

# GUIDELINES FOR INTEGRATED CATCHMENT MONITORING: ICM MIND MAP DEVELOPMENT AND DEMONSTRATION

N. Jovanovic<sup>1</sup>, S. Israel<sup>1</sup>, C. Petersen<sup>1</sup>, R.D.H. Bugan<sup>1</sup>, G. Tredoux<sup>1</sup>, W.P. de Clercq<sup>2</sup>,  
R. Rose<sup>3</sup>, J. Conrad<sup>3</sup> and M. Demlie<sup>4</sup>

<sup>1</sup>CSIR, Natural Resources and Environment, Stellenbosch, South Africa. E-mail: [njovanovic@csir.co.za](mailto:njovanovic@csir.co.za)

<sup>2</sup>Department of Soil Science, University of Stellenbosch, South Africa. E-mail: [wpc@sunac.za](mailto:wpc@sunac.za)

<sup>3</sup>GEOSS - Geohydrological & Spatial Solutions International (Pty) Ltd., Stellenbosch, South Africa.

E-mail: [julian@geoss.co.za](mailto:julian@geoss.co.za)

<sup>4</sup>Department of Geology, University of KwaZulu-Natal, Durban, South Africa. E-mail: [demliem@ukzn.ac.za](mailto:demliem@ukzn.ac.za)

## Abstract

Advances have been made in recent years in developing networks and databases for monitoring water systems in South Africa. However, these monitoring systems need to be consolidated and integrated amongst various components of catchment systems (groundwater, surface water, unsaturated zone, atmospheric monitoring). As water managers are usually not experts in all disciplines (geohydrology, hydrology, hydrogeology, meteorology), there was need to provide an Integrated Catchment Monitoring (ICM) tool that would direct the user in finding the appropriate guideline, database, methodology or information. The key question in the development of this tool was: “What does a catchment manager need?” To this end, an ICM mind map was developed to include guidelines and recommendations on the minimum monitoring requirements (e.g. site selection, type of variables, space and time frequency, methodologies, data handling and quality assurance, input data requirements for models etc.), as well as essential information and sources of information (e.g. available databases, roles and responsibilities in monitoring etc.) for a specific monitoring objective. The user-friendly ICM mind map is written in the free software FreeMind v. 0.9.0. The application of the ICM mind map was demonstrated in the pilot catchment of the Sandspruit, a seasonal tributary of the Berg river (quaternary catchment G10J). Collection of baseline data served to assess what data are available and what monitoring gaps exist for a comprehensive description of the Sandspruit catchment. An expanded monitoring network was then established, based on weather monitoring, hydrometry, vadose zone profiling, a geophysical study and isotope studies. Data gathered during this investigation allowed for the annual water balance to be quantified and the conceptual flow model to be refined for the Sandspruit catchment. The combination of monitoring data and modelling proved to be a powerful tool in the quantitative description of the system. This study confirmed the importance of establishing and maintaining sound water monitoring programmes in our catchments. The importance of monitoring the whole water cycle was particularly highlighted, as well as the consequential cause and effect relationship between geology, climate, soil and land use. The main target users of the ICM mind map are water management boards (e.g. Catchment Management Agencies) and similar institutions.

## 1. INTRODUCTION

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 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 hydrological research and practice, like for example groundwater protection, recharge and groundwater - surface water interactions. 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 guidelines for coordination of data collection, management and exchange amongst the different stakeholders (e.g. defining roles and responsibilities for data collection and management).

Monitoring programmes need to be reliable and make use of state-of-the-art monitoring technologies, while collected data need to be easy to handle and compatible with models. 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 are 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 have to be defined in order to facilitate the integration of the different components of catchment systems. Optimization of monitoring networks has to account for both spatial and temporal variations through the application of geostatistical analyses, as well as logistical and financial feasibility.

As water managers are usually not experts in all relevant disciplines (geohydrology, hydrology, soil science, meteorology), there was need to provide a product that would direct the user in finding the appropriate guidelines, database, methodology or information. The key question in the development of this product 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 objective of this study was the development of 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). The development of a user-friendly tool incorporating guidelines for integrated catchment monitoring (ICM mind map) and its application are presented.

## 2. DEVELOPMENT OF THE ICM MIND MAP

The Integrated Catchment Monitoring (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. 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.

A sketch of the full tree of the ICM mind map, compiled in FreeMind, is shown in Figure 1. 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 (Figure 1). Each component of the environment includes the following items:

- 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. The hyperlinks are used to connect directly to:

- Guideline documents (Word or pdf files) 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 documents (Figure 1):

- A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa (DWAf, 2006).
- Artificial Recharge Strategy (DWAf, 2007).
- 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).

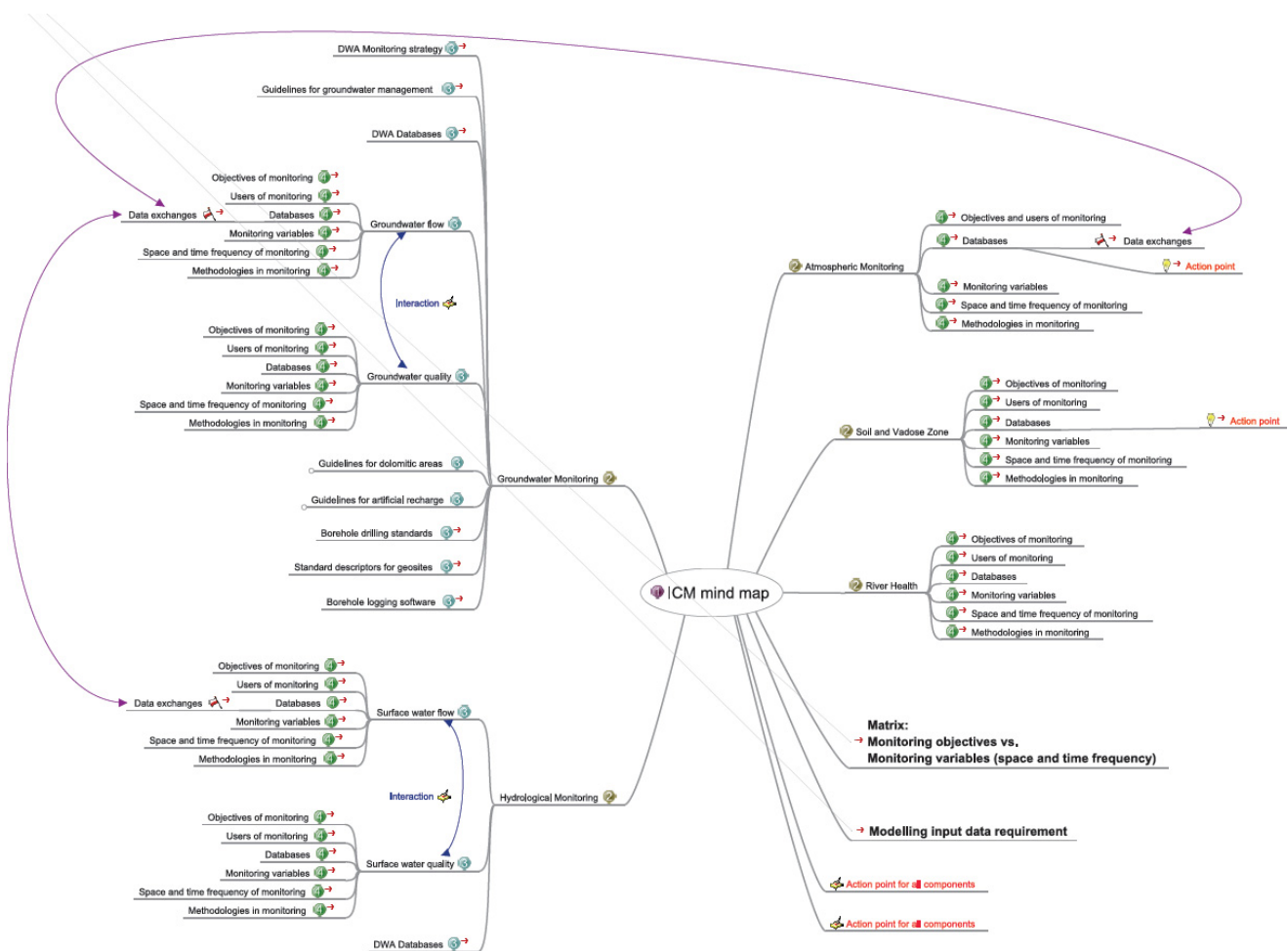


Figure 1. Printout of the integrated catchment monitoring mind map compiled in FreeMind v. 0.9.0.

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 1):

- 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 of monitoring objectives vs. space and time frequency of monitoring variables can be accessed by double-clicking on “Matrix”, and it is an Excel file (Figure 1). 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 (Figure 1) include a summary of typical minimum requirements for input data in hydrological and groundwater models.

The content of the ICM mind map was compiled through Water Research Commission (WRC) project No. K5/1846 on “Optimized Monitoring of Groundwater – Surface Water – Atmospheric Parameters for Enhanced Decision-Making at Local Scale“, by using existing and newly developed guidelines as well as through several stakeholder workshops and meetings. The content of the ICM mind map was described in detail by Jovanovic et al. (2011). The ICM programme can be easily expanded and updated by including any additional information.

### 3. ICM MIND MAP APPLICATION

#### Description of Catchment and Baseline Data Collection

The principles, guidelines and information included in the ICM mind map were applied to a demo/pilot study site, namely the Sandspruit catchment G10J. The Sandspruit (quaternary catchment G10J) is a seasonal tributary of the Berg River (Western Cape, South Africa) and it flows predominantly between May and November. The Sandspruit catchment is approximately 152 km<sup>2</sup> 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<sup>-1</sup>).

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. 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). 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.

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). Baseline and existing data were therefore collected and summarized below. A full report on data collected at Sandspruit can be found in Jovanovic et al. (2011). 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 the Department of Water Affairs (DWA) station No. G1H043. However, no monitoring of sub-catchments was taking place.
- *Groundwater monitoring.* The information from the National Groundwater Archives was used for the purpose of this study. 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 was 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* was also required, including the effects of man-made anti-erosion contours on water fluxes.

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; and
- 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 listed in Table 1. The purpose of data collection as well as the actions taken in the Sandspruit catchment to collect information are reported in Table 1.

**Table 1.** Data collection, purpose and actions taken to fill monitoring gaps in the Sandspruit catchment.

<b>Data collection</b>	<b>Purpose</b>	<b>Action taken in the Sandspruit catchment to fill monitoring gaps</b>
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 3 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 $^{18}\text{O}$ and $^2\text{H}$ in groundwater and surface water

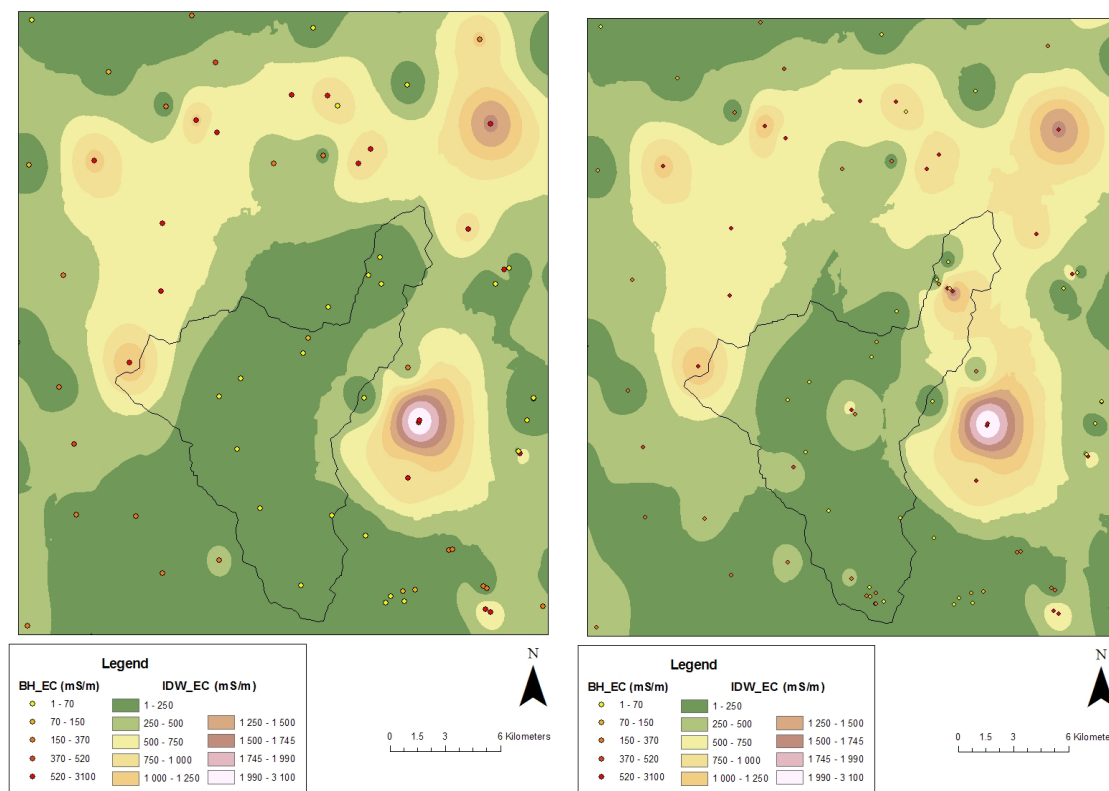
#### **Data Collection in Expanded Monitoring Program**

Two years of data (2009-10) were collected in the expanded monitoring program aimed at filling the identified monitoring gaps and requirements. In this section, some of the benefits of the expanded monitoring program are discussed.

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 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 temperatures (Annandale et al., 2002). Weather variables may vary greatly depending on the location within a catchment and particularly topography. Three weather stations were installed within the Sandspruit catchment at the Zwavelberg farm (upper reaches), Oranjeskraal farm (mid-reaches) and at the Sandspruit DWA station No. G1H043 (lower reaches in the vicinity of the confluence with the Berg River). 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). Measured rainfall tended to decline within the Sandspruit catchment from the upper reaches downstream (from 494 to 321 mm a<sup>-1</sup>). Daily air temperatures exhibited an increasing trend from the upper reaches downstream.

Three transects of boreholes were drilled across the Sandspruit catchment's slopes (at Zwavelberg farm, Oranjeskraal farm and at the Sandspruit DWA station No. G1H043) to represent the main geological environments and features of the Sandspruit catchment. Samples of representative sediment material were collected from layers (depths) that displayed characteristic features and different layering for measurements of water content, electrical conductivity and Cl analyses. Groundwater levels and temperatures were monitored with Solinst loggers in the boreholes for two years. Groundwater samples were collected after borehole purging for chemical analyses twice per year. 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.

The potentiometric surface using historic data of the National Groundwater Archive was updated using data from the new boreholes. Measurements of electrical conductivity (EC) of groundwater in the new boreholes were used to update the groundwater EC map and compare it to the historic EC map (Figure 2). 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. Caution should, however, be exercised in the interpretation of interpolated point data of groundwater EC.



**Figure 2.** Electrical conductivity (EC) of groundwater map of the Sandspruit catchment (interpolated with inverse distance weighting) drawn using National Groundwater Archive data only (1965-2008, left graph); and National Groundwater Archive data and data from new boreholes (1965-2008 and 2010, right graph).

Resistivity measurements were carried out at the borehole transects 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. Most of the area showed a higher general resistivity in deeper layers, which is due to the presence of fractured/weathered shale.

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 ( $^2\text{H}/^1\text{H}$ ) and oxygen ( $^{18}\text{O}/^{16}\text{O}$ ) were determined in surface water and groundwater samples. Isotope analyses 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. In the groundwater recharge area in the upper reaches of the catchment (Kasteelberg sandstone), rain water generally infiltrates relatively quickly through the sandstone without being subject to evaporation.

### **Improved Conceptual Model**

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 (Figure 3). The catchment receives 473 mm a<sup>-1</sup> precipitation on average. Higher rainfall (494 mm a<sup>-1</sup> 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<sup>-1</sup> at DWA station No. G1H043). Streamflow at DWA gauge G1H043 is measured to be approximately 30 mm a<sup>-1</sup>. Evapotranspiration makes up the remainder of the water balance (443 mm a<sup>-1</sup>), 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. The stream is seasonal and it is fed mainly through subsurface flow (interflow) during the winter rainy season. As groundwater recharge and discharge is less than streamflow (29 mm a<sup>-1</sup>), the historic values of groundwater recharge of 69-71 mm a<sup>-1</sup> estimated by Vegter (1995) for quaternary catchment G10J appear to be overestimated (assuming no other groundwater losses occur). 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.

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. 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 were estimated using the J2000 hydrological model (Krause, 2002; Krause *et al.*, 2006; [http://jams.uni-jena.de/jamswiki/index.php/Hydrological\\_Model\\_J2000](http://jams.uni-jena.de/jamswiki/index.php/Hydrological_Model_J2000), accessed on 13 April 2010). 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.

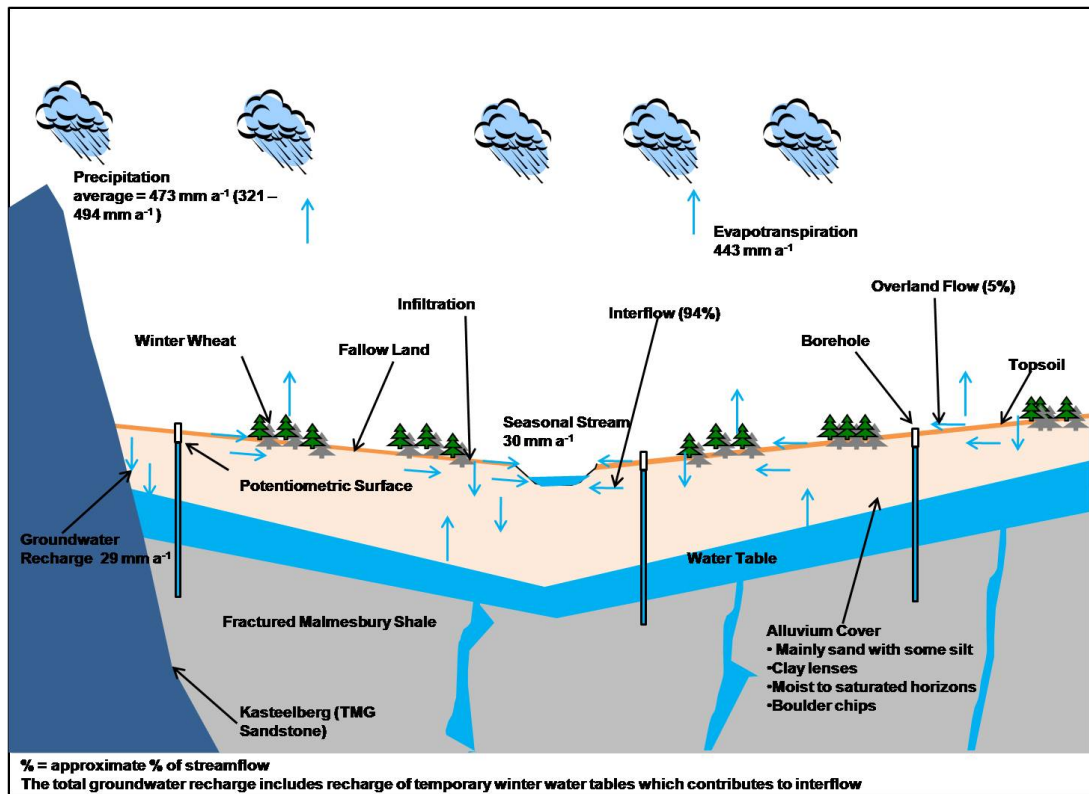


Figure 3. Conceptual flow model for the Sandspruit catchment.

#### 4. CONCLUSIONS

This study confirmed 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 ICM mind map developed in this study is meant to answer the key question: “What does a catchment manager need?”. It includes guidelines and information on how to monitor the various compartments of the environment. 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 led 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.

The products and knowledge gained through this study 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 to other catchments, in particular in semi-arid areas.

#### 5. ACKNOWLEDGMENTS

The authors acknowledge the Water Research Commission for funding project No. K5/1849 from which this paper emanated, the Department of Water Affairs for funding drilling of the boreholes, SA Rock Drill



for drilling the boreholes, the farmers in the Sandspruit catchment for making their land available and for supplying valuable insight into the environmental conditions, the team from the Friedrich Schiller University of Jena (Germany) for the support in hydrological modelling and the National Research Foundation for funding the Bilateral Programme.

## 6. REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998) *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*, United Nations Food and Agriculture Organization, Irrigation and Drainage Paper 56. Rome, Italy.

Annandale, J.G., Jovanovic, N.Z., Benade, N., and Allen, R.G. (2002) "User-friendly software for estimation and missing data error analysis of the FAO 56-standardized Penman-Monteith daily reference crop evaporation." *Irrigation Science*, 21, 57-67.

DWAF (1997) *Minimum Standards and Guidelines for Groundwater Resource Development for the Community Water Supply and Sanitation Programme*, Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (2004a) *Integrated Water Resources Management. Guidelines for Groundwater Management in Water Management Areas, South Africa*, Department of Water Affairs and Forestry, Pretoria, South Africa, DANIDA Funding Agency, March 2004.

DWAF (2004b) *Standard Descriptors for Geosites*, Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (2006) *A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa*, Edition 1, Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (2007) *Artificial Recharge Strategy, Version 1.3*, Department of Water Affairs and Forestry, Pretoria, South Africa.

Jovanovic, N., Israel, S., Petersen, C., Bugan, R.D.H., Tredoux, G., de Clercq, W.P., Vermeulen, T., Rose, R., Conrad, J., and Demlie, M. (2011) *Optimized Monitoring of Groundwater – Surface Water – Atmospheric Parameters for Enhanced Decision-Making at a Local Scale*, Water Research Commission report No. K5/1846, Pretoria, South Africa. In press.

Krause, P. (2002) "Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model." *Physics and Chemistry of the Earth*. 27, 663-673.

Krause, P., Base, F., Bende-Michl, U., Fink, M., Flugel, W., and Pfennig, B. (2006) "Multiscale investigations in a mesoscale catchment – hydrological modelling in the Gera catchment." *Advances in Geosciences*, 9, 53-61.

Rice, K., Hornberger, G.M. (1998) "Comparison of hydrochemical tracers to estimate source contributions to peak flow in a small, forested headwater catchment." *Water Resources Research*, 34, 1755-1766.

Usher, B., Pretorius, J.A., Dennis, I., Jovanovic, N., Clarke, S., Cave, L., Titus, R., and Xu, Y. (2004) *Identification and Prioritization of Groundwater Contaminants and Sources in South Africa's Urban Catchments*, Water Research Commission report No. 1326/1/04, Pretoria, South Africa.

Vegter, J.R. (1995) *An Explanation of a Set of National Groundwater Maps*. Water Research Commission report No 74/95, Pretoria, South Africa.