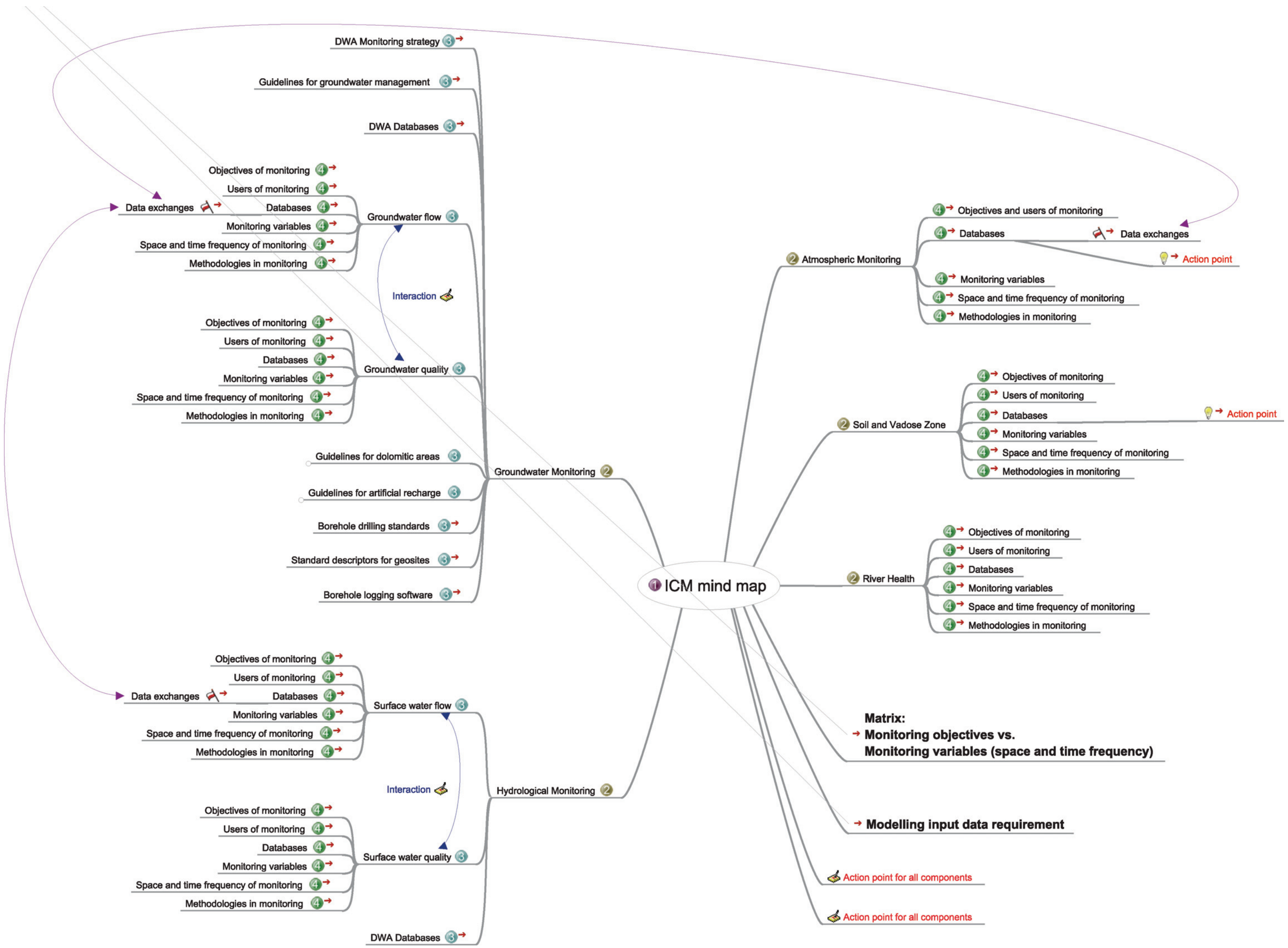
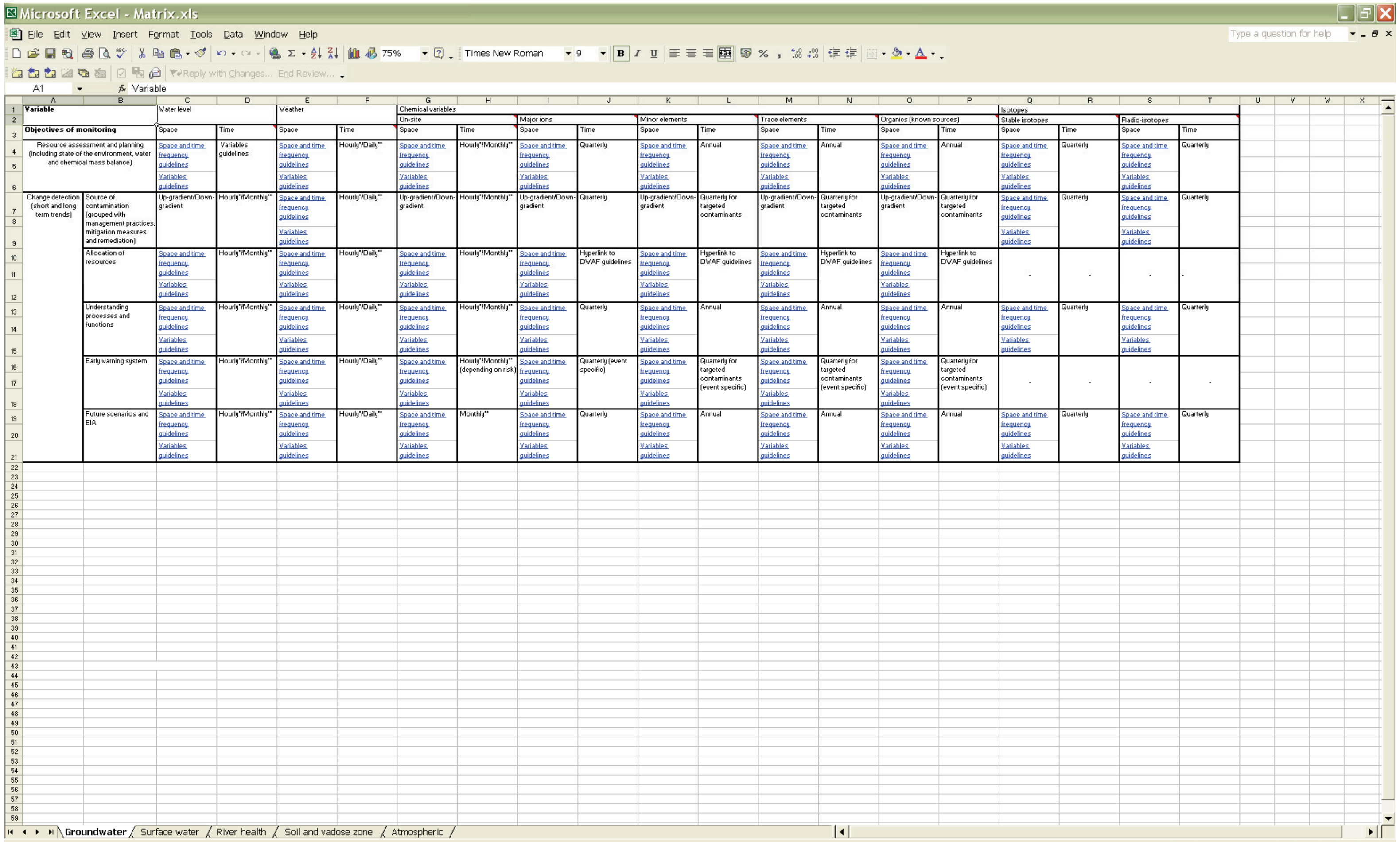


Figure 2

Printout of the integrated catchment monitoring mind map compiled in FreeMind v. 0.9.0



Variable		Water level		Weather		Chemical variables: On-site		Major ions	
Objectives of monitoring		Space	Time	Space	Time	Space	Time	Space	Time
Resource assessment and planning (including state of the environment, water and chemical mass balance)		Space and time frequency guidelines Variables guidelines	Variables guidelines	Space and time frequency guidelines Variables guidelines	Hourly*/Daily**	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Quarterly
Change detection (short and long term trends)	Source of contamination (grouped with management practices, mitigation measures and remediation)	Up-gradient/Down-gradient	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Hourly*/Daily**	Up-gradient/Down-gradient	Hourly*/Monthly**	Up-gradient/Down-gradient	Quarterly
	Allocation of resources	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Hourly*/Daily**	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Hyperlink to DWAF guidelines
	Understanding processes and functions	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Hourly*/Daily**	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Quarterly
	Early warning system	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Hourly*/Daily**	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly** (depending on risk)	Space and time frequency guidelines Variables guidelines	Quarterly (event specific)
	Future scenarios and EIA	Space and time frequency guidelines Variables guidelines	Hourly*/Monthly**	Space and time frequency guidelines Variables guidelines	Hourly*/Daily**	Space and time frequency guidelines Variables guidelines	Monthly**	Space and time frequency guidelines Variables guidelines	Quarterly

Variable		Minor elements		Trace elements		Organics (known sources)		Isotopes: Stable isotopes		Radio-isotopes	
Objectives of monitoring		Space	Time	Space	Time	Space	Time	Space	Time	Space	Time
Resource assessment and planning (including state of the environment, water and chemical mass balance)		Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Quarterly	Space and time frequency guidelines Variables guidelines	Quarterly
Change detection (short and long term trends)	Source of contamination (grouped with management practices, mitigation measures and remediation)	Up-gradient/Down-gradient	Quarterly for targeted contaminants	Up-gradient/Down-gradient	Quarterly for targeted contaminants	Up-gradient/Down-gradient	Quarterly for targeted contaminants	Space and time frequency guidelines Variables guidelines	Quarterly	Space and time frequency guidelines Variables guidelines	Quarterly
	Allocation of resources	Space and time frequency guidelines Variables guidelines	Hyperlink to DWAF guidelines	Space and time frequency guidelines Variables guidelines	Hyperlink to DWAF guidelines	Space and time frequency guidelines Variables guidelines	Hyperlink to DWAF guidelines	-	-	-	-
	Understanding processes and functions	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Quarterly	Space and time frequency guidelines Variables guidelines	Quarterly
	Early warning system	Space and time frequency guidelines Variables guidelines	Quarterly for targeted contaminants (event specific)	Space and time frequency guidelines Variables guidelines	Quarterly for targeted contaminants (event specific)	Space and time frequency guidelines Variables guidelines	Quarterly for targeted contaminants (event specific)	-	-	-	-
	Future scenarios and EIA	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Annual	Space and time frequency guidelines Variables guidelines	Quarterly	Space and time frequency guidelines Variables guidelines	Quarterly

Figure 3

Printout of the Excel matrix (monitoring objectives vs. type of variable, spatial and time frequency) in the ICM mind map

2.3 Content of the ICM mind map

The content of the ICM mind map was basically developed through the compilation of the deliverables of this project, in particular the deliverables compiled per component of the environment (Deliverables 2, 3, 4, 8 and 9). The ICM mind map was thoroughly discussed at the second Interim Workshop (Deliverable 11).

In summary, the ICM mind map includes the following information for each component of the environment (groundwater, surface water, soil and vadose zone, atmosphere, river health):

- Definition of objectives and applications of monitoring programme.
- Definition of data users.
- Available databases and custodians of data.
- Monitoring variables at specific sites.
- Selection of monitoring sites, spatial scale and frequency of monitoring.
- Guidelines on methodologies for data collection, handling, analysis, presentation and quality assurance, inventory of accredited laboratories.

These are summarized in the following sections. The sources for the material are both existing guidelines (web sites, .pdf and Word documents, etc.) and newly developed guidelines.

2.3.1 Definition of objectives and applications of monitoring programme

The section (link in the ICM mind map) includes a list of possible objectives and applications of monitoring programmes for each component of catchment systems. Data can be collected for a variety of monitoring objectives. These can be coarsely grouped and summarized as follows:

- Resource assessment and planning (including state of the environment, water and chemical mass balance)
- Change detection (short and long term trends)
    - ❖ Source of contamination (grouped with management practices, mitigation measures and remediation)
    - ❖ Allocation of resources
    - ❖ Understanding processes and functions
    - ❖ Early warning system
    - ❖ Future scenarios and environmental impact assessments

This classification of objectives was also used to develop the matrixes of monitoring objectives vs. type of variable, spatial and time frequency (Figure 3).

2.3.2 Definition of data users

The section (link in the ICM mind map) includes a list of possible users of monitoring programmes for each component of catchment systems (groundwater, surface water, unsaturated zone and atmosphere). Possible users can be summarized as:

- National government departments, local government and municipalities
- Parastatals
- Catchment Management Agencies (CMAs)
- Water User Associations (WUAs, irrigation boards)
- Individual landowners and licensed water users

- Research institutions and universities

Each of these users will have different monitoring requirements.

2.3.3 Available databases and custodians of data

The section (link in the ICM mind map) includes an inventory of past and current sources of data and databases for each component of catchment systems, as well as the definition of roles and responsibilities, and the institutional and legal interactions of different agencies responsible for various monitoring programmes.

Concerning groundwater and surface water resources, the National Water Act requires the Minister of Water Affairs to establish national monitoring systems. In the DANIDA document on Guidelines for Groundwater Resources Management (DWAF, 2004a), it is stated that these systems must provide for the collection of appropriate data and information on the following:

- Quantity of water in the various water resources,
- Quality of the water resources,
- Use of the water resources,
- Rehabilitation of water resources,
- Compliance with Resource Quality Objectives (RQOs),
- The health of aquatic ecosystems, and
- Atmospheric conditions which may influence water resources.

The DANIDA document (DWAF, 2004a) also proposed a procedure for groundwater monitoring and data management responsibilities. A summary of the main hydrological information systems relevant to integrated water resources management currently residing within the Department of Water Affairs is shown in Table 3. An additional information system that is currently operating is the AquaWorx. This is a PC-based information system managed by DWA through the Institute for Groundwater Studies (University of the Free State). It includes groundwater physical and quality data and it serves to support operational decisions at municipal level.

The Department of Water and Environmental Affairs, together with the Water Research Commission, are joint custodians of the River Health Programme (RHP). All data collected with the RHP are stored in the Rivers Database Version 3, 2007, which is a national storage and management database especially developed for the RHP. A combination of web-based and desktop applications are used and it allows registered (compulsory registration) users to transfer data from one to another, query and abstract RHP data for analysis (DWAF, 2007b). This database is comprehensive as it contains all river health data from the various indices.

Soil information can be obtained from the following sources:

- Agricultural Geo-referenced Information System (AGIS) managed by the Agricultural Research Council – Institute for Soil, Climate and Water in Pretoria (ARC-ISCW).
- Provincial Offices of the Department of Agriculture. These are connected to the AGIS system.
- University databases.
- Municipalities.
- Consulting firms.
- Accredited laboratories.

The two main sources of information on atmospheric inputs are:

- The South African Weather Service – www.weathersa.co.za

- Institute for Soil, Climate and Water – Agricultural Research Council (ISCW – ARC) www.arc.agric.za

The emphasis of the two institutions differs, where the primary focus of the SA Weather Service is weather forecasts, while the ISCW is dealing primarily with agricultural applications.

TABLE 3
MAIN HYDROLOGICAL INFORMATION SYSTEMS CURRENTLY RESIDING WITHIN DWA AND RELEVANT TO INTEGRATED WATER RESOURCES MANAGEMENT (DWAF, 2004a)

Information system	**HydStra**	**WMS**	**WSAM**	**WARMS**
Primary Function	Surface hydrology	Water quality	Water situation assessment	Authorized water use
Mapping component	Proprietary mapping formats, however this module can accept shape files	ArcView, using ESRI shape files	ArcView, using ESRI shape files	None present
Database	Proprietary	Informix	Access	Informix
Data exchange	ASCII tables	ASCII tables	ASCII tables	ASCII tables
Spatial data exchange	Shape files	Shape files	Shape files	N/A

2.3.4 Monitoring variables at specific sites

The section (link in the ICM mind map) includes guidelines on the type of environmental variables to be collected in order to provide enough information to water resource managers. The type of environmental variables to be monitored depends mainly on land uses and associated sources of pollution, as well as the purpose (e.g. monitoring for environmental needs vs. basic human needs). They can be summarized as follows:

- Groundwater and surface water
  - ❖ Water level/flow, abstraction, channel size (for surface water), borehole logs and aquifer properties (for groundwater)
  - ❖ Minimum water quality variables (depending on water use):
    - pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen, Eh, alkalinity
  - ❖ Additional and conditional variables (depending on specific site and purpose):
    - Temperature, microbiology, major cations and anions, minor elements, heavy metals and trace elements, nutrients, specific organic chemicals, stable and radioactive isotopes, taste, colour, scaling/corrosion, turbidity
- River health
  - ❖ The South African Scoring Index version 5 (SASS5, invertebrates)
  - ❖ Invertebrate Habitat Assessment System (IHAS)
  - ❖ Riparian Vegetation Index (RVI)
  - ❖ Geomorphological Index (GI)
  - ❖ Index of Habitat Integrity (IHI)
  - ❖ Fish Assemblage Integrity Index (FAII)
- Soil quality indicators for hydrology

    - ❖ Biological
        - Root depth, soil organic matter, C/N ratio, forms of N
    - ❖ Chemical
        - pH, electrical conductivity, Olsen P, cation exchange capacity, suspected contaminants
    - ❖ Physical
        - Infiltration, bulk density, texture, aggregate stability, soil layering
- Weather variables
    - ❖ Precipitation and temperature (essential)
    - ❖ Solar radiation, wind speed and vapour pressure (optional)
    - ❖ Rain water quality and isotopic composition

This list of monitoring variables was also used to develop the matrixes of monitoring objectives vs. type of variable, spatial and time frequency (Figure 3).

2.3.5 Selection of monitoring sites, spatial scale and frequency of monitoring

This section (link in the ICM mind map) includes guidelines on how to select existing monitoring sites that are of critical importance, design/establish new and optimize monitoring networks, as well as guidelines on network densities and frequencies of sampling, based on geostatistical applications to spatial and time-series data. ***In spatial applications, the recommended coordinate system is decimal degrees using the Hartbeeshoek94 datum, based on the WGS84 ellipsoid.***

Groundwater

Concerning the groundwater physical component, two examples of spatial and temporal optimization techniques for groundwater level monitoring are provided, i.e. where data are available and where no data are available. A geostatistical method is proposed in areas where monthly groundwater level data are available. The method uses the Statistica software package, and includes the Fourier, Factorial and Cluster Analyses. A more holistic approach is proposed in areas with no or little data based on recent work conducted by the Department of Water Affairs (DWAF, 2009). This approach includes geological and geohydrological characterization, hydrocensus, data collation and analysis, establishment of groundwater monitoring network, site selection and verification, drilling and equipping.

Concerning groundwater quality, collected data must have the following attributes: location, time of sampling and physical, chemical or biological variables measured in concentration units. The ICM mind map provides descriptive guidelines on preliminary survey of the area to be monitored, selection of new observation well sites, selection of existing wells and boreholes as monitoring sites, and multi-level monitoring sites. Criteria for site selection of groundwater quality monitoring are the proximity to pollution sources, points of interest, hydraulics and mixing of water bodies, safety, possibilities of vandalism, as well as potential changes in the area. The spatial scale of monitoring depend on the amount of human activity, diversity in human activity (e.g. type of agricultural activity), landscape, size of the population in the area and specific situation/element/pollutant to be monitored. Sampling frequency is a function of the type and objectives of the assessment programme, the groundwater issues to be addressed, the changes that need to be monitored, the nature of the groundwater body and the logistical and financial resources for sample collection and analysis. Generally, the most frequent sampling would be four times a year (before the beginning of the rainy season, mid-rainy season, at the end of rainy season and mid-dry season). If that is not economically and logistically feasible, twice a year (before the onset of rainy season and just at the end of rainy season) could be sufficient to capture recharge events and associated groundwater and solute fluxes. More frequent sampling is required for pollution source studies, especially in the case of a point source of pollution close to a potable water supply in a highly vulnerable aquifer with rapid fissure flow.

Since electronic monitoring devices are available, both groundwater level and quality monitoring can be done every hour to match the standard climatic monitoring resolution. It should be borne in mind that monitoring programmes must not be seen as static, but need to be continually assessed in the light of how useful the information collected is in aiding decision-making in groundwater management.

Surface water

A typical surface monitoring programme involves the monitoring of surface water levels, quality, abstraction and rainfall. From the practice followed by the Department of Water Affairs, it is customary to monitor only the high yielding sub-catchments and the main stream. Catchments can be divided into a number of distinctly recognizable morphological units. At the heart of this methodology is a very old approach, namely the Horton analysis of drainage pattern for a given basin. In the landscape, each of these drainage units has different characteristics and is generally linked to a specific geomorphology. Site selection is subject to stream length and site characteristics, rainfall data, runoff data and average daily abstraction from the streams. The number of places where sufficient measuring structures can be built is generally quite restricted. The accessibility is also a large problem. The position of a site is generally considered to be inter-related to various factors, for example land use, aspect, topography, rainfall interception, infiltration of rain, wetlands, natural lakes or depressions (natural storage), vegetation, soil and crusting conditions, and the restrictions posed by the measuring device.

As in the case of groundwater monitoring, the spatial scale of surface water monitoring depends on the amount of human activity, diversity in human activity (e.g. type of agricultural activity), landscape, size of the population in the area and specific situation/element/pollutant to be monitored. The time scale for monitoring depends on the change that needs to be monitored. Monitoring at every measuring station can be done every hour to match the standard climatic monitoring resolution.

Similarly to groundwater quality monitoring, criteria for site selection of surface water quality monitoring are the proximity to pollution and water sources, points of interest, hydraulics and mixing of water bodies, safety, possibilities of vandalism, as well as potential changes in the area. The national site set of DWA is comprised of sites ideally as close as possible to the downstream end of each tertiary drainage region. The individual Water Management Areas (WMA) sample site sets are based on the national set with the addition of all other sample sites within the WMAs. This was done to identify river reaches where water quality problems are prevalent. Sampling sites with sufficient record length of relatively regular frequency are considered. Sites are only excluded when their sampling frequencies are too erratic or sparse, or where there are better sample sites geographically close to them.

River health

To determine the ecological health of rivers and streams it is necessary to know the reference conditions of those sites. This becomes problematic when working in different regions with varying geology, geomorphology, climate, topography and the like, which would result in differences in ecological conditions and therefore differences in the riverine biota and flora. Two approaches have been developed in determining reference conditions: multimetric and multivariate. In the multimetric approach, physical and geographic regional attributes form the basis and the assumption made that the chosen monitoring site characteristics will match those of the reference sites. The multivariate approach uses multivariate analysis of macroinvertebrates to group sites with similar taxonomy and so sites with similar faunal assemblages are grouped (Dallas, 2000). The suggested criteria for selecting reference sites include consultation with local experts (local knowledge), representativity, level of impact (sites should preferably be unimpacted) and anthropogenic impacts, accessibility, bank stability and natural channel, natural hydrograph, natural riparian vegetation, linkage to on-going monitoring programmes, vicinity of DWA gauging weirs, and ground-truthing.

Monitoring sites are usually chosen randomly so as to reflect catchment-wide ecological conditions. Different biological indicators are used for the assessment of various water resources, e.g. flowing rivers for fish, and invertebrates or algae and zooplankton for lakes and estuaries (Roux, 2001). It should be borne in mind that the larger the number of sites selected and the more ecological indicators used in a monitoring programme, the more comprehensive the assessment and knowledge base. This becomes increasingly important when management decisions are required (Roux et al., 1999). However, logistical and cost constraints will be a determining factor (Mangold, 2001).

As aquatic fauna and flora provide insight into the long-term ecological conditions and prevailing water quality, biomonitoring sampling can occur less frequently than chemical monitoring. This is the main advantage of a biomonitoring programme such as the RHP especially with regard to costs and logistics. It is suggested that invertebrate and invertebrate habitat sampling occur more frequently than the other indices. This is due to the fact that invertebrates have shorter life-spans than vegetation or fish and as a result will be more responsive to ecological changes (Mangold, 2001). Sampling frequencies will differ for the different indices used by the RHP.

Soil and vadose zone

It is widely recognized that soil properties influence catchment hydrology. Soil measurements are generally point measurements and difficult to apply at catchment scale. However, it is possible to extrapolate point measurements into small hydrological units of land (areas having homogeneous soil, slope, climate, land use or any other relevant characteristics) or into toposequences (or hydrosequences) that describe the distribution of soils in transects (or their properties, like wetness) on hillslopes.

Collection of baseline data for hydrological monitoring should include a soil survey and soil mapping of the area under investigation. The aim of soil surveys on a grid basis is to collect spatial information on soil properties, whilst soil mapping consists in the delineation of areas occupied by different types of soil having similar characteristics in terms of climate, vegetation, parent material, topography and/or time-dependent soil forming processes. Soil survey data are acquired through field sampling and remote sensing (aerial or satellite photography). The most commonly used soil survey manual is the one compiled by the United States Department of Agriculture (USDA) (Soil Survey Division Staff, 1993) (http://soils.usda.gov/technical/manual/ accessed on 17 July 2009). In South Africa, the procedure for describing and mapping soils was developed by Turner (1991) and Le Roux et al. (1999) (http://www.uovs.ac.za/faculties/documents/04/116/Publications/Dr%20Pieter%20Le%20Roux/Volume1.pdf accessed on 17 July 2009).

Soil survey and soil mapping are generally executed at three different scales: pedon (1 to 10 m^2 usually represented on 1:2,000 to 1:5,000 maps), pedotop (10,000 m^2 represented on 1:50,000 to 1:250,000 maps) and mapping units (2,500,000 m^2 represented on 1:250,000 maps) (Kutilek and Nielsen, 1994). The preferred scale of data collection for hydrological monitoring is the pedotop both for baseline and continuous monitoring (continuous measurement of the same variable at a key location over time).

Transect measurements are typically used in hillslope hydrology. The transects should be representative of the landscape rather than of particular sections or known patterns of variability. Distances between measurements in transects may vary between 20 m and 1 km depending on the objectives of baseline studies. For continuous monitoring, three points on a hillslope are commonly recommended, including a position at the top of the hill, mid-slope and at the foot of the hill.

Variabilities in soil properties are studied in geostatistics in order to determine, amongst others, the appropriate sampling frequencies in space and time. The most common geostatistical methods are autocorrelograms and semivariograms, which can be used to calculate soil properties at locations where they are not measured, through interpolation methods like kriging and co-kriging.

In general, the spatial and temporal frequency of sampling depends on the purpose of monitoring. A set of tables was developed that summarizes recommended spatial scales and time frequencies of monitoring soil quality indicators (biological, chemical and physical) for different monitoring objectives. This was incorporated in the matrix of the ICM mind map (Figure 3).

Atmospheric measurements

The most suitable approach in site selection for hydrological monitoring purposes is given by the Hydrological Response Unit (HRU) defining process. This process defines the variability in a landscape based on a variation in parameters that defines the hydrology best (Flugel, 1995). This process is currently the only mechanism available to divide any landscape into segments of likewise response to climate.

To be able to characterize the climate for a certain area, irrespective of the specific need in the area, one can resort to the currently available monitoring networks and mapping. The time scale of monitoring of climatic parameters is universally set to a 1 hour resolution. Again, this is only changed to a finer resolution if the specific circumstances demand a finer resolution. Data are mostly reported in a coarser resolution, for instance per day, per month or per year. The latter are generally the only data widely accessible to the public,

The leading documents on monitoring the climatic and hydrological components (specifics around measurement standards and specifics on methodology) were published by the following organizations and can be obtained from the respective web sites: World Meteorological Organization (WMO), Food and Agricultural Organization (FAO), International Organization for Standardization (ISO), Environmental Protection Agency (EPA, USA), United States Department of Agriculture (USDA), World Health Organization (WHO) and World Bank.

2.3.6 Guidelines on methodologies for data collection, handling, analysis, presentation and quality assurance, inventory of accredited laboratories

This section (link in the ICM mind map) includes guidelines for methodologies on monitoring each component of catchment systems (groundwater, surface water, soil and vadose zone, atmosphere). The guidelines include methodologies on sampling, analytical procedures, data capture, handling, presentation of results and quality assurance, as well as an inventory of hardware and accredited laboratories countrywide.

Groundwater physical component

Guidelines on the physical monitoring of groundwater are provided through the Weaver et al. (2007) sampling guide, the National Microbial Monitoring Programme (Murray et al., 2007),

as well as the NORAD Programme documentation to assist water services institutions with sustainable groundwater use (http://www.dwa.gov.za/groundwater/norad.asp, accessed on 13 January 2010). Further to this, reference is made to a comprehensive database of accredited chemistry and microbiological laboratories in South Africa according to the South African National Accreditation System
(SANAS, http://www.sanas.co.za/directory/test_default.php, accessed on 23 December 2009).

Groundwater quality and isotopes

The ICM mind map links to:

- Guidelines for groundwater sampling of monitoring networks based dominantly on Weaver et al. (2007), Appelo and Postma (1996), Hem (1989), Chapman (1992), Keith (1988) and USEPA (http://www.epa.gov/r5water/uic/r5guid/monitor_well.htm and http://www.epa.gov/region5/water/uic/r5guid/supp_monitor_well.htm, accessed on 13 January 2010).
- Guidelines for field analytical procedures based on Weaver et al. (2007), and laboratory analytical procedures based on the U.S. EPA. (http://www.epa.gov/microbes/methmans.html, accessed on 13 January 2010).
- The latest inventory of hardware and accredited water chemical analysis laboratories available country wide can be downloaded from http://www.sanas.co.za, accessed on 13 January 2010.
- Guidelines for quality assurance based on Weaver et al. (2007), Appelo and Postma (1996), Hem (1989), Keith (1988) and Chapman (1992).
- Finally, guidelines for data capture, handling and presentation are included in this section.

Surface water physical component

The manual for water measurement published by Dodge (2001) is referred by a number of leading publications in South Africa and forms the basis to instruct measurement done in South Africa (Wessels and Rooseboom, 2009a and b). Measuring devices for surface water include:

- Weirs
- Flumes
- Submerged orifices
- Current meters
- Acoustic flow meters
- Other open-channel devices
- Other closed conduit devices
- Divers for depth, temperature, electrical conductivity and ion specific

Suppliers for surface water equipment are:

- DWA (http://www.dwaf.gov.za/hydrology, accessed on 13 December 2009)
- Eijkelkamp (http://www.eijkelkamp.com/, accessed on 13 December 2009)
- Solinst (http://www.solinst.com/, accessed on 13 December 2009)
- Ott (http://www.ott.com/web/ott_de.nsf/id/pa_home_e.html, accessed on 13 December 2009)

The main factors which influence the selection of a measuring device include accuracy requirements, cost, legal constraints, range of flow rates, head loss, adaptability to site conditions, adaptability to variable operating conditions, type of measurements and records needed, operating requirements, ability to pass sediment and debris, longevity of device for a given environment, maintenance requirements, construction and installation requirements, device standardization and calibration, field verification, troubleshooting and repair, user acceptance of new methods, vandalism potential and impact on environment.

Surface water quality

The ICM mind map links to:

- Water Quality Monitoring – A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes by UNEP (United Nations Environmental Programme) and WHO (Bartram and Balance, 1996).
- Quality of Domestic Water Supplies, Volume 2: Sampling Guide (First Edition) by WRC, DWAF and DoH (Department of Health) (DWAF and DoH, 2000).
- Quality of Domestic Water Supplies, Volume 3: Analysis Guide (First Edition) by WRC, DWAF and DoH (DWAF and DoH, 2000).

River health component

The ICM mind map provides links to files where the following methodologies for river health biomonitoring are explained:

- Habitat integrity assessment
- Riparian vegetation
- Diatoms
- The South African Scoring System (version 5) (SASS 5)
- Fish Assemblage Integrity Index (FAII)
- Geomorphological Index (GI)

Procedures and quality assurance for these methodologies are also described in the ICM mind map.

Soil and vadose zone

The ICM mind map provided links to material making use of the following key references:

- The soil survey manual of the USDA (Soil Survey Division Staff, 1993).
- The Agricultural Research Council – Institute for Soil, Climate and Water (ARC – ISCW) procedure for describing soil profiles (Turner, 1991)
- The procedure for soil survey and mapping by Le Roux et al. (1999) (http://www.uovs.ac.za/faculties/documents/04/116/Publications/Dr%20Pieter%20Le%20Roux/Volume1.pdf accessed on 17 July 2009).
- The methods of soil analyses monography series of the Soil Science Society of America.
- The relationship between soil water regime and morphology (Van Huyssteen et al., 2007).
- The South African soil classification proposed by the Soil Classification Working Group (1991).
- The revised classification of South African soils proposed by Fey (2010).

A number of techniques commonly used for measurements of soil water and soil salinity are described as well as procedures for preparation of soil water extracts for laboratory chemical analyses.

Atmospheric component

The guidelines on sampling, data capturing, handling, presentation and quality assurance are those given by the South African Weather Services (www.weathersa.co.za, accessed on

13 December 2009) and the Agricultural Research Council (Kaempfer and Germishuyse, 2009; http://www.eepublishers.co.za/images/upload/MeasT_1.pdf, accessed on 13 December 2010). Meteorological hardware in South Africa is available from:

- MCS (http://www.mcsystems.co.za/, accessed on 13 December 2009).
- Campbell Scientific (http://www.csafrica.co.za/default.aspx, accessed on 13 December 2009).
- ADCON (http://www.adcon.at/, accessed on 13 December 2009).
- Davis (http://www.davisnet.com/weather/, accessed on 13 December 2009).
- Hobo (http://www.onsetcomp.com/products/weather_stations, accessed on 13 December 2009).

Newer opportunities in remotely sensed information (Gennero et al., 2004) and radar rainfall distribution are also discussed in the ICM mind map.

2.4 Interactions, lessons learnt and sustainable strategies

2.4.1 Integrated monitoring approach

In the guidelines developed, the importance of monitoring the whole water cycle is particularly highlighted. This includes all environmental components, namely groundwater, surface water, unsaturated zone and atmospheric measurements. It is also highlighted that there is a consequential cause and effect relationship between geology, climate, soil and land use. In practice, this means that the monitoring approach should include the following:

- ***Hydrometry*** (surface water and groundwater flow and quality measurements)
- ***Geophysical studies*** (to analyze the geological layering and water occurrences in the sub-soil)
- ***Isotope studies*** (to analyze the flow paths in the catchment and hydrograph separation)
- ***Weather monitoring*** (representing the driving force of water fluxes in the catchment)
- ***Vadose zone profiling*** (to analyze the modalities of water flow and contaminant transport in the sub-surface)

Following workshops with stakeholders, it was stressed to keep separate databases for the different components of the environment, to strengthen interactions between custodians, as well as to integrate data and metadata.

2.4.2 Data exchanges

Four levels of interactions and data exchange between institutions that collect data were identified:

- ***Data exchange works well*** (e.g. DWA division for groundwater and surface water work in cooperation and use the same data systems where applicable; Department of Agriculture exchange data on soils with universities).
- ***The cooperation is uncertain*** (e.g. between DWA and the Catchment Management Agencies to be established).
- ***Data exchange occurs one way*** (e.g. the South African Weather Service supply DWA with rainfall data but not vice versa).
- ***Data exchange and cooperation is not formalized*** (e.g. CSIR and DWA exchange groundwater data, but the cooperation depends on individuals and it is not formalized).

A specific case of interest is the one of rainfall monitoring and data exchange. The Department of Water Affairs runs a rainfall monitoring system for specific objectives, in addition to the weather services network run by the South African Weather Services (SAWS). The SAWS data are available to the public upon request (free of charge if data are requested for research purposes) and they are easily obtainable by DWA. However, DWA data are not captured by SAWS mainly because of differences in monitoring standards. This project supplies the web site of SAWS where guidelines on rainfall and weather data collection are available. The monitoring standards used by SAWS in weather data collection are those of the World Meteorological Organization (WMO). It is envisaged that rainfall data can be collected by diverse institutions and it could be supplied to SAWS as long as data collection adheres to monitoring standards. Such data could also be flagged for source, or their level of confidence could be added in the database.

2.4.3 Collation of existing weather data

In addition to well-known sources (SAWS), a wide range of weather observations is available, primarily on rainfall, but it is not utilized by SAWS due to either limited time span of the measurements, their irregular nature or non-standard equipment used in observations. These are mainly research databases usually limited in both spatial and temporal extent. Besides research databases, there are also weather observations kept by farmers and schools, which are also not currently accessible to either general public or climate researchers. Sourcing these data may be complicated by substantial logistical difficulties and may not be feasible, since the value of adding them to existing national databases may be doubtful.

It may be recommended, however, that one of the government bodies (e.g. SAWS) should embark on sourcing and auditing the anecdotal information, particularly farmers' weather records, and maybe, in collaboration with the Department of Education, the school weather records to significantly expand the existing sampling grid, which may be very useful for research purposes. Quality control mechanisms for such data should be developed by climatologists. An inventory of the short-term research databases should also be made and submission of datasets to a centralized data bank should be considered.

2.4.4 Collation of existing soil data

The Agricultural Geographic Information System (AGIS) system is managed by ARC – ISCW and it represents the most comprehensive soil information database (land type maps, generalized soil information, point scale soil profile databases). This information is likely to be relevant to both regional and local scale. Provincial Offices of the Department of Agriculture are also in the process of developing detailed databases of soil information captured in GIS.

Concerning all the information available from the Provincial Offices of the Department of Agriculture, universities, municipalities, consulting firms and accredited laboratories, due to different report formatting and data attributes, as well as due to data being often available only in hard-copy, there is urgent need to capture data and include them in standardized databases within a GIS framework. It is suggested that this information be managed by the Provincial Offices of the Department of Agriculture and made available to the public.

It is recommended that a strategy for implementing monitoring programmes on soils be developed. This should include two broad phases to run in parallel:

1) In the first phase, a concerted effort should be put into collecting existing data that are scattered amongst different public institutions and private owners to be included into

standardized databases and managed by the Provincial Offices of the Department of Agriculture.

2) In the second parallel phase, guidelines for collecting new data need to be given. The data type and collection in new monitoring programmes will depend on the area (scale) and specific purpose of monitoring. For different scales and purpose, standardized land survey templates should be compiled. It should be noted that many land survey templates already exist or can be found in the literature. However, these are not standardized. The data originating from new monitoring programmes should be stored at the Provincial Offices of the Department of Agriculture. This project contributed to this effort through the development of guidelines for monitoring of soil and vadose zone.

2.4.5 Scale of application

The results, guidelines and tools developed in this project are applicable mainly to the catchment scale, which is the ideal and most appropriate operational scale for management and monitoring of natural resources, in particular water. It is likely to have 10 to 20 quaternary catchments managed by Catchment Management Agencies (CMAs) within Water Management Areas (WMAs). Both groundwater and surface water hydrologists manage waters at quaternary catchment scale. Consistency in data collection amongst the various environmental components is required at this scale.

2.4.6 Interactions between governance levels

Traditionally, the government roles in managing water resources have been:

1. Education and information
2. Coordination and facilitation
3. Policy development
4. Research and development
5. Monitoring and evaluation

(see Australian example on
http://www.connectedwater.gov.au/framework/roles_and_responsibilities.html,
accessed on 27 October 2008).

National, provincial (catchment) and local governments may have tiered tasks within this framework. The focus of this project was to identify and suggest “who does what and how?” for each component of catchment systems (groundwater, surface water, unsaturated zone and atmosphere), cutting across role 4 (Research and development) and role 5 (Monitoring and evaluation).

At the national level, water volumes and quality monitoring is the overall responsibility of the DWA as stipulated in Chapter 14 of the National Water Act of 1998. The monitoring systems are designed and operated under their supervision as they are responsible for the protection and rational use of the Nation’s water resources. However, Catchment Management Agencies (CMAs), water boards, municipalities or other local government organs, licensed users and water users associations have to monitor at provincial, regional catchment and local levels as all of them in one way or another are responsible for different aspects of water quality protection and management.

Therefore, results, guidelines and tools produced in this study are of interest at three levels of water governance, characterized by three different levels of data network densities:

1) The local most dense network of data should be handled by municipalities, local institutions, industries, water boards and similar with the objective of water delivery to users, day-to-day management and operation of water supply (e.g. from borehole fields), and

monitoring to comply with the Resource Quality Objectives (RQOs) as set out in the water license requirements. Local monitoring involves project specific and site specific monitoring of human impacts on water resources. This may include:

- Quality monitoring at point sources to measure the impact, detection, compliance, remediation and well head protection.
- Quantity monitoring to measure abstraction, water level drawdown and compliance for license requirements.

It is of vital importance that more attention be given to data concerning abstraction volumes.

2) A medium density network of data should be handled by Regional Offices of DWA and/or CMAs and similar institutions with the objective of catchment management to secure enough good quality water to different users. The collection and analysis of data on a catchment scale involves the collection of appropriate data for the management of groundwater management units, also for compliance with RQOs. This may include:

- Quality monitoring to assess impacts of non-point sources.
- Quantity monitoring to assess the impact of abstraction, quantify groundwater-surface water interaction and recharge-discharge characteristics.

3) The national lowest density network of data should be handled by DWA Head Office for assessment, management and planning purposes, with an auditing function of the regional aquifer scale. The collection and analysis of data on a national scale involves the selection of points based on conceptual models of major aquifers to represent ambient groundwater conditions that are not impacted by short-term human activities. National scale monitoring measures the natural response of aquifers to atmospheric conditions over a long term for resource planning and management purposes.

A hierarchical diagram of information requirements was put together by DWAF (2004a) to demonstrate that local water users require the most detailed information temporally and spatially whereas national strategic information should be based on the ground level data, but presented to feed into a strategic decision-making framework rather than data analyses. These guidelines are directly applicable to the local and catchment scales. The information from these scales is used to feed into the national scale, so a common database and common standards for data collection should still be a viable solution for all three monitoring scales.

The push toward development of CMAs in South Africa will change the use of data in such a way that these agencies also become primary users of the data collected in their catchments. The onus will therefore no longer be on DWA to manage and collect the entire country's data as DWA will provide a strategic context for water quantity and quality management.

The envisaged specific roles and responsibilities for DWA, once catchment management agencies are established, will be reduced to (DWAF, 2004a):

- Information required for international/national level water resource strategic and development planning.
- Information required for performing its custodianship role, in other words, auditing Catchment Management Agencies.
- Information needed to share with other government departments.
- Information to provide to other organizations as by agreements e.g. SADC (Southern African Development Community), UNEP, etc.

2.4.7 Modelling requirements

In the development of monitoring guidelines, particular emphasis was placed on collection of data that can be used in hydrological models to estimate recharge, aquifer yield, groundwater-surface water interactions, evapotranspiration, etc. Consideration was given to models and applications that are tried and tested for each component of the system. An extensive modelling discussion and review is available in Deliverable 8 of this project.

The main outcomes of the modelling review were that the current state-of-the-art models are based on the following principles:

1) Catchment models are distributed or semi-distributed to account for spatial variations in environmental parameters and variables. They are based on the delineation of Hydrological Response Units (HRUs), areas that are homogeneous in terms of their hydrological response. Several well-known hydrological models are developed based on these principles, e.g. ACRU (Schulze, 1995), PRMS (Leavesley et al., 1983, 1996), J2000 (Flugel, 1995), etc.
2) Modular systems are generally preferred nowadays as they allow the plug-in of dedicated models for specific processes and the construction of models that would fit the specific modelling objectives. An example of modular system is the OMS (Object Modelling System).
3) Coupling of models dedicated to specific processes is also a common approach. For example, the structural features of OMS allowed the development of GSFLOW (Ground-water and Surface-water FLOW), by coupling PRMS, the Unsaturated-Zone Flow Package (Niswonger et al., 2006) and MODFLOW-2005 (Harbaugh, 2005), the well-known groundwater flow model of the United States Geological Survey. For the purpose of coupling, methods were developed to spatially link and route flow between the PRMS HRUs and the MODFLOW finite difference cells. This is because HRUs and finite-difference cells can have different spatial extents.

In order to set up and run the models that are described above and other similar models, information and data are required. These data can be summarized as: DEM, weather data (rainfall and temperature), vegetation maps (root depth, water use, etc.), soil water retention properties, sub-surface routing coefficients, groundwater routing coefficients, groundwater flow parameters (conductivity, porosity, etc.) and groundwater levels. These are summarized in Table 4.

Additional input data and information are required for GSFLOW, specifically for the Unsaturated Zone Flow Package and MODFLOW-2005. For example, typical groundwater data sets for MODFLOW packages and other groundwater models include groundwater levels, groundwater abstraction, groundwater chemistry (mass transport modelling) as well as groundwater recharge. Additional data of the lithology and the individual lithological thicknesses are also useful and can be derived from drilling information. Ground surface elevation data such as DEM data are also a requirement to run most groundwater flow and transport models. It should be noted that groundwater models (e.g. FEFLOW, MODFLOW, GSFlow, etc.) are developed for specific purposes and applications. The purpose of application is linked to the scale. The ideal scales of application of commonly used groundwater models are the quaternary catchment or local scale. At national and regional scales, groundwater models are generally useful to identify generic trends (e.g. general water flows), however one needs to be aware of data limitations.

TABLE 4 SUMMARY OF MINIMUM DATA AND INFORMATION REQUIRED TO SET UP HYDROLOGICAL MODELS AND MAIN SOURCES OF INFORMATION	
Data/information	**Source**
Digital Elevation Models (DEM)	Chief-Surveyor General
Weather data (rainfall and temperature)	South African Weather Services
Vegetation maps	Land use maps
Soil water retention properties	Inferred from soil maps: soil surveys and Land Type Maps (Agricultural Research Council) Inferred from geology maps: Council for Geosciences
Sub-surface routing coefficients	Calibration and parameter optimisation: Modelling Modular System
Groundwater routing coefficients	Calibration and parameter optimisation: Modelling Modular System
Groundwater flow parameters (conductivity, porosity, etc.)	Department of Water and Environmental Affairs, National Groundwater Archive: MODFLOW in GSFLOW
Groundwater levels and abstraction	Department of Water and Environmental Affairs, National Groundwater Archive: calibration of MODFLOW in GSFLOW

In general data collection for modelling purposes should be done using an iterative approach, starting with initial modelling with a limited data set to get a feel of the monitoring requirements. The monitoring programme can then be expanded and the data collection frequency in space and time can subsequently be changed depending on the requirements.

2.4.8 Financial and practical feasibility

Financial constraints are often the biggest constraints in a monitoring programme. At a stakeholder meeting organized on 5 May 2009 with the participation of officers from the Regional DWA, Hydrology Division, some of the practical difficulties in implementing monitoring programmes were highlighted:

- Limited budgets and budget cuts in the government.
- Volatility of yearly government budgets allocated to monitoring.
- Lack of staff and capacity, e.g. in automated recording and real time data handling.
- Theft and vandalism, where selected sites need to be appropriate but also safe.
- Specific requirements, for example an environmental impact assessment is required for the establishment of gauging weirs for surface flow monitoring, as it is a listed activity in terms of environmental regulations (Government Notice No. 386, Department of Environmental Affairs and Tourism, April 2006).
- Reliability, maintenance and replacement of equipment, e.g. common problems encountered in the field are seasonality of flow, fires, along with limited life span of equipment.

For these reasons the terminology “optimal” monitoring network was replaced with “ideal” monitoring network, as it is not always financially feasible to achieve optimal monitoring and not even the minimum requirements.

Another important point to consider is that, although water managers are often required to deal with integration of environmental components, data collection and equipment handling per environmental component needs to be done by specialists. Uncertainty still exists on which institution will do the monitoring (e.g. CMAs are not yet established).

In the ICM mind map as well as in Deliverable 9 of this project, the link is provided to the list of accredited laboratories nation-wide. The importance of using accredited laboratories is stressed in terms of quality assurance (e.g. for chemical analyses).

A large number of sampling and training manuals were written in the past and they reside in government Offices. However, these are often not used or they are not found due to turnover of staff, where new staff is not aware of the existence of these documents. Awareness on currently available guidelines and manuals should be increased and an assessment undertaken on the usage and usability of such documents. The ICM mind map facilitates, to a certain extent, water managers as all key documents (guidelines, manuals) or links thereto are included in one programme.

3 EXAMPLE OF APPLICATION, DEMO/PILOT STUDY SITE

3.1 Selection of demo/pilot study site

In the initial proposal of this project, it was stated that the project team has experience in different catchments that are representative of the different groundwater zones of South Africa and that several catchments were equipped with some groundwater, surface water and weather monitoring equipment for integrated monitoring purposes. Four demo/pilot study sites were therefore mentioned for consideration, namely:

1. The West Rand basin (A21D drained by the Rietspruit and its tributaries, the Tweelopie- and Blougatspruits);
2. The Kogelberg Oudebosch catchments and the Purgatory catchment in the Table Mountain Group aquifer (G40D);
3. The Shingwedzi catchment in the lowveld of the Kruger National Park (B90H); and
4. The Sandspruit catchment, a tributary of the Berg River (catchment G10J).

Discussions were held at the initial workshop of the research team held on 15 September 2008 at CSIR, Stellenbosch. It was noted that the West Rand basin was initially suggested because of its importance as a Dolomitic aquifer and that DWA, the Council for Geoscience and CSIR are already doing research in this catchment. It was also noted that Kogelberg is very complex due to the presence of fractured rock aquifers, whilst Shingwedzi may be logistically too far. It was therefore decided to use the Sandspruit catchment as the demo/pilot study site. The main motivation for choosing the Sandspruit catchment as demo/pilot study site was:

1. The existence of ***long-term hydrological data*** (almost 30 years) at DWA station No. G1H043.
2. The existence of ***boreholes included in DWA's National Groundwater Archive*** (NGA).
3. The catchment serves as ***study site to another Water Research Commission project*** (K5/1503) on dryland salinity. It was envisaged that rationalization of resources would be achieved by using this study site for two research projects with different aims.
4. ***Logistics***. The site is close to the researchers in the Western Cape.

3.2 Definition of objectives of monitoring programme, data users and applications

The primary objectives of the monitoring programme in the Sandspruit catchment were to quantify the water balance and the refinement of the conceptual model for this catchment. A catchment's water yield is a fundamental problem in hydrology, particularly the volume of water available at the catchment outlet over a fixed time period (Poncea and Shetty, 1995). The catchment water balance is even a more fundamental issue under the impacts of significant human-induced land use change. Optimising the water yield from catchments within South Africa has become an essential component of catchment management as increased pressure is being placed on the country's water resources, primarily due to population growth and inadequate management of the resource. Both physically-based hydrological models and simple conceptual water balance models are useful tools to address a range of hydrological problems, including the description of hydrological processes and their controlling factors (Xu, 1999). Conceptual models do not usually take into account the detailed geometry and small-scale variability of catchments, but rather consider the catchment as an ensemble of interconnected conceptual storages (Jothityamgkoon et al., 2001). A lack of capacity and inadequate infrastructure does however mean that detailed information pertaining to all terms of the water balance equation is rarely available to catchment hydrologists (Everson, 2001). The establishment of integrated monitoring programmes and data collection are usually required to fill those gaps and develop/refine conceptual models.

The main users of the water balance and conceptual model of the Sandspruit catchment were envisaged to be government departments (in particular Water Affairs and Agriculture), local authorities (municipalities and Catchment Management Agencies), private entities (environmental impact assessment and consulting practitioners, farming communities, etc.), the general public as well as the scientific community. Applications of the water balance and conceptual model were envisaged to be in water resource assessment and planning (including state of the environment, water and chemical mass balance), but also in change detection (identifying short- and long-term trends). These are also the two main groups of monitoring objectives indicated in the matrix of the ICM mind map (Chapter 2, Figure 3). Additional applications were envisaged to be in hydrological modelling with distributed parameter models as well as in the development of water and pollution management strategies.

3.3 Description of the catchment and baseline data

The demo/pilot study site is located in the Berg River basin. The Sandspruit (quaternary catchment G10J) is a seasonal tributary of the Berg River (Figure 4) and it flows predominantly between May and November. The Sandspruit catchment is approximately 152 km^2 in size and it is located in a semi-arid area that receives less than the average rainfall of the Berg River basin (approximately 350 mm a^{-1}).

Before undertaking a monitoring programme in any region of interest, an initial desk study and review of existing data are pre-requisites (topography, climate, geology, hydrology, soils and land use). A brief description of the Sandspruit catchment is therefore provided through the collection of baseline and existing data. A full description of the Sandspruit catchment was compiled in Deliverable 5 of this project.

3.3.1 Topography

The topography of the catchment is relatively flat, exhibiting a gently undulating surface. The elevation ranges between 40 mamsl in the low elevation areas (north-west) to 900 mamsl in the high elevation southerly parts of the catchment (Table Mountain Group sandstone Kasteelberg, Figure 5). About 61% of the catchment has slope gradients between 0 and 0.025 and 27% of the areas has slopes between 0.025 and 0.04. The average topographic gradient across the catchment is 0.013. The Berg River flows north-westwards and lies North-East of the catchment.

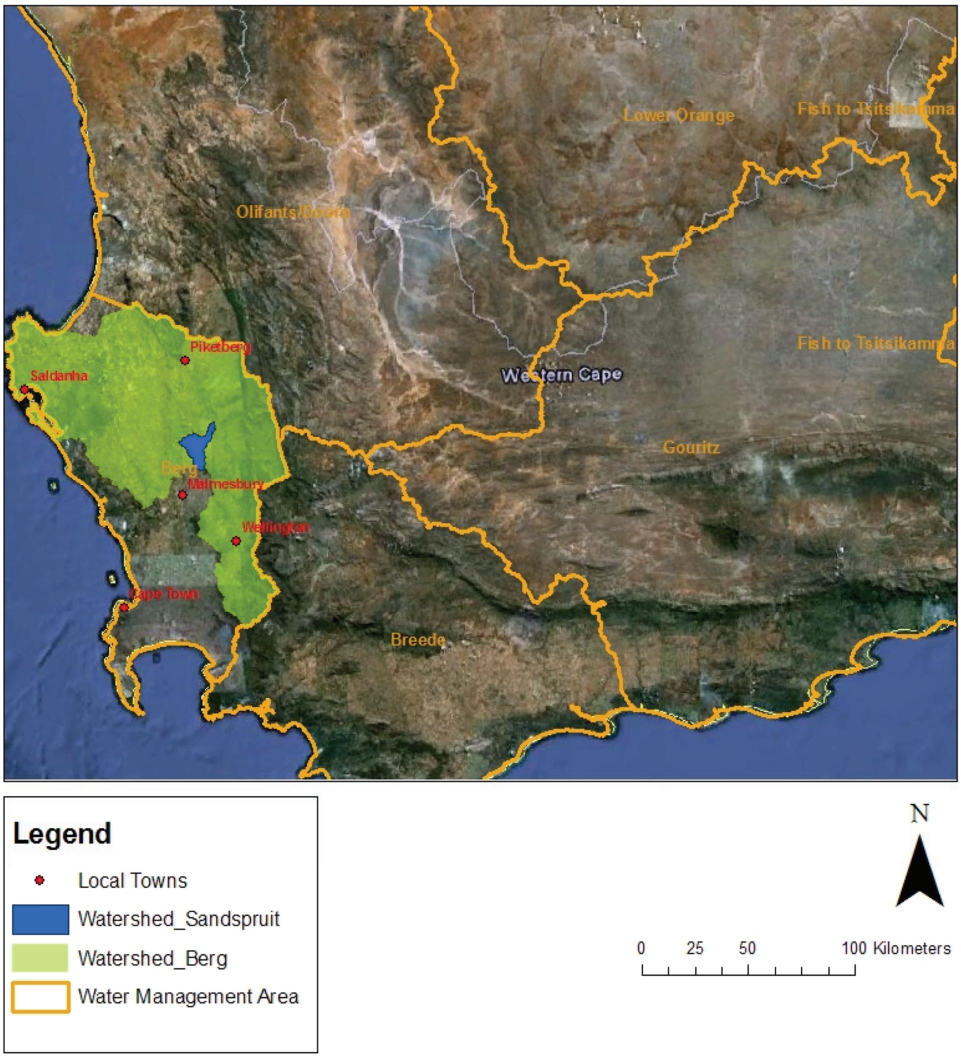


Figure 4

The loacation of the Sandspruit catchment in the Western Cape

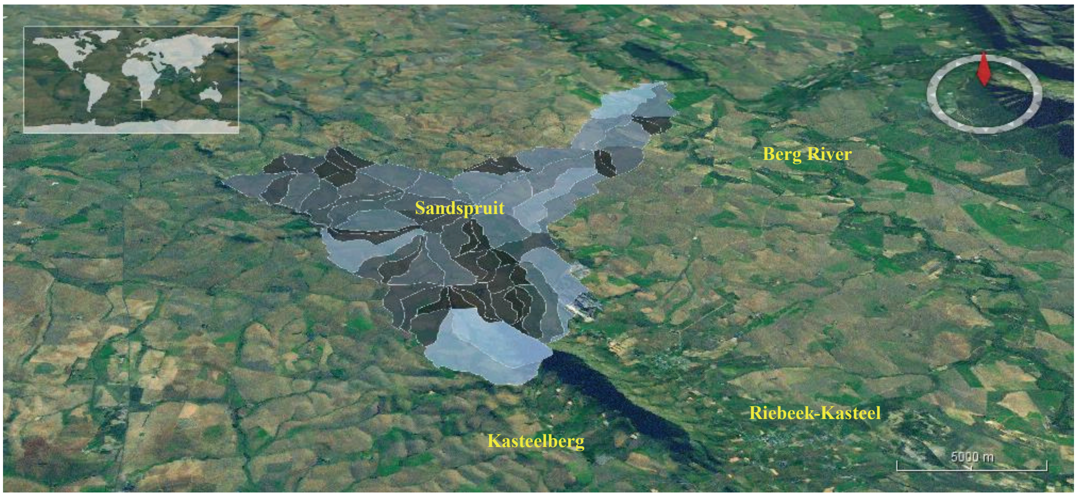


Figure 5
Map of the Sandspruit catchment with grey shades representing Hydrological Response Units, overlain on the catchment view in GeoWind v. 0.2 (http://geowind.javaforge.com, accessed on 3 March 2009)

3.3.2 Climate

The Berg River catchment experiences a Mediterranean climate with warm dry summers and cool wet winters. Rainfall is generally in the form of frontal rain approaching from the North-West, extending normally over a few days with significant periods of clear weather in between. Climate maps obtained from the Agricultural Geo-referenced Information System AGIS (www.agis.agric.za, accessed on 31 October 2008) indicated that mean annual rainfall in the Sandspruit catchment is between 300 and 500 mm, with slightly higher rainfall in the upper southern reach in the vicinity of Kasteelberg (Riebeek Wes). Rainfall occurs mainly in winter (from April until October). The average long-term annual temperature is between 15 and 21°C. Annual evaporation is predominantly between 1800 and 2000 mm, and lower in the vicinity of Kasteelberg (Figure 6). Annual rainfall is therefore well below the evaporative demand.

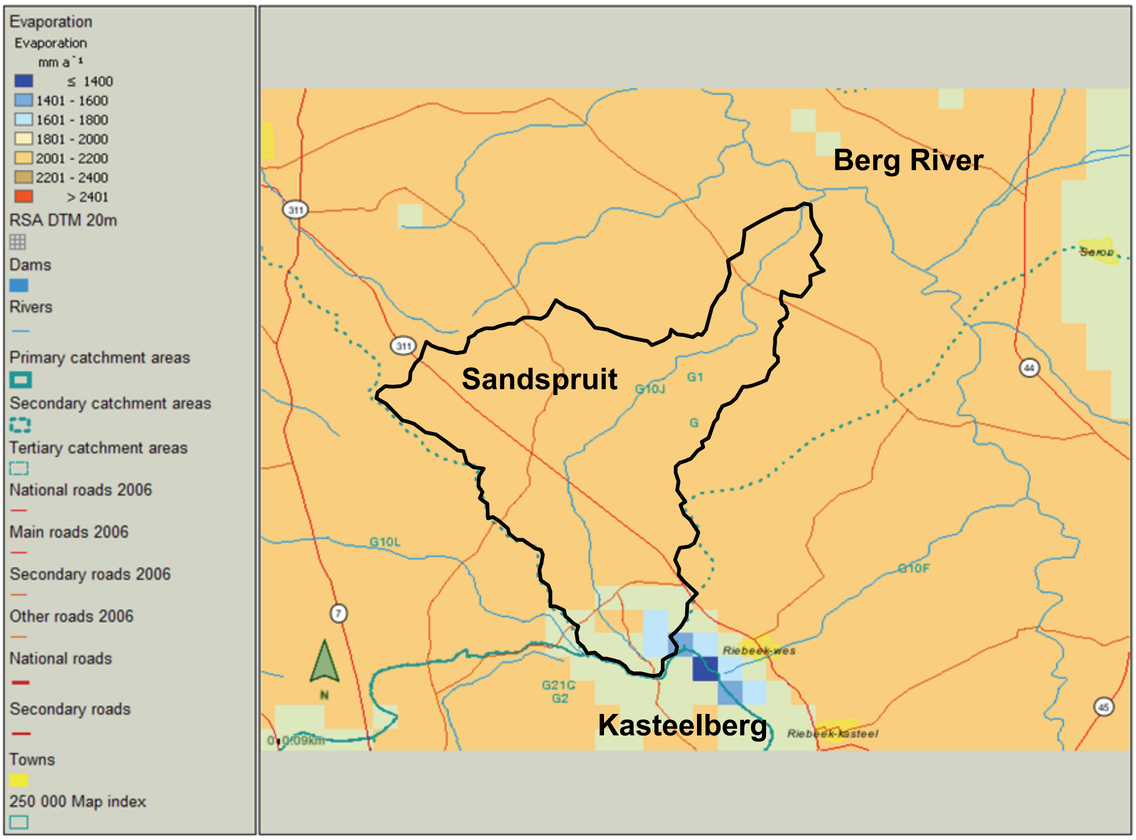


Figure 6
Annual evaporation in the Sandspruit catchment (Agricultural Geo-referenced Information System, AGIS, www.agis.agric.za, accessed on 31 October 2008)

3.3.3 Geology

The geology in the Sandspruit catchment shows minimal variation, being dominated by Table Mountain Group (TMG) sandstone in the high elevation areas and Malmesbury shale in the mid to low elevation parts. An alluvium cover is also evident, which increases in thickness towards the lower elevation areas of the catchment.

Table 5 and Figure 7 show a summary of the different geological formations and groups that occur within the catchment. The Sandspruit catchment is covered by sedimentary and plutonic rocks ranging in age from quaternary to Precambrian. The TMG is represented by Kasteelberg (900 mamsl). It is a light-grey quartzitic sandstone outcrop, exhibiting thin siltstone, shale and polymictic conglomerate beds. It is part of the Peninsula Formation. The remainder of the watershed is dominated by the Malmesbury Group shales. These are represented by low grade metamorphic rocks such as phyllitic shale, quartz and sericrete schist, siltstone, sandstone and greywacke (Meyer, 2001). It is part of the Moorreesburg Formation. Field investigations have revealed that there are granite hills, essentially granite plutons intruded into the Malmesbury Group, surrounded by clay soils typically derived from weathered granite. The alluvium cover is represented by fine sediment, which may be characterised as loam and sandy loam.

TABLE 5
DESCRIPTION OF THE GEOLOGY OF THE SANDSPRUIT CATCHMENT

Period	Group	Formation	Lithology
Quaternary	-	-	Silcrete/Ferricrete
		-	Loam and Sandy loam soil
		Springfontyn	Light-grey to pale-red sandy soil
Paleozoic	Table Mountain	Graafwater	Light grey quartzitic sandstone with thin siltstone, shale and polymictic conglomerate beds
		Piekenierskloof	Grey to reddish quartzitic sandstone with miner grit, conglomerate and reddish shale lenses
		Peninsula	Light grey quartzitic sandstone with thin siltstone, shale and polymictic conglomerate beds
Proterozoic	Malmesbury	Bridgetown	Greenstone with dolomite and chert lenses
		Moorreesburg	Greywacke and phyllite with beds and lenses of quartzite schist, limestone and grit.
		Klipplaat	Quartz schist with phyllite beds and minor limestone and chlorite schist lenses
		Berg River	Schist and fine grained greywacke with beds and lenses of quartz schist and limestone
Pre- to Early Cambrian	Cape Granite suit	-	Hybrid granodiorite

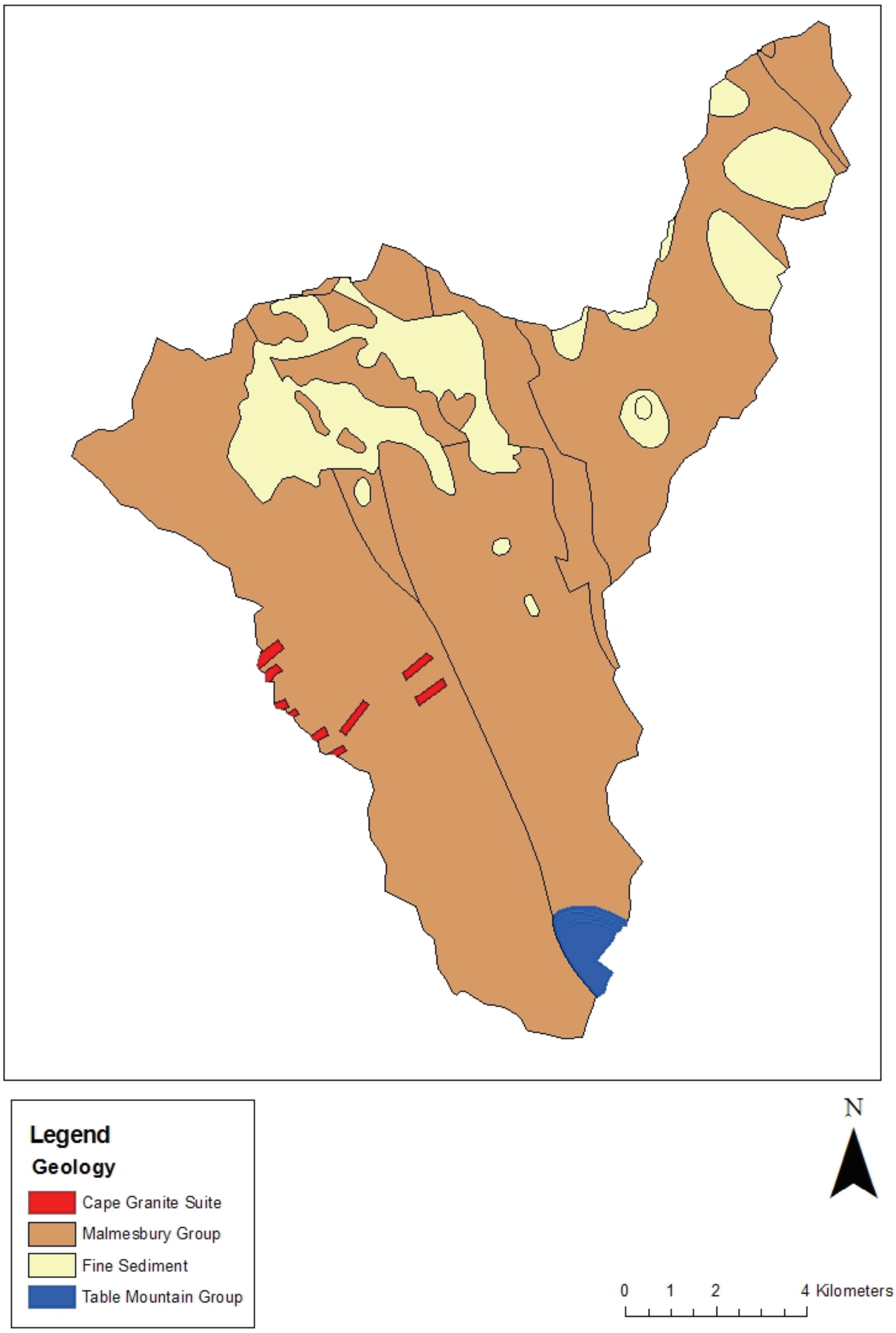


Figure 7
Geological map of the Sandspruit catchment

3.3.4 Hydrology

Streamflow data for the Sandspruit catchment were obtained from the hydrological database of the Department of Water Affairs for station No. G1H043 from 01/05/1980 to 08/12/2009 (http://www.dwaf.gov.za/IWQS/wms/WebInventory/Other_G.html, accessed on 31 March 2008). The following data are measured by DWA at the Sandspruit weir (Figure 8):

- **Water flow.** Water level is measured with water level meters installed in enclosures above a well connected to the stream.
- **Water quality.** Inorganic chemical analyses are done on grab water samples bi-weekly to monthly.

Daily flow in $m^3 s^{-1}$ is shown in Figure 9. Annual average runoff was estimated to be ~ 30 mm a^{-1}.

Water quality data for the monitoring station at Sandspruit (G1H043) were also obtained from the DWA office in Pretoria for the period from 1980 to 2010. These were EC, TDS, pH, Ca, Mg, K, Na, alkalinity, Cl, F, Si, SO_4, NH_4, NO_3 and PO_4. All data were supplied in .csv files, including the statistical analyses on the time-series.

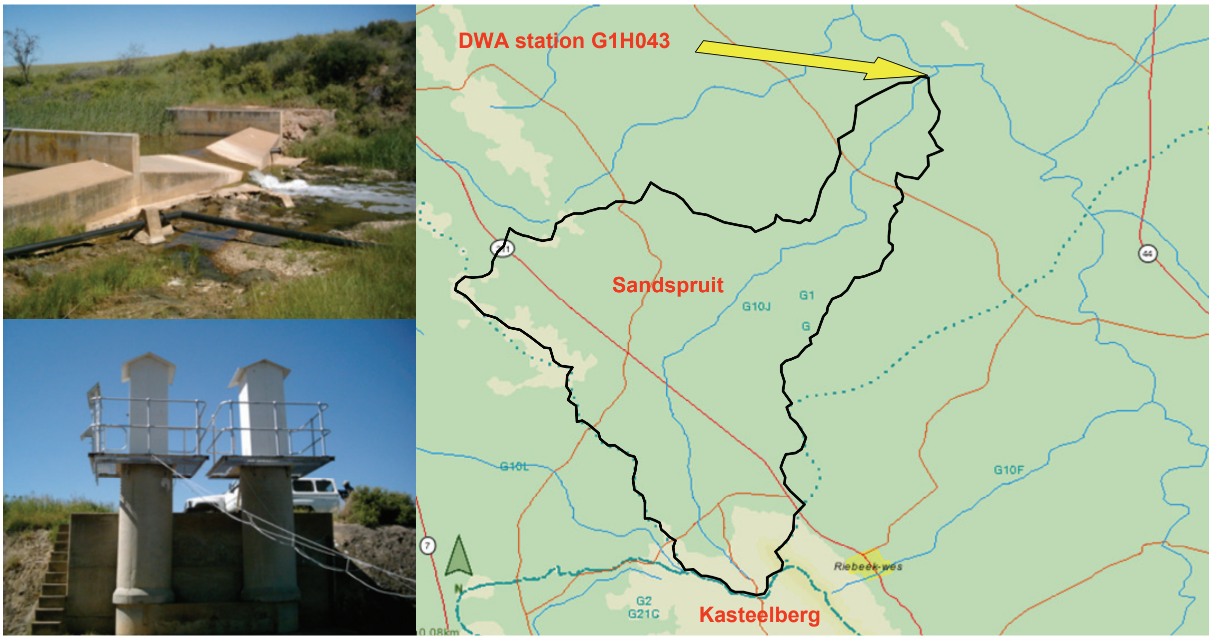


Figure 8
Daily flow measured at station No. G1H043 by the Department of Water Affairs from 1980 to 2009

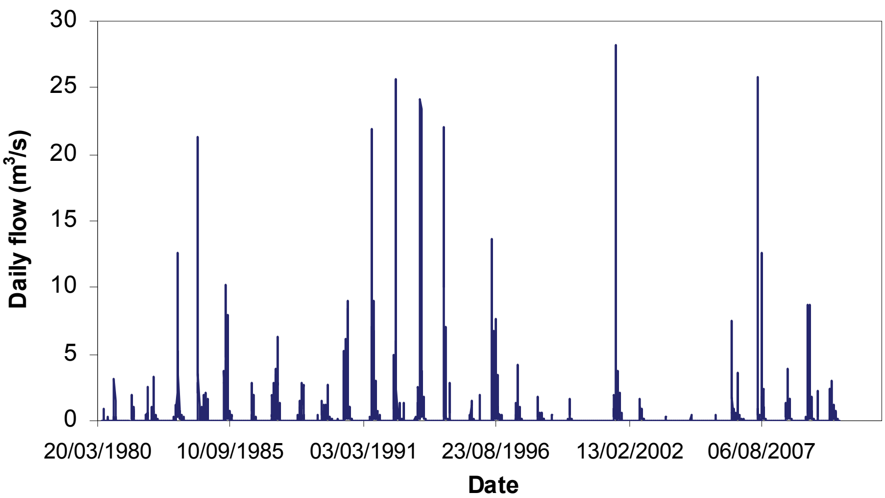


Figure 9
Daily flow measured at station No. G1H043 by the Department of Water Affairs from 1980 to 2010

3.3.5 Hydrogeology

Aquifer characteristics

The Sandspruit catchment is characterized by fractured aquifer systems. The formations of the Table Mountain, Malmesbury and the Cape Granite suits form low to moderately productive fractured aquifers. Aerially limited quaternary age primary aquifers also exist in the northern sector of the catchment. The catchment is therefore classified into four main aquifer types based on the geological make-up as illustrated in Figure 10a. In terms of aerial extent, the Malmesbury Group fractured aquifer is dominant and it is classified as Minor Aquifer System (Parsons, 1995). These are defined as fractured or potentially fractured rocks that do not have a high primary permeability, or other formations of variable permeability. Secondary aquifers attribute their water-bearing properties to weathering, fracturing and faulting processes. However, the argillaceous nature of most of the rock and poor groundwater quality limit the exploitation potential of these aquifers. Although these aquifers seldom produce large quantities of water, they are important both for local supplies and in supplying baseflow to rivers, and they have a moderate vulnerability to pollution.

Specific yield data for each aquifer type in the catchment is lacking. Based on the yield map developed for the greater Berg River basin, the catchment is divided into two broad yield classes (Figure 10b), namely a fractured aquifer with yield ranging from 0.1 to 0.5 L s^{-1} and a fractured aquifer with yield from 0.5 to 2 L s^{-1}. This classification and Figure 10b show that the relatively high frequency of faulting has contributed to the high yield in the North-West striking central sector of the catchment. The groundwater recharge seems to be influenced by topographic elevation and decreases from South to North (Figure 10c). Recharge is generally episodic, thus only occurring during intense rainfall events or during periods of prolonged rainfall. Recharge was reported to be 71 mm a^{-1} around Kasteelberg and 69 mm a^{-1} in the rest of quaternary catchment G10J (Vegter, 1995).

Groundwater level and flow characteristics

Groundwater level data gathered from the NGA allowed for a potentiometric surface within the catchment to be interpolated via inverse distance weighting (IDW). A summary of the characteristics of existing boreholes, chemical analyses and lithology can be found in Deliverable 5 of this project. The groundwater depth ranged between 0.10 and 43.35 mbgl (meters below ground level). The interpolated potentiometric surface and groundwater flow are presented in Figure 11a. Groundwater flow is expected to occur perpendicular to equipotential lines. Groundwater flows in a north to north-westerly direction in the southern parts and in a north-easterly direction in the northern parts of the catchment. The contrasting direction of flow in the western and north-western parts of the catchment suggests that a groundwater divide could exist in this area. A temporal water level observation also showed that there was a slight groundwater level rise in the 1990’s from the 1960’s level.

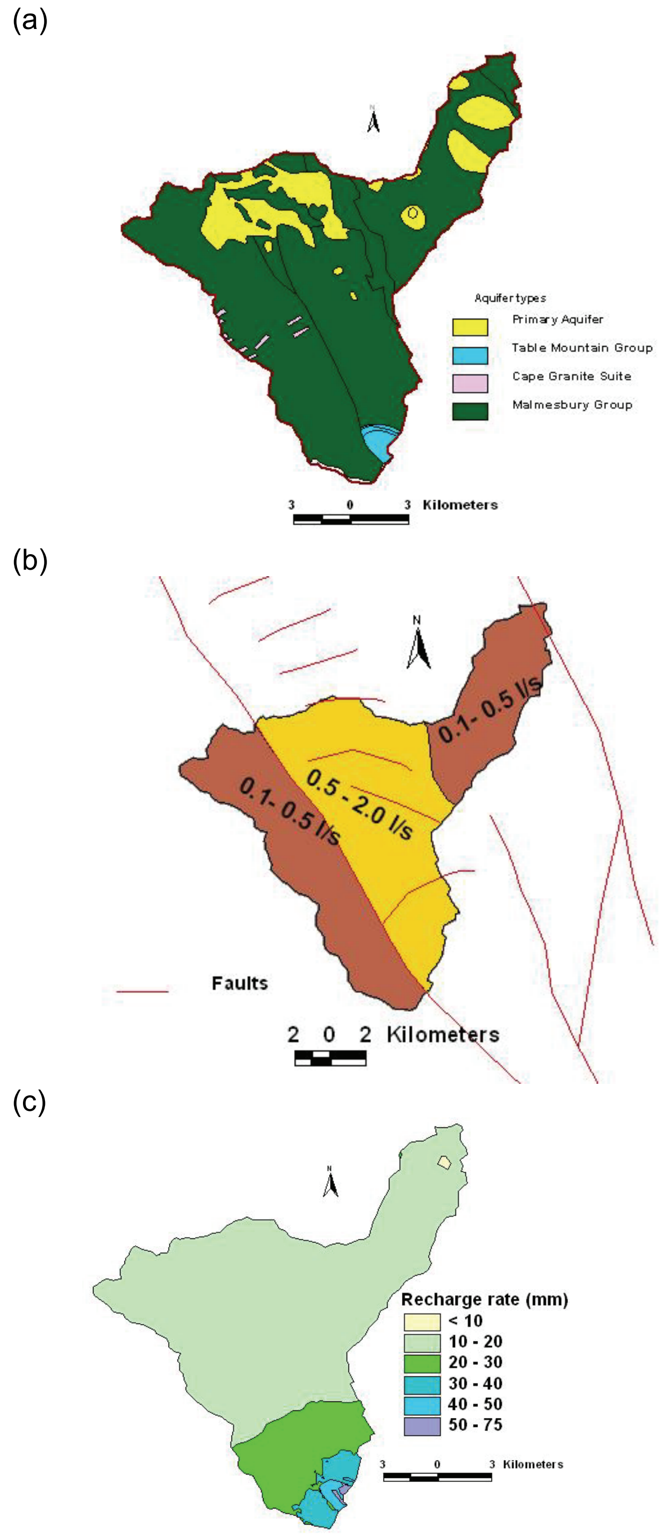
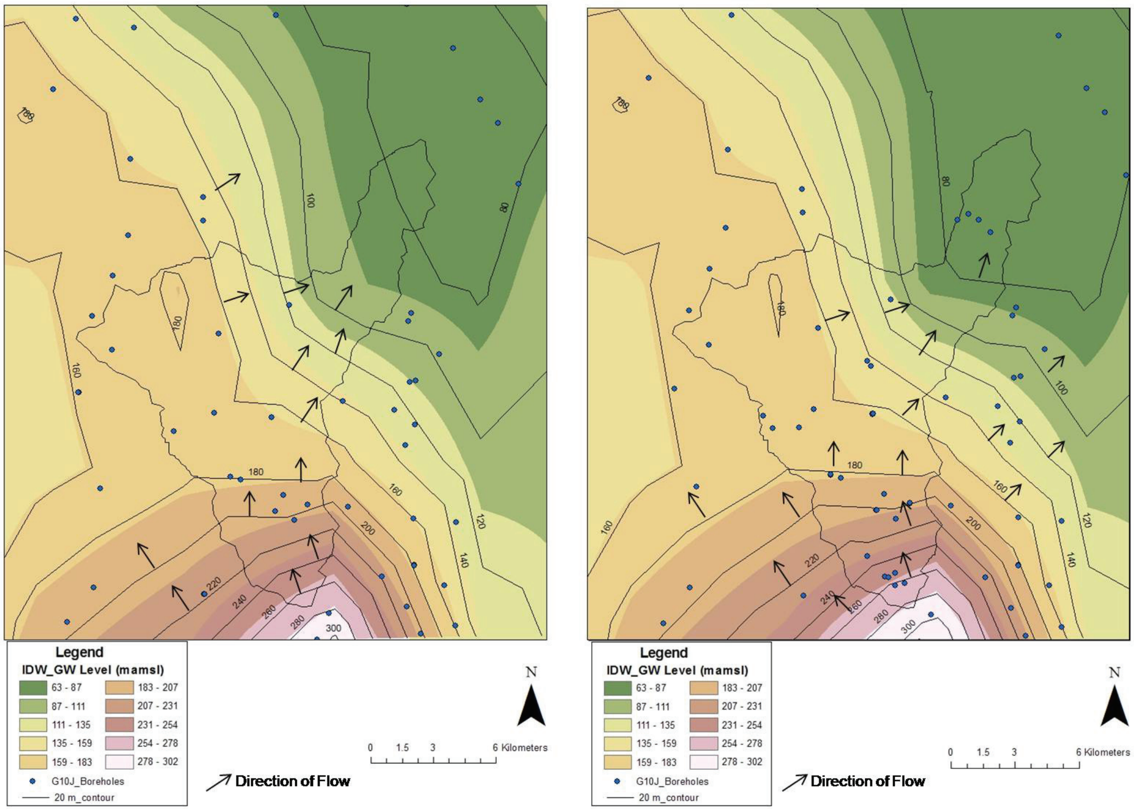


Figure 10

Maps of aquifer types (a), aquifer yield (b) and groundwater recharge (c)



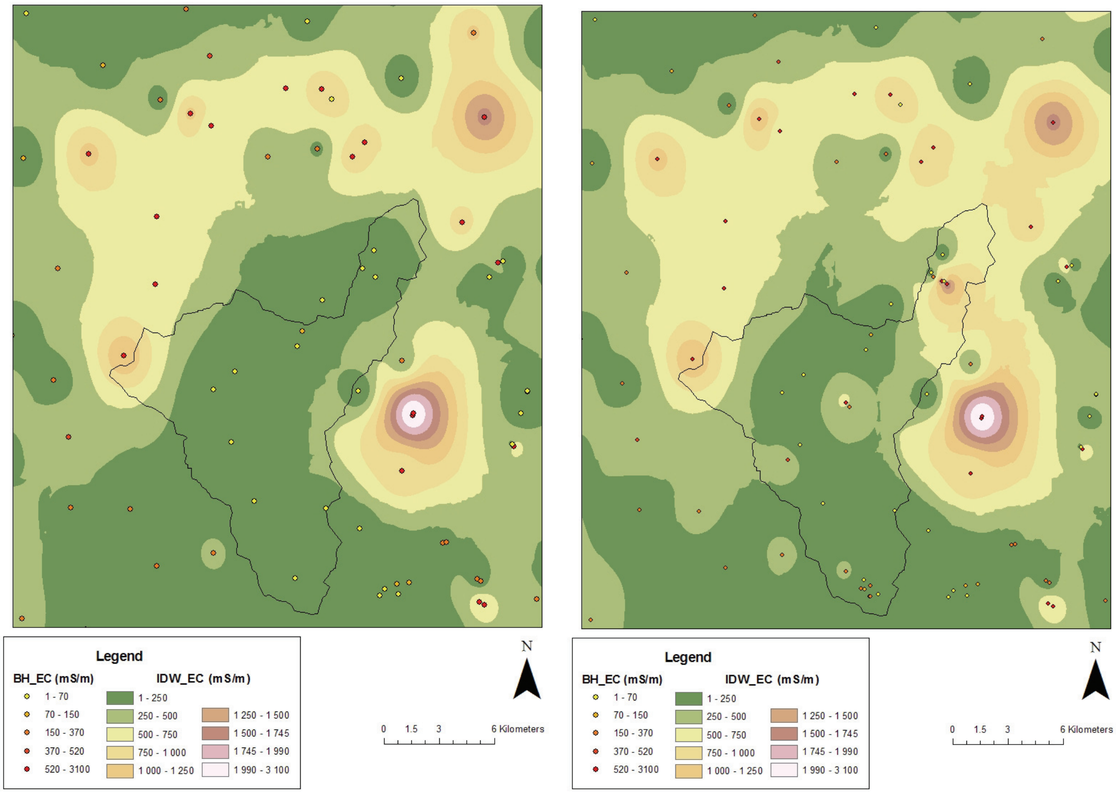
a) **b)**

Figure 11
The groundwater potentiometric surface across the Sandspruit catchment (interpolated with inverse distance weighting) and the direction of groundwater flow drawn using a) National Groundwater Archive data only (1924-2003) and b) National Groundwater Archive and data from new boreholes (1924-2003 and 2009)

Groundwater chemistry and main groundwater facies

Groundwater chemistry was first investigated using data gathered from the NGA. Adequate historic chemical data within the catchment were only sampled in 1990 and in 1992. Figure 12a represents the historic map of groundwater EC. The IDW interpolation method was used to describe EC spatially, identify trends and gradients across the catchment as well as generate spatial data that could be used in hydrological models. Caution should, however, be exercised in the interpretation of interpolated point data of groundwater EC. Historic data revealed two areas with exceptionally high EC, that is North and East of the catchment (Figure 12a). An EC greater than 300 mS m^{-1} breaches the maximum allowable limit for domestic use (DWAF, 1996). These areas occur North-West and North-East within the catchment. It was observed that EC is dependent on lithology, whereby areas of high EC (170-1,000 mS m^{-1}) coincide with areas underlain by the sericitic Malmesbury Group. Based on historic data, groundwater is generally brackish and, in some instances, saline groundwater having total dissolved solids of 13,253 mg L^{-1} was reported. Salinity increases in the direction of groundwater flow and also with decreasing recharge. Electrical conductivity ranged from fresh water (as low as 23 mS m^{-1}) near the catchment boundaries in the southern reach to brackish (EC as high as 2,264 mS m^{-1}) following flow paths to the North-East (Figure 12a). There was no relationship between EC and the depth to groundwater.

The dominant water type is Na-Cl, especially in areas where depth to groundwater is shallow and where flow vectors converge. In recharge areas, characterized by relatively deeper groundwater and where groundwater flow vectors diverge, the dominant water types are Na-Mg-Cl, Na-Mg-Cl-HCO3, Na-Cl-HCO3 and in some instances Na-Ca-Cl-HCO3 (Figure 13). Even though the hydrochemical evolution pattern seems not unique, the Na-Cl type of waters is evolved perhaps from Na-Mg-Cl-HCO3 type water.



a) **b)**

Figure 12

Electrical conductivity of groundwater map of the Sandspruit catchment (interpolated with inverse distance weighting) drawn using a) National Groundwater Archive data only (1965-2008) and b) National Groundwater Archive and data from new boreholes (1965-2008 and 2010)

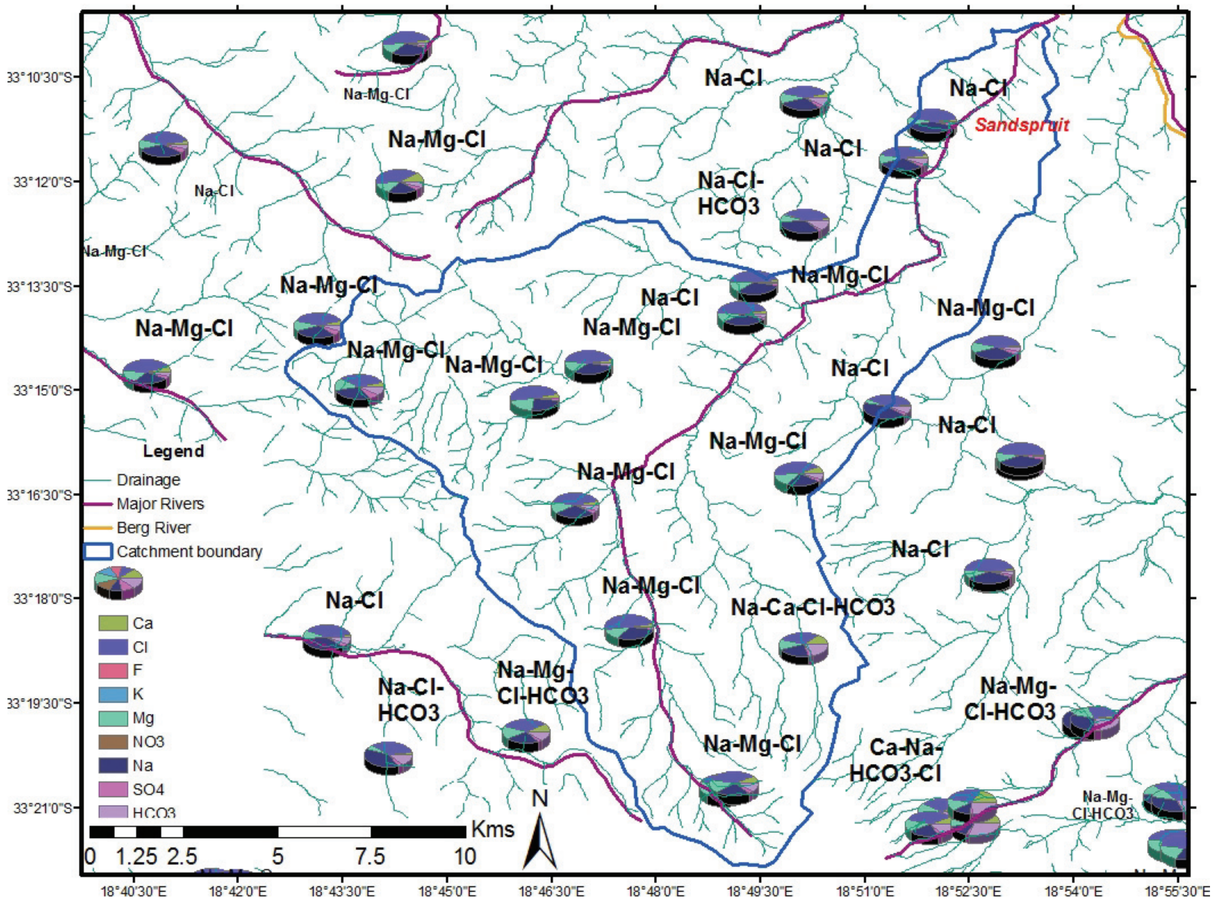


Figure 13
Groundwater type map of the Sandspruit catchment and its surroundings

3.3.6 Soils and land use

Soil maps were obtained from AGIS (www.agis.agric.za, accessed on 31 October 2008). The terrain types are low mountains and open high hills or ridges in the upper southern reach, rolling and irregular plains with some relief in the mid-reaches, and plains with some relief in the lower reaches. Soils are generally poorly developed, shallow on hard or weathering rock, brownish sandy loams with lime generally present in most of the landscape. Some red and yellow soils with low to medium base status are also present. Soil depth usually varies between 0.5 and 1 m, and the soil water holding capacity is predominantly between 20 and 40 mm, but it can be up to 80 mm in the upper and lower reaches of the Sandspruit catchment (Figure 14). Soil drainage is somewhat impeded by the low hydraulic conductivity of the semi-weathered Malmesbury shale throughout the Sandspruit catchment and it is particularly poor in the lower reaches (Figure 15). Low to moderate swelling clays are also present. Soil salinity is moderate, whilst the vegetation biome is fynbos.

Much of the natural vegetation, i.e. *Swartland renosterveld* and *Hawekwas fynbos* North and South of the catchment respectively, has been replaced by agriculture. Land use in the Sandspruit catchment is dominated by cultivated lands and pastures. Surface water as well as groundwater is utilized for irrigation. The catchment falls within the “bread basket” of the Western Cape and thus agriculture is dominated by wheat cultivation. The growing of grapes, lupins and canola is also common. Farmers in the area generally follow a three year planting rotation, i.e. cultivation only occurs every 3rd year. Lands are left fallow between planting seasons and used for grazing. Soil erosion is minimized through the use of man-made anti erosion contours, which are evident throughout the catchment.

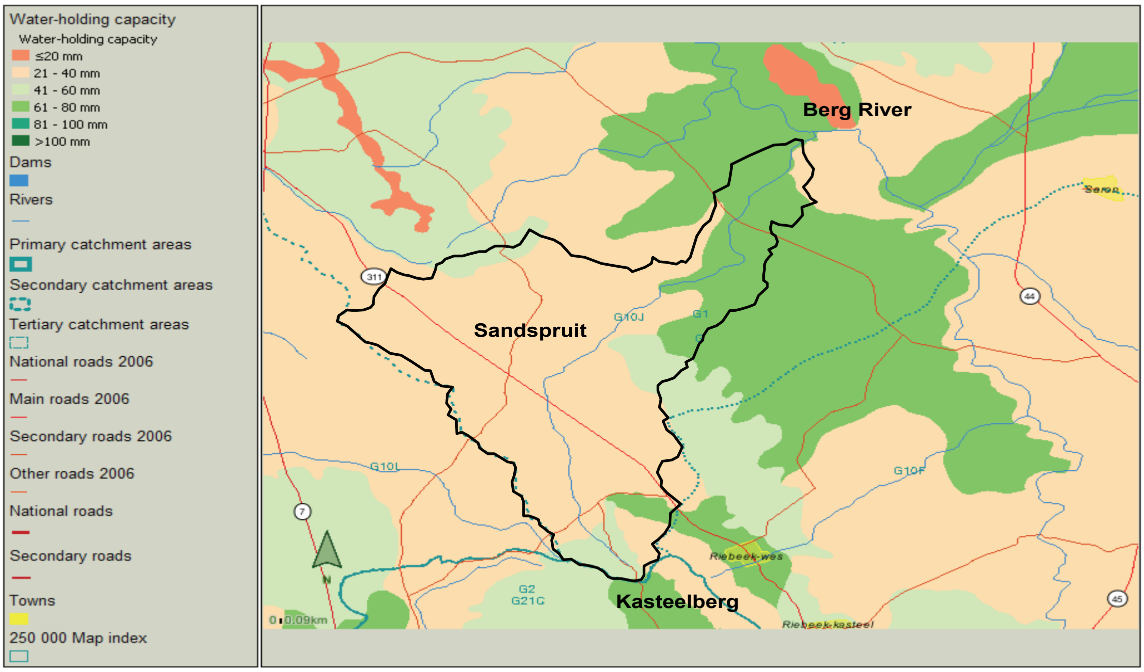


Figure 14

Water holding capacity of soils in the Sandspruit catchment (Agricultural Geo-referenced Information System, AGIS, www.agis.agric.za, accessed on 31 October 2008)

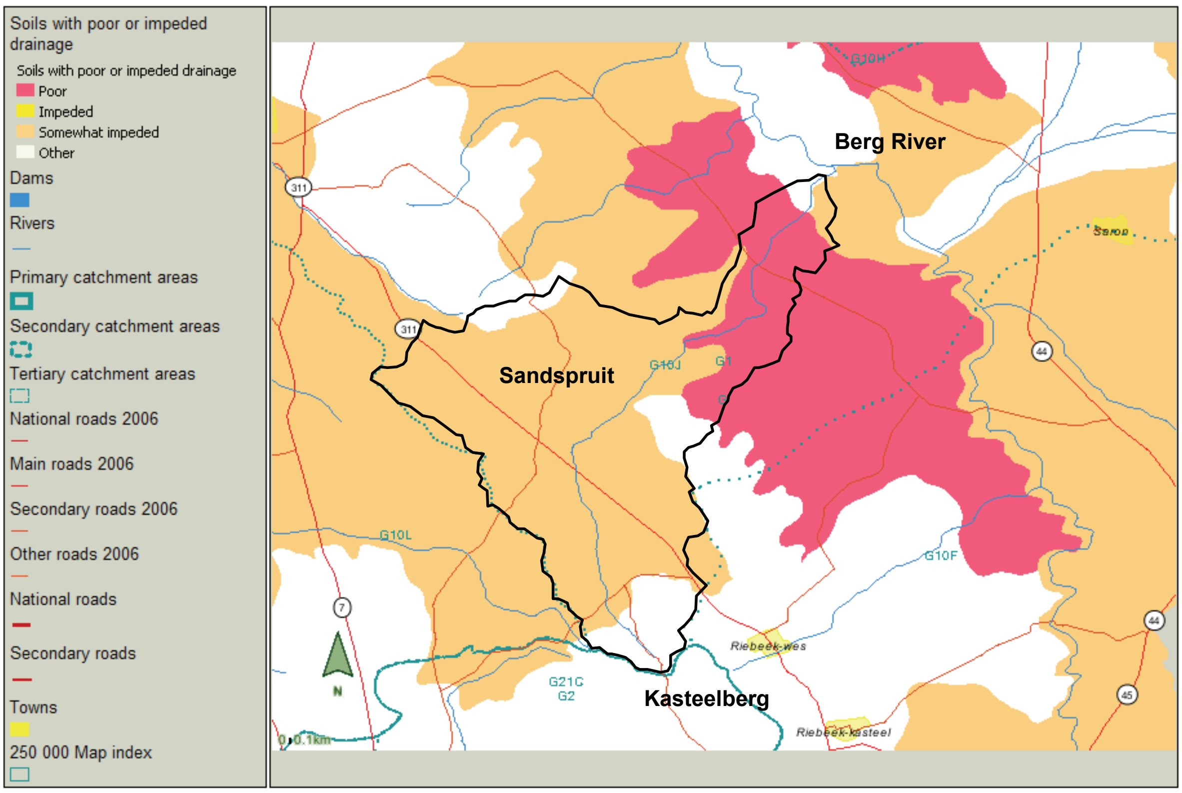


Figure 15

Soils with poor or impeded drainage in the Sandspruit catchment (Agricultural Geo-referenced Information System, AGIS, www.agis.agric.za, accessed on 31 October 2008)

3.4 Monitoring gaps and requirements

Collection of baseline data served the purpose of assessing what data were available and what monitoring gaps existed for a comprehensive conceptualization of the Sandspruit catchment. In particular the following monitoring gaps were identified:

- ***Atmospheric monitoring.*** No weather station or known rain gauge was found within the Sandspruit watershed. The closest weather stations were at Morreesburg and De Hoek (South African Weather Services), Langgewens (Department of Agriculture and South African Weather Services) and Goedertrou (research weather station for WRC project No. K5/1503). It was therefore deemed necessary to install weather stations within the Sandspruit catchment.
- ***Surface water monitoring.*** Long records of water flow and chemistry data were available from DWA station No. G1H043. However, no monitoring of sub-catchments was taking place.
- ***Groundwater monitoring.*** The information from the NGA was used for the purpose of this project. However, it was deemed necessary to drill more boreholes for a comprehensive monitoring programme in the Sandspruit catchment due to:
  - ❖ Borehole data (groundwater levels and chemistry) were erratic and seldom with any time series.
  - ❖ Borehole log data (both geological and geophysical) were not found and the vertical extent of aquifers, non-aquifers and their hydraulic properties were not defined.
  - ❖ A trend in water level rise through time appeared.
  - ❖ Brackish groundwater was measured in close proximity to fresh water.
  - ❖ Existing data had inconsistencies (e.g. the same data measured at different times and locations appeared in more than one borehole).
- ***Soil and vadose zone monitoring.*** No continuous record of soil and vadose zone was taking place. Due to the geological nature of the catchment with soil and weather material overlying Malmesbury shale characterized by low permeability, a strong interflow component is expected. It was therefore suggested to monitor this flow component through the installation of piezometers at the interface between the soil cover and the Malmesbury shale, where temporary perched water tables may occur especially during the rainy winter season.
- A more detailed description of ***land use*** is also required, including the effects of man-made anti-erosion contours on water fluxes.

Following a recognizance trip undertaken in November 2008, three broad sections of the Sandspruit catchment were identified based on the geological environments:

1) Sandstone/Malmesbury shale geology in the upper reaches
2) Undulated Malmesbury shale in the mid-reaches
3) Malmesbury shale with alluvial sandy soils in the lower reaches

It was therefore decided to investigate each of these sections in detail and use them as a basis for a more comprehensive monitoring programme. The geological environments are strongly linked to the type of soils present in the catchment and this is associated with land uses (type of farming) in the area. In this way, in the design of the integrated catchment monitoring programme, the consequential concept of geology, climate, soil and land use was adopted. In addition the concept of integrated monitoring included data summarized in Table 6. The purpose of data collection as well as the actions taken in the Sandspruit catchment to collect information is reported in this Table.

TABLE 6 DATA COLLECTION, PURPOSE AND ACTIONS TAKEN TO FILL MONITORING GAPS IN THE SANDSPRUIT CATCHMENT		
Data collection	**Purpose**	**Action taken in the Sandspruit catchment to fill monitoring gaps**
Weather	Rainfall and evaporation represent the driving force of water fluxes in the catchment	Establishment of 3 rain and temperature stations within the catchment
Hydrometry	Surface water and quality measurements	Feasibility investigation on monitoring surface water flow in sub-catchments
	Groundwater flow and quality measurements	Drilling of 24 boreholes along 4 cross-sectional transects
Vadose zone profiling	Analyses of modes of water flow and contaminant transport in the sub-surface	Water content, EC and Cl analyses on disturbed sediment samples collected during borehole drilling
Geophysical study	Analyses of geological layering and water occurrences in sub-soil	Resistivity measurements along 3 cross-sectional transects
Isotope studies	Analysis of flow paths and hydrograph separation	Sampling and analyses of ^{18}O and ^{2}H in groundwater and surface water

3.5 Data collection and results

In this section of the report the establishment of the expanded monitoring programme and data collection in the Sandspruit catchment are discussed for the atmospheric, surface water and groundwater components.

3.5.1 Atmospheric data

Atmospheric variables are drivers of the hydrological cycle. In particular, rainfall amounts and intensity affect hydrological processes like infiltration, runoff, drainage and the components of the hydrograph. Monitoring of other weather variables is essential for estimating evapotranspiration and, indirectly, groundwater recharge. The four main factors affecting evapotranspiration are air temperature, solar radiation, wind speed and relative humidity. In order to estimate reference evapotranspiration with the Penman-Monteith equation (Allen, et al., 1998), the minimum required weather data are daily maximum and minimum temperature (Annandale et al., 2002). Weather variables may vary greatly depending on the location within a catchment and particularly topography. The spatial representation of precipitation and rainfall can be obtained by lapsing these two variables as a function of differences in elevation, slope and aspect in relation to the weather station (Leavesley et al., 1983), through exhaustive search techniques (Hay and McCabe, 2002), or by downscaling weather data from regional climate models (Hay et al., 2002; Hay and Clark, 2003).

The network of existing weather stations (De Hoek, Goedertrou, Langgewens and Mooreesburg) was expanded to include locations at the Zwavelberg farm, Oranjeskraal farm and at the Sandspruit DWA station No. G1H043 (Figure 16). The new stations included temperature sensors installed in a Gill screen and automatic rain gauges for hourly collection of data with MCS loggers (Mike Cotton Systems, Cape Town) (Figure 17). Annual rainfall data for all stations are summarized in Table 7. It is evident from these data that differences in annual rainfall occur spatially. In particular, rainfall appears to decline within the Sandspruit catchment from the upper reaches (Zwavelberg station) downstream (Oranjeskraal and Sandspruit DWA station No. G1H043). This is also visible from the daily rainfall distribution graphs (Figure 18). Daily air temperatures exhibit an increasing trend from the upper reaches downstream (Figure 19).

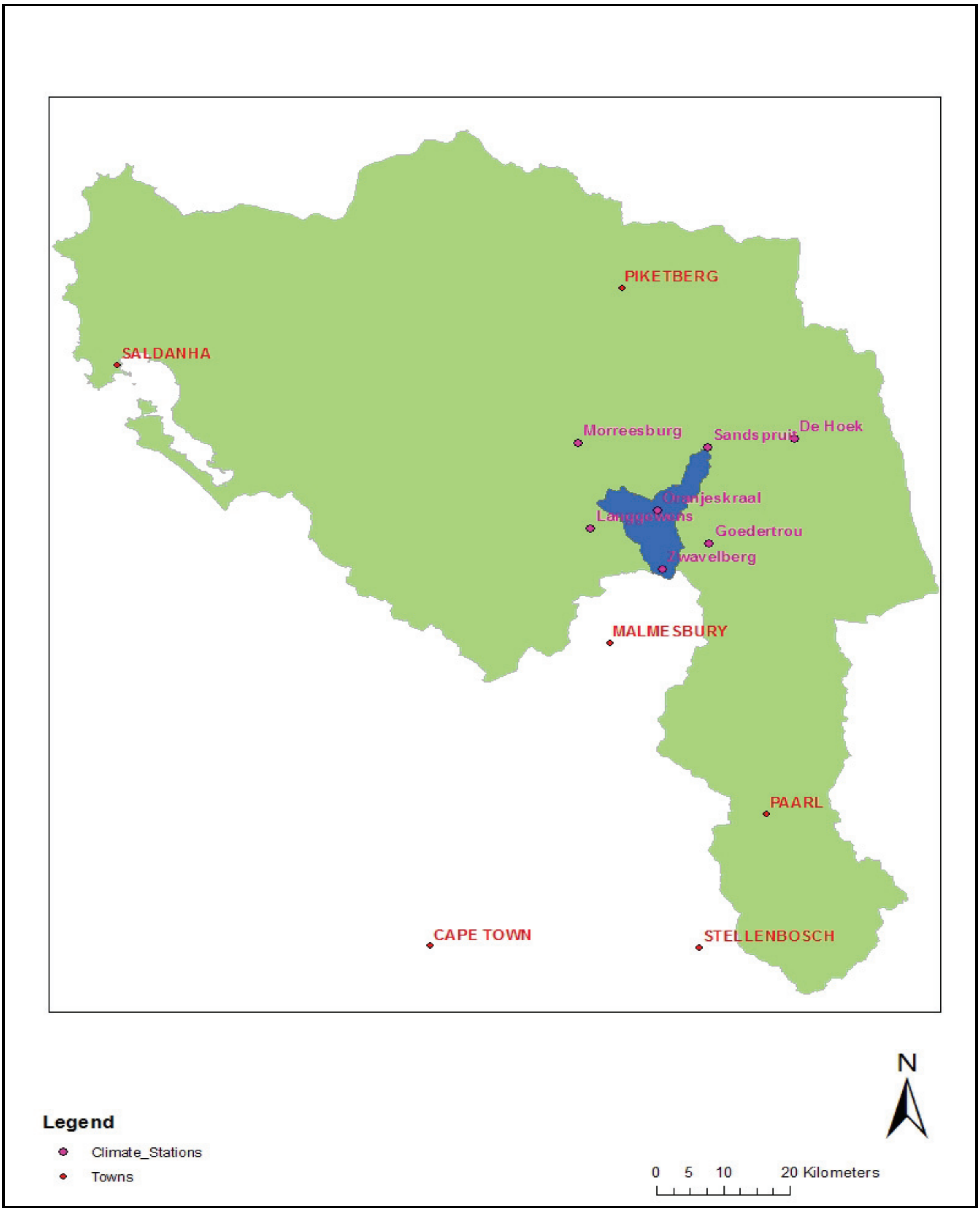


Figure 16

Location of existing and new weather stations (rainfall and temperature logging sensors) in the Sandspruit catchment (blue). The Berg river basin is outlined in green

Figure 17
Rainfall and temperature logging sensors equipment installed in the Sandspruit catchment

TABLE 7
ANNUAL RAINFALL IN THE SANDSPRUIT CATCHMENT AND SURROUNDING STATIONS

Water Year[1]	De Hoek[2]	Langgewens[3]	Moorreesberg[2]	Goedertrou[4]	Sandspruit[5] (DWA station No. G1H043)	Oranjeskraal[5]	Zwavelberg[5]	Average
1990	597	409	392					466
1991	755	471	493					573
1992	644	389	409					481
1993	554	458	404					472
1994	438	360	387					395
1995	620	321	383					441
1996	793	502	538					611
1997	468	294	290					351
1998	518	357	401					425
1999	645	372	375					464
2000	471	302	334					369
2001	838	544	526					636
2002	618	416	393					476
2003	494	297	288					360
2004	476	388	301					388
2005	505	358	330					398
2006	695	474	527	436				533
2007	854	678	626	460				655
2008	844	482	538	406	323			519
2009	577	407	477		319	391	494	444
Average	620	414	421					473
Minimum	438	294	288					351
Maximum	854	678	626					655
St. dev.	136	94	95					91

[1]from 1 April to 31 March; [2]South African Weather Services; [3]Department of Agriculture; [4]WRC project K5/1503; [5]Newly established station (rainfall and air temperature)

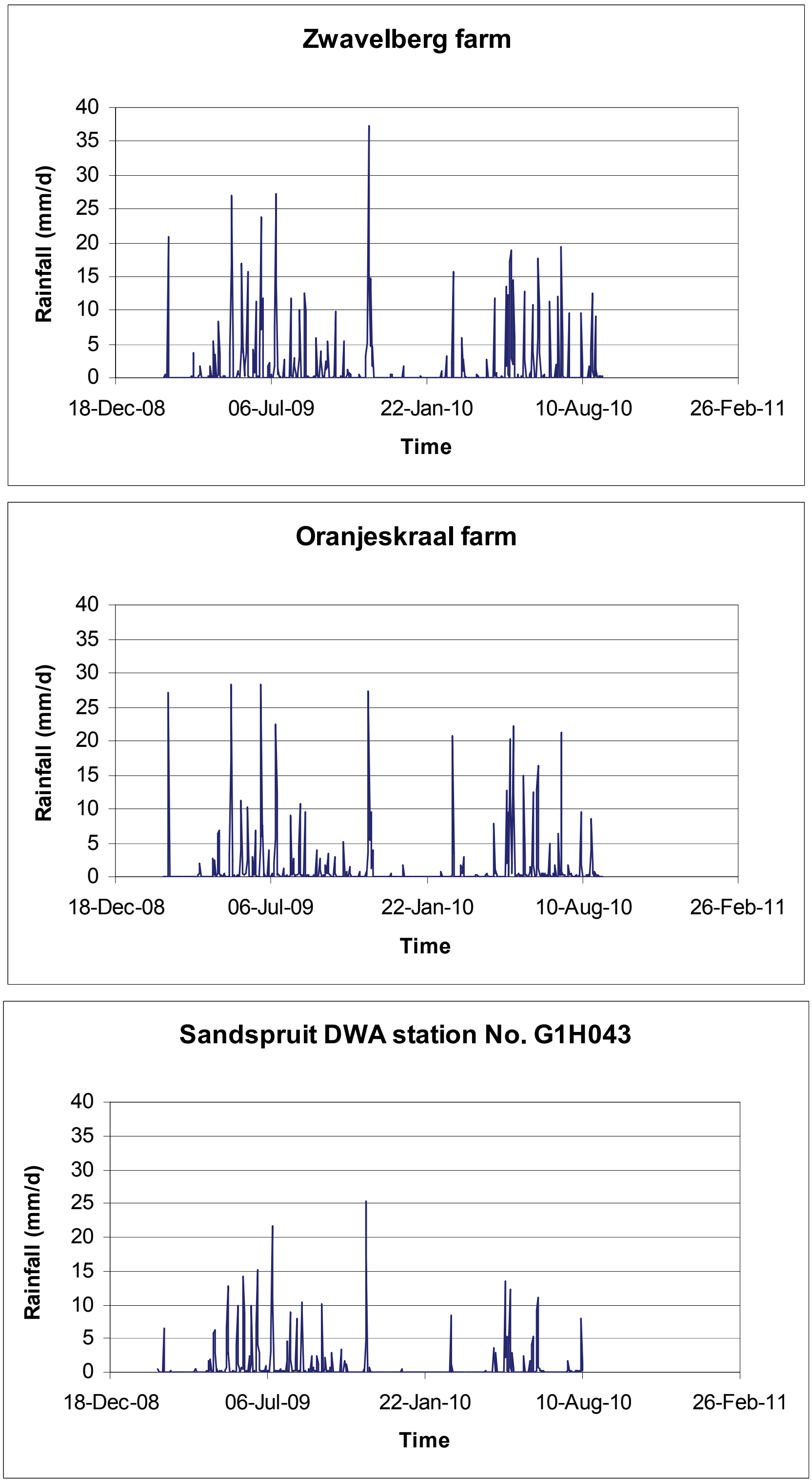


Figure 18

Comparison of daily rainfall at Zwavelberg (top), Oranjeskraal (middle) and Sandspruit DWA station No. G1H043 (bottom graph)

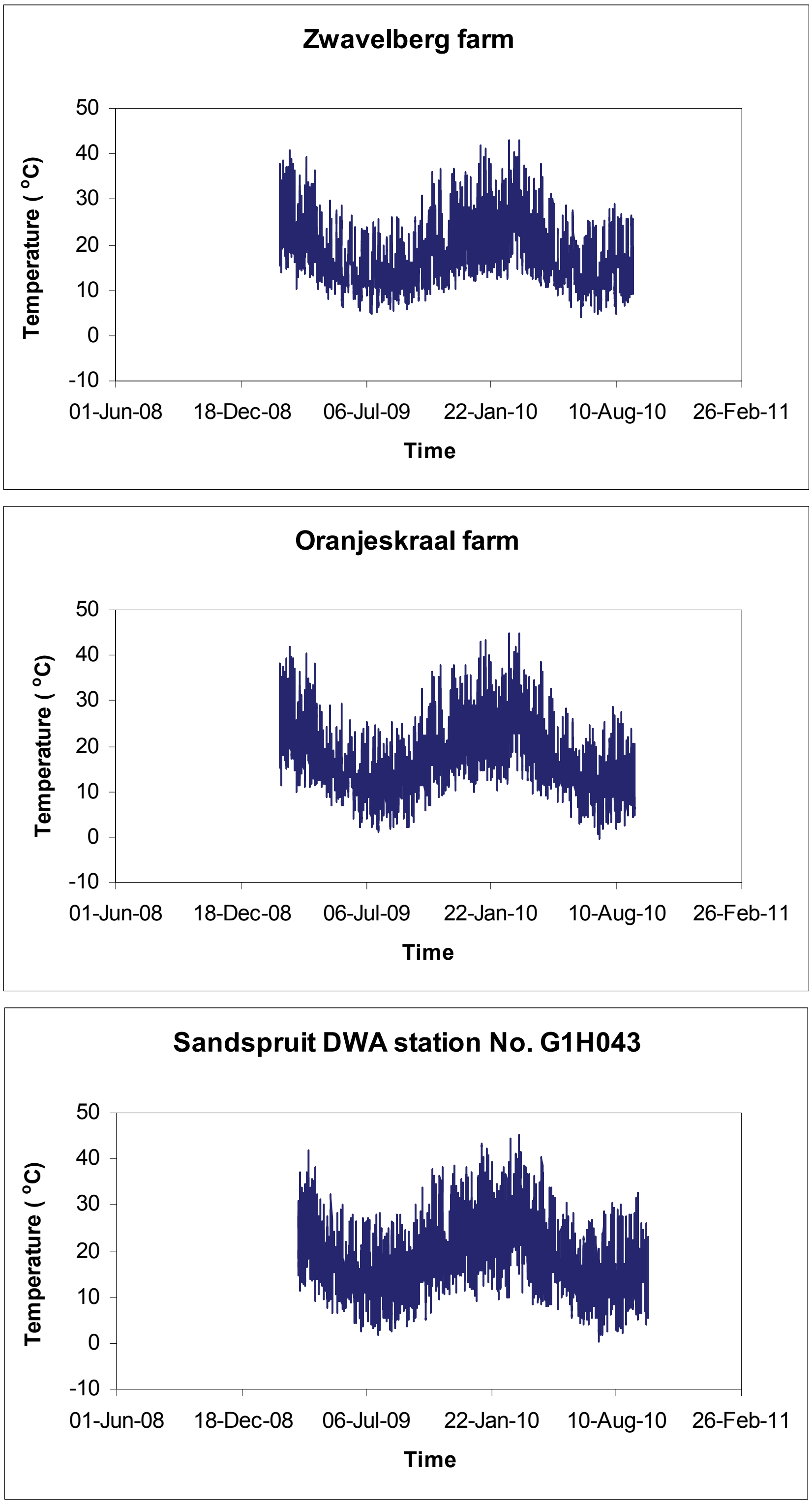


Figure 19

Comparison of daily air temperatures at Zwavelberg (top), Oranjeskraal (middle) and Sandspruit DWA station No. G1H043 (bottom graph)

3.5.2 Surface water monitoring

Water flow and quality data from the monitoring station at Sandspruit (G1H043, Figure 8 in section 3.3.4) were obtained from DWA. An additional monitoring site was proposed at culverts built by Road Services, in order to monitor flow and water quality representing the upper reaches of the Sandspruit (Figure 20). It was realized, however, that an environmental impact assessment would be required for the installation of a monitoring weir as this is a listed activity in terms of section 24 (Government Notice No. 386, Department of Environmental Affairs and Tourism) of the National Environmental Management Act (NEMA, 1998) and regular manpower for maintenance would be required for the establishment of any water level monitoring devices. This would have considerably increased the expense of the monitoring programme and so the idea was abandoned.

Figure 20

Proposed locations for installing equipment for monitoring water flow and quality representing the upper reaches of the Sandspruit (at culverts built recently by Road Services), and location of DWA monitoring station No. G1H043

3.5.3 Borehole drilling and vadose zone profiling

The Department of Water Affairs funded the drilling, installation and development of boreholes in the Sandspruit catchment. A tender was published in December 2008 according to the specific research requirements for borehole drilling and monitoring (the borehole specifications are available in Deliverable 5 of this project). The tender was awarded to SA Rock Drill. Borehole drilling commenced on 22 April 2009 and lasted until 30 June 2009.

Three main transects were identified for the installation of boreholes across the Sandspruit catchment's slopes. The location of transects were chosen to represent the main geological environments and features of the Sandspruit catchment. The geological environments are strongly linked to the type of soils present in the catchment, and this is linked to associated land uses (type of farming) in the area. The three main transects were located in the upper, mid- and lower reaches of the Sandspruit (Figure 21). Transect 1 (Zwavelberg, Figure 21) in the upper reach, including 10 boreholes, was located on the lower slopes of the Kasteelberg mountain. The geology in the area is characterized by Table Mountain Group (TMG) sandstone (towards the mountain), and alluvium/colluvium overlying Malmesbury shale on the opposite slope. Transect 2 (Oranjeskraal, Figure 21), including 3 boreholes, represents the mid-reach of the Sandspruit, a Malmesbury shale dominated environment. Malmesbury shale is also dominating at the location of transect 3 (Uitvlug, Figure 21, including 5 boreholes), but the alluvial cover is somewhat different in texture (generally sandier) compared to transect 2. Upon completion of the first three transects an additional transect was drilled (Malansdam, Figure 21, including 4 boreholes) representing the upper northern reach of the Sandspruit. Table 8 summarizes the location of all boreholes. A detailed description of the borehole sites is available in Deliverable 5 of this project.

At some locations two water strikes were encountered. Shallow boreholes (marked with "a" in Table 8) were therefore drilled adjacent to deep ones and both were sealed to allow water level and quality monitoring of different aquifers in the vertical profile. Shallow boreholes served the purpose of piezometers to measure interflow as their depths generally coincided with the interface between the sand/silt cover and the Malmesbury clayey shale with low hydraulic conductivity, where build-up of temporary perched water tables is possible during the rainy season.

Drilling samples of 2-3 kg of representative sediment material were collected from layers (depths) that displayed characteristic features and different layering. The samples were sealed in sampling bags and used to measure soil water content by drying sub-samples in the oven at 105°C for at least 2 days. The sub-samples were subsequently used to prepare 1:5 solid:solution extracts. The sub-samples were first weighed, distilled water was added, the mixture shaken for about 45 minutes, left overnight and centrifuged for about 10 minutes. The resulting solution was used to measure electrical conductivity (EC) and Cl content of 1:5 solid:solution extracts and draw EC and Cl profiles for sediments. The upper reaches of the catchment coincide with the recharge area from the Kasteelberg sandstone formation and low levels of salinity were recorded here. In the mid- and lower reaches of the catchment, high salinity levels were measured due to the presence of natural salts of meteoric origin trapped in sediments. It was deemed that this natural salinity would somewhat interfere with the interpretation of Cl profiles at these locations. Chloride profiles were therefore not described in the mid- and lower reaches of the catchment. They were determined only in the upper reach (Zwavelberg, Figure 21). All sediment samples collected during the drilling campaign were stored for further analyses.

Figure 22 includes the gravimetric water content profile, chloride profile (Cl concentration solid:solution 1:5 ratio extracts) and the geological log of borehole ZB003 as an example. The borehole log was drawn in the Excel-based software Borehole Logging v. 1.0 developed by H. Jia (University of Fort Hare) and Y. Xu (University of the Western Cape) and funded by the Water Research Commission. Peaks of Cl concentrations can be observed in the top soil due to evaporation-driven accumulation of salts close to the surface, as well as at depths approaching saturation conditions (Figure 22).

The drilling exercise proved very valuable to obtain new data and update the knowledge on conditions occurring in the catchment. The full report on borehole drilling and sediment analyses can be found in Deliverable 10 of this project. No soil monitoring took place but piezometers installed at the interface of alluvial cover and weathered shale were used to monitor the important process of interflow.

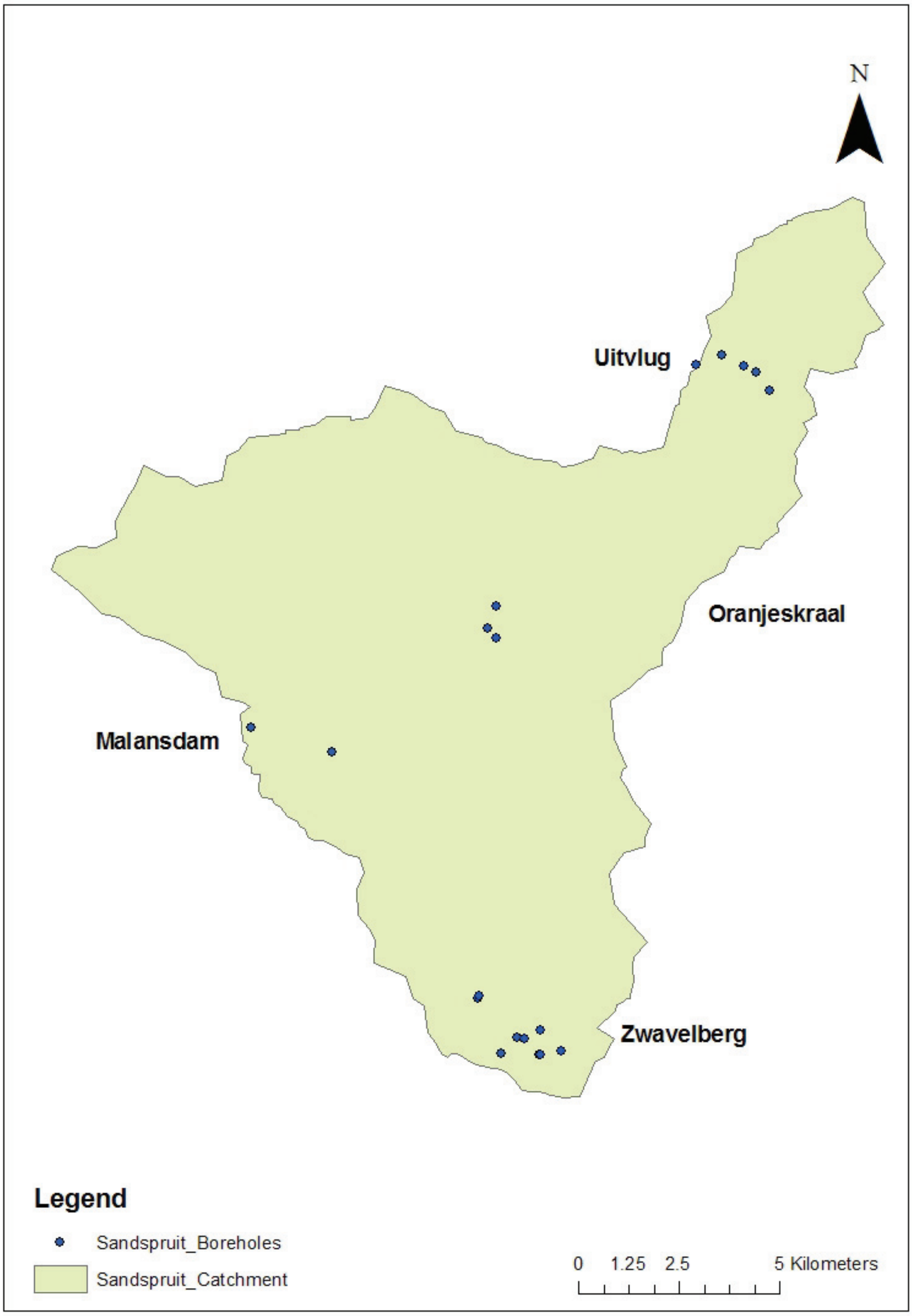


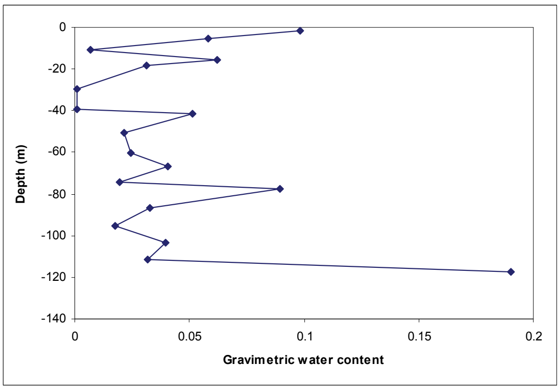
Figure 21
Map of the Sandspruit catchment with positions of boreholes and names of farms

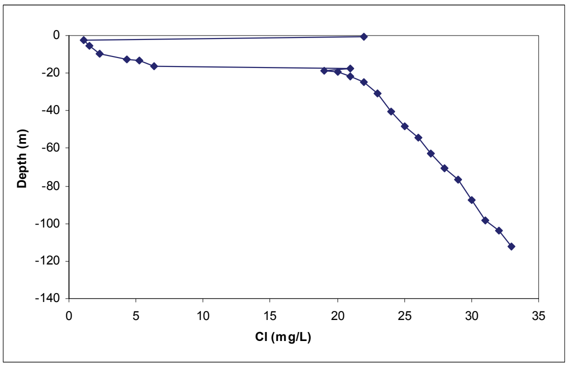
TABLE 8 LOCATION OF BOREHOLE TRANSECTS IN THE SANDSPRUIT CATCHMENT					
Farm	**Borehole No**	**Latitude S**	**Latitude E**	**Altitude (m)**	**Borehole depth (m)**
Zwavelberg	ZB001	33.35245	18.81108	309	12
	ZB002	33.34896	18.81472	278	18
	ZB003	33.34921	18.81642	272	120
	ZB003a	33.34921	18.81642	272	12
	ZB004	33.35187	18.82455	361	115
	ZB005	33.35187	18.82455	361	15
	ZBJD[1]	33.35187	18.82457	361	6
	ZB006	33.35279	18.81962	303	151
	ZB006a	33.35284	18.81973	303	12
	ZB007	33.34745	18.81996	303	85
	ZB007a	33.34745	18.81996	303	12
Oudekraal (adjacent to Zwavelberg)	OKR1	33.34023	18.80592	219	84
	OKR1a	33.34023	18.80592	219	12
	OKR2	33.33972	18.80619	219	30
Oranjeskraal	OK001	33.25959	18.80986	107	103
	OK002	33.25757	18.80806	118	30
	OK003	33.25256	18.80997	125	36
Uitvlug	UV001	33.19636	18.86041	70	72
	UV002	33.19873	18.86535	62	30
	UV003	33.20017	18.86819	64	42
	UV004	33.20425	18.87108	81	48
	UV005	33.19855	18.85466	119	120
Malansdam	DM1	33.27970	18.75520	231	120
	DM1a	33.27970	18.75520	231	12
	DM2	33.28504	18.77325	144	78
	DM2a	33.28504	18.77325	144	12

[1]Logged, but not used for research and monitoring

Boreholes marked with “a” are shallow boreholes adjacent to a deep one. ZB005 is a shallow borehole adjacent to deep borehole ZB004.

ZB – Zwavelberg farm; OK – Oranjeskraal farm; UV – Uitvlug farm; OKR – Oudekraal farm; DM – Malansdam farm





Well ID	ZB003	Well Log: Lithology and Construction					
		Sandspruit					
Drilling method:		Rotary pneumatic		Contract No.			
Coordinate		X	18.81642	Scale	H	6	
		Y	-33.34921		V	800	
Surface Elevation (m)		272		Diameter (mm)		75	
Well depth (m)		120		Commencing date		20090428	
Casing depth (m)		108		Ending date		20090506	
Layer No.	Strata	Thick (m)	Elev. (m)	Depth (m)	Column map	Lithology	Remark
1	Q	1	271	1		Very thin top soil (<1 m), sandy clayey material, pale yellow colour. Quartz and boulder chips. High clay content.	
2	Q	2	269	3		Pale yellow colour, some clay, fine sand. Boulder chips.	
3	Q	3	266	6		Light brown, fine sand. Low clay content. Minimal boulder chips.	
4	Q	2	264	8		Light brown, fine sand. Some clay material.	
5	MS	2	262	10		Mixture of light brown sand and shale fragments.	
6	MS	9	253	19		Fine shale fragments (weathered), clayey material.	Moist at 18-19 m.
7	MS	21	232	40		Grey shale. Majority coarse fragments.	
8	MS	30	202	70		Grey shale. Coarse and fine material.	Very little moisture in shale samples.
9	MS	7	195	77		Grey shale, coarse and fine.	
10	MS	1	194	78		Grey shale, coarse and fine.	Sample moist due to water addition to minimize dust.
11	MS	42	152	120		Grey shale, coarse and fine.	Water strike: 116-117 m.

Figure 22

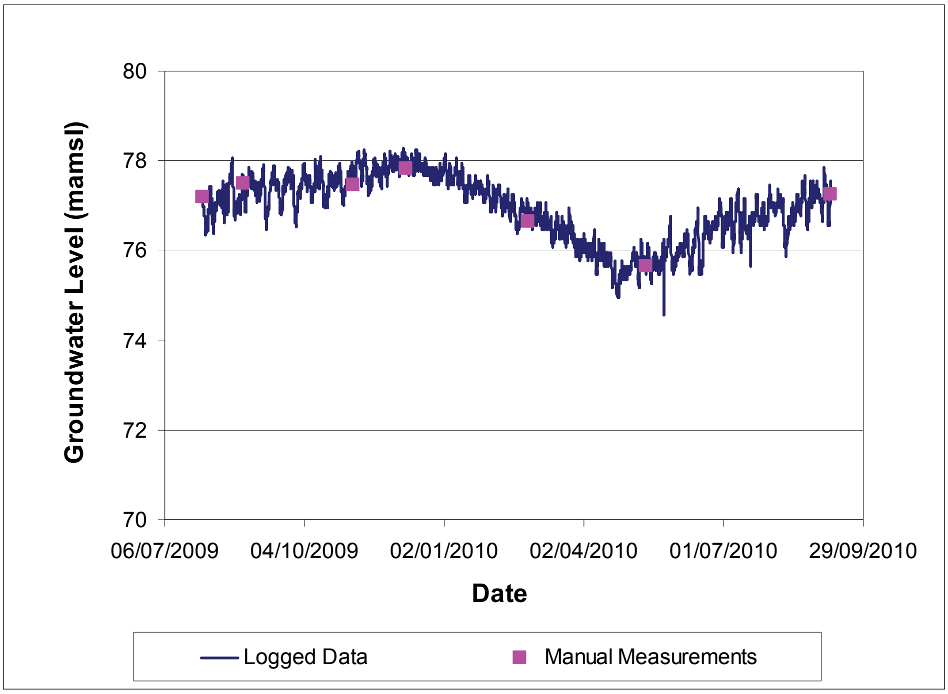
Water content profile (top, units in g water g^{-1} sediment), chloride profile (Cl concentration of solid:solution 1:5 extracts) (middle) and log of borehole ZB003 (Zwavelberg farm)(bottom)

3.5.4 Groundwater monitoring

Nine Solinst loggers were installed in boreholes drilled in the Sandspruit catchment for hourly measurements of groundwater level and temperature (Table 8: ZB003, ZB004, ZB006, ZB007, OK002, DM1, UV001, UV004 and UV005). In addition, an Eijkelkamp CTD diver was installed in borehole UV002 for hourly measurements of groundwater level, temperature and EC. Groundwater level readings were corrected for atmospheric pressure with an Eijkelkamp barometer logger. Manual measurements of groundwater level were also taken with a dip meter in all boreholes during field visits. The purpose of these measurements was to facilitate the conceptualization of groundwater flow in the catchment, including the identification of seasonal and human-induced trends.

Seasonal trends of groundwater levels were observed. Groundwater level fluctuations varied between 1.36 m in the mid-reaches (borehole DM1 at Malansdam) to 5.68 m in the upper reaches on the sandstone slopes (borehole ZB006 at Zwavelberg). This indicates that groundwater recharge/discharge processes may be occurring at seasonal scale and that these processes tend to be slow due to low hydraulic conductivities and transmissivities. These physical parameters could, however, not be accurately determined as pumping tests were not conducted. Groundwater temperatures were between about 18.7 (upper reaches, borehole ZB004, Zwavelberg farm) and 22.0°C (lower reaches, borehole UV005, Uitvlug farm). They varied very little at each borehole with variations between 0.04 and 0.19°C. Figure 23 shows an example of groundwater levels and temperatures recorded at UV004 in the lower reaches of the Sandspruit catchment (Uitvlug farm). Groundwater level and temperature records for all other boreholes are available on the CD attached to this report.

The potentiometric surface was interpolated using historic data of the National Groundwater Archive and data from the new boreholes. The potentiometric map was updated in Figure 11b and compared to the historic map (Figure 11a).



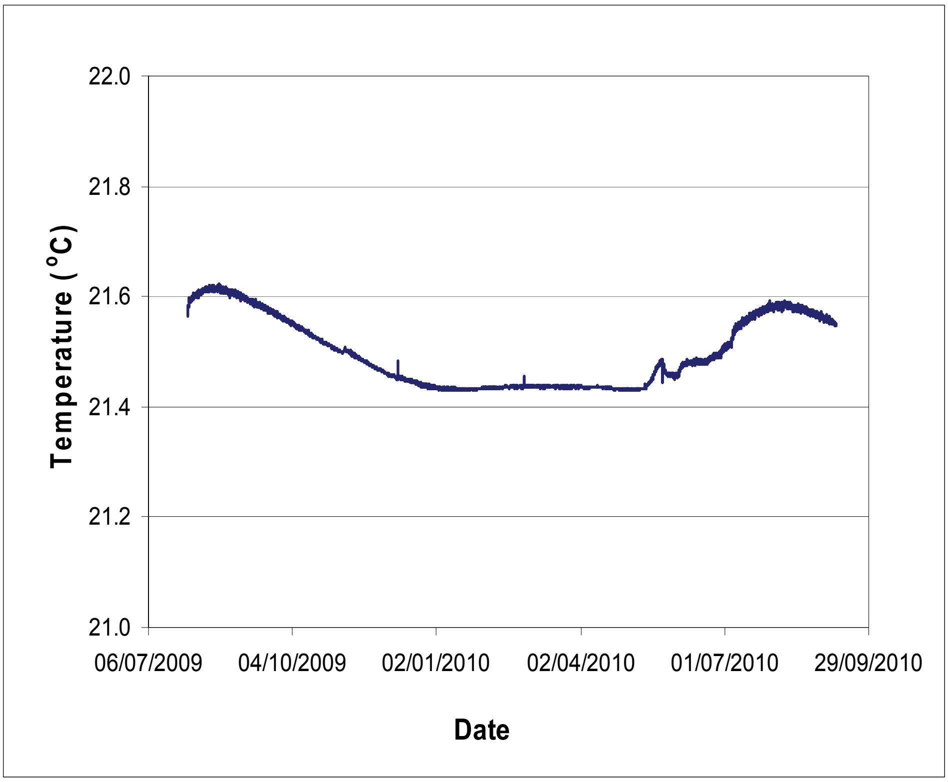


Figure 23

Groundwater level (top graph) and temperature data (bottom graph) logged with Solinst loggers at borehole UV004

Groundwater samples were collected for groundwater chemistry analyses on 6-8 September 2010. Samples were collected after purging 3 volumes of groundwater from boreholes, by filling sampling bottles to the top and sealing them to prevent contamination. The samples were analyzed at the CSIR inorganic chemistry laboratory in Stellenbosch. The groundwater samples were handled according to the guidelines and the samples were analyzed for EC, pH and major cations and anions according to standard laboratory procedures.

The results are presented in Table 9. The piper diagram of the groundwater chemistry is shown in Figure 24. The following can be deduced from the chemical analyses:

- The quality of groundwater from the Table Mountain Group sandstone is good with EC ranging between 35 and 280 mS m^{-1} (Zwavelberg farm boreholes).
- Groundwater salinity increases downstream. Electrical conductivity in groundwater ranged from 33 mS m^{-1} at ZB004 and ZB005 in the vicinity of the sandstone formation to 2,200 mS m^{-1} at UV003 underlain by the Malmesbury Group shales.
- A salinity hotspot was identified in the lower reaches of the catchment with groundwater EC ranging from 290 to 2,200 mS m^{-1} (Uitvlug farm).
- Na and Cl are the dominant ions present in groundwater at all boreholes. Magnesium, calcium and sulphate are occasionally elevated in the upper reaches of the catchment (Zwavelberg farm).
- Very low concentrations of K were measured in all boreholes.
- Nitrate was negligible in most cases. A few exceptions probably occurred around homesteads.
- Cu and Zn were generally very low, whilst Fe and Mn were occasionally elevated, possibly originating from the mineralogy at specific sites.
- The Sandspruit river is highly saline at DWA station No. G1H043 and NaCl is the dominant salt.

Measurements of groundwater EC in the new boreholes were used to update the groundwater EC map (Figure 12b) and compare it to the historic EC map (Figure 12a). The new groundwater EC map showed a more extensive area of high salinity in the downstream reaches and to the East of the catchment, compared to the historic map.

TABLE 9
GROUNDWATER CHEMISTRY ANALYSES IN THE SANDSPRUIT CATCHMENT FOR SAMPLES COLLECTED ON 6-8 SEPTEMBER 2010

Sample	EC at 25 ºC (mS m^{-1})	pH at 20 ºC	TDS (mg L^{-1})	Alk. as $CaCO_3$ (mg L^{-1})	SAR	K (mg L^{-1})	Na (mg L^{-1})	Ca (mg L^{-1})	Mg (mg L^{-1})	SO_4 (mg L^{-1})	Cl (mg L^{-1})	NO_3 + NO_2 (mg L^{-1})	Cu (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})	Zn (mg L^{-1})	% diff. cations and anions
Sandspruit river at G1H043	1020	8.3	6528	435	19.1	20	1653	151	251	495	2910	<0.1	0.01	0.17	0.01	0.02	0.22
ZB002	245	7.2	1568	283	5.7	2.9	302	77	81	162	504	1.3	0.01	19.12	1.04	0.08	0.84
ZB003	98	7.3	627	116	2.8	1.5	100	49	29	107	165	<0.1	0.01	27.99	1.43	0.06	0.10
ZB003a	72	6.8	461	57	3.1	1.3	86	17	25	111	113	<0.1	0.09	80.78	1.25	0.24	0.30
ZB004	35	7.0	224	78	1.5	4.1	34	19	12	28	54	<0.1	0.01	32.95	0.79	0.04	2.08
ZB005	35	6.6	224	36	2.5	1.1	40	8.3	7.2	7.0	74	<0.1	0.01	3.77	0.46	0.05	3.08
ZB006a	280	6.9	1792	80	6.1	0.5	330	58	101	171	703	1.9	0.01	0.87	0.24	0.16	0.88
OKR1	335	7.8	2144	230	7.0	6.8	432	123	100	268	782	4.9	0.08	117.1	1.90	0.24	1.16
OKR1a	320	7.8	2048	175	7.2	4.6	405	100	85	240	748	<0.1	0.03	50.12	0.58	0.16	0.21
DM2	460	7.6	2944	183	8.8	9.4	606	124	142	244	1230	<0.1	0.01	37.01	8.66	0.07	1.17
DM2a	460	7.1	2944	121	8.8	15	606	103	154	355	1130	21	0.01	10.86	0.27	0.03	1.54
OK001	220	7.9	1408	124	6.2	2.7	281	68	54	96	545	<0.1	0.01	0.12	0.26	0.07	0.61
OK002	740	7.3	4736	158	15.6	23	1133	112	175	304	2040	16	0.01	10.15	0.31	0.09	1.23
UV001	290	7.5	1856	79	7.1	10	367	77	76	71	784	0.2	0.01	0.07	0.00	0.03	2.03
UV002	2000	7.1	12800	183	15.4	49	2592	614	936	1197	6640	<0.1	0.01	1.30	5.85	0.02	1.32
UV003	2200	7.2	14080	379	29.1	29	3773	284	600	635	7220	<0.1	0.01	1.74	0.62	0.02	0.87

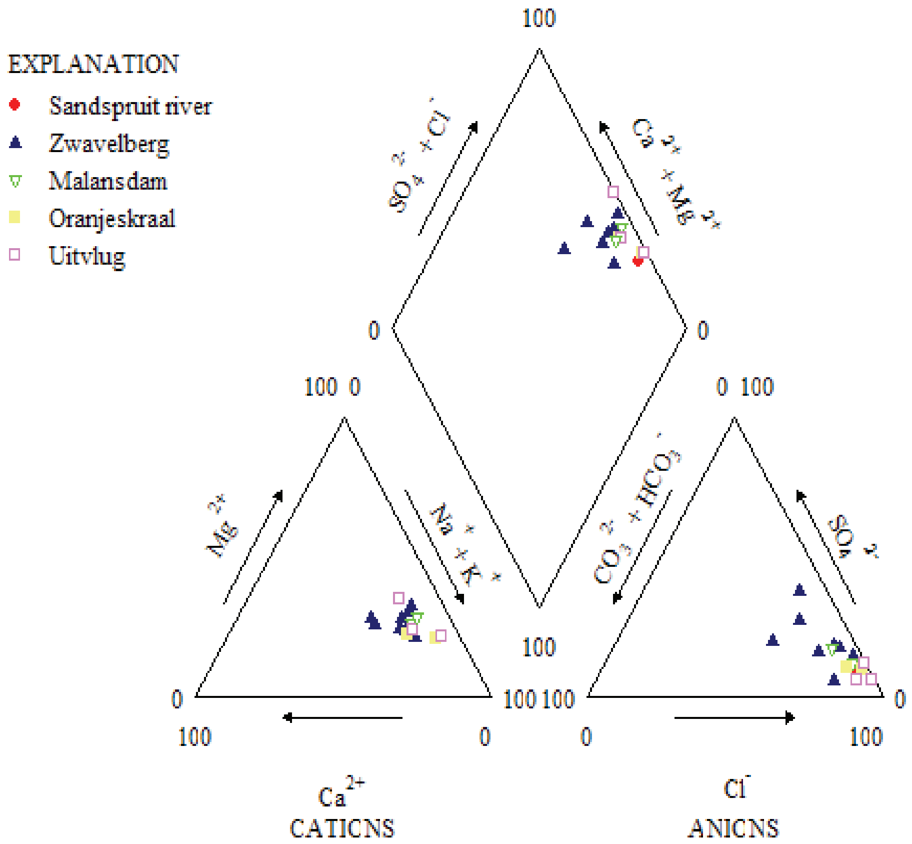


Figure 24
Piper plot of groundwater chemistry data in the Sandspruit catchment

3.5.5 Geophysical study

Resistivity measurements were carried out at the borehole transects (Figure 21) with a Lund imaging system. The resistivity tomography method was used to provide a pseudo-section of change in electrical properties in the subsurface along a specified line or transect. The bulk resistivity of different geological strata varies mostly because of changes in salinity of the pore fluid or changes in porosity of the host rock (Archie's empirical formula from Telford et al., 1990). In our case, the aim of resistivity measurements was to detect changes in geological strata down to 15 m depth and along lines (transects) about 120 m in length. A total of 12 resistivity transects were measured. Resistivity measurements took place between February and March 2009 (end of drought season).

Two multi-core cables with 32 electrode take-outs every 2 m were used for the shallow profiles. These cables were laid out on the ground, consecutively from start to end, in a straight line to cover about 128 m. An electrode (metal stake) was inserted into the ground next to every electrode take-out on the cable. The electrode take-out was then connected to the electrode with a short cable jumper. The multi-core cables were connected to the ABEM electrode selector ES464 that controlled the measurement sequence. The electrode selector was connected to the ABEM Terrameter SAS1000 that took the apparent resistivity measurements. The data were collected using a standard protocol with the Wenner array. The apparent resistivity data acquired in the field were inverted using the RES2DINV software (Loke, 2001) to provide a true-depth resistivity section. The depth of the inverted section is often over-estimated in very conductive conditions. Depth sounding data is then abstracted for a single representative lateral position on every profile to be able to adjust the depth to more realistic levels.

On the large scale, changes in lithology could be broadly delineated along the resistivity profiles. Most of the area shows a higher general resistivity in deeper layers, which is due to the presence of fractured/weathered shale. For example, the high resistivity deeper in the profile close to borehole ZB003 (Figure 25) is an indication of the presence of shale, which was verified during borehole logging and sampling (Figure 22). The high resistivity is due to the clayey texture of the material and very dry conditions, as measurements were taken at the end of the dry summer season. All resistivity results from the geophysical study can be found in Deliverables 6 and 10 of this project.

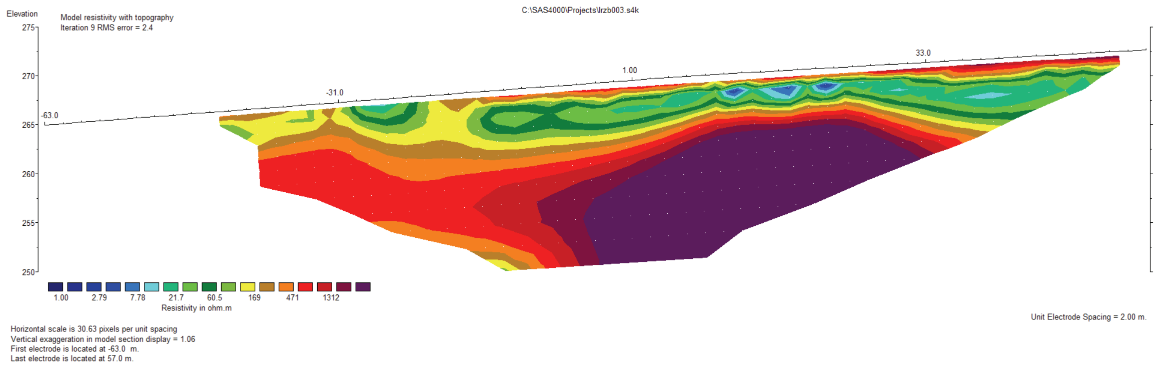


Figure 25

Cross-section of resistivity measurements at site ZB003 (Zwavelberg farm)

3.5.6 Isotope studies

Isotope studies were conducted in order to determine the dominant flow pathways in the system (overland flow, throughflow and baseflow) (Rice and Hornberger, 1998). For this purpose, stable isotope ratios of deuterium/hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$) were determined in surface water and groundwater samples. Samples were taken in November 2009 (only groundwater as no surface water flow occurred) and September 2010. Samples were collected after purging three volumes of groundwater from boreholes, by filling sampling bottles to the top and sealing them to prevent air entry. Measurements were carried out at the University of KwaZulu-Natal, School of Bioresources Engineering and Environmental Hydrology (Pietermaritzburg). The detailed methodologies for sample preparation, measurement and analysis are available in Deliverable 10 of this project.

The results of the isotope study are shown in Figure 26. The Global Meteoric Water Line (GMWL, representing the world average; Craig, 1961) and the Local Meteoric Water Line (LMWL, representing Tulbagh located ~30 km East of the Sandspruit catchment; Diamond and Harris, 1997) are plotted on the graph in Figure 26.

Box 1: Interpretation of isotope analysis of water samples
Data points tending to plot below the meteoric water line (right/top right of the graph) indicate that samples originate from a surface water body that has undergone evaporation (enriched in stable isotopes). In the case of groundwater samples, this indicates groundwater recharge occurred from water bodies that have undergone evaporation.
Data points close to, or tending to plot above the meteoric water line (left/bottom left of the graph), indicate that samples are relatively depleted with respect to δ^2H and $\delta^{18}O$. In the case of groundwater samples, this would indicate direct recharge from precipitation.

In general the data points originating from the isotope analyses shifted from GMWL but they plotted close to the LMWL. Groundwater samples collected in the upper reaches of the Sandspruit catchment (boreholes at Zwavelberg farm), which represents the main recharge area, had data points generally plotting above the LMWL (Figure 26, green ellipse) indicating direct recharge from precipitation. Favourable conditions for quick recharge occur in the upper reaches, like for example exposed bedrock, minimal soil covering, higher rainfall and the fractured nature of the TMG. All other groundwater data in the mid- and lower reaches plotted below the LMWL (Figure 26, orange ellipse), indicating that groundwater recharge occurred from surface water bodies that have undergone evaporation. Larger variations in isotopic signatures were observed in the upper reaches compared to the mid- and lower reaches. This may indicate that younger groundwater subject to variations in rain water isotopic composition occurs in the upper reaches, whilst a large groundwater storage capacity in the mid- and lower reaches may buffer the rain water signature. Isotope analyses of river water samples showed a similar signature to the groundwater samples in the mid- and lower reaches, indicating that the main water pathway in the system is through the subsurface (interflow and, to a lesser extent, baseflow). Two surface water data points plotting in the top right of the graph along LMWL (Figure 26) may be an indication of a mixture of groundwater and recent rain water. Isotope measurements of rain water samples and a more comprehensive event-based sampling programme are required in order to facilitate a full interpretation of the isotope analyses (Harris et al., 2010).

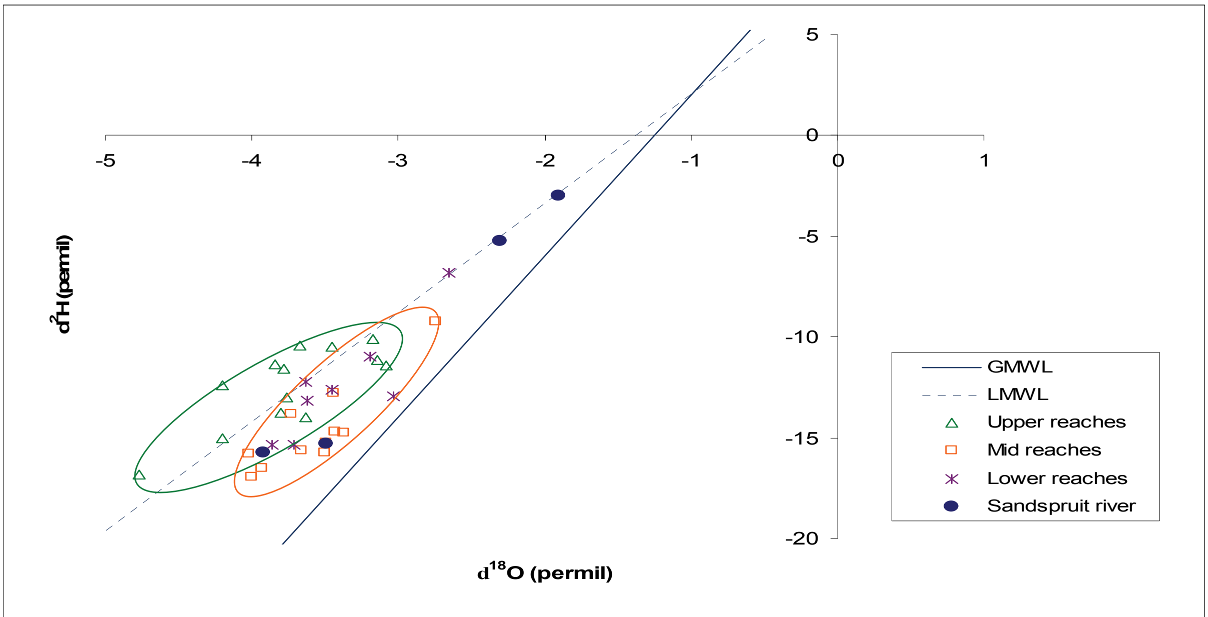


Figure 26
Environmental isotope groundwater samples collected in the upper, mid- and lower reaches of the Sandspruit catchment, and river water samples plotted together with GMWL (Global Meteoric Water Line; Craig, 1961) and LMWL (Local Meteoric Water Line; Diamond and Harris, 1997)

3.5.7 Water balance of the Sandspruit catchment

Data gathered during this investigation allowed for the annual water balance to be quantified and a conceptual flow model to be developed for the Sandspruit catchment (Figure 27). The catchment receives 473 mm a^{-1} precipitation on average (Table 7). Higher rainfall (494 mm a^{-1} at the foot of Kasteelberg) was recorded in the upper reaches of the catchment where groundwater recharge mainly occurs through the Sandstone fractured rock system, compared to the lower reaches (321 mm a^{-1} at DWA station No. G1H043). Streamflow at DWA gauge G1H043 is measured to be approximately 30 mm a^{-1} (Figure 9). Evapotranspiration makes up the remainder of the water balance (443 mm a^{-1}), assuming there are no other losses of water, e.g. regional groundwater losses directly through discharge into the Berg River. Soil water and groundwater storage are negligible components of the water balance in the long run.

Seasonal fluctuations of the groundwater potentiometric surface suggested that evaporation impacts the groundwater table and that a seasonal groundwater recharge-discharge mechanism exists (Figure 23). The stream is seasonal and it is fed through subsurface flow (mainly interflow) during the winter rainy season. As groundwater recharge and discharge is less than streamflow (30 mm a^{-1}) the historic values of groundwater recharge of 69-71 mm a^{-1} estimated by Vegter (1995) for quaternary catchment G10J appear to be overestimated (assuming no other groundwater losses occur). A simple theoretical equation can be applied to estimate groundwater recharge based on the chloride mass balance method (Eriksson and Khumakasem, 1969):

$$R_T = P \times Cl_P / Cl_{gw}$$

R_T – Groundwater recharge (mm a^{-1})
P – Annual precipitation (mm a^{-1})
Cl_P – Chloride concentration in rain water (mg L^{-1})
Cl_{gw} – Chloride concentration in groundwater (mg L^{-1})

The chloride mass balance method assumes steady state between the chloride flux at the surface and the chloride flux beneath the evapotranspiration and mixing zone, and no atmospheric deposition or other source of chloride. For borehole ZB003 (Zwavelberg farm), chloride concentration in groundwater was measured to be 165 mg L^{-1} (Table 9), which is consistent with the chloride profile in Figure 22, where Cl concentration in a 5:1 water:sediment extract was about 33 mg L^{-1} in proximity of the groundwater depth. Annual rainfall was measured to be 494 mm a^{-1} (Table 7). Cl_P was measured to be 19 mg L^{-1} in the vicinity of the Sandspruit catchment (Bugan, 2008), which is in the range of values obtained by Weaver and Talma (2005) for the West Coast. Groundwater recharge can therefore be calculated as R_T = 494 mm a^{-1} x 19 mg L^{-1} / 165 mg L^{-1} = 57 mm a^{-1}. Using the empirical equation developed by Beekman et al. (1996) for semi-arid areas in Botswana ($R_T = 148 \ln(P) - 880$), a more realistic value of 29 mm a^{-1} was calculated for groundwater recharge.

The information from the expanded monitoring programme and the time series of data allowed us to better understand the system. The seasonal nature of the stream and the depth of the water table suggested that the regional groundwater contribution to streamflow is minimal, leaning towards negligible. Streamflow is driven by quick flow, which comprises overland flow and especially interflow from the alluvium cover. Temporary seasonal perched water tables occur at the interface of the alluvium cover and Malmesbury shale with low permeability, as identified in borehole logs during drilling (Figure 22). Infiltration is facilitated by preferential pathways created by root channels (winter wheat) as well as the minimization of overland flow rates by the dense wheat cover. In addition, man-made anti-erosion contours that are common in the area represent micro-areas where overland flow of water is barraged and water infiltrates. The dominant contribution to the stream hydrograph is therefore interflow, originating from the recharge of temporary groundwater tables in winter. The contribution of baseflow to the stream and streamflow occurs generally until November, about two months after the end of the rainy season. The percentage contributions to the hydrograph components (Figure 27) were estimated in the next section 3.5.8 on hydrological modelling.

Isotope analyses (Figure 26) indicated that groundwater was subject to evaporation before recharge took place, in particular in the mid- and lower reaches of the catchment. This is the same water that discharges and predominantly contributes to the stream. The poor correlation between average annual streamflow and average rainfall ($R^2 < 0.4$) suggested that a variety of factors may influence streamflow, e.g. rainfall distribution, cropping systems and evapotranspiration, etc. Streamflow is therefore more dependent on the rainfall distribution in time than on annual rainfall.

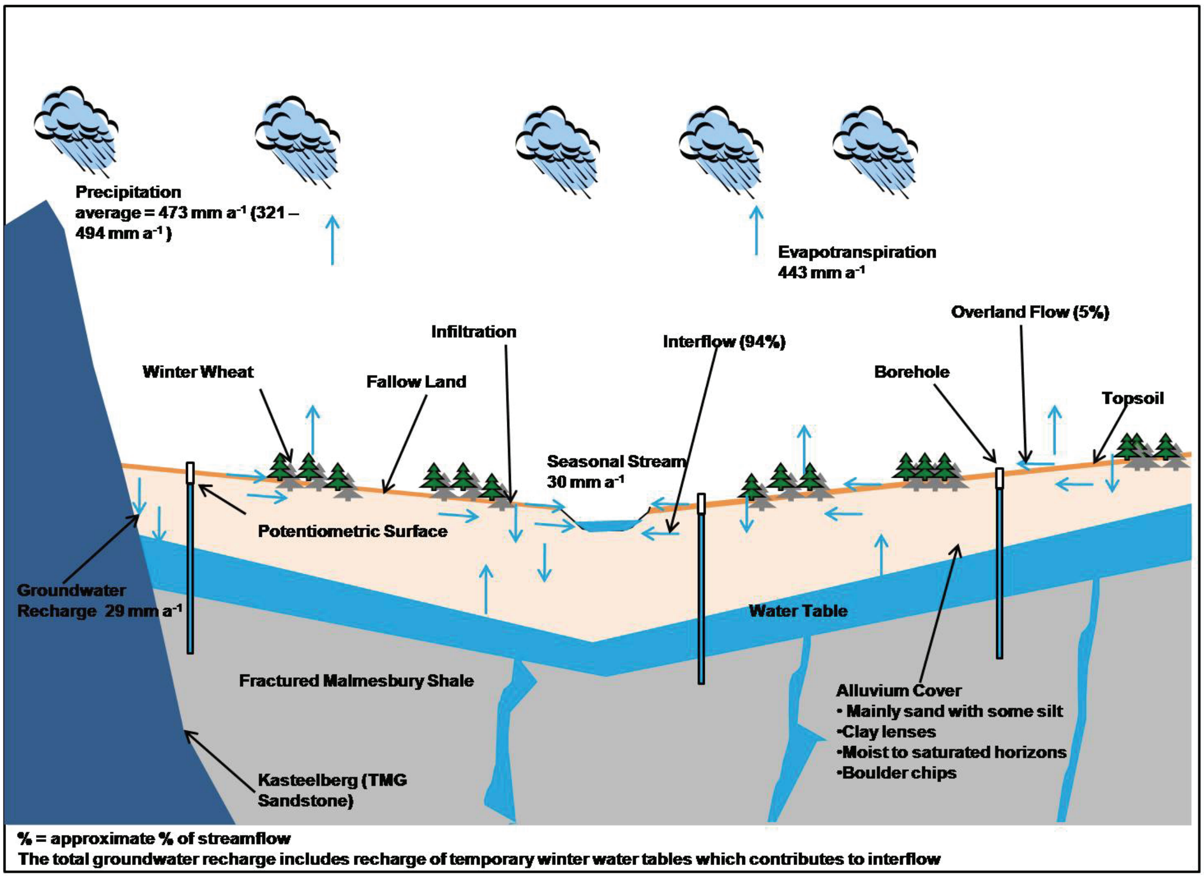


Figure 27
Conceptual flow model for the Sandspruit catchment

3.5.8 Hydrological modelling

In this section, data collected in the pilot study site at Sandspruit were applied for hydrological modeling with J2000. J2000 is a hydrological modelling system that simulates hydrological processes, the water balance, runoff and its concentration time as well as the components of the hydrograph (Krause, 2002; Krause *et al.*, 2006; http://jams.uni-jena.de/jamswiki/index.php/Hydrological_Model_J2000, accessed on 13 April 2010). Conceptually, J2000 is a distributed parameter hydrological model, similar to the Precipitation-Runoff Modelling System (PRMS) of the United States Geological Survey (USGS) (Leavesley *et al.*, 1983; 1996) and to the Agricultural Catchment Research Unit (ACRU) (Schulze, 1995). J2000 is generally applicable to meso- and macro-catchments

(> 1000 km^2), although it can be applied to smaller scales depending on the density of available data. The code is structured in modules, each representing hydrological processes independently that can be modified, added to or removed for a specific simulation. The spatial set-up makes use of a GIS platform (ArcGIS) and requires databases of topography, aspect, soil, geology, land use and climate. These data are used to delineate Hydrological Response Units (HRUs) or areas where hydrological processes can be described with unique functions and input parameters. Additional features of the modelling system include the regionalization of point data of climate and precipitation, as well as the link between land use and evapotranspiration. The separation of the components of the hydrograph includes: i) fast direct runoff – overland flow (RD1); ii) slow direct runoff – interflow within the soil zone (RD2); iii) fast base runoff – interflow from permeable weathering zones (RG1); and iv) slow base runoff – baseflow from joint aquifer or homogeneous loose rock aquifer (RG2). The contribution from each of the runoff components is dependent on the water storage capacity in the various zones and transfer coefficients and/or functions.

Input data to J2000 are static parameters that don't change over time (e.g. slope) and temporal variables (e.g. weather data). Both input parameters and variables were prepared for the Sandspruit catchment in text files, in the particular format that is required by the model. HRUs are delineated in an ArcGIS environment, based generally on topography, slope, aspect, geology, soil properties and land use. Input parameters are then allocated to each HRU and prepared in the following text files:

- landuse.par – land use
- hgeo.par – hydrogeology
- soils.par – soil types
- reach.par – water course network
- hru.par – a master file that indicates which land use, soil and hydrogeological IDs are assigned to each Hydrological Response Unit (HRU).

Input variables are also prepared in text files. These data include absolute humidity, relative humidity, precipitation, sunshine duration, maximum temperature, mean air temperature, minimum temperature, wind speed and observed runoff. Input variables may refer to one or more sites that are identified through coordinates. The model uses these data for regionalization of climatic and precipitation data, i.e. to assign climatic data and precipitation to each HRU.

Generally, hydrological models are calibrated to minimize the difference between measured and simulated streamflow (objective function). The streamflow data at DWA station No. G1H043 represented measurements for testing the objective function in modelling with the J2000 hydrological model. A printout of the main screen of J2000 is shown in Figure 28. In the main screen the user specifies the workspace directory containing input and output files, the start and end of simulation and the time for which efficiencies of model performance (statistical indicators) are calculated. Besides being able to manually edit the text files with input parameters and variables, the interface of the model allows the user to fine tune the calibration by changing certain inputs. These inputs can be accessed by clicking on tabs (left side of the printout in Figure 28). An extensive calibration exercise was performed for data collected in 2009 at Sandspruit by changing values of each of these inputs within a justifiable range and at certain intervals until optimal efficiencies of model performance (statistical indicators) were observed. Particular focus was given to the transfer coefficients used to characterize the contributions to streamflow via RD1, RD2, RG1 and RG2. The main purpose of the model calibration exercise was therefore to accurately quantify the different contributions to streamflow. The full description of the calibration procedure is available from the authors.

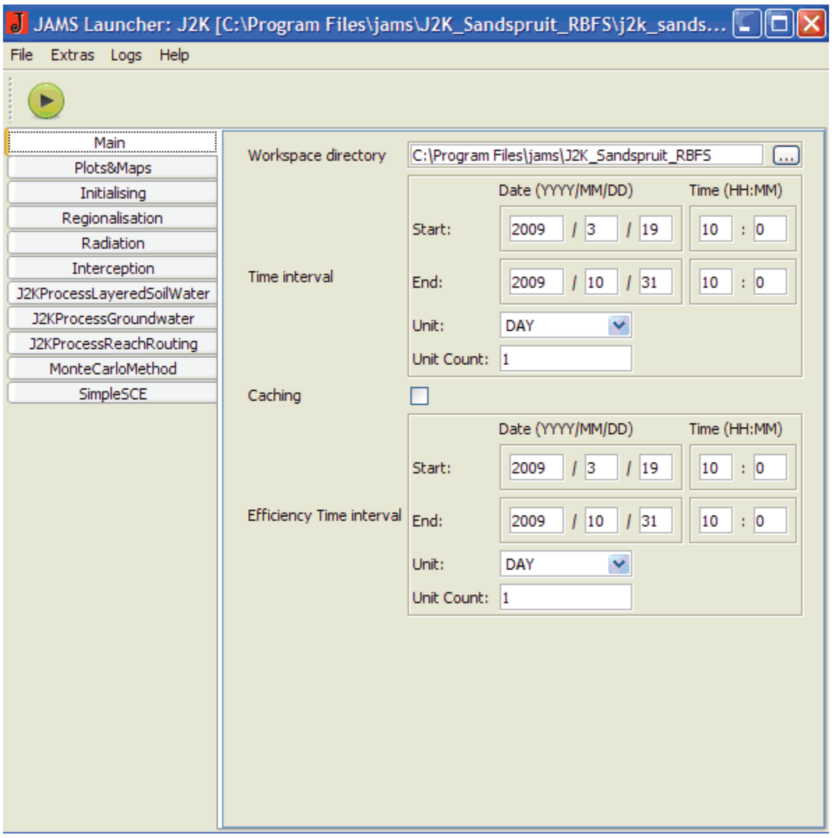


Figure 28

Main screen printout of the J2000 hydrological model

The J2000 model calibration was carried out using data from the Sandspruit catchment for the period from 19/03/2009 to 31/10/2009. The results of the simulation can be viewed in the graphical interface of the model and the model's performance can be assessed using several statistical indicators. The statistical indicators of performance, their definitions, and the values obtained in the simulation are reported in Table 10. The statistical indicators were calculated by comparison of simulated and observed runoff (station No. G1H043). In general, the statistical indicators showed an excellent performance of the model in simulating runoff during 2009. This is also visible from the comparison between simulated and observed runoff shown in Figure 29. However, more years of data collection and simulations will be required in order to fully validate the model.

TABLE 10 STATISTICAL INDICATORS OF MODEL'S PERFORMANCE AND VALUES OBTAINED FOR THE SIMULATION AT SANDSPRUIT – COMPARISON OF SIMULATED AND OBSERVED RUNOFF DURING 2009			
Symbol	Definition	Value	
		All weather stations	Excluding new weather stations[1]
e1	Modified Nash-Sutcliff efficiency (differences are not squared but their absolute values are applied)	0.66	0.43
e2	Nash-Sutcliff efficiency with power 2 (classic form)	0.84	0.60
Log (e1)	Modified Nash-Sutcliff efficiency (the logarithm of the values is taken; differences are not squared but their absolute values are applied)	0.54	0.10
Log (e2)	Modified Nash-Sutcliff efficiency (the logarithm of the values is taken)	0.63	0.08
ioa1	Modified index of agreement according to Willmott (differences are not squared)	0.83	0.73
ioa2	Index of agreement according to Willmott	0.95	0.89
r^2	Coefficient of determination	0.85	0.65
Grad	Slope of the regression line	0.79	0.81
wr^2	Coefficient of determination, weighted for the slope of the regression line	0.66	0.52
AVE	Absolute volume error	4.23	14.92
RMSE	Root mean square error	0.36	0.57
[1]Excluding weather stations installed for this project: Zwavelberg, Oranjeskraal and Sandspruit DWA station No. G1H043			

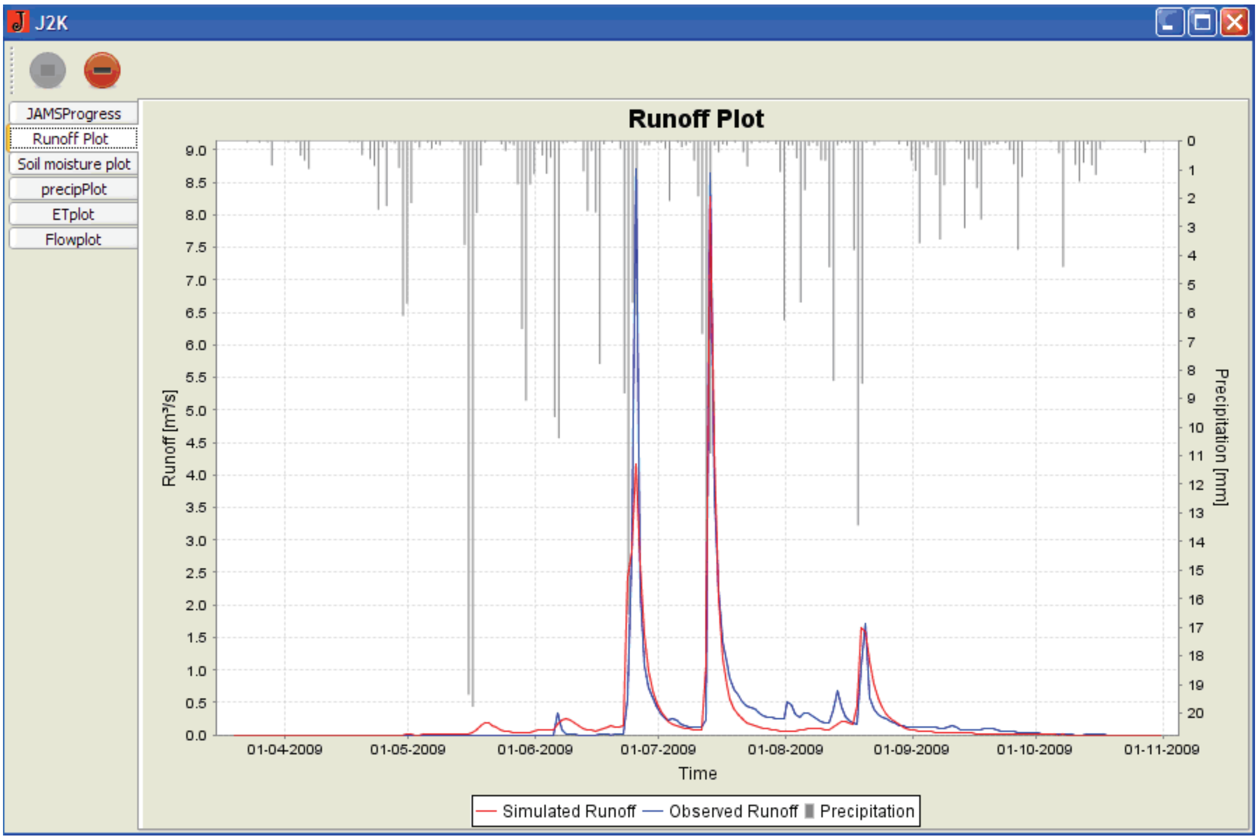


Figure 29
Screen printout of simulated and observed runoff, and precipitation for year 2009 at Sandspruit

The calibration of the model consisted mainly in varying input values of relevant parameters to match intensity and timing of flow peaks in Figure 29. This resulted in an accurate hydrograph separation as the contributions of RD1, RD2, RG1 and RG2 occur with different intensities and delays (for example, the contribution of RD1 – overland flow to the hydrograph occurs faster after a rainfall event than RD2 – interflow). Figure 30 represents the hydrograph separation. From this graph it is evident that the dominant contribution to runoff in the Sandspruit catchment was from interflow, occurring at the interface between the soil cover (generally sand) and weathered shale with very low permeability. Three main runoff events occurred during 2009 with interflow being the main contributor (94%). Contributions from overland flow (5%) and baseflow (1%) also occurred but they were minor. These estimates were used in the conceptual model and water balance described in Section 3.5.7 (Figure 27).

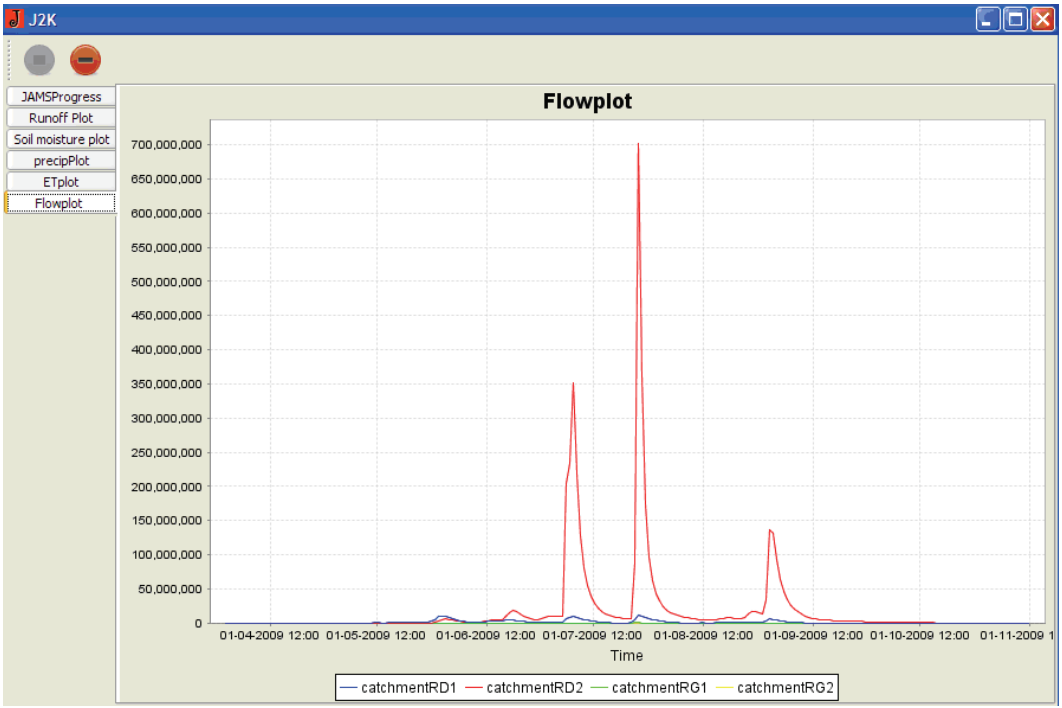


Figure 30

Screen printout of simulated contributions to runoff from overland flow (RD1), soil interflow (RD2), deep weathering zone interflow (RG1) and groundwater (RG2)

A sensitivity analysis was carried out to investigate how important it is to collect weather data, in particular rainfall, within the catchment, and whether the weather stations located outside the catchment can provide extrapolated data that would result in a sufficient accuracy of runoff simulation. For this purpose, a simulation was run for the same period and with the same input data, but using only weather stations outside the catchment. The statistical indicators of the simulation are shown in Table 10. The accuracy of the simulation was lower when only weather stations outside the Sandspruit catchment were used (lower Nash-Sutcliffe efficiencies, Willmott's index of agreement and r^2; higher absolute volume error and RMSE). This underlines the importance of monitoring weather within the study catchment and the benefits of installing the weather stations at Zwavelberg, Oranjeskraal and DWA station No. G1H043, in particular rain gauges due to the gradient in annual rainfall from the upper reaches downstream, as demonstrated in Figure 18.

Although only one example of model sensitivity analysis to weather input data is shown in this report, benefits were gained from all additional equipment and expanded monitoring programme. Borehole drilling, logging, groundwater level and quality monitoring in shallow and deep boreholes, isotope sampling and analyses as well as geophysical studies facilitated a better understanding and conceptualization of the system. Collection of additional data resulted in the generation of inputs for the J2000 model and accurate predictions of streamflow.

3.6 Benefits of the expanded monitoring programme at Sandspruit

An expanded monitoring network was designed and established in the Sandspruit catchment. The design was driven by two main principles:

1. The **consequential concept of geology, climate, soil and land use**, where these environmental features are linked in a cause and effect relationship.
2. the **concept of integrated catchment monitoring** that includes monitoring of the various components of the environment in an integrated system
    - ***Weather monitoring***
    - ***Hydrometry*** (surface and groundwater flow and quality measurements)
    - ***Vadose zone profiling*** (analyses of modes of water flow and contaminant transport in the sub-surface)
    - ***Geophysics*** (analyses of geological layering and water occurrences in sub-soil)
    - ***Isotope studies*** (analysis of flow paths and hydrograph separation)

The following benefits were drawn from the expanded monitoring programme in the Sandspruit catchment:

- All additional equipment and monitoring, namely weather stations, borehole drilling, logging, groundwater level and quality monitoring in shallow and deep boreholes, isotope sampling and analyses as well as geophysical studies facilitated a better understanding and conceptualization of the system. As a result, the conceptual model of the system was refined.
- A correct conceptual model is the basis for a scientifically sound description of the system and numerical modelling. Data collected in the expanded monitoring programme were used to generate inputs for the J2000 hydrological model.
- Quantification of the water balance (Figure 27).
- Weather stations installed within the watershed showed a gradient in rainfall (decreasing) and air temperature (increasing) from the upper reaches downwards (Figures 18 and 19).
- Drilling and installation of boreholes gave the opportunity to start a long-term, continuous monitoring programme with the use of water level and temperature loggers with minimal manpower required.
- An invaluable set of sediment samples was collected at 1 m depth intervals during the borehole drilling campaign, analyzed and stored for further use.
- Groundwater potentiometric and EC maps were updated and refined (Figures 11 and 12).
- Interflow is the dominant component of the hydrograph, followed by overland flow. This was evident from borehole logs and resistivity tomography imagery (the interface between alluvium cover and Malmesbury shale with low permeability tends to accumulate water in the rainy winter season), time series of surface water (streamflow generally occurs until November, two months after the end of the rainy winter season), borehole water levels (logger records indicated seasonal fluctuations and a recharge/discharge process mechanism) and isotope results (δ^2H and $\delta^{18}O$ analyses on groundwater samples indicated this water was subject to evaporation and discharges into the stream).

- Groundwater recharge is much less than the estimates of Vegter (1995) and the chloride mass balance method, assuming no regional groundwater losses, e.g. to the Berg river.
- The contribution of baseflow to streamflow is negligible, as modelled through hydrograph separation.
- Correlations between observed streamflow, average rainfall and actual evapotranspiration were poor, indicating that a variety of factors may influence streamflow, e.g. rainfall distribution, cropping systems and evapotranspiration, etc. The data record from stations located within the Sandspruit catchment (Figure 16) was not sufficiently long to investigate this. It is of utmost importance that an adequate network of spatial monitoring of climatic variables is established, particularly rainfall. It is recommended that daily rainfall be recorded at key positions within the study catchment.
- Data were collected that can allow evaluation of errors and uncertainties. Distributed hydrological modelling could be used to validate any uncertainty associated with monitoring results, i.e. baseflow, groundwater recharge, streamflow, evapotranspiration, etc. An example of uncertainty analysis was presented using rainfall and temperature records from different weather stations.
- Hydrological modelling was beneficial in terms of describing some processes and mechanisms occurring in the catchment, for example spatial variability of rainfall, the reduced actual evapotranspiration and the dominant contribution of interflow to runoff.
- Estimates of overland flow, interflow and baseflow with the hydrological model were 5%, 94% and 1% respectively.
- Knowledge gained from this investigation could potentially be applied in other semi-arid areas.

4 OVERALL CONCLUSIONS AND RECOMMENDATIONS

The following general conclusions can be made:

- This research project provided new insights into the importance of establishing and maintaining sound water monitoring programmes in our catchments.
- The importance of monitoring the whole water cycle was particularly highlighted. This includes integration of all environmental compartments, namely groundwater, surface water, unsaturated zone and atmospheric measurements.
- The aims of the project were achieved through the development of an integrated catchment management (ICM) mind map. The ICM mind map is meant to answer the key question: “What does a catchment manager need?”
- The ICM mind map provides guidelines on the minimum monitoring requirements (e.g. type of variables, space and time frequency, etc.) in order to obtain a meaningful amount of data for a specific monitoring objective. It includes the institutional and legal interactions of different agencies responsible for various monitoring programs, guidelines for monitoring best practices for the different components of catchment systems (groundwater, surface water, soil and vadose zone, atmosphere), as well as guidelines for integrated monitoring so that fluxes are consistently measured in time and space.
- The main target users of the ICM mind map are Catchment Management Agencies (CMAs), but also government departments, private practitioners and water users as well as research institutions.

The integrated monitoring guidelines were applied to a demo/pilot study site in the Sandspruit catchment (quaternary catchment G10J). It was highlighted that there is a consequential cause and effect relationship between geology, climate, soil and land use.

Such baseline data were collected and a monitoring gap analysis was performed that lead to the design of a more comprehensive monitoring programme. The benefits of the expanded monitoring programme were supported with data evidence and resulted in a better understanding of the natural system and in the development of an improved conceptual model and quantification of the water balance fluxes. The combination of monitoring data and modelling proved to be a powerful tool in the quantitative description of the system.

Lessons learned from this project and sustainable strategies were discussed in detail in Chapter 2, including:

- An integrated monitoring approach is recommended (hydrometry, geophysics, isotope measurements, weather monitoring and vadose zone profiling) where monitoring is done by specialists in the particular field.
- Monitoring standards need to be adhered to in data collection and exchanges between custodians of databases.
- A large amount of information, especially on rainfall and soils, exists and it needs to be collated and included in current databases. The sources of this information are universities, laboratories, private consultants, local government, schools, etc.
- The scales of monitoring and interactions between governance levels need to be regulated. A common database with common monitoring standards and different network densities is recommended for all levels.
- Data collection needs to account for input requirements typical of distributed, coupled modular, hydrological modelling systems.
- Financial constraints are often the major constraints in a monitoring programme and this need to be taken into consideration in designing an ideal monitoring network.

The products and knowledge gained through this project fit into the broader programme of development of supporting tools to Catchment Management Agencies and other similar water management boards. These can be part of an implementation programme where a toolbox could be made available to water managers. The ICM mind map can be easily expanded to update guidelines and include more guidelines as they get developed (e.g. guidelines on soil erosion and sediment monitoring, microbiological monitoring, etc.). Similarly, monitoring programmes should be seen as dynamic, they can be updated, expanded and reduced as necessary. On-going refinement is possible through feedback loops between monitoring programmes and hydrological modelling. It is envisaged that the knowledge gained from this investigation could potentially be applied in other catchments, in particular in semi-arid areas.

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6 APPENDIX A: A STEP-BY-STEP PROCEDURE FOR DESIGNING A GOUNDWATER MONITORING SYSTEM (DWAF, 2004A)

STEP 1 SET MONITORING GOALS

Who	Groundwater coordinator, monitoring task team
What	Decide on monitoring objectives
How	Establish current and potential groundwater use in the catchment Establish requirements for the Reserve and Resource Quality Objectives (from RDM) Establish requirements for Source Directed Measures Establish areas and requirements for non-point source pollution monitoring
Outputs	Statement of monitoring goals

STEP 2 ESTABLISH MONITORING *STATUS QUO*

Who	Groundwater coordinator, monitoring team
What	Collect information on existing systems and available financial/human resources
How	Collect information from DWAF, Local government, Water Users Consider: What data is currently collected? Will this be continued? What infrastructure is in place and in what condition? What historical data is available? What are the available resources and capabilities in terms of manpower, vehicles, analytical facilities, etc.? Where can additional resources be obtained?
Outputs	Status of existing monitoring efforts in the catchment

STEP 3 COORDINATE WITH OTHER MONITORING INITIATIVES

Who	Groundwater coordinator, monitoring team, other agencies involved in monitoring
What	Adopt a multi-media approach, taking into account monitoring of all natural resources in the catchment
How	Consult surface water & water quality managers in the CMA, DWAF, local authorities, NGOs, universities, science councils, environmental organisations, nature conservation organisations, SA Weather Service, etc. Find out who is involved in monitoring resources in the catchment, e.g. surface water, wetlands, air quality, meteorology, biological indicators (invertebrates, fish tissue), soil/sediments, waste/effluent discharge, etc. Look for areas of overlap, possible cooperation and sharing of resources / manpower / travel costs (Don't send 3 different people to the same place in 3 different vehicles) Try to coordinate sampling sites for different media to maximise data value, e.g. soil, groundwater and surface water quality at a particular site. Develop data sharing agreements with other organisations where complementary data may lead to better understanding of the system
Outputs	Partnerships, Data sharing agreements

STEP 4 DESIGN MONITORING PROGRAMME

Who	Groundwater coordinator, monitoring team,
What	Develop conceptual model of groundwater behaviour Decide on network requirements and sampling and data collection protocols to achieve monitoring goals
How	Design networks taking into account aquifer geometry and flow characteristics Design networks around resource classification or land-use/cover type Decide on number and location of monitoring points, type of installation, the use of new, dedicated sites or existing boreholes Decide on sampling frequency Select type & frequency of measurements to be made Develop standardised protocols for sampling, data capture, retrieval and analysis for consistency across the catchment management area (use government regulated guidance if this exists) A checklist of activities that may need consideration for the monitoring programme appears in the box below.
Outputs	Record of decisions on monitoring network and sampling requirements

STEP 5 ADDRESS SUPPORT SERVICES AND TRAINING REQUIREMENTS

Who	Groundwater coordinator, IWRM manager
What	Establish opportunities and gaps in support for monitoring programme implementation
How	Identify analytical service requirements: what analyses are needed? what facilities are available for analysing these? can they be done in-house or contracted out? Identify information support requirements: who will handle data capture, database maintenance, data retrieval? how will this be structured? see Chapter 8 on Information Systems Identify staff and training requirements: do field staff & data management staff have the necessary skills? can experienced personnel be appointed / technical staff be trained to undertake new monitoring functions? Organise training sessions to meet skills requirements: where possible, train staff to take a variety of samples, e.g. groundwater, biological, weather measurements for collaborative monitoring efforts
Outputs	Network of supporting services for the monitoring programme

STEP 6 SET UP QUALITY ASSURANCE/QUALITY CONTROL PROCEDURES

Who	Groundwater coordinator, monitoring team, risk expert
What	Put procedures in place to ensure high quality data
How	Ensure that staff collecting samples are trained to take good quality, representative samples. Ensure that sub-contractors are qualified and experienced, laboratories are accredited and both have adequate quality control procedures in place. Design quality control measures into the monitoring programme, e.g. use of duplicate samples, blanks, certified standards, etc. Design data checking routines into data capture procedures.
Outputs	QA/QC guidelines and procedures for various aspects of monitoring

STEP 7 DRAW UP PLANNING DOCUMENT

Who	Groundwater coordinator, monitoring team
What	Draw up a detailed planning document covering all monitoring activities
How	Include: Appropriate information from steps 1-6 Framework of time and place for activities Role-players and responsibilities Opportunities for linking/support with other individuals and organisations Budget (allowing contingencies) Guidelines for subcontractors or support staff tasked with specific activities
Outputs	Groundwater monitoring strategy document for the catchment management area

STEP 8 IMPLEMENT & UPDATE GROUNDWATER MONITORING PROGRAMME AND FEEDBACK TO THE DWAF REGIONAL OFFICE

Who	Groundwater coordinator, monitoring team, field & data management staff
What	Commence monitoring and review success, feedback to Regional DWAF office
How	Commence planned activities once network and supporting structures are in place Refine the strategy by conducting regular updates as more information becomes available, e.g. work on a five-year cycle of information-gathering, plan development, implementation of monitoring, assessment of data, prioritisation of key areas.
Outputs	Catchment groundwater monitoring programme and feedback to DWAF Regional Office

Box 2: Checklist of monitoring activities to be considered in monitoring programme design

MONITORING ACTIVITIES

Network Design
Sampling station location
Variable selection
Sampling frequency
Representativity

Sample Collection
Sampling technique
Field measurement
Sample preservation
Sampling point
Sample transportation

Data Handling
Data reception
Laboratory
Outside sources
Screening and verification
Storage and retrieval
Reporting
Dissemination

Data Analysis
Basic summary statistics
Regression analysis
Water quality indices
Quality control interpretation
Time series analysis
Water quality models

Information Utilisation
Information needs
Reporting formats
Operational procedures
Utilisation evaluation