# REVIEW OF THE USE OF EARTH OBSERVATIONS AND REMOTE SENSING IN WATER RESOURCE MANAGEMENT IN SOUTH AFRICA

Report to the

WATER RESEARCH COMMISSION

by

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**WRC Report No. KV 329/15**
**ISBN 978-1-4312-0526-4**

**October 2015**

**Obtainable from**

Water Research Commission
Private Bag X03
GEZINA, 0031

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The publication of this report emanates from a project entitled *Review and use of earth observations and remote sensing in water resource management in South Africa* (WRC Project No. K8/1016).

# EXECUTIVE SUMMARY

The Water Research Commission (WRC) commissioned the study the Review of the Use of Earth Observations and Remote Sensing in Water Resource Management in South Africa (K8/1016).

The main aim of this study is to assess the use of Earth observation (EO) and remote sensing (RS) technologies in the efficient and integrated management of water resources in South Africa and to identify research gaps that constrain the full use of these technologies.

## a. Rational

South Africa is facing increasing water stress, while water quality and availability issues are becoming more acute. The WRC's meaningful contribution to the development of the capacity of the water sector and the broadening of the country's water centred R&D base has resulted in the country being much better prepared to deal with water management challenges. The use of modern technologies, such as Earth observation and remote sensing, further contribute to the efficient and integrated management of this limited resource. However, the need to ensure that full use is made of these technologies requires investigation so that gaps can be identified and research agendas adapted.

## b. Objectives and aims

The main aim of this study is to assess the use of EO and RS technologies in the efficient and integrated management of water resources in South Africa and to identify research gaps that constrain the full use of these technologies. The specific objectives for the study are to:

i. Scope the current EO and RS landscape as it relates to water resource management (including identifying capacity and competencies available and gaps) in South Africa;

ii. Review the current South African state of knowledge on the application of EO and RS technologies in water management in South Africa (including the identification of knowledge gaps and potential applications);

iii. Identify and review the research and operational EO data sources being used in or required for water resource management and identify any gaps and constraints on availability and access to EO data: and

iv. Make recommendations on harnessing collective knowledge on EO and RS systems, R&D requirements and capacity building needs to obtain the information required.

## c. Methodology

This report is based on a study of available literature both published in scientific journals and that which is available in scientific reports and other documents. The study comprises four parts.

**Part 1** scopes the EO and RS landscape in South Africa as it pertains to water resource management and includes identifying capabilities and competencies as well as identifying gaps.

**Part 2** describes the status of RS applications to water resource management and addresses the main variables that can be observed using remote sensing and in situ observation instrumentation.

**Part 3** describes the status of EO data sources for water resource management and addresses the same variables as in Part 2 but with a focus on the data sources available for observing these variables in South Africa.

**Part 4** addresses the available capacity and the need for capacity development and summarises the priority areas for research and development.

This report is based on a study of available literature and other documents. An initial literature study was presented at the SA-GEO symposium held at the University of Fort Hare, 10-12 September 2013, where further input and the identification of gaps were discussed. Participants' inputs were incorporated into the report. Another workshop was held on 09 April 2014 in Pretoria. This workshop reviewed the content of the draft report and additional inputs were included in the final report.

## d. Results and discussion

The summary of the literature and studies sourced is reflected in the report under the four main objectives of the study.

The most important variables for water resource management were identified as:

- Precipitation;
- Soil moisture / soil water: surface / subsurface;
- Soil temperature: surface / subsurface;

- Evapotranspiration – from land surface;
- Evaporation – lakes and wetlands;
- Runoff  stream flow;
- River discharge (to ocean coastal zones / estuaries);
- Water quality;
- Groundwater recharge / discharge rates;
- Aquifer – volumetric and change;
- Elevation / topography; and
- Lake / reservoir levels (including other surface storage).

Users need operational access to the required information when they need it and in a format that they can readily use. Although much data are collected and are available for water resource management, users still face challenges in accessing information and products when and how they need it.

Remote sensing and in situ data are available, not only as processed products, but as raw data to retrieve different water cycle components that can be used in water resource management.

This study has illustrated the manifold advantages of using Earth observation and remote sensing in managing the country's water resources. It illustrates the current uses and applications as well as the many sources of data that can be exploited. The need for capacity, competencies and infrastructure required to fully utilise the potential of Earth observation and remote sensing is discussed. Building these competencies and infrastructure will expedite the use of Earth observation in water resource management.

## e. Conclusions and recommendations

EO and RS techniques have become valuable tools in supplying data necessary for water resource management and are gaining impetus due to their capability of providing better spatial and temporal information. RS techniques have been widely used to estimate meteorological and hydrological variables (such as temperature, precipitation, and soil moisture / soil water), to estimate fluxes such as total evaporation and to delineate water bodies.

The WRC should consider focused research on the use and development of integrated operational observation systems that will supply the required observations of variables essential for informed water resource management decisions.

A research agenda should be developed with the EO water community and should be revised periodically as technologies change.

In anticipation of South Africa's first operational earth observing satellite being developed over the next five years, the opportunity to conduct research that will ensure the water community is ready and prepared to fully utilise this capability, will require significant investment in EO and RS research over the next few years.

Finally, the report should be kept 'alive & current' by establishing a Wikipedia based on the report.

## ACKNOWLEDGEMENTS

The authors would like to thank WRC Research Manager Wandile Nomquphu for his assistance and constructive discussions during the course of the project. Our thanks are also due to the SA-GEO symposium and workshop participants for their comments and inputs.

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# LIST OF ABBREVIATIONS

| Acronym | Description |
|---|---|
| AARSE | African Association of Remote Sensing of the Environment |
| ACCESS | Applied Centre for Climate and Earth Systems Science |
| ADCP | Accoustic Doppler Current Profiler |
| AFIS | Active Fire Information Service |
| AFWCCI | Africa Water Cycle Coordination Initiative |
| AGIS | Agricultural Geospatial Information system |
| AIPs | Alien Invasive Plants |
| ALOS | Advanced Land Observing Satellite |
| AMCOW | African Ministerial Council on Water |
| AMESD | African Monitoring of the Environment for Sustainable Development |
| AMSR | Advanced Microwave Scanning Radiometer |
| ARC | Agricultural Research Council |
| ARC-ISCW | Agricultural Research Council's Institute for Soil, Climate and Water |
| ASAR | ENVISAT Advanced Synthetic Aperture Radar |
| ASTER | Advanced Space-borne Thermal Emission and Reflection Radiometer |
| AU | Africa Union |
| CBD | Convention on Biological Diversity |
| CBERS2 | 2nd China- Brazil Earth Resources Satellite |
| CD: NGI | Chief Directorate: National Geo-spatial Information |
| CDOM | Coloured dissolved matter |
| CEOS | Committee on Earth Observation Satellites |
| CGA | Centre for Geographical Analysis |
| CGS | Council for Geo-Science |
| CMA | China Meteorological Administration |
| CMA | Catchment Management Agency |
| CMORPH | Climate Prediction Centre Morphing Technique |
| CPCAPC | Climate Prediction Centre African Daily Precipitation Climatology |
| CSI | Committee for Spatial Information |
| CSIR | Council for Scientific and Industrial Research |
| CWP | Crop water productivity |
| CWRR | Centre for Water Resources Research |
| DAFF | Department of Agriculture, Forestry and Fisheries |
| DEA | Department of Environmental Affairs |
| DEM | Digital elevation model |
| DMSP | Defence Meteorological Satellite Program |
| DSM | Digital surface model |
| DST | Department of Science and Technology |
| DWA | Department of Water Affairs |
| EEO | Ecosystems Earth Observations |
| EO | Earth observation |
| EODC | Earth Observation Data Centre |

| | |
|---|---|
| EOS | Earth Observation Satellite |
| ERSDAC | Earth Remote Sensing Data Analysis Centre |
| ESA | European Space Agency |
| ET | Evapotranspiration |
| EU | European Union |
| EUMETSAT | European Organisation for the Exploitation of Meteorological Satellites |
| EVI | Enhanced vegetation index |
| FEWS | Famine Early Warning System |
| FEWS NET | Famine Early Warning Systems Network |
| FFG | Flash Flood Guidance |
| G8 | Group of Eight Countries |
| GCGC | Global Change Grand Challenge |
| GDEM | Global Digital Elevation Model |
| GEMS | Global Environmental Monitoring System |
| GEO | Group on Earth Observations |
| GEOSS | Global Earth Observation System of Systems |
| GIS | Geographic Information System |
| GLOWA | Global Change and the Hydrological Cycle |
| GM | Global mode |
| GNSS | Global Navigational Satellite Systems |
| GPCP | Global Precipitation Climatology Project |
| GPM | Global Precipitation Measurement |
| GPS | Global Positioning System |
| GRACE | Gravity Recovery and Climate Experiment |
| HE | Hydro-Estimator |
| HP | Harvest Potential |
| ICMA | Inkomati Catchment Management Agency |
| IGBP | International Geosphere and Biosphere Program |
| IGOS-P | Integrated Global Observing Strategy Partnership |
| IGWCO | Integrated Global Water Cycle Observing Theme |
| IHP | International Hydrological Programme |
| IR | Infrared |
| ISCW | Institute for Soil, Climate and Water |
| ITC | Faculty of Geo-Information Science and Earth Observation |
| IWP | Ice water path |
| IWRM | Integrated water resource management |
| LCBC | Lake Chad Basin Commission |
| LCCS | Land Cover Classification System |
| LIDAR | Light detection and ranging |
| LISS | Linear Imaging Self-scanning Sensor |
| LST | Land surface temperature |
| LULC | Land use / Land cover |
| LWP | Liquid water path |
| MERIS | Medium Resolution Imaging Spectrometer |
| MESA | Monitoring for Environment and Security in Africa |

| | |
|---|---|
| METRIC | Mapping EvapoTranspiration at high Resolution with Internalized Calibration |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MPE | Multi-sensor Estimate |
| MPH | Maximum peak height |
| MSG | Meteosat Second Generation |
| NAP | Non-algal particles |
| NASDA | National Space Development Agency |
| NDVI | Normalised difference vegetation index |
| NEOSS | National Earth Observations and Space Secretariat |
| NGA | National Groundwater Archive |
| NGDB | National Groundwater Data Base |
| NGI | National Geospatial Information Chief Directorate |
| NGIS | National Groundwater Information System |
| NLC | National Land Cover |
| NOAA | National Oceanic and Atmospheric Administration |
| NOAA/CPC | National Oceanic and Atmospheric Administration/Climate Prediction Centre |
| NRF | National Research Foundation |
| NSST | National Space Science and Technology Strategy |
| NWP | Numerical weather prediction |
| NWRS | National Water Resource Strategy |
| PALSAR | Phased Array type L-band Synthetic Aperture Radar |
| PERSIANN | Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks |
| PM | Precipitation Radar |
| PUMA | Promoting the Use of Meteosat in Africa |
| RISKOMAN | Risk-based Operational Water Management |
| RLA | River Lake Altimetry product |
| RLH | River Lake Hydrology |
| RS | Remote sensing |
| SAC | CSIR Satellite Application Centre |
| SADC | Southern African Development Community |
| SAEON | South African Environmental Observation Network |
| SAEOS | South African Earth Observation Strategy |
| SAEOSS | South African Earth Observation System of Systems |
| SAES | Southern African Earth Systems |
| SAF | Satellite Application Facility |
| SAFFG | South African Flash Flood Guidance |
| SA-GEO | South African Group on Earth Observations |
| SAHG | Satellite Applications and Hydrology Group |
| SANBI | South African National Biodiversity Institute |
| SANSA | South African National Space Agency |
| SAR | Synthetic aperture radar |
| SARVA | South African Risk and Vulnerability Atlas |
| SASDI | South African Spatial Data Infrastructure |
| SAWS | South Africa Weather Services |
| SBA | Societal benefit areas |

| | |
|---|---|
| SCS CN | Soil Conservation Service Curve Number |
| SeaWiFS | Sea-viewing Wide Field-of-view Sensor |
| SEBAL | Surface Energy Balance Algorithm for Land |
| SEBS | Surface Energy Balance System |
| SERVIR | Spanish acronym for ‘Mesoamerican Regional Visualization and Monitoring’ System” |
| SHARE | Soil Moisture / Soil Water for Hydrometeorological Applications for the SADC Region |
| SICF | Sun-induced chlorophyll fluorescence |
| SM | Soil moisture / soil water |
| SMMR | Scanning Multichannel Microwave Radiometer |
| SMOS | Soil Moisture / Soil Water and Ocean Salinity |
| SPM | Suspended particulate matter |
| SRTM | Shuttle Radar Topography Mission |
| SSI | Soil Saturation Index |
| SSM/I | Special Sensor Microwave / Imager |
| STREAM | Sealing and Transfer by Runoff and Erosion Related to Agricultural Management 59 |
| SUDEM | Stellenbosch University Digital Elevation Model |
| SUP | Sustainable Utilisable Potential |
| SVAT | Soil-Vegetation-Atmosphere Transfer |
| SWI | Soil Wetness Index |
| T/P | NASA/CNES TOPEX/POSEIDON (satellite) |
| TAMSAT | Tropical Applications of Meteorology using SATellite and other data |
| TCBF | TIGER Capacity Building Facility |
| TIGER | An Initiative of ESA to promote Earth observation for WRM in Africa |
| TOPKAPI | TOPographic Kinematic APproximation and Integration |
| TRMM | Tropical Rainfall Measuring Mission |
| TRMM-TMI | Tropical Rainfall Measuring Mission Microwave Imager |
| UKZN | University of KwaZulu-Natal |
| UNCCD | United Nations Convention to Combat Desertification |
| UNCCD | United Nations Convention to Combat Desertification |
| UNCED | United Nations Conference on Environment and Development |
| UN-ECA | United Nations Economic Commission for Africa |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USGS | United States – Geological Survey |
| VIRS | Visible and Infrared Scanner |
| WATPLAN | Operational Monitoring Product for Planning and Water Allocation |
| WC-COP | Water Cycle Community of Practice |
| WCI | Water Cycle Integrator |
| WCI | Water Cycle Initiative |
| WfW | Working for Water |
| WMO | World Meteorological Organization |
| WOIS | Water Observation Information System |
| WRC | Water Research Commission |
| WSSD | World Summit on Sustainable Development |
| WUE | Water use efficiency |

# 1. INTRODUCTION

The Water Research Commission, commissioned the study the **Review of the Use of Earth Observations and Remote Sensing in Water Resource Management in South Africa**. The main **aim** of this study is to assess the use of earth observation (EO) and remote sensing (RS) technologies in the efficient and integrated management of water resources in South Africa and to identify research gaps that constrain the full use of these technologies.

The **specific objectives** for the study are outlined below:

i. Scope the current EO and RS landscape as it relates to water resource management (including identifying capacity and competencies available and gaps) in South Africa;

ii. Review the current South African state of knowledge on the application of EO and RS technologies in water management in South Africa (including the identification of knowledge gaps and potential applications);

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iv. Make recommendations on harnessing collective knowledge on EO and RS systems, R&D requirements and capacity building needs to obtain the information required.

This report is based on a study of available literature both published in scientific journals and that which is available in scientific reports and other documents. An initial literature study was presented at the SA-GEO symposium held at the University of Fort Hare, 10-12 September 2013, where further input and the identification of gaps were discussed. Participants' inputs were incorporated into the report. Another workshop, attended by 34 participants from the EO water community, was held on 09 April 2014 in Pretoria. This workshop reviewed the content of the draft report and additional inputs were included in the final report.

The chapters that follow address the objectives of the study. Chapter 2 scopes the current EO and RS landscape in South Africa as it pertains to water resource management. Chapter 3 summarises the use of RS technologies in water resource management in the country, while Chapter 4 discusses the sources of EO data for water resource management. Chapter 5 and 6 reflects the research needs and the requirements for capacity development so that Earth observation and remote sensing can be optimally used in water resource management in South Africa. Chapter 7 ends the report with conclusions and recommendations.

# 2. A SCOPE OF THE CURRENT EARTH OBSERVATION AND REMOTE SENSING LANDSCAPE AS IT RELATES TO WATER RESOURCE MANAGEMENT IN SOUTH AFRICA.

South Africa is one of the countries in Africa with limited water resources and is renowned as a water-stressed country due to limited annual rainfall, as reflected in the South African Water Sector Induction Manual (http://www.dwa.gov.za/IO/Docs/CMA/CMA%20GB%20Training%20Manuals/gbtrainingmanualchapter1.pdf). Water security has become the most important challenge in the sustainable development of Africa at large. Reliable information on the supply, use and availability of water in order to adequately plan, manage and predict the changes in water resources has become a matter of priority for water managers, policy makers and water users (National Water Resource Strategy, 2012 . EO data acquired from space, in situ and from airborne instruments contribute immensely to this need. In order to satisfy the demand for information, good synchronisation is required by water managers, who must indicate their specific information needs, developers of the data gathering and monitoring systems, who must know what information is needed, and the knowledge institutes that must transfer their knowledge on collection and dissemination to users.

The objective of water resources management is to ensure that water resources are protected, used, developed, conserved, managed and controlled to achieve optimum and environmentally sustainable social and economic benefits. The National Water Resource Strategy (NWRS) describes how this vision is to be carried out in accordance with policy and regulatory requirements. The first priority is to ensure that water resource management supports the provision of water services. Geographical information and remote sensing are essential for monitoring water resources. A number of EO applications to improve water resource management in South Africa include, inter alia, land cover and land use mapping, flood risk mapping, wetland mapping, water quality monitoring and pollution source detection.

A number of organisations in South Africa are involved in water resource management. These include government departments, academia, research councils, private industry and other interested groups. The figure below illustrates the EO environment value chain as it relates to water resource management in South Africa.

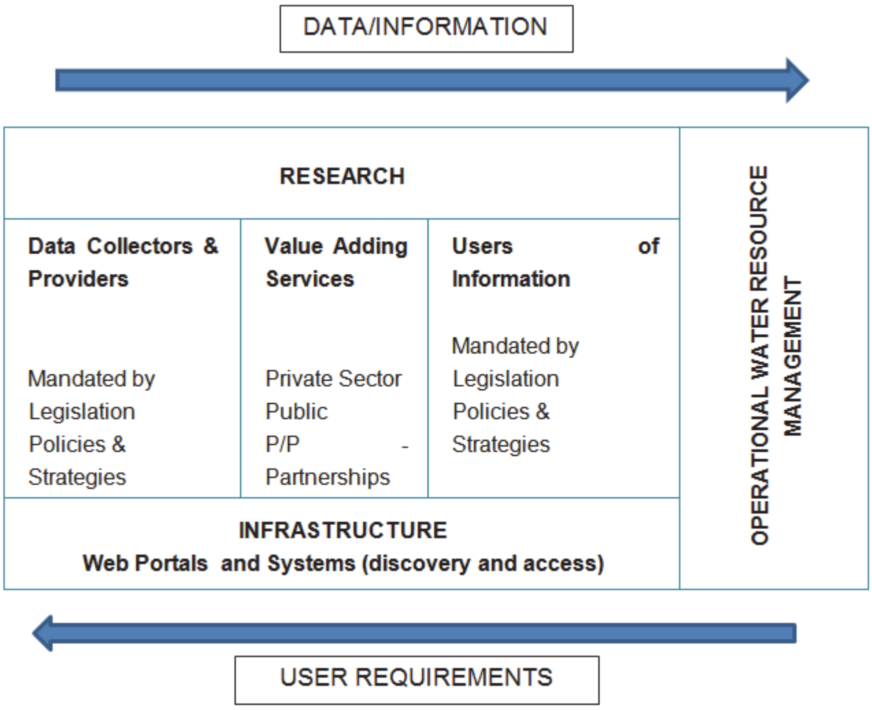

*Figure 1: Water resource management in South Africa*

## 2.1 Policy and Legal Environment

### 2.1.1 Policy Framework

A number of policies, strategies and principles exist to support Earth observation for water resource management in South Africa (Table 1). The main policy supporting the management of the water resources is the National Water Policy. This policy was preceded by the development of 28 fundamental principles and objectives for a new South African Water Law. The relevant principle is particularly principle 7, which states:

“The objective of managing the quantity, quality and reliability of the nation’s water resources is to achieve optimum, long-term, environmentally sustainable social and economic benefit for society from their use.”

With water security being one of South Africa’s biggest challenges, EO and RS technologies provide authorities with the information they need to manage water resources by providing essential information for policy- and decision-making.

The key overarching national framework for EO activities in South Africa is the South African Earth Observation Strategy (SAEOS) 2007. This instrument serves as a national response to the need for coordinating the collection, assimilation and dissemination of EO data so that they can be fully utilised to support policy- and decision-making, economic growth and sustainable development. SAEOS contributes to the Global Earth Observation System of Systems (GEOSS), an initiative of the Group on Earth Observation (GEO), wherein the South African Earth Observation System of Systems portal (SAEOSS) will form a 'national node' of GEOSS. Under this strategy, the Department of Science and Technology (DST) has also established the National Earth Observation and Space Secretariat (NEOSS) that provides the secretariat to SA-GEO, the South African EO community. SA-GEO is a vehicle for the co-ordination of EO activities in South Africa.

SAEOS is complementary to the National Space Science and Technology Strategy and Implementation plan. This Strategy provides guidelines, building blocks and the expected outcomes of the National Space Programme. The Strategy, significantly, supports the development of EO applications in support of a number of societal benefit areas (SBAs), including water.

The major benefit of these strategies to water resource management lies in the facilitation and coordination of EO data collection, data discovery and access as well as the development and availability of EO data derived products and information sources. SAEOS (Chapter 5) also sets out an EO data policy for South Africa.

### *2.1.2 Legislative Framework*

EO activities in South Africa reside within various organisations which all have major ongoing needs to acquire and use EO data in support of their national priorities and statutory responsibilities. Legislation and various regulations exist that support Earth observation and water resource management in South Africa. (Table 1)

Regarding water resource management, the South African Constitution Act (Act No 108 of 1996) offers the primary legal framework for the government's water policy and is the basis for formal legislation. Water resource management, in terms of the constitution, is exclusively a national government function and responsibility. National government, in cooperation with the other spheres of government, must ensure that the limited water resources, which are regarded as a natural resource, are protected and preserved in order to achieve optimum, long-term, environmentally sustainable social and economic benefit for society from their use.

The National Water Act (Act No 36 of 1998) also falls within the ambit of the national government functional areas. The Act mandates the Minister of Water Affairs and Forestry to establish national monitoring systems that monitor, record, assess and disseminate information regarding, amongst many other things, the quality of water resources. An old management principle that states, “If you can’t measure it, you can’t manage it”, is recognised explicitly in Chapter 14 of the Act and requires monitoring of water resource quality to be an integral part of water resource management in South Africa.

Regarding information management, the constitution (Section 32(1a) provides that everyone has the right to access information held by the state. EO data and information falls within this category and plays a crucial role in the management of water resources. Specific to water resources management, which requires the availability of data and information from various sources, the Promotion of Access to Information Act, passed in 2000 (Act No 2 of 2000), is the primary legislation that encourages sharing of information in the public domain. This legislation encourages direct electronic access to databases by authorised users in government, and provides that extracts, available in electronic or paper format, are to be available to users on request, free of charge or at a nominal cost.

Spatial information, on the other hand, is governed by the Spatial Data Infrastructure Act (Act No 54 of 2003), which is administered by the Department of Rural Development and Land Affairs, through the Committee for Spatial Information (CSI). The Act establishes the South African Spatial Data Infrastructure (SASDI) as the national technical, institutional and policy framework to facilitate the capture, management, maintenance, integration, distribution and use of spatial information. The Act and its regulations create an environment that facilitates co-ordination and co-operation among all stakeholders regarding access to spatial information, promotes universal access to such information and facilitates the protection of the copyright of the state in relation to spatial information.

*Table 1: A table of EO and Water Resource Management National Frameworks*

| Category | Name | Summary description (message data availability and access) |
|---|---|---|
| **Policies** | The National Water Policy, 1997 | The fundamental framework for managing water resources |
| **Legislation** | The Constitution of RSA, No 108 of 1996 | Encourages access to state information and management of water resources |
| | The National Water Act, No 36 of 1998 | Provides for the protection of water resources |
| | Spatial Data Infrastructure Act, No 54 of 2003 | Legal framework facilitating the capture, management, maintenance, integration, distribution and use of spatial information |
| | Promotion of Access to information Act, No 2 of 2000 | Encourages the sharing of information in the public domain |
| | South African National Space Agency Act, No 36 of 2008 | Mandates SANSA to acquire, assimilate and disseminate space satellite imagery to any organ of state |
| | Council for Geo-Science Act, No 54 of 2003 | Mandates CGS to do the collection and curation of all geoscience data, systematic mapping, reconnaissance and documentation of the geology of the earth's surface both on shore and off shore |
| | South African Weather Service Act, No 8 of 2001 | Mandates SAWS to improve the quality of the meteorological service by providing services in respect of weather, climate and related products |
| | Agricultural Research Act 1990, No 86 of 1990 | Mandates the ARC to undertake programmes related to climate change, conservation agriculture and water resource management as well as collect data and maintain databases on soil and climate |
| | Water Research Commission Act 1971, No 34 of 1971 | Established the WRC and the Water Research Fund |
| **Strategies** | South African Earth Observation Strategy, 2007 | Provides for co-ordination of EOs data so they can be fully utilised to support policy, decision making. Also provides for open dissemination and data archiving mechanisms |
| | National Space Science and Technology Strategy, 2008 | Promotes the development of applications of space science and technology and the use of integrated space based and ground based observations |

Data custodians have certain obligations in terms of this Act to take reasonable steps to effect adequate and appropriate security against the loss of spatial information in his, her or its custody or any unauthorised or unlawful access to and modification or disclosure of that spatial information and ensures the protection of the copyright of the state and other interested parties. The Act applies to all organs of state and to all users of spatial information. Private users outside organs of state have to acknowledge state copyright when using spatial data supplied by organs of state.

EO data and information is crucial for decision-making and legislation mandates various institutions to collect and supply the different types of data for different societal benefits.

Regarding satellite observations, the South African National Space Agency (SANSA) Act (Act No 36 of 2008) mandates SANSA in terms of Section 5 (d), *"to acquire, assimilate and disseminate space based imagery for any organ of state."* SANSA is one of the contributing agencies to SAEOS and fulfils this function through the SANSA Earth Observation Directorate. The satellite data from SANSA is made available and can be accessed through the Earth Observation Data Centre (EODC) that is also linked to the SAEOSS portal.

The national authority for weather and climate forecasting in South Africa is the South African Weather Services (SAWS) established by the South African Weather Services Act (Act No 8 of 2001). The Act gives SAWS the legislative responsibility to maintain, extend and improve the quality of the meteorological service by providing services in respect of weather, climate and related products that contribute to sustainable development in South Africa and the African continent. SAWS is also responsible for ensuring that any data relating to the state of the atmosphere is stored, archived and disseminated. In terms of its climate data policy, access to the climate data of the SAWS database is available free of charge, or for a nominal fee, or by a mutually beneficial agreement and is available, on stipulated terms and conditions, to researchers, government departments, the private sector and the general public..

The Geoscience Act (Act No 100 of 1993) mandates the Council for Geoscience (CGS) to undertake the collection and curation of all geoscience data and knowledge on South African geology in the national geoscience repository. This repository houses a large and growing collection of geoscience information for all the countries of the African continent. This information also includes data that were received from mining companies, universities and research institutions worldwide. Public access to all geoscience information is subject to existing legislation and is arranged through the mandate of the CGS. The mandate also includes the compilation of all geoscience data and information, particularly the geological, geophysical, geochemical and engineering geological data in the form of maps and documents, which are placed in the public domain.

The Agricultural Research Council (ARC) was established by the Agricultural Research Act (Act No 86 of 1990, as amended) and is the principal agricultural research institution in South Africa. Cross-cutting ARC programmes comprise research on, climate change, conservation agriculture and water resource management. The Institute for Soil, Climate and Water (ISCW) is one of the 10 ARC institutes and has a mandate to promote the sustainable use and management of the agricultural natural resources soil, climate and water and includes the collection and curation of soil and climate data. Access to this data is by arrangement with the ARC.

The CSIR, Constituted by an Act of Parliament in 1945 as a science council, undertakes directed and multidisciplinary research, technological innovation as well as industrial and scientific development to improve the quality of life of the country's people, confirmed by the Scientific Research Council Act (Act No 46 of 1988, as amended by Act 71 of 1990) maintains the Active Fire Information Service (AFIS) on a commercial basis. Divisions of the CSIR, such as the Natural Resources and Environment division, conduct research and development focused on water resource management that includes the use and applications of Earth observations.

State departments, in the execution of their legislated mandates, also collect and archive Earth observations relevant to water resource management. These include the Department of Water Affairs (DWA) hydrological (Weir) and water quality data, the Department of Agriculture, Forestry and Fisheries (DAFF) datasets on cultivated field and land suitability and the Department of Environmental Affairs (DEA) dataset on invader alien vegetation.

In general, existing legislation covers the need for the use of Earth observation for water resource management and the necessity to collect and archive the relevant data and information in order to inform decision-making. However, the mechanism for the dissemination of the data that is in the public domain is not clearly defined. This leaves it to the discretion of the suppliers to determine the manner in which they can disseminate or the data make accessible. Some suppliers classify the mechanism through policies and agreements and some on an ad hoc basis. The collection, supply, discovery and access to Earth observations for water resource management is summarised in ***Figure 2*** below.

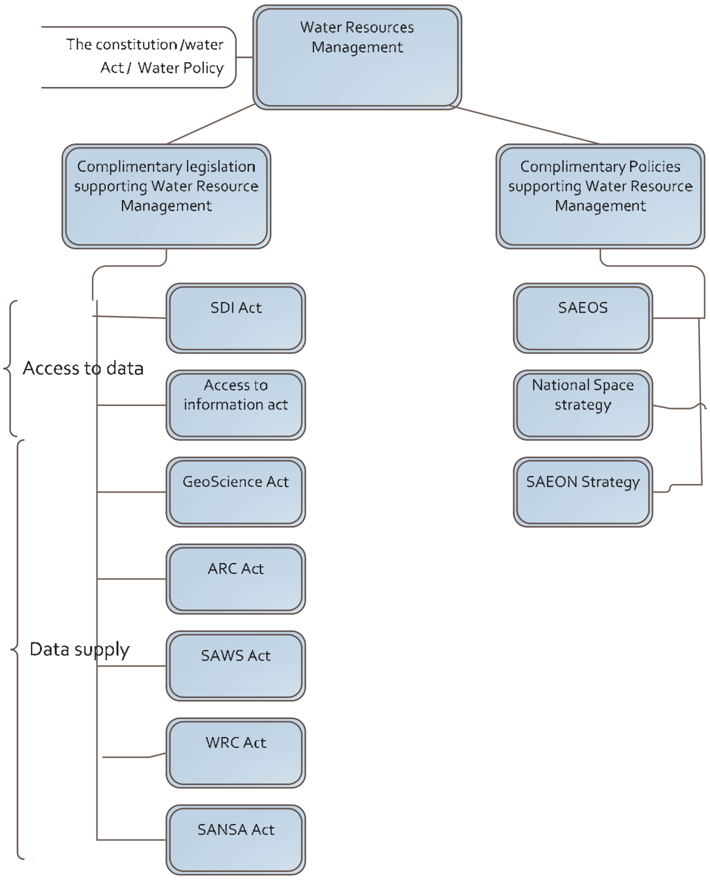

*Figure 2: EO and water resource management legislation and policies*

### 2.1.3 International Frameworks and Initiatives Environment

#### 2.1.3.1 International Conventions and Principles

Trans-boundary water resources are often a cause of conflict among states. Earth observation is crucial in cross-boundary water sustainability and catchment management. South Africa is a party to a number of international conventions that relate to EO applications such as the United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change UNFCCC. All these conventions require regular reporting in which Earth observations can make a significant contribution.

The fundamental legal principles for the sharing of RS data are the UN Principles Relating to Remote Sensing of the Earth from Outer Space (Resolution 41/65 of 3 December 1986). The principles provide a set of non-binding yet agreed and politically relevant principles to guide the activities of remote sensing by the United Nations member states. The RS principles of non-discrimination and equality are recognised in international customary practice as part of general international law, judicial decisions and treaty law. A number of organisations such as CEOS, GEO and the WMO have developed principles to encourage their members to have continuing activity in Earth observation. CEOS and GEO encourage their members to make full access to data available to the international community on a non-discriminatory basis. The data is made available free of charge or for no more than the cost of reproduction for research and education purposes, in the case of GEO.

A number of other policies of different space agencies across the globe promote open and equal access to RS data. These include the revised Earth Observation Data Policy of the European Space Agency (ESA), which encourages full and open access to its datasets, the Principles on Data Policy of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), ESA Envisat Data Policy and the Directive of the European Parliament and the Council on the legal protection of databases (1996) EU Directive 96/9/EC. The United States Geological Service (USGS) has made Landsat data freely available for both its historical archives and its most recent satellite (Landsat 8).

#### *2.1.3.2 International Initiatives*

Many initiatives dealing with Earth observation and water management are ongoing internationally and on the African continent.

## 2.2 Integrated earth observation for water resource Management

One of the most noteworthy initiatives is the Group on EO (GEO) which provides a framework for integrated Earth observation for water resource management. GEO is a voluntary partnership of governments and international organisations in which South Africa is also a member. As of 2013, GEO's members include 90 governments, including the European Commission. Water is one of the nine societal benefit areas in the implementation plan of GEO and is implemented through the Water Task (WA-01). The task seeks to address a number of areas and many variables impacting on the amount of freshwater available for human consumption and for ecosystem services. GEOSS seeks to track missing variables required for water resource management by filling in existing information gaps about water resources, integrating data sets from various monitoring systems, developing better forecasting models and disseminating the results to a wider range of decision makers (GEOSS Implementation Plan, 16 February 2005). GEOSS also seeks to combine water level data from satellite based radar altimeters with data from ground level, in situ monitoring in order to improve the ability of water managers to map the water cycles of major rivers.

GEO is facilitating the standardising of metadata and improving the accuracy of data and predictions. It aims to establish global prediction models and then develop national level models and finally river basin or catchment level models. These models will eventually become interoperable, creating a 'system of systems' that will facilitate the global exchange of observation data and forecasting information.

The Water Cycle Community of Practice of GEO provides a networking platform and a unique perspective on the information needs of the water community by bringing together representatives who have knowledge of the decision processes in the water sector with those who have an interest in seeing Earth observation being used more effectively to address those questions. Coordination of actions in GEOSS is pursued by the GEO member countries and affiliated institutions. South Africa is a member and co-chair of GEO.

The Global Water Cycle theme was established by the Integrated Global Observing Strategy Partnership (IGOS-P). The overall objective of the IGWCO is to develop and promote strategies for the coordination of diverse global water cycle observing systems and to make progress towards an integrated water cycle observation system that unites data from different sources (such as satellite systems, in situ networks, field experiments and new data platforms) with emerging data assimilation and modelling capabilities. Responsibility for maintaining the various global observing systems lies within the scope of the diverse activities of the IGWCO partners. This initiative forms one of the components of the GEO Water Task.

The Global Environmental Monitoring (GEMS) Water Programme is dedicated to providing environmental water quality data and information of the highest integrity, accessibility and interoperability. These data are used in water assessments and capacity building initiatives around the world. GEMStat is designed to share surface and ground water quality data sets collected from the GEMS Water Global Network, including more than 3000 stations, close to four million records and over 100 parameters. In 2002, South Africa began participating in GEMS/Water, the first country in the southern African region to do so. This offered the opportunity to design a data acquisition network that supplies relevant and reliable data, and the submission of data into the GEMS/Water database. South Africa has designated 19 water management areas covering the nine provinces. The water programme is currently under review.

### *2.2.1 The Use of Earth Observation for Integrated Water Resource Management*

The TIGER initiative is one of the initiatives that promote the use of Earth observation for improved Integrated Water Resources Management (IWRM) in Africa. The overall objective of the initiative is to assist African countries to overcome problems faced in the collection, analysis and use of water related geo-information by exploiting the advantages of EO technology. The aim is to fill existing information gaps relevant for effective and sustainable water resource management at the national to regional scale, thus helping to mitigate the widespread water scarcity in Africa. TIGER has been endorsed by the African Ministerial Council on Water (AMCOW) and is promoting a new Water Observation Information System (WOIS) for monitoring, assessing and taking inventory of water resources in a cost-effective manner. The new system integrates satellite information such as flood monitoring and forecasting, water body mapping for irrigation and livestock, lake water quality, hydrological modelling for water management and urban sanitation planning. The WOIS is currently implemented in five African water authorities (Lake Chad Basin Commission, Nile Basin Initiative, Volta Basin Authority, Department of Water Affairs of Namibia and South Africa), which use it to support their decision-making.

The Africa Water Cycle Coordination Initiative (AFWCCI) aims at addressing integrated water resource management in the context of climate change. The initiative has evolved as one of the regional activities of GEOSS and is adopting principles of the GEOSS Water Cycle Integrator (WCI). The WCI emphasises the importance of data integration, inter-disciplinarily and trans-disciplinarily, for, among other applications, the sustainable development of water and environmental resources.

### *2.2.2 Other Initiatives*

A number of initiatives exist such as the AMESD project of the EU and the African Union (AU), the Famine Early Warning Systems Network (FEWS NET) of the USGS, the global change and hydrological cycle or GLOWA projects, and several other national and bilateral programmes. Other major initiatives being undertaken include the Monitoring for Environment and Security in Africa (MESA) project, funded by the EU and executed by the AU. Other world regions are also increasingly focusing on Earth observation for Africa. An example of one of these projects is the (CBERS2) for Africa project, executed by Brazil and the People's Republic of China, and the SERVIR project from the US.

All these activities require knowledgeable resource persons on the ground, provide useful information and knowledge, and offer South African scientists various opportunities for participation. A disturbing observation is that currently there is not sufficient absorption capacity in Africa to exploit fully the benefits of these initiatives, highlighting the need for focused capacity development in water resource management.

### *2.2.3 Earth Observations Data Supply*

EO data is required for the sustained management of the water resources in South Africa. This data is available from the mandated institutions, departments and agencies. The challenge with the data is that it is not easily discoverable as most of the data sets are not discoverable within SAEOSS or other searchable portal systems. This is largely due to two reasons. Firstly metadata on the datasets either does not exist or is not in a standardised format and secondly the data is not available on web connected servers or in web service systems. EO data sources are comprehensively addressed in Chapter 3 and 4 of this report.

### *2.2.4 Earth Observations Value Adders*

EO data needs to be converted into decision, planning and policy support information and products. In order for this to happen, three activities are required:

1.) Research and academic institutions need to innovate and develop suitable products and services according to user specifications;

2.) These products and services need to be tested, demonstrated and accepted by the user community; and

3.) The systems, products and services need to be institutionalised, operationalised and sustained.

In South Africa, research and development on the applications of Earth observation is largely uncoordinated and ad hoc, yet as reflected in Chapter 3, a number of applications relevant to water resource management have been developed. There are also a number of public and private entities that provide services in this field, the private sector being one of the significant suppliers of GIS and RS data in the water resource management domain (Table 2).

The challenge is that the information and services from the private companies is not easily accessible in the public domain as it is subject to a number of restrictions for distribution and re-use.

## 2.3 Infrastructure

Management of geospatial and EO data through databases that are accessible through web based portals is critical as it enables discovery of, and access to, data, information and services as well as data visualisation. A number of EO infrastructures exist to support water resource management. These include, the GEOSS portal, the SAEOSS portal, the South African Risk and Vulnerability Atlas (SARVA), the Applied Centre for Climate and Earth Systems Science (ACCESS), SANSA's EODC, the Agricultural Geospatial Information System (AGIS) and the WEIRS infrastructure. The details of some of the relevant national portals are summarised below.

### *2.3.1 South African Earth Observation System of Systems (SAEOSS)*

The importance and value of the SAEOS portal is described in its manifesto which seeks to:

"*Ensure in the public interest that scientific data is described properly, preserved properly and discoverable. Once discovered, its utility, quality and scope can be understood, even if the data sets are huge. Once understood, it can be accessed freely and openly. Once accessed, it can be included into distributed processes, preferably automatically and on large scales. Once processed, the knowledge gathered can be re-used.*"

This objective is achieved through facilitating EO activities by engaging main holders of relevant datasets of Earth observation in various societal benefit areas including water to make the information available to a broad spectrum of users such as the science community, policy-makers at all three levels of government, industry and civil society in an integrated, timely and easily accessible form. SAEOS serves as a 'system of systems', rather than a centralisation of existing activities in the EO domain, which is exceptionally broad and diverse.

*Table 2: Private sector companies and their area of interest*

| COMPANY NAME | AREA OF INTEREST |
|---|---|
| Acudraft Enterprises | Specialising in geological and survey draughting. |
| Afminex | Consultancy on mineral and oil exploration, environmental services and policy research to public and private companies. |
| Afri-Coast Engineers | Consulting engineering & GIS company. |
| AfriGIS | Providers of geographical information system (GIS) solutions in Southern Africa. |
| DigitalGlobe | Supplies QuickBird Imagery. Supplier of high resolution satellite imagery, commercially available to Africa, South of the Sahara. Also provides the AgroWatch system imagery for environmental management and assessment, given complete soil charts, green vegetation mapping and GPS referencing. |
| AOC | Aerial survey and digital orthophotography. |
| Aspire Solutions | A Geographic Information Systems (GIS) and Information Management Systems consultancy that specializes in the use of GIS technology in developing client solutions. |
| Conservation Support Services | Services include alien vegetation mapping and management plans, land cover mapping, GIS customisations, natural resource management and cartographic productions. |
| Data Design | Sole distributor for ERDAS geospatial desktop software and enterprise solutions in Southern Africa, Ghana, Nigeria & Uganda. Support and training for ERDAS products. Supplies high resolution satellite imagery including GeoEye1, IKONOS, Quickbird, Aster & Radarsat, GIS datasets for South Africa and Africa, GIS projects and Image processing services. |
| Data World | GIS consulting, scanning, image processing. |
| Digital Perspectives | Publisher of commercial Satellite Image and Aerial Photograph based maps and posters. |
| Dynamic Mapping | Thematic Mapping and training in Cartography, Computer-assisted Cartography (CAC) and Geographical Information Systems (GIS). |
| Environmental Management Consultants | Specialising in Environmental-, Communications- and Project-Management, in various sectors, including; mining, industry, transport, tourism, agriculture, conservation, commerce and water. |
| Geo Terra image | Provides GI services and products to a wide range of public and commercial sectors in support of business intelligence and planning decisions .Typical clients include Telecoms organisations, Banks, Agricultural and environmental institutions, Municipalities, Commercial organisations, NGO's, and national and provincial Government Departments. |
| Geographic Information Management Systems | Implementation and support for GIS. |
| Geo-Hydro Technologies (GHT) | Geohydrological exploration & interpretation, including pollution and landfill site investigation, contaminant mapping and environmental impact assessments. |
| GeoSense Ltd | Suppliers of satellite & aerial imagery; offshore/onshore exploration, orthorectification, mapping and GIS. |
| Geospace International | A leading digital aerial photography (DAP) and GIS/GPS/remote sensing solution provider in Africa. GeoSpace operates two large format Digital Mapping Cameras (DMC's). |
| GEOSS – Geohydrological & Spatial Solutions | Groundwater exploration, development, monitoring, modelling and management with GIS consulting services. |
| Rison Groundwater Consulting | Specialists in all aspects of hydrogeology. Services geophysical borehole citing, sustainable water supplies, mine dewatering, groundwater contamination investigations, groundwater quality monitoring services, aquifer testing and contract drilling. |
| South GIS | Provides the Environmental industry with common maps such as biodiversity, sensitivity, catchment maps and more. Provides correct mapping for such applications and renewals. |
| Southern Mapping Company | Airborne Lidar and Hyperspectral surveys for all over Africa. For government and private. Lidar for high accuracy DTMs & Ortho-images for mining, infrastructure, urban, environmental, etc. Hyperspectral for agriculture/forestry/vegetation mapping, pollution mapping, mineral mapping, etc. |
| Umvoto Africa (South Africa) | Specialists in hydrogeology and groundwater resource assessment and development. Integrated water resource planning. GIS, remote sensing and geo-spatial information management. Contamination and remediation studies. Geo-hazard assessment, Gerick Prevention and disaster risk reduction studies. |

### 2.3.2 South African Risk and Vulnerability Atlas (SARVA)

The SARVA is a platform for global change information transfer from research to policy- and decision-makers. The SARVA programme provides a centralised repository for global change research (www.rvatlas.org.za) as well as a collection of integration and awareness tools aimed at improving evidence based decision-making concerning global change.

SARVA is an initiative of the Department of Science and Technology (DST) and is a project managed by the CSIR, with key content and technological inputs from South African institutions and research groups. This project is aimed at equipping decision-makers with information on the impact and risk associated with global change in the region. It provides easily understood global change sensitivity and vulnerability information at regional, national, provincial and municipal levels. It also helps support national initiatives such as the National Disaster Management Framework. The Atlas also provides an electronic geographical information system and involves South African researchers from various disciplines to continuously update the content with new research. It captures data related to aspects such as groundwater, surface water, forests, biodiversity, human health, crops, demographics, economics and social dimensions, much of which is based on Earth observation.

### 2.3.3 Applied Centre for Climate and Earth Systems Science (Access)

ACCESS is a consortium of several agencies, research councils, research programmes, universities and research groups that have combined efforts to deliver a range of outputs aligned to the DST's Global Change Grand Challenge (GCGC). It is a platform for integrated and end-to-end research and education, services and training outputs and outcomes related to the opportunities and challenges emanating from a varying and changing environment, collectively referred to as Earth Systems Science. ACCESS provides an opportunity for unprecedented cooperation across a range of disciplines which reflects the inter-connected nature of the Southern African Earth System (SAES). Earth observation form the basis for many of ACCESS studies.

### 2.3.4 Earth Observation Data Centre (EODC)

The EODC located at SANSA has the mandate to ensure the secure archiving and curatorship of satellite EO data, and the provision of those data that are deemed to be in the public domain to users free of charge. In some cases the archiving can take place within the organisations supplying the data, in which case the function of the EODC is to promote the application of the appropriate standards. The EODC is also mandated to acquire EO data from any source as identified by SAEOS, for placement in the archive. This applies particularly, but not exclusively, to the regular acquisition of remotely sensed satellite images. The EODC maintains other spatially and temporally referenced data that are within the SAEOS domain as well.

### *2.3.5 Agriculture Geospatial Information System (AGIS)*

Timely availability of reliable geo-referenced land, climate, plant nutrients, production and water information, integrated with infrastructural and socio-economic factors, are essential for stakeholders, policy-makers and land users to exercise the best choices in using these resources to achieve sustainable levels of food production and development in an increasingly complex environment.

### *2.3.6 Hydrologic and Weirs Infrastructure (DWA)*

A system of hydrological weirs has been established by the Department of Water Affairs: Directorate Hydrology over a period of many decades, starting in 1916.

The weirs are maintained by the provincial offices of DWA and the water level data are captured and quality-controlled there. The data, partly integrated with rainfall and water quality data, are stored in a centralised database (about 6 GB currently) maintained by DWA in Pretoria. Online access to this database is by DWAF officials only, but in principle it is viewed as a public domain dataset. Data requests, predominantly by water planners and consultants, are satisfied through e-mail, magnetic media or fax, at no cost to the user. There are a few hundred users of the system, of which about 70% are external to DWA. A printed summary of hydrological data 1960-1990 is available as a book.

### *2.3.7 South African Environmental Observation Network (SAEON)*

The SAEON, an initiative of the National Research Foundation (NRF), is an institutionalised network of departments, universities, science institutions and industrial partners that has three mandates relating to long term, in situ environmental observation which includes observations, information and education. This initiative has recently assumed responsibility for the historic research catchments and now maintains the infrastructure for catchment monitoring of these catchments. The long term hydrological datasets are available from the SAEON web portal and from the various SAEON node offices.

In conclusion, the need for and access to spatial information in South Africa for use in decision-making and development planning is a topical issue and inevitably leads to discussions on uncoordinated effort, a lack of funding and expertise and the unavailability of good quality, standardised data.

### *2.3.8 Users of Earth observations data*

In order for water resource managers and decision-makers at various levels (the users of EO data and derived information products services and systems) to take management decisions regarding water resources and related issues, they need reliable information on which to base those decisions and actions. Much of the information needed will be generated from water resource monitoring programmes that are in turn supplied with EO data from various observing systems. The correctness of the decisions or actions being taken will, to a large degree, depend on the reliability, accuracy and adequacy of the information supplied. Users therefore need operational access to the required information when they need it and in a format that they can readily use. Although much data is collected and is available for water resource management, users still face challenges in accessing information and products when and how they need it. The DWA, for example, has nine monitoring programmes to collect in situ data but has only recently started integrating the systems into the user friendly integrated National Information System.

# 3 REVIEW ON THE STATUS OF REMOTE SENSING APPLICATIONS INWATER RESOURCE MANAGEMENT

The Group on Earth Observations (GEO) is an intergovernmental organisation working to improve the availability, access and use of Earth observations to benefit society. GEO focuses on Earth observation for nine areas of societal benefit (SBA): Agriculture, Biodiversity, Climate, Disasters, Ecosystems, Energy, Health, Water, and Weather. An activity under GEO, known as Task US-09-01a, examined users' needs for Earth observation in order to establish and conduct a process to identify critical EO priorities common to many of the GEO SBAs (GEO, 2010). For example, the 48 observations with the highest global ranking in the Water SBA are listed (Table 3) but not all of these are of critical importance.

*Table 3: The 48 observations listed below have the highest rankings for the global perspective and thus are considered to be observation priorities for the Water SBA*

| Parameter and Description |
|---|
| Precipitation – Liquid, Solid and Mixed Phase |
| Soil moisture / soil water – Surface / Sub-Surface |
| Soil Temperature – Surface / Sub-Surface |
| Evaporation – Lakes and Wetlands |
| Evapotranspiration – from Land Surface |
| Runoff / Stream Flow |
| River Discharge _ to Ocean Coastal Zones / Estuaries, Surface / Sub-terra, Major Rivers |
| Glaciers & Ice Sheets – Extent / Depth |
| Ground Water & Aquifer Volumetric Change |
| Land Cover, Vegetation Cover / Type |
| Elevation / Topography |
| Water Quality – Large Water Bodies, Major Rivers, Estuaries, Nutrients / Contaminants such as Nitrates, Sulphates, Phosphates; Dissolved Oxygen Content |
| Lakes / Reservoirs Levels – Including Other Surface Storages |
| Snow – Cover/Depth / Type, Snow Water Equivalent |
| Air Temperature – Surface Met / Hydromet |
| Air Moisture / Humidity – Surface Met / Hydromet |
| Winds – Surface Met / Hydromet |
| Evaporation – Oceans |
| Freeze / Thaw / Melt State & Margin |

| |
|---|
| Permafrost / Frozen Ground |
| Soil Type – Classification |
| Soil Properties – Texture / Porosity, Hydraulic Conductivity, etc. |
| Surface Radiation Budget – Incoming / Outgoing Shortwave & Longwave |
| Top of Atmosphere Outgoing Longwave Radiation |
| Surface Albedo and Emissivity – often a derived / estimated parameter |
| Clouds – Liquid Water Content – Optical Depth / Extinction Coefficients |
| Cloud Properties |
| Agricultural Water Use – from Surface Storages such as Reservoirs, Rivers, Channels, Canals |
| Agricultural Water Use – Ground Water Draw |
| Energy Non-Hydro Power Generation – Water Demand / Use |
| Urban Water Demand / Use – Large Mega-Cities |
| Water Regulation – Trans-Boundary – Regional / International |
| Soil Composition – Chemical, Mineral, Nutrient, including soil pH, C, N, P, K |
| Ground Water Recharge / Discharge Rates |
| Water Infiltration / Percolation & Rates – Land Surface |
| Cloud Properties – Cloud Condensation Nuclei, Particle-Size distribution and Phase / State |
| Cloud Liquid Water Content |
| Aerosols |
| Sea Level Pressure – Surface Met / Hydromet |
| Agriculture, Urban, Industrial, etc. |
| Geologic Stratification and Geomorphological Classification |
| Water Quality & Composition – organic / inorganic contaminants, isotopic, suspended particulates, turbidity, salinity, colour |
| Water Quality – Drinking / Potable Water |
| Water Quality – Ground Water |
| Hydro-Energy Water Demand / Use |
| Urban Water Demand / Use – Small Cities |
| Sub-Urban Water Demand / Use – Distributed |
| Water Regulation – National |
| Water Regulation – Trans-Boundary – State / National |

- ***Note**: In this report, the terms ‘Soil Water’ and ‘Soil Moisture’ are used interchangeable. The authors regard both terms as acceptable in the context of this document.*

In Task US-09-01a, the team firstly identified critical, priority observations for each SBA followed by a meta-analysis across the individual SBA results, combining and prioritising observations common to many SBAs. The Water Team identified 24 critical observation priorities for the Water SBA, all of which have approximately equal importance. However, from these the '15 most critical observations' (Table 4) for the Water SBA were identified (Group on Earth Observations, 2012).

The major finding by the Water Team (GEO, 2012) was that global observing systems still fail to measure some critical water cycle variables, such as Evaporation / Evapotranspiration. This particular parameter is important because the water budget at the terrestrial surface at any one point is determined by the difference between Precipitation and Evaporation / Evapotranspiration. According to the Water Team, whilst Precipitation is routinely measured using a combination of in situ rain gauges and various RS techniques, such as radar and space based satellite systems, Evaporation / Evapotranspiration from land and ocean surfaces is poorly observed from in situ instruments and not readily observable using remote sensing. Thus the Water Team recommended that progress in the measurement of Evaporation / Evapotranspiration should be a primary focus of the water community over the next decade.

*Table 4: 15 most critical observations identified by the Water SBA*

| **Observation** | | **Relevant for the region (Y/N)** |
|---|---|---|
| Precipitation | Liquid, solid and mixed phase | Y |
| Soil moisture / soil water | Surface / sub-surface | Y |
| Soil temperature | Surface / sub-surface | Y |
| Evaporation | Lakes and wetlands | Y |
| Evapotranspiration | Land surface | Y |
| Runoff / stream flow | | Y |
| River discharge | To ocean coastal zones / estuaries | Y |
| Aquifer | Volumetric and change | Y |
| Land cover | Vegetation cover / type | Y |
| Elevation / Topography | | Y |
| Water quality | Large water bodies, major rivers, estuaries | Y |
| Lake / Reservoir level | Including other surface storage | Y |
| Groundwater | Recharge / discharge rates | Y |
| Snow | Cover / depth / type, snow water | N |

| **Observation** | | **Relevant for the region (Y/N)** |
|---|---|---|
| | equivalent | |
| Glaciers and ice sheets | Extent / depth | N |

This chapter is structured around the 15 critical observations identified by the GEO Water Task Team. However those two observations indicated as being not relevant to the region (*Table 4*) are excluded thus the 13[1] critical observations discussed in this report (with Chapter numbers included) are:

0 3.1 Precipitation
3.2 Soil moisture / soil water: Surface / subsurface
3.3 Soil temperature: Surface / subsurface

Evapotranspiration – from land surface
3.5 Evaporation – Lakes and wetlands
3.6 Runoff / stream flow
3.7 River discharge (to ocean coastal zones / estuaries)
3.8 Water quality
3.9 Groundwater recharge / discharge rates:
3.10 Aquifer – Volumetric and change
3.11 Land Cover – vegetation cover / type
3.12 Elevation / topography
3.13 Lake / reservoir levels (including other surface storage)

However, before beginning on this, the terms ‘Earth observation’ and ‘remote sensing’ used in this report need to be explained.

## Earth observation

The term ’Earth observations’ is not always used consistently in the scientific community and it is often used interchangeably with the term ‘remote sensing’. For the purpose of this report Earth observations in the context of natural resources is defined by the authors as: “data of the Earth system captured from satellite and airborne remote sensing platforms together with in

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[1] Of the 15 most critical parameters identified by GEO, only 13 are deemed applicable to water resource management in the region. For example, it may be that snow cover extent mapping is applicable to other applications such as disaster management, however since it is not applicable to water resource management in the region, it was excluded.

situ measurements which are used in the understanding and management of the lithosphere, biosphere, hydrosphere, or atmosphere."

**Remote sensing**

Remote sensing is defined as: "the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area, or phenomenon under investigation" by Lillesand et al. (2004). For the purpose of this report, remote sensing is limited to active or passive sensors which record electromagnetic energy from either airborne (sensor mounted on an aircraft) or spaceborne (sensor mounted on a satellite) platforms.

In Chapter 3, the status of remote sensing applications in water resource management is reviewed.

## 3.1 Precipitation

Precipitation is one of the major inputs in the hydrologic cycle. GEO listed precipitation as being the highest ranked EO parameter in all SBAs. Furthermore, it is listed as a critical observation parameter in each of the nine SBAs (GEO, 2012). Therefore the accurate measurement of precipitation is also critical to fields outside water resource management. The Water SBA (GEO, 2010) drew up data requirements for precipitation measurements which are presented in Table 5.

*Table 5: Water SBA summarised requirements for precipitation measurements*

| Scale | Horizontal resolution | Temporal resolution | Accuracy and/or precision | Latency |
|---|---|---|---|---|
| Local | 1 km | </~ 1 hr | 0.1 mm/hr-1 mm/hr and/or/5% | 0.1 h to 24 hr to 7 d to 30d; App Dependent |
| Regional | 10 km | 3 hr | | |
| Global | 50 to 100 km | 3 hr -1 d | | |

Rainfall data is obtained using three methods: rain gauges, radar and satellite technology. Each of these methods has its limitations; the rain gauge network is fast diminishing, meaning there are gaps and errors in the data, radar data quality decreases with radius coverage (good up to 50 km, 50-70 km reasonable and questionable 70+ km); limitations due to base scan height above the ground, partial beam filling, bright band ground clutter and anomalous propagation due to density variations in the atmosphere; and satellites have errors associated with spatial resolution of imagery and issues of in situ data availability for validation purposes.

Historically, precipitation has been measured using rain gauges installed at weather stations and the data was then used as representative of the precipitation for the region. However, satellite remote sensing has the advantage of providing data with greater spatial distribution and higher temporal frequency. Further, for forecasting purposes, most southern African countries are heavily reliant on satellite remote sensing due to limited surface and upper air observations (De Coning & Poolman, 2011).

According to Stephens and Kummerow (2007), understanding and quantifying the real capabilities of satellite based precipitation observing systems is a complex task, causing difficulty in estimating associated uncertainties. Both active and passive remote sensing methods are used in precipitation retrievals as interactions and thus information content between precipitation and electromagnetic radiation varies according to the spectral region in which it is captured. Properties typically derived from these systems can be broadly categorised as 1) cloud optic properties that categorise the interaction of clouds with radiation, and 2) the water content property of clouds and precipitation.

*Table 6: Satellite remote sensing retrieved parameters relevant to precipitation, the method employed and the parameter sensed to enable the retrieval (adapted and summarised from Stephens &and Kummerow, 2007).*

| **System** | **Method** | **Parameter sensed** | **Retrieval parameter** |
|---|---|---|---|
| Passive | Infrared emission: Thick clouds | Emission from near-cloud-top temperature | Cloud-top temperature and surface rainfall |
| | Microwave emission: Precipitating clouds | Column precipitation water | Surface precipitation |
| | Microwave emission: Clouds | Vertically weighted emission by water vapour and cloud water | Column water vapour and liquid water |
| Active | Microwave scattering | Column ice with contributions from non-precipitating ice and water vapour profile | Surface precipitation |
| Active and passive | Combinations of microwave scattering and emission | Emission and scattering signatures from different levels in the column | 1D precipitation profiles |

Remote sensing techniques developed to estimate precipitation involve the use of infrared and microwave remote sensing imagery data using different approaches as can be interpreted from Table 6 and the text which follows describes the basic theory behind each of these methods. The application of passive systems is discussed first, followed by active systems and finally the combination systems are discussed. Thereafter, available data products are discussed and finally, applications in South Africa are presented.

Emission of infrared and microwave radiation tends to be limited to the upper portion of cloud layers thereby restricting the application of passive systems in precipitation retrieval largely to estimating cloud-top temperature. Cloud-top temperature retrieved via infrared emission is used as an indicator for the probability and the amount of precipitation (Heinemann et al., 2002) and is most usefully applied to precipitation layers where the emission is integrated throughout the layer (Stephens & Kummerow, 2007). These methods are largely based on temperature retrievals via the split window algorithm where brightness temperature is calculated from radiance data collected at or near 10.8 and 12 um wavelengths (Stephens & Kummerow, 2007).

Secondly, microwave emission algorithms, using differing forms of atmospheric model and different solution forms of the radiative transfer equation, have been developed to extract precipitation profiles and surface rain rates (Stephens & Kummerow, 2007).

Finally, differential emission of microwave radiation by clouds and water vapour can be used to estimate the liquid water path (LWP) which is the vertically integrated cloud water content. Since this method is principally used over oceans, it is, for the most part, not applicable to water resource management. Overland emissions are more variable and therefore the algorithms are more prone to errors (Stephens & Kummerow, 2007), hence it is inappropriate to use these algorithms over land surfaces.

Beyond 50 GHz, ice particles, commonly found towards the top of raining clouds, appreciably influence the scattering of signals from active microwave sensors (active systems). There is a theoretical relationship between microwave scattering at various frequencies and the ice water path (IWP) of clouds. The sensitivity to IWP increases with microwave frequency and microwave depressions occur. These microwave depressions result from scattering effects which reflect upwelling microwave radiation back to the surface, thus lowering the brightness temperatures observed from space. Although there is no unique relationship between ice scattering and rainfall, empirical relationships between precipitation and microwave depressions are used to map out precipitation over land (Stephens & Kummerow, 2007).

Combination systems are those which combine the data products from both active and passive systems in order to provide the best possible precipitation estimations. Data products resulting from combination systems will be discussed in the following section.

Current precipitation methodologies commonly combine the high temporal and spatial resolution of passive IR-imagery with the more accurate instantaneous rain rate retrieval from scattered microwave data. Spatially distributed precipitation data can be obtained from the Tropical Rainfall Measuring Mission (TRMM) satellite or from EUMETSAT's METEOSAT satellites. TRMM is a joint mission between NASA and NASDA of Japan. The objectives of TRMM are to measure rainfall and energy exchange of tropical and subtropical regions of the world (between 35°N and 35°S) using three primary rainfall instruments that combine satellite borne passive and active sensors (Kummerow et al., 1998). The three instruments are 1) the TRMM Microwave Imager (TMI) to quantify the water vapour, cloud water and rainfall intensity in the atmosphere; 2) Precipitation Radar (PM) to provide information on the intensity and distribution of rain, rain type, storm depth and height at which snow melts to rain; and 3) the Visible and Infrared Scanner (VIRS) to provide cloud-top temperatures (http://pmm.nasa.gov/TRMM/VIRS). The spatial resolution of the data varies between 1 to 5 km, with a temporal resolution at intervals of 15 minutes. The TRMM products are validated at the NASA Goddard Space Flight Centre in Greenbelt, Maryland.

EUMETSAT has various precipitation data products available (such as the Multi-Sensor Precipitation Estimate product) to address the challenge of 'now-casting' through the combined use of the SEVIRI sensor on the geostationary Meteosat Second Generation (MSG) weather satellite delivering data every 5-15 minutes together with other sensors. Data products can be found at: http://www.eumetsat.int/website/home/Data/Products/Atmosphere/index.html.

Similar to EUMETSAT, the National Oceanic and Atmospheric Administration (NOAA) has a variety of operational precipitation data products based on combination systems available at: http://www.ospo.noaa.gov/Products/atmosphere/rain.html. Notably, the Hydro-Estimator (which will be discussed in the next section) uses infrared brightness temperatures from METEOSAT data (over Europe and Africa) to identify regions of rainfall and retrieve rainfall rates (http://www.ospo.noaa.gov/Products/atmosphere/ghe/index.html).

The Global Precipitation Measurement (GPM) mission, launched in early 2014, is an international network of satellites which will provide global observations of rain and snow (http://pmm.nasa.gov/GPM). GPM is an international mission which will extend on TRMM in that it will measure precipitation at higher latitudes, will sample more frequently, and will focus on research aimed at a more complete understanding of the global hydrological cycle (Schwaller & Morris, 2011). It is expected that the dual-frequency precipitation radar instrument onboard GPM will be capable of measuring more high and low intensity rain with estimated measurable rates given as ~0.2-110 mm.hr$^{-1}$. Further, GPM products will be available with a three-hour average revisit time over 80% of the globe and data will be available to users within three hours of observation and products will include the size of precipitation particles and the drop size distribution of rain (Schwaller & Morris, 2011).

As explained above, precipitaiton data products are available from the various sources for download from the internet. However, data validation and uncertainties associated with the data products remain a challenge (Stephen & Kummerow, 2007).

SAWS is making use of the Hydro-Estimator (HE) data product. This algorithm, developed by Scofield and Kuligowski (2003) uses the 10.8 um infrared band to estimate cloud-top temperature. SAWS combines the stratiform rainfall field from the Unified Model with the HE to estimate a rainfall rate (De Coning & Poolman, 2011) since the HE sometimes misses the rainy conditions along the coasts due to passing cold fronts and ridging high pressure systems (De Coning, pers. comm). Research to bias correct the HE with rain gauge data over a five year period is currently in progress.

Finally, SAWS also uses satellite RS data products to issue flood warnings. The South African Flash Flood Guidance system (SAFFG) uses hourly input from rain gauges, radar rainfall and satellite rainfall which is combined with catchment hydrological information to release one, three and six hourly forecasts of possible flooding. Currently this is only operational in those areas where ground radar is installed and thus the three centres shown on the map in ***Figure 3*** are the only areas covered by this service in South Africa.

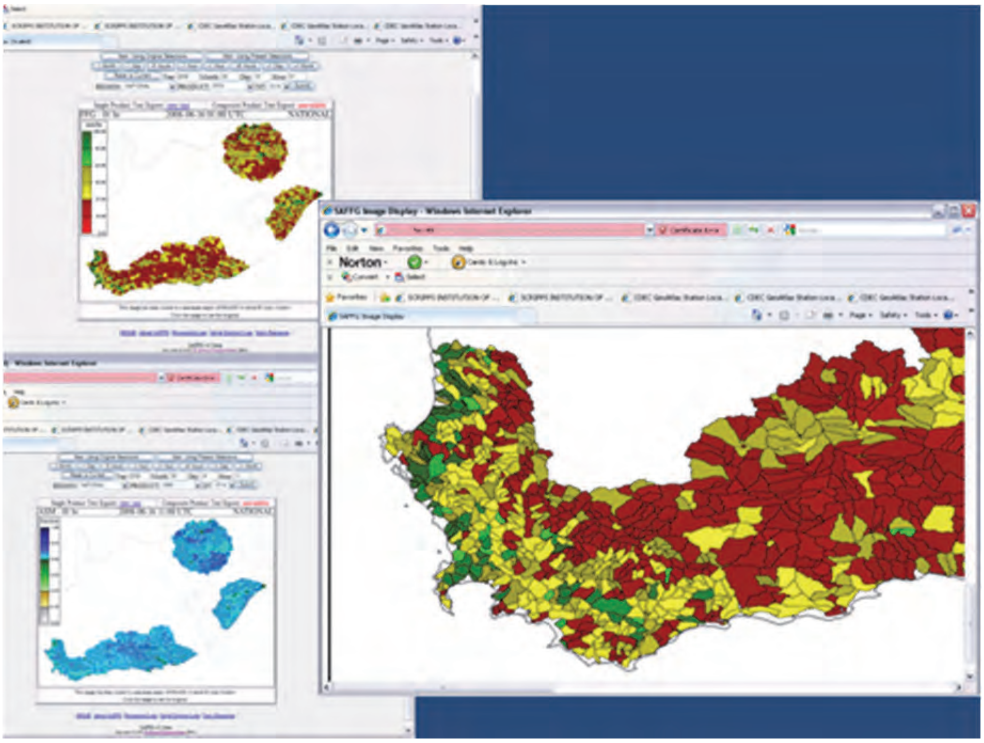

*Figure 3: Areas covered by the SAFFG system for the short term forecasting of flooding*

## 3.2 Soil moisture / soil water: Surface / subsurface

The interest in soil moisture / soil water pertains to moisture flux in the vadose zone that determines groundwater recharge. The possible upward flux which would lead to a loss of groundwater through evaporation can be significant when the water table is within the capillary zone and a moisture gradient is maintained (Meijerink, 2007). Further, infiltration and therefore also runoff, is influenced by soil moisture / soil water making it an important parameter to consider for water resource management. The Water SBA (GEO, 2010) drew up data requirements for soil moisture / soil water measurements which are presented in *Table 7:* ***Water SBA summarised requirements for soil moisture / soil water measurements***.

*Table 7: Water SBA summarised requirements for soil moisture / soil water measurements*

| **Scale** | **Horizontal resolution** | **Temporal resolution** | **Vertical resolution or height depth** | **Accuracy and/or precision** | **Latency** |
|---|---|---|---|---|---|
| Local | 0.1 km to 1 km | 1 to 6 hrs (1-10 d for vadose zone) | 10 cm Res. to 1 m depth; 30 cm-100 cm for vadose zone or to depth of water table | 0.02 $m^3/m^3$. Or stated variably as 5 g/kg to 10 g/kg, or 10 g/kg to 50 g/kg. Other units also used: Pascals, or cm/mm per 100 cm, or g/kg | Stated variably as NRT or 0.5 d to 1 d; 1-5 d to 10 d to 30 d to 144 d to 720 d (App. Dependent) |
| Regional | 10 km | 1 d to 3 d to 1 wk | | | |
| Global | 50 to 100 km to 500 | 1 d to 30 d to 3 months for some appl | | | |

RS techniques, that is optical, thermal infrared and microwave, have presented the opportunity to estimate spatiotemporal variation of soil moisture / soil water, at the top 5 cm of the earth's surface. According to Gibson et al. (2009), a considerable amount of research has been devoted to estimating soil surface parameters including soil moisture / soil water from remote sensing data which can be derived by using either passive or active remote sensing data.

\Microwave systems, both passive and active, have the best potential to estimate soil moisture / soil water because of the large contrast in emissivity between the land and water. This emissivity contrast is due to the large dielectric constant of water which is approximately 80 while that of most dry soils ranges between three and five. This causes an emissivity contrast of 0.6 or less for wet soils, with changes of a corresponding magnitude in the soil's reflectivity, to about 0.95 for dry soils. Also, there is little atmospheric transmissivity at microwave wavelengths, presenting very little or no atmospheric interruptions; and vegetation is semi-transparent. Also, microwaves are not dependent on solar illumination and provide all-weather coverage of the earth. In general, synthetic aperture radar (SAR) systems show a relatively high sensitivity to soil moisture / soil water due to the large contrast in the dielectric constant of dry and wet soils at microwave frequencies (Engelbrecht, 2009).

The ESA's Data User Element – Tiger project, known as the SHARE project (http://www.ipf.tuwien.ac.at/radar/share/), introduced a semi-operational soil moisture / soil water monitoring service which started in December 2005 and finished in January 2012. The experimental high resolution soil moisture / soil water product is based on ENVISAT ASAR Global Mode data for Australia and the entire Southern African Development Community (SADC) region. The Advanced Synthetic Aperture Radar (ASAR) global mode data represent soil moisture / soil water in the uppermost soil layer (<5 cm) with potential application in drought, yield, flood forecasting or modelling.

Further to SHARE, in South Africa, Engelbrecht (2009) tested soil moisture / soil water retrieval algorithms (linear regression and multiple-polarisation models) based on SAR. Due to lack of field validation data however, a statement on the accuracy of the results was not made but comparison with rainfall event data suggested a link between the soil moisture / soil water and rainfall.

Sinclair and Pegram (2010) compared two independent remotely sensed soil moisture / soil water estimates over South Africa. The first estimate is an indirect use of RS data to estimate soil moisture / soil water using the TOPKAPI model which uses remotely sensed inputs (rainfall and $ET_0$) in order to model soil moisture / soil water as a Soil Saturation Index (SSI). TOPKAPI is an acronym which stands for TOPographic Kinematic APproximation and Integration and is a physically based distributed rainfall-runoff model proposed by Liu and Todini (2002). The second method tested is derived from a data product (Surface soil moisture / soil water) produced from data obtained by the ASCAT instrument onboard EUMETSAT's METOP polar orbiting satellite which is temporally filtered to obtain a Soil Wetness Index (SWI). It was reported that for a large proportion of South Africa, there was a good agreement between the results of both approaches.

## 3.3 Soil temperature: Surface / subsurface

Water SBA users require land surface temperature and related soil temperature characterising the water cycle (GEO, 2012). The Water SBA (GEO, 2010) drew up data requirements for soil temperature measurements which are presented in Table 8.

*Table 8: Water SBA summarised requirements for soil temperature measurements*

| Scale | Horizontal resolution | Temporal resolution | Vertical resolution or height depth | Accuracy and/or precision | Latency |
|---|---|---|---|---|---|
| Local | 0.1 km to 1 km | 1 to 6 hrs (1-10d for vadose zone) | 10 cm res. To 1 m depth; 30 cm-100 cm for vadose zone or to depth of water table | 0.5°K to 1.0°K. Also stated variably as 0.3K to 2K or 1oK to 2oK , or 2K to 5K | 3 hr to 6 hr for land surface T. Other requirement follow SM: 1 d-5 d to 7 d to 10 d to 30 d (App-dependant) |
| Regional | 10 km | 1 d to 3 d to 1 wk; | | | |
| Global | 50 to 100 km to 500 | 1 d to 1 m to 3 months | | | |

Land surface temperature (LST) provides information on the temporal and spatial variations of the surface equilibrium state (Li et al., 2013) and is an important observation particularly in the estimation of land surface atmospheric fluxes. However, the strong heterogeneity of land surface characteristics such as vegetation, topography and soil, lead to a rapidly changing LST in both space and time resulting in RS satellite data offering the only possibility for measuring LST over the entire globe with sufficiently high temporal resolution (Li et al., 2013; Kalma et al., 2008). For example, when using an energy balance approach to estimate evapotranspiration, land surface temperature is used in the estimation of net radiation and to estimate the sensible heat flux. Although there were early doubts as to whether satellite based radiometric temperature could be used in the estimation of evapotranspiration (Kalma et al., 2008), it has since been established that to estimate evapotranspiration with a better than 10% accuracy, LST must be retrieved at an accuracy of 1 K or better (Li et al., 2013). This reinforces the need to obtain accurate LST as the estimation of a critical observation (ET) in hydrology is dependent on this.

Apart from radiometric temperature measured by the satellite sensor, land surface emissivity and atmospheric effects are generally required in the estimation of LST. However, methods have been developed where LST can be estimated despite these remaining unknown. The approaches reported on in the literature and the assumptions made are shown in Table **9** which is a summarised version of the same in Li et al. (2013).

*Table 9: LST retrieval methods summarised from Li et al. (2013)*

| General method | Specific method | Assumptions |
|---|---|---|
| Retrieval with known emissivity | Single-channel algorithms | No special assumption |
| | Multi-channel algorithms | Different atmospheric absorptions in adjacent TIR channels |
| | Multi-angle algorithms | 1) LSTs are independent of the view zenith angle;<br>2) The atmosphere is horizontally uniform and stable over the observation time |
| Retrieval with unknown emissivity | Classification based emissivity method | Surface materials in the same class have the same emissivity |
| | NDVI based emissivity methods | 1) Surface is composed of soil and vegetation;<br>2) Variation of land surface emissivity is linearly dependent on the fraction of vegetation in a pixel |
| | Day/night temperature independent spectral indices based methods | Emissivity ratios are the same or do not change significantly between two times. i.e., day and night |
| | Two-temperature methods | Emissivity is invariant at two times |
| | Physics based day/night operational methods | 1) Land surface emissivity does not change significantly at day and night times;<br>2) Angular form factor has very small variation in MIR channels |
| | Gray body emissivity methods | There exists a flat region in the emissivity spectrum. |
| | Temperature emissivity separation methods | Relationship between the minimum land surface emissivity and spectral contrast holds true over the entire gamut of surface materials |
| | Iterative spectrally smooth temperature emissivity separation method | Land surface emissivity spectrum is smoother than the spectral absorption of the atmosphere |
| | Linear emissivity constraint temperature emissivity separation methods | 1) Emissivity spectrum can be divided into M segments;<br>2) Emissivity in each segment changes linearly with wavelength |
| Retrieval with unknown emissivity and unknown atmospheric quantities | Artificial neural network methods | No special assumption |
| | Two-step physical retrieval methods | 1) Specular surface reflection and a constant angular form factor are used to simplify the radiative transfer equation;<br>2) Principle component analysis can be used to reduce the number of unknowns without significant loss of accuracy |

## 3.4 Evapotranspiration – from land surface

Evapotranspiration (*ET*[2]) is the sum of water lost to the atmosphere from the soil surface (including intercepted water) through evaporation and from plant tissues via transpiration and is a vital component of the water cycle, which includes precipitation, runoff, stream flow, soil water storage and ET (Mu et al., 2007). Accurate knowledge of temporal and spatial variations in precipitation and

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[2] *ET* throughout this text refers to actual evapotranspiration unless specific reference is made to reference evapotranspiration in which case the abbreviation will be $ET_0$.

*ET* is critical for improved understanding of the interactions between land surfaces and the atmosphere (Mu *et al*., 2007), and owing to increasing human consumption, climate impacts and decreasing availability, methods for monitoring the water balance at both fine and regional scales are important in order to preserve and manage water resources (Melesse et al., 2006).

The estimation of total evaporation (ET), which includes evaporation from land and water surfaces and transpiration by vegetation, is one of the most important processes in the determination of the exchanges of energy and mass between the hydrosphere, atmosphere and biosphere. In agriculture, ET is a major consumptive use of irrigation water and precipitation on agricultural land (Gowda et al., 2007).

The dependency of the physical process of evaporation, whereby a liquid (water) is transformed to a gas (water vapour), on water availability and incoming solar radiation, reflects the interactions between surface water processes and climate (Sobrino et al., 2007). In meteorology, evaporation is usually restricted to the change of a liquid to gas without a change in temperature. Sensible heat is that part of the energy flux from a surface which produces a temperature change and this must be distinguished from latent energy which is used to describe the evaporation process. Evaporation is a cooling process since there is a removal of energy when water evaporates from a surface. Part of this energy remains latent in the atmosphere and is released when water vapour condenses. Water vapour is therefore an energy carrier and energy must be available to allow the water to evaporate (Savage et al., 2004).

The GEO Water Societal Benefit Area (Water SBA) task team recommends that progress in the measurement of evaporation / evapotranspiration should be a primary focus of the water community over the next decade since evaporation / evapotranspiration is central to Earth system science and is linked to other SBAs (GEO, 2012). The Water SBA (GEO, 2010) drew up data requirements for evapotranspiration and evaporation measurements which are presented in Table 10***.***

The accurate estimation of *ET* remains a challenge to researchers in the field of micrometeorology and hydrology as well as for water resources managers and planners (Jarmain et al., 2009). *ET* can be measured or estimated using empirical formulae from taking measurements in the field or more indirectly rather than as a result of a specific evapotranspiration experiment. The field based measurements are generally point based and therefore not practical over a large area. Internationally it is now recognised that RS based models hold great potential for the spatial estimation of ET at both field and catchment scale. EO data can be used in ET estimation methods to extend point measurement of ET to much larger areas, even areas where measured meteorological data may be sparse (Jarmain et al*.,* 2009). Remote sensing based ET models can provide representative measurements of several physical parameters at scales from field (local) and catchments to regional, and are in addition better suited for estimating water use of different vegetation surfaces (Allen et al., 2007).

*Table 10: Water SBA summarised requirements for evapotranspiration and evaporation measurements*

| **Scale** | **Horizontal resolution** | **Temporal resolution** | **Vertical resolution or height depth** | **Accuracy and/or precision** | **Latency** |
|---|---|---|---|---|---|
| Local | 0.1 km to 1 km | 1 to 6 hrs | Surface (E), and LS veg cover or canopy height for ET | 0.1 mm or 5% | Same as Precip. or SM for point data assimil/water budget models |
| Regional | 10 km | 1 d | | | |
| Global | 50 to 100 km to 500 | 1 d to 1 m | | | |

Research on the use of remotely sensed land surface temperature data to estimate ET started towards the end of 1970s (Jackson et al., 1977). Over the years, numerous RS based models that vary in complexity have been developed for estimating regional ET. The complexity of these different methods depends on the balance between the empirical and physically based modules used (Courault et al., 2005). Four model categories are proposed by Courault et al. (2005): empirical direct methods; residual methods of the energy balance; deterministic methods; and vegetation index methods. Empirical direct methods are based on empirical relationships where remote sensing data are introduced directly in semi-empirical models to estimate ET.

Similarly, a comprehensive review of different methods used to estimate ET is discussed in detail by Verstraeten et al. (2008b) (Table 11). Residual methods of the surface energy balance combine some empirical relationships and physical modules. Most current operational models (such as SEBAL, METRIC, SEBS, and S-SEBI) use remote sensing directly to estimate input parameters and ET. Deterministic methods are based on more complex models such as Soil-Vegetation-Atmosphere Transfer models (SVAT). Vegetation index methods are based on the use of remote sensing to compute a reduction factor (such as crop factor *Kc* or Priestley Taylor-alpha parameters) for the estimation of the actual ET.

A review of the evolution of the research in remote sensing ET methods in South Africa is given by Gibson et al. (2013). According to Gibson et al. (2013), the Surface Energy Balance Algorithm for Land (SEBAL) model is the most widely applied model in South Africa. However, with the exception of the original published algorithm which researchers may programme into software themselves, it is protected by intellectual property law and is not available for unaffiliated researchers to use. Conversely, the Surface Energy Balance System (SEBS) is an open source model widely used for teaching and training purposes. In South Africa, research into remote sensing ET methods has evolved from a review of methods to the historic estimation of ET and to the operational use of these methods using near real time data (Table 12).

Various RS data applications applicable to water resource management at catchment scale have been investigated for catchment hydrology (Kongo & Jewitt, 2006), water use estimation (Gibson et al., 2009; Hellegers et al., 2011) and, most recently, operational water planning and allocation purposes (WE Consult, 2011). A review by Gibson et al. (2013), freely available journal Water SA, expands on the South African examples listed in Table 12, so this will not be repeated here.

*Table 11: A list of selected ET assessment methods based on EO techniques (simplified from Verstraeten et al., 2008)*

| Concept | Method | Parameters | | Selected references |
|---|---|---|---|---|
| | | EO[3] | Other | |
| **Parameterisation of the energy balance** | SEBAL<br>(Surface Energy Balance Algorithm for Land) | $T_0$, , *NDVI* | $T_a$, *u*, , *RH*, $z_0$ | Bastiaanssen *et al.* (1998), Bandara (2006), Timmermans *et al.* (2007) |
| | SEBS<br>(Surface Energy Balance System) | $T_0$, , *NDVI* | $T_a$, *u*, , *LAI*, $e_a$ & $e_{sat}$, $z_0$ | Su (2002), Jia *et al.* (2003) |
| | S-SEBI<br>(Simplified Surface Energy Balance Index)<br>iNOAA<br>(ET of European forests from NOAA-imagery) | $T_0$, , *NDVI* | $T_a$, , *(RH)* | Roerink *et al.* (2000) |
| **Penman-Monteith (PM) based** | Trapezoidal Shape<br>(Relationship between land surface temperature and vegetation indices used to estimate ET) | $T_0$, *SAVI* | $T_a$, , vpd, LAI | Moran *et al.* (1994), Moran *et al.* (1997) |
| | Wang<br>(Combination of day and night land surface temperatures with NDVI) | $T_0$,, *VI* | Meteorological data | Wang *et al.* (2006) |
| | Cleugh<br>(Remote sensing inputs into PM equation) | , *VI* | Meteorological data | Cleugh et *al.* (2007) |
| **Water balance based** | SWAP<br>(Soil, water, atmosphere, plant) | , *VI* | Meteorological, soil, groundwater table data | Santhi *et al.* (2005), Kaur *et al.* (2003) |
| **VI/LST based** | Jackson<br>(Relationship between VI and land surface temperature) | $T_0$, *VI* | $T_a$, *u*, calibration coeff. | Jackson *et al.* (1977) (In Verstraeten *et al.* (2008) |

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[3] $T_0$ = land surface temperature; $\alpha$ = albedo; *NDVI* = normalised difference vegetation index; *SAVI* = soil adjusted vegetation index; *VI* = vegetation index; $\mu$ = wind speed; $\varepsilon$ = surface emissivity; *RH* = relative humidity; $z_0$ = roughness length; *LAI* = leaf area index; $e_{sat}$ = saturation vapour pressure, $e_a$ = water vapour pressure; *vpd* = vapour pressure deficit.

*Table 12: Summary of studies conducted in South Africa. Different methods for estimating ET were assessed and their usefulness in various water resources applications and across various spatial and temporal scales were assessed in historical and operational mode (expanded from Gibson et al., 2013).*

| **Type** | **Study focus** | **Parameters** | **Temporal scale** | **Spatial scale / resolution** | **Reference** |
|---|---|---|---|---|---|
| Review | Methodology | ET, energy balance | Instantaneous, day, week, month | Field / 30 m | Jarmain et al. (2009) |
| Review | Literature review | NA | NA | NA | Gibson et al. (2013) |
| Historic | Catchment water use | ET | One day | 30 m | Ahmad et al. (2005) |
| Historic | Catchment water use | ET, rain, runoff, groundwater recharge | Day, month, year for 1 year | Catchment / 1 km | Gibson et al. (2009) |
| Historic | Catchment water use efficiency | ET | Day, 2-weekly for 3 years | Field, catchment / 250 m | Hellegers et al. (2011) |
| Historic | Natural veld water use | ET | Day, season, annual | Regional / 1 km | Palmer and Weideman (2011)** |
| Historic | IAP, natural veld water use | ET, rain, rain-ET | Daily, two-weekly for 3 years | Provincial / 250 m | Jarmain and Meijninger (2012) |
| Historic | Catchment hydrology | ET, energy balance | 90 days | Catchment / 250 m | Kongo and Jewitt (2006) |
| Historic | Agricultural water use efficiency | ET | 3 years | Field, regional / 30 m | Klaasse et al. (2008) |
| Operational | Agricultural water use efficiency | ET, soil moisture / soil water, energy balance | Weekly, 8 months (grape growing season) | Field, regional / 30 m | Klaasse et al. (2011); Jarmain et al. (2011a) |
| Operational | Agricultural water use efficiency | ET, energy balance | Weekly, for a period of 12 months | Field, farm, region / 30 m | Jarmain et al. (2011b) |
| Operational | Agricultural water management | ET, soil moisture / soil water, energy balance | Weekly, 8 months (grape growing season) | Field, regional / 30 m | Jarmain and Klaasse (2012) |
| Operational | Catchment scale planning and water allocation | ET, rain, rain-ET | Weekly for a period of 12 months | Field, catchment, region / 30 m | WE Consult (2011) |

** This study did not apply the energy balance approach for estimating ET.

Arising from past and current operational projects has been the realisation that field validation of remotely sensed ET estimates is a necessary component of these operations to allow for data products to be used with confidence. In addition, the need to find further users of and uses for the data products has become apparent. The presentation of the end product and its usability differs from historic studies where a map may have been an acceptable deliverable. For operational applications of remote sensed ET estimates to be adopted, there is a need to integrate the ET data products into other systems such as irrigation scheduling, allowing for ease of use and interpretation.

A number of freely downloadable ET data products also exist for example, the Landsaf data (EUMETSAT; www.eumetsat.int) and MODIS16 ET products. The MOD16 ET product, specifically, has generated interest. The MODIS Science Team, in 2011, released a MODIS ET data product (MOD16) available freely for download. The MOD16 ET products are regular 1-km$^2$ global land surface ET datasets for vegetated land areas at eight day and monthly intervals (Mu et al., 2011). The MOD16 ET product is created using MODIS global land cover (MOD12Q1), a daily meteorological reanalysis dataset from NASA's Global Modelling and Assimilation Office, and MODIS biophysical parameters (albedo, leaf area index and enhanced vegetation index) as input into the Penman-Monteith equation. The algorithm performance has been validated against 46 flux tower measurements across seven biomes but validation in Africa has not been published to date.

## 3.5 Evaporation – Lakes and wetlands

Allen et al. (1998) describe evaporation as the process whereby liquid water is converted to water vapour (vaporisation) and removed from the evaporating surface (vapour removal). The basic physical principle behind evaporation is that energy is required to change the phase of molecules from liquid into gas. In natural environments, this energy is provided through direct solar radiation and to a lesser degree the ambient temperature of the air. After the application of energy, the water vapour is removed from the evaporating surface into the atmosphere through differences in the vapour pressure of the evaporating surface and the air pressure of the surrounding atmosphere (the vapour pressure deficit). As evaporation proceeds, the surrounding air increases in saturation and hence the vapour pressure deficit is decreased and the rate of evaporation decreases. Through wind replacing saturated air with drier air, the vapour pressure deficit once again increases and the rate of evaporation will increase. From this description, it can be seen that the climatological variables required to estimate evaporation are: solar radiation, air temperature, air humidity and wind speed.

The Water SBA (GEO, 2010) requirements for evaporation measurements are the same as those for evapotranspiration and are thus presented together with evapotranspiration in Table 10. However, quantifying evaporation from a water body can be very difficult (Herting et al., 2004). The major source of difficulty being the fact that the required meteorological parameters are rarely measured over water surfaces and the thermal lag between water and land surfaces implies that land based measurements will be inaccurate (Abreham, 2009). The complexity of the method used is largely dependent on the required accuracy of the measurement with the complexity of the method increasing with the accuracy required (Herting et al., 2004). For example, pan evaporation is easy to measure however it is notoriously unreliable due to the metal pan which can heat up and lead to large errors in evaporation estimates (Herting et al., 2004). Further, pan evaporation measurements are erratic as they are susceptible to the microclimatic conditions under which the pan is operated as well as the standards of station maintenance (Allen et al., 1998).

Another relatively simple approach of estimating evaporation for a larger water body is the water balance method (also known as the mass balance method) where evaporation from a water body is calculated based on the differences between storage volume, inflows and outflows over discrete time periods (Sinclair, Knight, Merz, 2010).

More complex, the Penman equation, developed in 1948, combines the energy balance with the mass transfer method to compute evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed (Allen et al., 1998).

Remote sensing energy balance methods for estimating evaporation from surface water differ from evapotranspiration methods as there is no soil heat flux component and change in heat storage becomes a factor. The simplified expression is given as:

$$\mathrm{R_n} = \mathrm{H} + \lambda\mathrm{E} + \Delta\mathrm{S}$$

Where $R_n$ is net radiation, H is the sensible heat flux, $\lambda E$ is the latent heat flux and $\Delta S$ is the change of energy storage in the lake fluxes (Abreham, 2009).

However, some surface energy balance over land methods have been adapted for use over open water. For example, the SEBAL algorithm was used to estimate evaporation from Menindee Lakes in Australia (Sinclair, Knight, Merz, 2010). For shallow lakes, evaporation is calculated using the Penman-Monteith equation using a sinusoidal heat storage function to account for energy losses to/from the water body. The amplitude and phase of the heat storage term varies with the depth of the water body and annual variations in air temperature; climates with strong amplitudes in air temperature are assumed to have a large heat storage term. For deep lakes, evaporation is calculated using a bulk transfer equation in which the heat storage is calculated as a fraction of the net radiation. The fraction is adjusted to the prevailing annual cycle of net radiation, ensuring the annual heat storage is neutral. Finally, dry lakes are treated as per the surrounding land and the standard SEBAL routine applied.

The SEBS model has also been adapted for open water bodies where only the sensible heat flux at the wet limit was calculated and rather than a soil heat flux being used, a water heat flux term (equivalent to ΔS in the above equation) is used in its place (Chinyepe, 2010).

## 3.6 Runoff / stream flow

Surface runoff is one of the major outputs from the system in the water balance equation. From a scientific perspective stream flow is also a critical water cycle variable because it integrates all the processes, for example runoff and evapotranspiration, taking place over the area of the basin and provides one final variable that can be readily measured (GEO, 2010). The development of methods to estimate the discharge of rivers using remotely sensed data can fill in gaps within the existing stream flow gauging network and can be used to obtain stream flow information from inaccessible regions which, due to their locations, have not been gauged in the past (Bjerklie et al., 2005). Surface runoff is generally not directly measured using remote sensing and its estimation using RS methods is through the use of other RS data products within hydrological models. The Water SBA (GEO, 2010) drew up data requirements for runoff and stream flow which are presented in Table 13.

Precipitation is arguably the most important variable in land surface hydrology since the stream flow or runoff from a catchment is limited by the amount of precipitation which has fallen in that catchment. Another important parameter is soil moisture / soil water which determines the partitioning of rainfall into runoff and infiltration within a catchment (Brocca et al., 2010) particularly in ungauged basins.

Although understanding runoff generation and the mechanisms of water release in catchments is a central question in hydrology, the corollary to this is the need to improve understanding of how catchments retain water (Hrachowitz et al., 2013). Parameters which affect this are land cover and underlying geology which determine the soil type and the soil's capacity to retain water. It has also been found (Rogger et al., 2012a, 2012b in Hrachowitz et al., 2013) that the spatial distribution of headwater storage is critical for determining which parts of a catchment contribute to runoff and the efficiency of a catchment to generate runoff from precipitation depends on where water is stored and on how accessible the storage is to the outlet.

It can be seen therefore that surface runoff or stream flow is not a direct RS measurement, rather RS data products of other critical observations such as precipitation, soil moisture / soil water and land cover are used within hydrological models to retrieve surface runoff. For example, McNamara et al. (2005) (in Hrachowitz et al., 2013), state that in order to generate runoff, water moving through the soil towards the stream needs to first satisfy soil moisture / soil water deficits along its flow path. Furthermore, a certain precipitation threshold needs to be exceeded before runoff occurs. In this scenario it is obvious that accurate spatial representations of precipitation and soil moisture / soil water within a catchment are essential in the modelling of accurate runoff. Hence the focus should be on these RS parameters rather than on runoff per se.

However, the hydrological modelling of runoff using remote sensing parameters as input has been and remains an important area of research in hydrology. Data assimilation has been identified as an area for future research given the increased availability and quality of remote sensing data (Troch et al., 2003 in Hrachowitz et al., 2013). For example, Vazifedoust et al. (2009) report that research results have been inconclusive as to whether assimilating remotely sensed soil moisture / soil water products improves estimates of stream flow, while Van Dijk and Renzullo (2011) argue that the effectiveness of data assimilation hinges on the degree to which the target variables are influenced by the processes improved by assimilation.

The Soil Conservation Service Curve Number (SCS CN) method is a technique that has become almost universal for relating runoff to rainfall (Jacobs et al., 2003). The basic assumption of the SCS CN is that, for a single storm event, potential maximum soil retention is equal to the ratio of direct runoff to available rainfall, while considering the effect of land use and land cover, various soil cover and preceding moisture condition on runoff. The SCS CN, as the ratio of actual storage to potential storage of a basin, is equal to the ratio of potential runoff to actual runoff (Jacobs et al., 2003). According to Jacobs et al. (2003), the SCS CN method is intended to perform well on average with much of the variability attributed to antecedent soil moisture / soil water. For this reason, microwave remote sensing can be used to determine soil moisture / soil water and adjust curve numbers and resulting runoff estimates.

Various other hydrological modelling methods can be used to estimate surface runoff from a catchment and with the advent of remote sensing and GIS technologies, many of these models have developed into catchment spatial models rather than relying on single values to represent each parameter at catchment scale. For example, Anbazhagan et al. (2005) used satellite data to create land cover classes and through spatial analysis (using GIS) obtained a weighted by intersecting land cover classes with hydrological soil groups. This resulted in land units with weighted curve numbers which could then be used to identify and prioritise suitable sites for artificial recharge.

Similarly, Souchère et al. (2005) predicted runoff using the STREAM-TED model. The STREAM-TED model is the remote sensing version of the STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Management) model and is used to estimate and map runoff according to various scenarios of rain events and land use distribution in a cultivated catchment. Quattara et al. (2004) developed a methodology, based on the combined use of optical and radar images, for evaluating the runoff potential in high relief, semi-arid environments. Multisource satellite images were used – the optical images for information on land use and the radar data for information on texture and roughness.

In South Africa, the Pitman model, developed in 1976, is one of the most widely used water resource estimation models (Hughes, 2006). A particular challenge in the southern African region are ungauged basins – basins with inadequate hydrological observations, in terms of both data quantity and quality, to enable a computation of hydrological variables, at appropriate spatial and temporal scales, at a level of accuracy acceptable for practical water resource management (Sivapalan et al., 2003 in Kapangaziwiri, 2009). According to Kapangaziwiri (2009), the fundamental hydrological problem is the derivation of a relationship between basin rainfall and the resultant runoff. The Pitman model is a monthly rainfall runoff model of which the inputs are monthly time series of rainfall totals and long term estimates of annual potential evapotranspiration to calculate runoff (***Figure 4)***. According to Hughes (2006), the Pitman model has been demonstrated to be applicable to large parts of southern Africa with respect to the way in which it represents real basin responses to runoff. However, whether it is reliable enough for simulating flow regimes in ungauged catchments after the determination of suitable parameter values has not yet been established.

In another South African example of runoff estimation using remote sensing data, Gibson et al. (2009) used the GIS based WetSpass model. The WetSpass model (Batelaan, 2006) simulates runoff in two stages: firstly potential surface runoff is calculated based on vegetation type, soil texture, slope and groundwater saturated areas. In stage two, the potential surface runoff is adjusted for recharge areas taking the seasonal precipitation intensity in relation to the soil infiltration capacity into account.

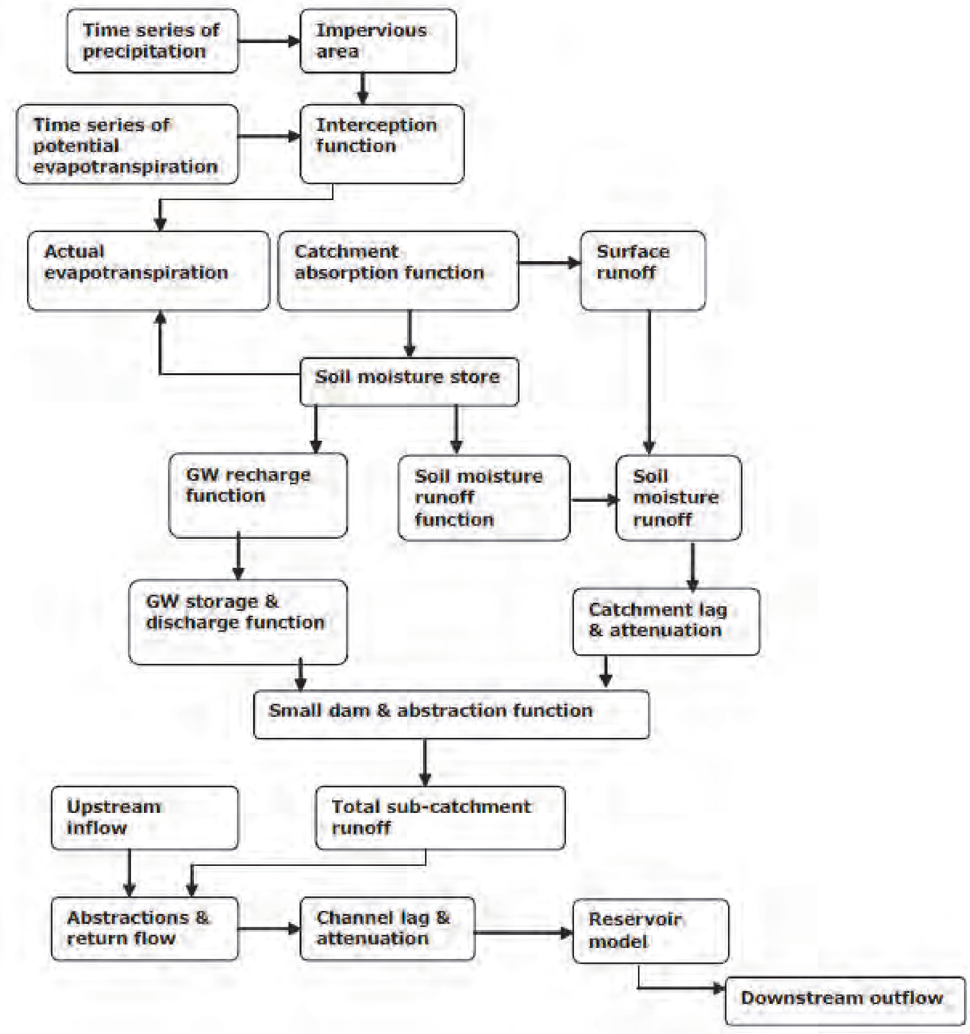


*Figure 4: The Pitman model (Hughes, 2006 in Kapangaziwiri, 2007)*

The PyTOPKAPI model developed by UKZN, is a python coded version of the TOPKAPI model which is a physically based distributed rainfall-runoff model. When tested for the first time in Africa on the Liebenbergsvlei catchment (Vischel et al., 2008), the model showed good ability in modelling the river discharges at a small (six hourly) time step with a limited adjustment of the parameters and low computation times.

With the development of higher resolution and more accurate remote sensing data products, the assimilation of remote sensing data into hydrological models such as the Pitman, PyTOPKAPI and WetSpass models becomes feasible.

## 3.7 River discharge (to ocean coastal zones / estuaries)

River discharge is an important quantity of the hydrologic cycle as it is essential for both scientific and operational applications related to water resources management and flood risk prevention (http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1269629).

Discharge is typically calculated at a particular location in a river from measured water levels by means of a transformation or rating curve developed for the particular channel cross-section at which the water level is measured (GEO, 2010). Because flow in a channel can be influenced by many factors (such as changes in land use, withdrawal for water use, or contributions from artificial water storage reservoirs) discharge does not necessarily represent a response to climatic conditions alone (GEO, 2010). Thus, although precipitation is vitally important it is not the only parameter that should be considered. The Water SBA (GEO, 2010) drew up data requirements for river discharge which are presented in Table 13.

*Table 13: Water SBA summarised requirements for river discharge measurements*

| Scale | Horizontal resolution | Temporal resolution | Accuracy and/or precision | Latency |
|---|---|---|---|---|
| Local | 1-10 km or point data [River Basins] | 1 to 6 hrs | 5%-10% | Hrs – 1 d (near real time) for Point Data and local to regional Appl; 1 d-1 m-3 m for delayed mode/Glob App |
| Regional | 10-100 km | 1-7 d-10 d-1 m [Appl. Dependent] | | |
| Global | 50 km-200 | 1-7 d-10 d-1 m [Appl. Dependent] | | |

As with surface runoff, the development of methods to estimate the discharge of rivers using remotely sensed data can fill in gaps within the existing stream flow gauging network or from inaccessible regions which due to their locations, have not been gauged in the past (Bjerklie et al., 2005). River discharge is also generally not directly measured using remote sensing and its estimation using remote sensing methods is through the use of other remote sensing data products within hydrological models. For example, rainfall runoff models are common tools for river discharge estimation in the field of hydrology (Sun, 2010).

It can be seen in the schematic of the Pitman model (***Figure 4***) that discharge (called downstream outflow in the schematic) is the final output of the model. As with surface runoff, remote sensing data products can be assimilated into these models as the products become more reliable and accurate. As with other indirectly measured parameters, the focus on research and development largely lies in decreasing the uncertainties in the remote sensing inputs into models. For ungauged catchment, the discharge at a watershed outlet is limited by the amount of precipitation on the watershed. Since precipitation is highly variable in space and time, accurate spatial and temporal measurements of rainfall are required.

According to Bjerklie et al. (2005), remote sensing has been shown to be a feasible method to track changes in river discharge where ground based data is difficult to obtain. One application of discharge is related to urbanisation which has an effect on the surface runoff and ultimately discharge into estuaries or the coastal zone (Weng 2001 & Arthur-Hartranft et al., 2003). While Alsdorf et al. (2005) and Le Favour & Alsdorf (2005) used SRTM data to model discharge at a very large basin scale (Amazon River Basin).

The calculation of actual river discharge outside of hydrological modelling using remote sensing techniques is addressed by Bjerklie et al. (2003) and Bjerklie et al. (2005). Remote sensing has been utilised in developing general approaches to tracking floods and changes in river discharge, however few studies have attempted to calculate river discharge entirely from remotely obtained information (Bjerklie et al., 2003). To better understand how remote sensing may be used in calculating river discharge, it is necessary to highlight those parameters which are taken into account when calculating discharge. The strong correlation between quantities of river cross-sectional water surface width obtained from remote sensing and corresponding in situ gauged river discharge has been verified by many researchers (Sun, 2010) and is exploited in remote sensing discharge estimate techniques. Bjerklie et al. (2003) state there are a variety of equations which can be used to calculate river discharge and that the hydraulic elements which are considered in these equations include: average velocity, water surface width, average water depth and channel slope. There are also key hydrographic variables that cannot be directly measured from satellite information or other remote data sources such as: average depth and average cross-sectional velocity. In 2005, Bjerklie et al. developed a methodology to estimate river discharge exclusively from remotely sensed hydraulic data (water surface width and maximum channel width) and channel slopes obtained from topographic maps.

In ungauged basins, the dependence on observed river discharge data for calibration restricts applications of rainfall runoff models but Sun (2010) reported that satellite observation of the river width is a competent surrogate of observed discharge for the calibration of rainfall runoff model. Further, empirical relationships of discharge to river width and water surface elevation have been studied both which can be measured using remote sensing techniques (Sun, 2010). However, the current radar altimeters, for example TOPEX/Poseidon and Envisat, only provide one dimensional spot water level measurements along orbit track, leaving large areas between orbits unobserved (Sun, 2010).

## 3.8 Water quality

Water quality refers to the chemical, physical and biological characteristics of water, usually taking into account its suitability for an intended purpose, for instance domestic, farming, mining or industrial purposes, or its suitability to maintain a healthy ecosystem. These characteristics are influenced by substances, which are either dissolved or suspended in water. Water quality is affected by both natural processes and human activities; it varies from place to place depending on seasonal changes, climate change and soil type, rocks and surfaces through which it moves. A variety of human activities, for example agricultural activities, urban and industrial development, mining and recreation, also significantly alter water quality. Deteriorating water quality leads to increased treatment costs of potable and industrial process water, and decreased agricultural yields due to increased salinity of irrigation water. The occurrence, transport and fate in the aquatic environment of numerous persistent and toxic metals and organic compounds, such as pesticides, are a cause for serious concern.

Contamination of groundwater resources or sediments deposited in riverbeds, impoundments and estuaries, by toxic and persistent compounds can cause irreversible pollution, sometimes long after the original release to the environment has ceased. On the other hand, not all health, productivity and ecological problems associated with deteriorating water quality are ascribed to man's activities. Some water quality related problems are inherent in the geological characteristics of the source area.

Water quality can be monitored by remote sensing techniques specifically through the detection of phytoplankton, turbidity, suspended matter and dissolved organic matter (Usali & Ismail, 2010). Only optically active constituents in the water column and the surface water temperature can be mapped directly using remote sensing, however these measurements can be combined in ways so as to produce indices of water quality (www.earthobservations.org/ts.php?id=182). According to GEO (www.earthobservations.org/ts.php?id=182), it is feasible to implement a global, fully operational, spatially comprehensive water quality information system based on observations from past, present and planned future satellite systems however, this has not yet happened. The

Water SBA (GEO, 2010) drew up data requirements for water quality which are presented in Table 14**.**

*Table 14 Water SBA summarised for water quality measurements*

| Scale | Horizontal resolution | Temporal resolution | Accuracy and/or precision | Latency |
|---|---|---|---|---|
| Local | 1 m-1 km [Point Data] | Typical WQ data sampling networks and techniques do not correspond to the grid-based space-time resolutions as specified for other geophysical observational variables | 10% | Various |
| Regional | 10 km-50 km | | | |
| Global | 50 km to 100 km to 500 km | | | |

In South Africa, much of the water quality research has been carried out by Mark Matthews (Matthews et al., 2010; Matthews et al., 2011; Matthews et al., 2012; Matthews & Bernard, 2013a; Matthews et al., 2013b) who has focused on mapping the presence of phytoplankton since these toxic cyanobacterial blooms are seen to be the greatest water quality issue related to inland water bodies. Matthews et al. (2012) developed a novel algorithm, known as the maximum-peak-height algorithm, for detecting trophic status (chlorophyll-a), cyanobacterial blooms, surface scum and floating vegetation in coastal and inland waters. Top of atmosphere Medium Resolution Imaging Spectrometer (MERIS) data is used in the maximum peak height (MPH) algorithm which uses a baseline subtraction procedure across the red and near infrared MERIS bands, to calculate the height of the dominant peak caused by sun-induced chlorophyll fluorescence (SICF) and particulate backscatter.

## 3.9 Groundwater recharge / discharge rates:

Despite its relatively small contribution to the total water supply in South Africa, (~13%), groundwater, represents an important strategic water resource. Two-thirds of South Africa's surface area is largely dependent on groundwater and although irrigation is the largest user of groundwater, it provides the water to more than 300 towns and rural areas, as evidenced by the names of many towns, such as De Aar (the Afrikaans for 'artery', an underground water source), Springs, the Fountains at Pretoria and the many towns ending with '-fontein'. In over 90% of the surface of South Africa, groundwater occurs in hard rock with no pore spaces. Here it is contained in faults, fractures and joints and in dolomite and limestone, in dissolved openings called fissures.

Groundwater exploration is done using various methods and the most basic is measuring groundwater level and quality. Groundwater levels are measured using the piezometer tubes and dip meters. Agricultural and domestic production wells can be used for measuring groundwater levels, in addition to dedicated monitoring wells. Groundwater recharge can also be determined using isotopes, carbon-14, Chloride and the water balance among other methods. Groundwater quality monitoring is also done to check for environmental isotopes, trace and radioactive elements.

Remote sensing has the general advantage of providing a spatially distributed measurement on a temporal basis, but only observes the surface of the Earth. Therefore, a link must be established between the surface observation and the subsurface, the groundwater. Much of the application of remote sensing to groundwater is around the mapping of geological features from satellite images and subsequent hydrogeological interpretation. According to Meijerink et al (2007), this interpretation focuses on the hydrogeological subsurface configuration and surface features that influence recharge and show evidence of groundwater outflow. For example, the mapping of geological lineaments as an indication of groundwater recharge or vegetation associated with lineaments may indicate groundwater exploration targets. The drainage density of an area can be indicative of the permeability of the surface and subsurface. Drainage density mapped from satellite images can thus indicate whether a region is located in a groundwater recharge zone.

Despite groundwater's status as a subsurface resource not directly measured by remote sensing, as with previously mentioned runoff and stream flow, there are indirect inferences that can be made around groundwater recharge and discharge using remote sensing data products within hydrological models such as the Pitman model.

Groundwater recharge becomes important in arid and semi-arid areas that are mainly dependent on groundwater as a primary water source. In areas of extensive agriculture, high levels of extraction could lead to decreased groundwater levels and natural recharge could be negatively affected (Gibson et al., 2009). According to Münch et al. (2013), remote sensing techniques can be and have been used to quantify recharge and as part of sustainable groundwater exploitation by using relationships that exist within the water balance. This is particularly relevant in data poor semi-arid regions where there is large uncertainty associated with recharge rates (Münch et al., 2013). The Water SBA (GEO, 2010) drew up data requirements for groundwater recharge and discharge which are presented in Table 15.

In a South African example, Münch et al. (2013) demonstrated how remote sensing data products (ET and precipitation) can be used in semi-arid areas to identify recharge and discharge zones within a catchment and to help in the hydrogeological conceptualisation of a semi-arid catchment. As with runoff, as the accuracies of the input data increases, so do the reliability of data products further down the data processing chain.

*Table 15: Water SBA summarised requirements for groundwater recharge and discharge measurements*

| *Scale* | **Horizontal resolution** | **Temporal resolution** | **Accuracy and/or precision** | **Latency** |
|---|---|---|---|---|
| Local | 1-10 km | 1 m to 3 m to 1 year depending on variability | 5%-7% (Depth to WTable); 20% for fluxes | 1 m to 3 m |
| Regional | 50-100 km | | | |
| Global | 50-100 km | | | |

## 3.10 Aquifer – Volumetric and change

GRACE (Gravity Recovery and Climate Experiment) deals with gravity field change and the variations in terrestrial water storage. The most promising method to explore groundwater, the GRACE twin satellites were launched by NASA in 2002, with a very coarse spatial resolution of 200-300 km and monthly temporal resolution. The change in distance is in principle a result of the change in gravity field caused by change in terrestrial water storage (soil moisture / soil water, groundwater, wetlands, icecaps) on Earth. Therefore, to estimate groundwater storage, the contribution of the other factors to gravity has to be subtracted by incorporating other data sources and models.

The GRACE satellite has been used in large basins to study seasonal fluxes such as in the Ganges (Khan et al., 2013), and monitors water storage in La Plata Basin (Pereira et al., 2012). The GRACE-satellite has not yet been utilised in South Africa as it must first be determined if it is a dataset applicable to the scale of the basins that are found in South Africa.

## 3.11 Land cover – vegetation cover / type

There is an unquestionable although complex link between land cover (the observed biophysical cover on the Earth's surface) and water resource management with linkages existing at a wide variety of spatial and temporal scales (La Frenierre, undated). The land cover represented in a catchment directly impacts on the partitioning of precipitated water into evapotranspiration, runoff or infiltration and thus has an impact on the availability of water for human and ecosystem use. Further, changes in land cover alters both runoff behaviour and the balance that exists between evaporation, groundwater recharge and stream discharge in specific areas, with climate models even showing that land change affects global precipitation and temperature patterns, which drive the global hydrological cycle in the most fundamental ways (Chase, et al., 2000).

It was already stated in 1996, that for large areas, satellite remote sensing techniques had become the single most effective method for land cover acquisition (Thompson, 1996). When land cover classification is conducted using remotely sensed imagery, features are grouped into clusters according to their occurrence and spectral similarity. Remote sensing has developed to the point where data archives now extend over a period of decades. For example, the first Landsat satellite was launched in 1972 and the Landsat programme has thus been monitoring the earth from space on a near continual basis for over four decades.

The Water SBA (GEO, 2010) drew up data requirements for land cover including surface roughness which are presented in Table 16.

*Table 16: Water SBA summarised requirements land cover including surface roughness*

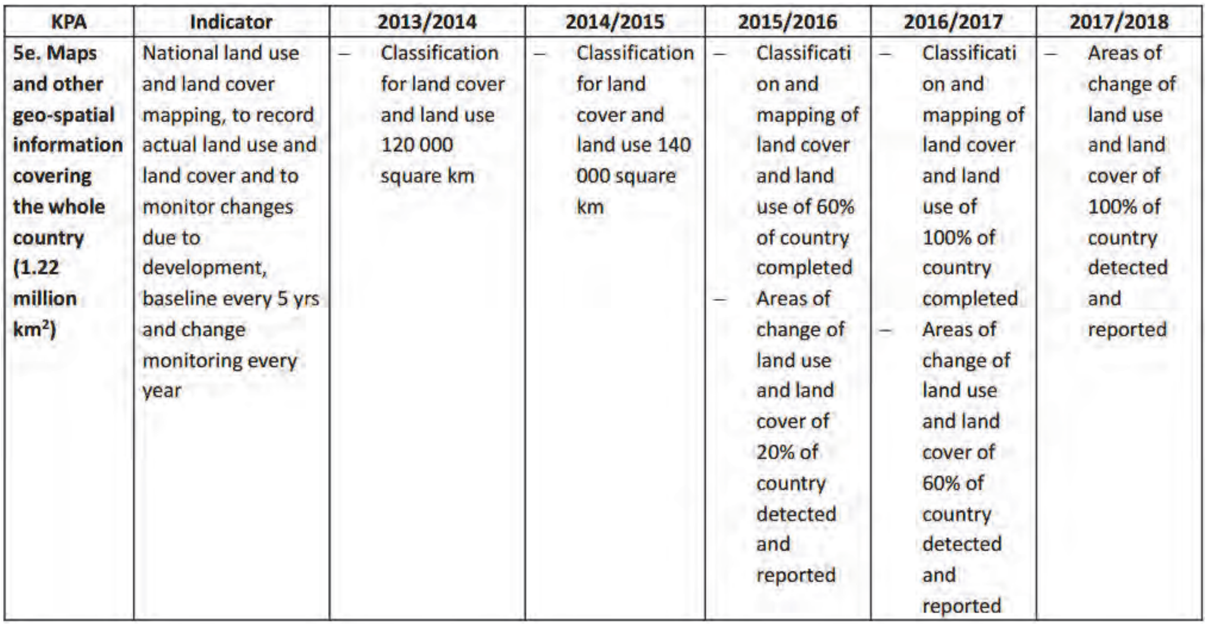
| **Scale** | **Horizontal resolution** | **Temporal resolution** | **Accuracy and/or precision** | **Latency** |
|---|---|---|---|---|
| Local | 1-10 km | 10d to 1m to 3m to 1yr to 5yr to 10yrs [Depending on measurement/ instrument/ observation type] | 5% in units of $km^2$<br>10% in units of m for roughness length ($Z_0$).<br>[Global accuracy of 20% is stated to be sufficient for some applications] | 1d to 7d to10d to 1m to 1 yr [App. Dependent] |
| Regional | 10-100 km | | | |
| Global | 10-100 km | | | |

The use of a predetermined classification system devised a priori and acceptance by the scientific community ensures the repeatability of methods allowing for land cover change studies to be achieved. In South Africa, a hierarchical system, emanating firstly from the standard proposed by Thompson (1996) and finally the Land Cover Classification System (LCCS) proposed by the FAO (Di Gregorio & Jansen, 2000) has been accepted as the standard by

National Geospatial Information (NGI) – the organisation mandated to mapping land cover in South Africa. The LCCS used in South Africa is shown in Figure 5.

Although the NGI is mandated to collecting land cover data, budgetary constraints have limited the achievement of this mandate. However, there is a plan in place to complete the land cover mapping of the entire country in the next five years as indicated in the NGI strategic plan (Table 17). Schoeman et al. (2013) produced a land cover change map of South Africa using a multi-year data archive, however this was to determine the extent of land cover transformation over a 10 year period rather than to produce a countrywide land cover data product. Previous countrywide land cover efforts date back to 2000 in the form of the South African National Land Cover 2000 project (Van den Berg et al., 2008), which leads to the conclusion that countrywide coverage of land cover is long overdue.

*Table 17: NGI strategic plan for land cover mapping*



| KPA | Indicator | 2013/2014 | 2014/2015 | 2015/2016 | 2016/2017 | 2017/2018 |
|---|---|---|---|---|---|---|
| **5e. Maps and other geo-spatial information covering the whole country (1.22 million km²)** | National land use and land cover mapping, to record actual land use and land cover and to monitor changes due to development, baseline every 5 yrs and change monitoring every year | – Classification for land cover and land use 120 000 square km | – Classification for land cover and land use 140 000 square km | – Classification and mapping of land cover and land use of 60% of country completed<br>– Areas of change of land use and land cover of 20% of country detected and reported | – Classification and mapping of land cover and land use of 100% of country completed<br>– Areas of change of land use and land cover of 60% of country detected and reported | – Areas of change of land use and land cover of 100% of country detected and reported |

It should however be noted that NGI maps land cover at a high resolution (10 m) when compared with the required resolutions for hydrological applications determined by the Water SBA (Table 16).

This should be considered when decisions are made around the choice of which land cover product to use for hydrological purposes. It may be that a land cover data product with a high temporal resolution may be better suited to some hydrological applications than the NGI data product with a very high spatial resolution but a planned temporal resolution of five years.

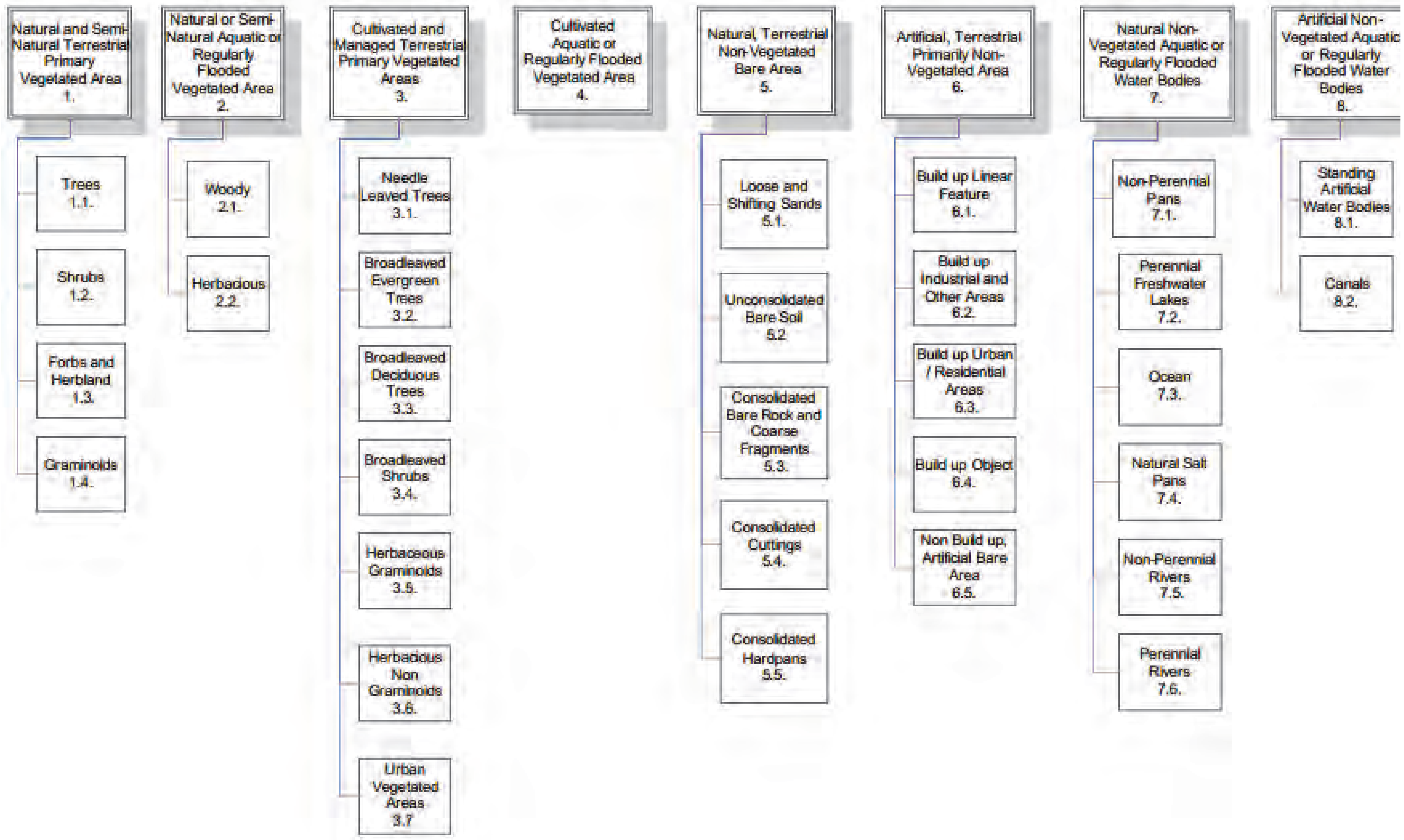


*Figure 5: Land cover classification system used by NGI in South Africa (Lück et al., 2010).*

## 3.12 Elevation / topography

Digital elevation models (DEMs) are digital representations of the topography of a landscape and are an important data source used in numerous hydrological and geo-hydrological models (Weepener et al, 2011). Further, data products derived from DEMs such as catchment boundaries, sub-basins and streamlines play an important role in hydrological studies (Mashimbye, 2013). The Water SBA (GEO, 2010) drew up data requirements for elevation and topography measurements which are presented in Table 18

*Table 18: Water SBA summarised requirements for elevation and topography measurements*

| Scale | Horizontal resolution | Temporal resolution | Vertical resolution or height depth | Accuracy and/or precision | Latency |
|---|---|---|---|---|---|
| Local | 30 arc sec grid; 120 postings per degree lat/long. Also stated as 1-100 km and/or 100 m to 1000 m, and 250 m to 10000 m. [Appl.Dependent] | 5yr-10yr-50yr. [Also stated as 240-360 months for e.g., Geoid] [updating w/new technology & better resolution] | N/A or sometimes stated as 1 cm to 1 m | 1 m to 5 m to 10 m vertical [Also stated variably as: +/-50 m to 200 m; 500 m in vertical in steep areas; 1000 m in horiz or better; 1 cm to 5 cm for Geoid] | 30d to 600d to 720d [Also stated as 12yr to 24 yr for e.g., Geoid] [App.Dependent] |
| Regional | | | | | |
| Global | | | | | |

In the past, expensive and time consuming ground surveys and photogrammetric data collection had to be done to collect topographic data for the production of DEMs (Els, 2011) but recently DEMs derived from spaceborne remote sensing have become available both at increasingly high resolutions and at approaching global coverage (Mashimbye, 2013). Notably, the SRTM DEM (90 m spatial resolution) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) (30 m spatial resolution) enable hydrological analyses and modelling on a regional, national and even international (trans-boundary basins) scale (Weepener et al, 2011).

At the opposite end of the scale spectrum, very high resolution DEMs, as derived from airborne light detection and ranging (LIDAR) data, are usually captured for a specific purpose covering a small area of interest, as the mobilisation and technology costs can be prohibitively expensive. As with other remote sensing observations, the trade-off between price and scale is apparent. However for most hydrological applications (with the exception of catastrophic extreme events such as large scale flooding and tsunami's) a frequent revisit time is not necessary and a dataset remains valid many years after the data capture.

Mashimbye (2013) reviewed the application of DEMs to hydrological analysis and found that the recent availability of medium (90 m) and high resolution (30 m) near global DEMs has opened up new possibilities for hydrological analyses at national and regional scales. Researchers are primarily making use of these datasets as they are freely available however, little is known about the quality of the products that are derived from these DEMs (Mashimbye, 2013).

Prior to 2011, very limited DEM data was available for South Africa (Els, 2011) for hydrological applications such as flood modelling (Table 19). Most notable, subsequent to 2011, Weepener et al. (2012) hydrologically improved the SRTM DEM for South Africa and trans-boundary basins by filling voids using 20 m 1:50 000 contours and ASTER GDEM data. In the accuracy assessment it was found that 99.2% and 91.8% of generated stream lines were within two (180 m) and one (90 m) pixel of the actual stream line respectively. At that point, it was claimed that the generated dataset was the best elevation data available at national level in South Africa. In addition to streamlines, catchments (primary to quaternary) were generated from the DEM (Weepener et al., 2012).

*Table 19: Topographical data source in South Africa (Els, 2011)*

| **Type** | **Dataset** | **Resolution/ Interval** | **Coverage** | **Source** |
|---|---|---|---|---|
| Contour | CD:NGI 1: 10 000 contours | 5-20 m* | South Africa (partial coverage) | CD:NGI |
| | CD:NGI 1: 50 000 contours | 20 m* | South Africa | |
| DEM | CD: NGI 25 m DEM | 25 m | South Africa (partial coverage) | CD:NGI |
| | ASTER GDEM | 30 m | Global | ERSDAC |
| | CD: NGI 50 m DEM | 50 m | South Africa (partial coverage) | CD:NGI |
| | SRTM 90 m DEM | 90 m | Global | ERSDAC |
| | GTOPO30 | 1 km | Global | |

*Vertical interval Chief Directorate: National Geo-Information (CD: NGI)
Earth Remote Sensing Data Analysis Centre (ERSDAC)

Other DEM datasets are available in South Africa such as the Stellenbosch University Digital Elevation Model (SUDEM L1) which was developed by the Centre for Geographical Analysis (CGA) at the University of Stellenbosch (Van Niekerk, 2013). Strictly speaking this is not a remote sensing data product as it was created from topographic contour line and spot heights although the SRTM dataset was used in the generation of the second version of SUDEM (SUDEM L2). SUDEM is a high resolution (5 m) DEM for South Africa and is a commercially available product. Mashimbye (2013) evaluated SUDEM accuracies for streamline extraction and catchment delineation against SRTM and GDEM, in the Berg River catchment. It was reported that of the DEMs, SUDEM L2 returned the highest levels of accuracies in both the catchment delineation and streamline delineation.

For developing countries such as South Africa, LIDAR technology remains for the most part prohibitively expensive, particularly for non-income or low income generating applications such as is the case in many hydrological applications. Therefore other sources of DEMs are considered for hydrological studies at national or regional scale (Mashimbye, 2013).

As technologies and computer processing and storage improve, the possibility of generating global datasets at high resolution becomes a reality. For example, the WorldDEM™, intended to be the replacement dataset for SRTM, will have a 12 m spatial resolution with a relative and absolute vertical accuracy of 2 m and 10 m respectively (http://www.astrium-geo.com/en/168-tandem-x-global-dem). WorldDEM™ is created from the high resolution radar satellites TerraSAR-X and TanDEM-X which together form a high-precision radar interferometer in space. However, since this dataset will only become available in 2014, the improved SRTM DEM by Weepener et al. (2012), at 90 m resolution, arguably remains the best freely available option for regional and national hydrological applications.

## 3.13 Lake / reservoir levels (including other surface storage)

Remote sensing of surface water level is based on two principles: mapping surface water extent and radar altimetry. Using the first principle, the extent of the surface water is mapped and using topographic information (DEM), the volume change in water levels over time can be calculated. Further, the volume of water stored can be estimated using this approach as the area of water surface measured from satellite images can be transformed into the volume of water stored using the relationship between the area of water surface and the volume of water stored. The second method using radar altimetry operates on the principles of radar in that the altimeter emits a radar wave and analyses the return signal. The height of the surface (in this case the water level) is the difference between the satellite's position in orbit and the satellite-to-surface range which is calculated by measuring the time taken for the signal to be emitted and return to the altimeter (http://www.altimetry.info/html/alti/principle/welcome_en.html).

Remote sensing techniques are very useful for calculating the capacity of reservoirs because of their synoptic and repetitive coverage. Using mapping of surface water extent approach, the size of the water bodies which can be mapped, and the change in water level which can be detected, will be dependent on the spatial resolution of the satellite imagery and DEM available. Furthermore, the temporal period at which changes in water level can be detected will be dependent on the revisit time of the satellite and since high resolution imagery generally has a low revisit time, the temporal and spatial resolution are often inversely related. A method based on mapping surface water extent was first documented by Gupta and Banerji (1985) who proposed a method for estimating water volumes using Landsat MSS data along low-gradient channels based on computing lake surface area. The relationship between water surface area and water volume has been corroborated by other authors (Van de Giesen et al., 2004; Wang et al., 2005).

Water level measurement by satellite altimetry was originally developed for open oceans but currently radar altimetry is used for, and has improved, the estimation of inland water levels. Satellite radar altimetry can provide lake level variations with an accuracy ranging from centimetres to decimetres depending on their size and on their location (Crétaux et al. 2011). According to Crétaux et al. (2011), although altimetry has some limitations, it is a technique that has a proven potential for hydrology and it is often the only source of information for most lakes in remote areas.

A programme was launched to monitor the changing water levels of selected large lakes using data from the NASA/CNES TOPEX/POSEIDON (T/P) and Jason-1 satellites. Launched in 1992, the T/P mission provides a historic archive while Jason-1 continues the observing period from 2002. Lake level variations are measured for 350 of the world's largest lakes at 10 day intervals with high levels of accuracy – 10 cm for the larger lakes (Birkett & Doorn, 2004). The Global Reservoir and Lake Elevation Database uses near real time radar altimeter data over inland water bodies in a semi-operational manner and display the results on the Internet (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir) as does http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/. According to Crétaux et al. (2011), combined global altimetry datasets have a more than two-decade-long history and are expected to be continuously updated in the coming decade with missions. Crétaux et al. (2011) list the upcoming missions of such as Altika, Jason-3, Cryosat-11, Sentinel-3 and SWOT as potential successors of current sensors.

# 4. REVIEW ON THE STATUS OF EARTH OBSERVATION DATA SOURCES FOR WATER RESOURCE MANAGEMENT

Various remote sensing based global and/or regional products of these hydrological elements are available freely online. The objective of this review is thus to inventory, characterise and evaluate the hydrological datasets, both in situ and remote sensing based, available for water resource management in South Africa. The review will focus on identifying gaps in datasets, challenges and opportunities in improving the data pool available for water resource management. The essential components of the hydrological cycle that will be investigated include precipitation, soil moisture / soil water, evapotranspiration, groundwater, surface water level, water quality, land use / land cover, topography, open water evaporation, runoff / stream flow and river discharge.

In situ data sources of each element will be examined in this section, with special attention being paid to South Africa. Where there are data gaps, this exercise hopes to expose them.

## 4.1 Precipitation

Precipitation is the most important variable in the water cycle, as this is the main way atmospheric moisture is delivered to the surface. Precipitation is the primary driver of hydrologic climate, and water resource studies. Accurate measurement of this variable is hence important.

Rainfall data is obtained using three methods: rain gauges, ground radar and satellite technology. Remote sensing techniques developed to estimate precipitation involve the use of infrared (IR) and microwave remote sensing imagery using various approaches. Some techniques are based exclusively on IR data (e.g. Arkin and Meisner 1987), or exclusively on microwave data (e.g. Kummerow et al. 2001), whereas others combine both IR and microwave satellite data (e.g. Jobard and Desbois 1994) or include other types of data such as ground based rainfall observations (e.g. Grimes et al. 1999) or numerical weather prediction (NWP) model information (e.g. Huffman et al. 1995). Most recent methods now use blended techniques combining all available sensors to improve resolution, coverage and accuracy.

### *4.1.1 In situ data sources*

South Africa has an in situ network of manual and automatic rain gauges (Table 20) that records rainfall at varying time scales, including daily and five minute intervals, as well as a radar network across the country. These stations are operated by various organisations, including SAWS, research and academic institutes.

*Table 20: In situ data sources and their accessibility*

| **Data Available** | **Period of availability** | **Institution** | **Accessibility** |
|---|---|---|---|
| ± 1500 rain gauges recording daily rainfall<br>± 150 automatic rain gauges recording rainfall at 5 minute intervals<br>12 ground radar stations | Since 1836 | South African Weather Services | Data is free for research or academic purposes; and available at a cost for commercial purposes. To order, email info4@weathersa.co.za or phone 082 233 8484 |
| >500 countrywide automatic and 90 mechanical weather stations | Since 1940 | Agricultural Research Council | Available at a cost |

Figures 6 and 7 llustrate the meteorological stations network from SAWS and the ARC that record rainfall, temperature, wind speed and direction, radiation and humidity.

The biggest challenge is that the rain gauge network in the country is diminishing fast (Rouault et al., 2001; Sawunyama & Hughes, 2008), meaning there are gaps and errors when using these data. This also affects the validation of remote sensing products when using these data.

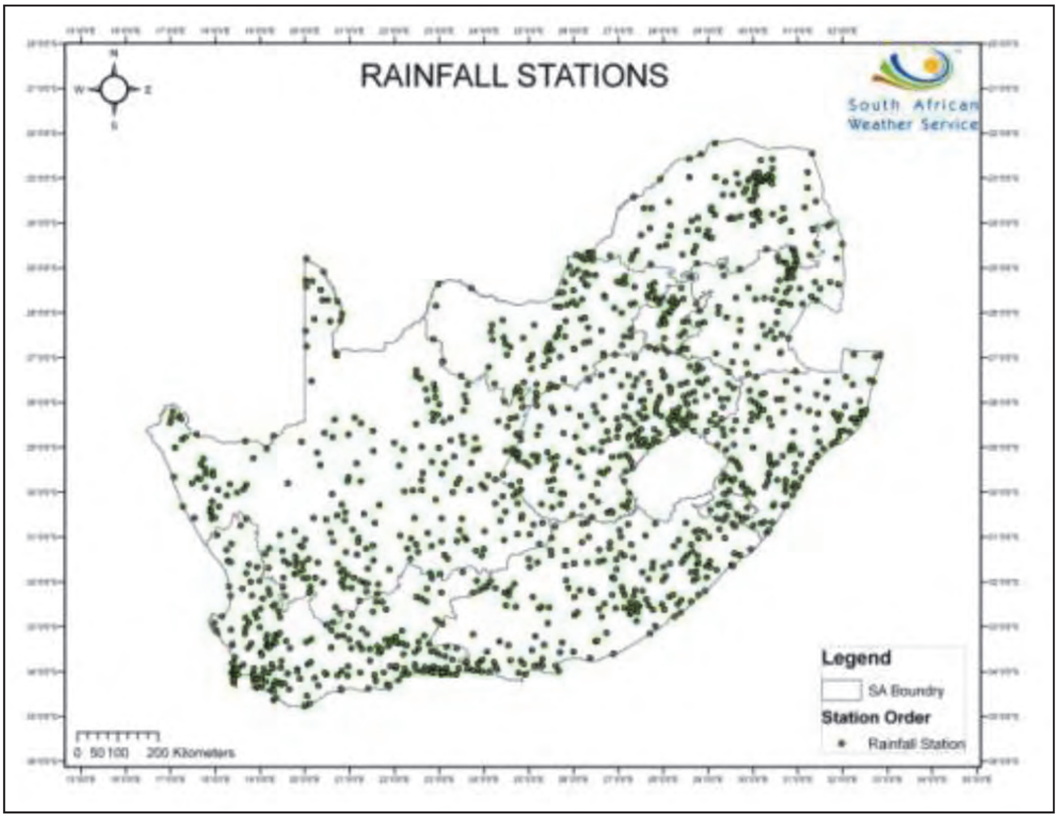


*Figure 6: Distribution of SAWS weather station network in South Africa (Source: http://www.weathersa.co.za/web/index.php/sclimate 2013)*

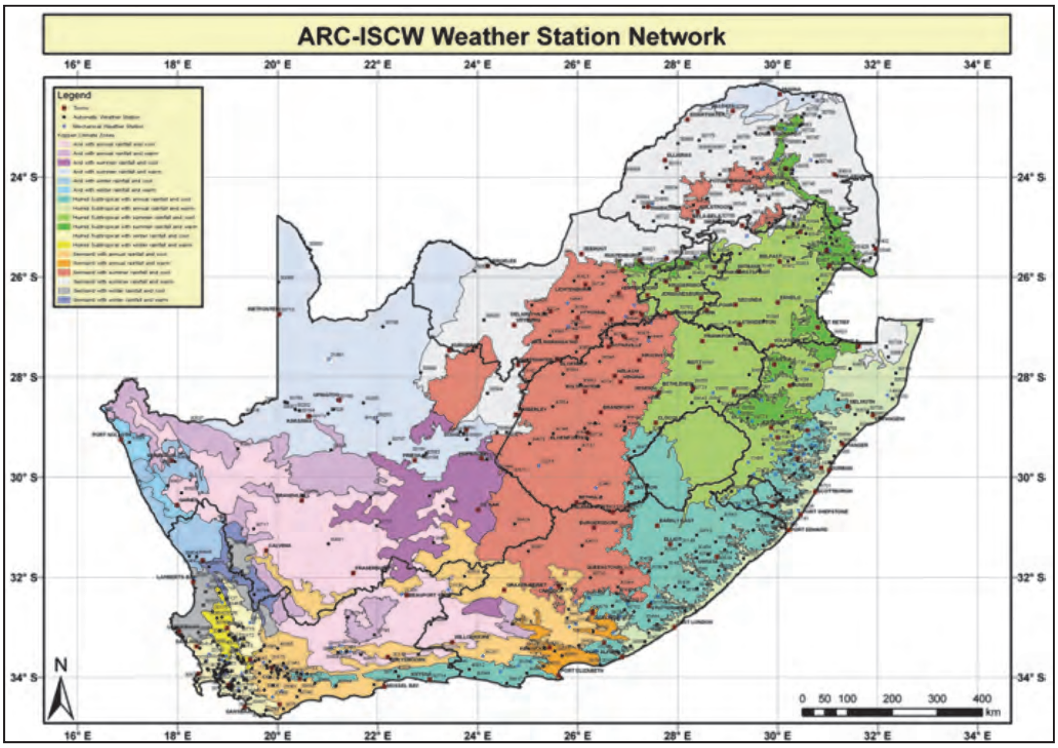


*Figure 7: Distribution of ARC weather station network in South Africa (2013)*

### 4.1.2 *Remote sensing data sources*

Most precipitation products available are global precipitation products freely downloadable online, including TRMM, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), Multi-sensor Estimate (MPE) and Climate Prediction Center Morphing Technique (CMORPH), to mention a few. These products are summarised in ***Table 21***. The Hydroestimator trial version product provides rainfall estimated for the Southern African region (Coning & Poolman, 2011; De Coning et al., 2011). The SAWS has been designated with the dissemination of the product, (http://rsmc.weathersa.co.za/RSMC/login.php). This product is based on an algorithm developed by Scofield and Kuligowski (2003) using the 10.8um Infrared channel from Meteosat MSG satellites to estimate cloud top temperature coupled with Numerical Weather Prediction Model fields from the Unified Model to estimate a rainfall rate. Coning and Poolman (2011; 2011) report that the Hydro-Estimator product overestimates precipitation amounts whilst it underestimates and/or misses some stratiform events.

*Table 21: List of global remote sensing products that are available for use by the South African community*

| Satellite product | Period of Record | Resolution | | Spatial coverage (longitude, latitude) | Source | Reference |
|---|---|---|---|---|---|---|
| | | Temporal | Spatial | | | |
| TAMSAT (Tropical Applications of Meteorology using SATellite and other data) | June 1996 to date | 10 day | Pixel | 20°W–52°E, 28°N–2°S | Request data from TAMSAT group of University of Reading (Reading, UK)<br>http://www.met.rdg.ac.uk/tamsat/ | Grimes et al. (1999). |
| RFE-2.0 (RainFall Estimation) | Jan 2001 to date | Daily | 0.10° | 20°W–55°E, 40°N–40°S | Contact tim.love@noaa.gov for data<br>http://www.cpc.ncep.noaa.gov/products/fews/data.html | Herman et al. (1997) |
| GSMaP-MVK (Global Satellite Mapping of Precipitation) | Jan 2003 to 31 Dec 2006 | Hourly | 0.25° | Global, 60°N–60°S | http://www.GSMaP.aero.osakafu-u.ac.jp/index.html | Ushio et al. (2009) |
| GPCP-1dd (Global Precipitation Climatology Project) | Oct 1996 to date | Daily | 1 ° | Global | datasets are distributed in a monthly file<br>ftp://precip.gsfc.nasa.gov/pub/1dd | Huffman et al. (2001). |
| TRMM-3B42 (Tropical Rainfall Measuring Mission) | Jan 1998 to date | 3 hourly | 0.25° | Global, 50°N–50°S | Product provided and archived by the Goddard Earth Sciences Data and Information Services Center | Kummerow et al. (2001); Huffman et al. (2007) |
| PERSIANN | Mar 2000 to date | 6 hourly | 0.25° | global, 50°N–50°S | http://hydis8.eng.uci.edu/hydis-unesco/ | Hsu et al. (1997) |
| CMORPH (Climate Prediction Center MORPHing technique) | Dec 2002 to date | 30 min | 0.07° | global, 60°N–60°S | available about 18 hours after real time<br>http://www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html | Joyce et al. (2004) |
| TRMM 3B42-RT (real time) | Jan 2002 to date | 3 hourly | 0.25° | global, 60°N–60° | available about 9 hours after real time<br>ftp://trmmopen.gsfc.nasa.gov/pub/merged/mergeIRMicro/ | Huffman et al.,(2007) |
| GPI (GOES Precipitation Index) | Jan 1996 to date | Daily | 1° | global, 40°N–40°S | http://www.cpc.noaa.gov/products/global_precip/html/wpage.gpi.html | Arkin and Meisner (1987) |
| Hydro-Estimator | 2002 to date | 30 min, 1, 3, 6 hour, daily/ multi-daily | 4 km | Global | http://www.star.nesdis.noaa.gov/smcd/emb/ff/auto.html | Scofield (1987;), Scofield & Kuligowski(2003) |
| GPM | To be launched in 2014 | | | | | Hou et al. (2008); Smith et al. (2007) |

## 4.2 Evapotranspiration

Evapotranspiration (ET) is the second most important variable of the hydrological cycle after precipitation because it facilitates the continuation of precipitation by replacing the vapour lost through condensation (Brutsaert, 2009). This process involves evaporation which is the loss of water through vaporisation of water from the surface (water, land and/or plant) and transpiration where water vapour is transferred to the atmosphere by the plant leaf stomata. These processes happen simultaneously, hence they are called evapotranspiration. It is a crucial process in the continuation of the hydrological cycle and global energy transfer.

Conventional in situ methods for estimating ET include i) direct measurements using porometry and lysimeters (Allen et al., 1991); ii) atmospheric measurements, including energy balance and micrometeorological techniques like Bowen ratio (Bowen, 1926), eddy covariance (Monteith & Unsworth, 1990), scintillometry (Jarmain, Everson et al., 2009), as well as equations based on weather data, for example calculation of the Penman-Monteith reference grass evapotranspiration (ETo) in combination with a crop coefficient (Allen et al., 1998); iii) soil measurements (Hillel, 1982); and iv) the application of the soil water balance and hydrological models. Remote sensing techniques that have been used to estimate spatial ET are mainly based on i) empirical methods that involve the use of statistically-derived relationships between ET and vegetation indices such as normalized difference vegetation index (NDVI) or the enhanced vegetation index (EVI) (Glenn et al., 2007; Nagler et al., 2005); ii) residual methods of surface energy balance (single- and dual- source models) (Bastiaanssen et al., 1998; Su, 2002) and these include the Surface Energy Balance Algorithm over Land (SEBAL), Surface Energy Balance System (SEBS) (Su, 2002) and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) (Allen et al., 2007), and iii) physically-based methods which involve application of the combination Penman-Monteith type of equations (Cleugh et al., 2007; Mu et al., 2007; Mu et al., 2011).

### *4.2.1 In situ data sources*

A relatively large scattered and historic ground based ET dataset exists in South Africa, mainly from different agricultural land uses that were collected for specific purposes and projects (Gibson et al., 2013). These data have been used to evaluate various remote sensing based ET algorithms that include SEBS, SEBAL and METRIC (Jarmain, Mengitsu et al., 2009). Longer ground based ET time series are only available at the Skukuza and Malopeni flux towers (savanna biome). Actual ET is derived from these measurements. A summary of the in situ datasets is given in **Table 22**. There is an insufficient network of ET stations to cover the different biomes around the country to ensure ET monitoring, calibration and validation of regional and global remote sensing products. Historic data were generally not collected for remote sensing applications and suffer important drawbacks when it comes to compare with satellite imagery. Ground based ET footprint is usually much smaller than the footprint or pixel size of the satellite imagery and sites are selected in areas where the land cover heterogeneity is high at the pixel scale, affecting the comparison between ground and satellite data. There is an urgent need to expand the current network across the country.

*Table 22: Available ET data sources*

| **Location** | **Measuring system** | **Period of measurement** | **Institution** | **Accessibility** |
|---|---|---|---|---|
| Skukuza | Eddy covariance | Jan 2008 to date | Fluxnet http://www.fluxnet.ornl.gov/fluxnet/ | Data is requested from the regional network or the site PI |
| Malopeni | Eddy covariance | Jan 2000 to date | | |
| Seven Oaks | Large Aperture Scintillometry | 9 Sept 2006 to 24 June 2007 | Water Research Commission, CSIR | Data available from these organisations |
| Midmar Dam | Scintillometry | 29 June to 13 July 2007 | | |
| St Lucia | Eddy covariance | 8 to 13 Aug 2008 | | |
| Kirkwood | Eddy covariance | 17 Sept 2008 to 7 Oct 2008 | | |

### 4.2.2 *Remote sensing data sources*

METEOSAT LSA-SAF and the MOD 16 ET products are the only ones available at present at global scale. These products are currently being validated in using the South African flux tower data. High resolution (20-30 m) operational ET products are also being generated in South Africa for assessing crop water use efficiency and helping farmers optimise irrigation schemes in the grape and fruit growing region of the Western Cape, as well as for water resource management in the Incomati River Basin. These products are based on the SEBAL algorithm. Details of these products and globally available products are given in Tables 23 and 24 respectively.

*Table 23: Remote sensing products available in South Africa and their accessibility*

| Product | Timeframe | Data Provided | Accessibility |
|---|---|---|---|
| WATPLAN (Incomati River Basin) | February 2011 to date | ET, Rainfall, Rainfall-ET weekly at 30 m spatial resolution for the entire basin | Data available for the Incomati Basin, login required www.watplan.com |
| Fruitlook (grapes and deciduous fruits in the Western Cape) | 2011 to 2012 | Actual ET, ET deficit, crop factor, biomass, water use efficiency weekly at 20 m spatial resolution and weekly updates | Data available at a price for farmers. They have to register on the website www.fruitlook.co.za |
| Grainlook and sugarcanelook (sugarcane and other grain crops) | 1 April 2011 to March 2014 | Actual ET, ET deficit, crop factor, biomass, water use efficiency | Request more information from Dr Caren Jarmain<br>www.sugarcanelook.co.za/<br>www.grainlook.co.za |

*Table 24: Global ET products*

| Satellite product | Period of record | Resolution | | Spatial coverage | Source | Reference |
|---|---|---|---|---|---|---|
| | | Temporal | Spatial | | | |
| MOD16 ET | Jan 2000 to 2012 | 8 day, monthly and annual | 1 km | Global | Download from http://www.ntsg.umt.edu/project/mod16 | Mu et al. (2007, 2011) |
| LSA-SAF ET | 2007 to date | 30 minute, daily | 3 km | Global | Log in to their website and request product http://landsaf.meteo.pt/ | Van den Hurk et al. (2000) |

## 4.3 Soil moisture / soil water

Surface soil moisture / soil water is defined as water that is in the upper 10 cm of the soil layer, whereas root zone soil moisture / soil water is the water that is available to plants, which is generally considered to be in the upper 200 cm of soil (http://www.ghcc.msfc.nasa.gov/landprocess/lp_home.html). Although it is a small fraction of the total water volume in the water cycle, it is one of the most important variables in hydrological processes, which influences the exchange of water and energy fluxes at the land surface / atmosphere interface. It is of fundamental importance to many hydrological, biological and biogeochemical processes, and is critical for numerous environmental studies, including meteorology, hydrology, agriculture and climate change (Topp et al., 1980; Jackson et al., 1982; Fast and McCorcle, 1991; Engman, 1991; Entekhabi et al., 1993; Betts et al., 1994; Saha, 1995;.

The standard technique for determining soil moisture / soil water is the gravimetric method, which is the ratio of the mass of water in the soil to the mass of dry soil. Other techniques include the volumetric method, feel method, neutron attenuation probe, time domain reflectometry, capacitance sensors, heat dissipation sensors and the velocity differentiation domain. Soil water potential can be measured with tensiometers, gypsum blocks, granular matrix sensors, psychrometers and pressure plates.

Optical, thermal infrared and microwave remote sensing techniques can be used to estimate spatiotemporal variations of soil moisture / soil water at the top 0-15 cm of the earth's surface. Microwave systems, both passive and active, have the best potential to estimate soil moisture / soil water because of the large contrast in emissivity between the soil and water, and its capacity to assess directly subsurface soil water content. Also, the atmospheric is transparent at microwave wavelengths and microwaves are not dependent on solar illumination, providing a day / night and all-weather monitoring capacity.

Passive instruments, in other words radiometers and scanners, measure the microwave radiation, naturally emitted from Earth, in their field of view. Because of the small amount of energy emitted by the Earth's surface, passive microwave remote sensors produce image at a low spatial resolution, but do have a high temporal frequency on a daily basis. In active microwave methods – imaging (radar) and non-imaging sensors (altimeters, scatterometers) – a microwave pulse is sent and received, and the power of the received signal is compared with the one that was sent to determine the backscattering coefficient of the surface (http://envisat.esa.int/envschool_2006/lectures/su2.pdf); this has been shown to be sensitive to soil moisture / soil water. The most common imaging active microwave configuration is the synthetic aperture radar (SAR), which transmits a series of pulses as the radar antenna traverses the scene.

### *4.3.1 In situ data sources*

There is limited in situ soil moisture / soil water data available in South Africa. Most data originate from the private agricultural sector or research institutions for specific projects. For instance, a private network in the Northern Cape, GWK, has 1000+ soil moisture / soil water probes recording soil moisture / soil water and temperature at various depth (10, 50, 60 and 80 cm). This data is freely available. There is also a large network of soil moisture / soil water probes maintained by the agricultural sector that they use for irrigation scheduling. The ARC also has a network of soil moisture / soil water measurements for their research.

### *4.3.2 Remote sensing data sources*

Currently a number of soil moisture / soil water products are available for download online. The passive microwave sensors include the Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7, the Special Sensor Microwave/ Imager (SSM/I) on Defence Meteorological Satellite Program (DMSP), the Tropical Rainfall Measuring Mission Microwave Imager (TRMM-TMI), the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) on Aqua satellite, the Soil moisture / soil water and Ocean Salinity (SMOS) from the European Space Agency (ESA), NASA hydrospheric states (HYDROS) mission, and the Soil moisture / soil water Active and Passive (SMAP) mission. (Dorigo et al., 2010; Gruhier et al., 2010; Liu et al., 2011; Narayan et al., 2004). The SHARE (Soil moisture / soil water for Hydrometeorological Applications for the SADC Region) was part of ESA's DUE TIGER project aimed at providing operational soil moisture / soil water monitoring services for the Southern African Development Community (SADC) The soil moisture / soil water information was retrieved from ENVISAT's ASAR sensor operated in global mode (GM) and came in a 1 km medium spatial resolution and weekly temporal resolution (Bartsch et al., 2010; Wagner et al., 2007). The ASAR global mode data represent soil moisture / soil water in the upper most soil layer (<5 cm) and is developed for applications. The soil moisture / soil water products have been summarised in Table 25.

*Table 25: Remote sensing based soil moisture / soil water products that are accessible online.*

| Satellite product | Type | Period of Record | Resolution | | Spatial coverage (longitude, latitude) | Source |
|---|---|---|---|---|---|---|
| | | | Temporal | Spatial | | |
| Advanced Scatterometer (ASCAT) onboard METeorological OPerational satellite (METOP) | Active | 2007-2010 | Near real time | 50 km and 25 km | Global | http://www.eumetsat.int/Home/Main/News/Features/708786 |
| Advanced Microwave Scanning Radiometer (AMSR-E) | Passive | June 2002 to 2011 | 3 days | 25 km | Global | Available via ftp http://nsidc.org/data/docs/daac/ae_land3_l3_soil_moisture.gd.html |
| Soil moisture / soil water and Salinity (SMOS) | Passive | Jan 2010 to date | 3 days | 40 km | Global | http://www.esa.int/esaMI/smos/ |
| WindSat | Passive | Feb 2003 to date | 1-3 days | 10 km and 50 km | Global | http://geobrain.laits.gmu.edu/windsat/index.jsp |
| SHARE (Soil moisture / soil water for Hydrometeorological Applications for the SADC Region) | Active | Dec 2004 to 2012 | Weekly or less | 1 km | Africa south of 12°N and east of 8.6°E and Australia | www.ipf.tuwien.ac.at/radar |
| Advanced Microwave Scanning Radiometer-2 (AMSR-2) | Passive | 2012-date | 2 days | 50 km | Global | Register for data access https://gcom-w1.jaxa.jp/auth.html |
| SMAP (Soil moisture / soil water Active Passive Mission) | Combined | Future mission | 3 days | 10 km | Global | |

## 4.4 Groundwater

Groundwater currently contributes about 13 % of the total water use in South Africa. And although irrigation is the largest user of groundwater, it provides water to more than 300 towns and rural areas, as evidenced by the names of many towns, such as De Aar (the Afrikaans for 'artery', an underground water source), Springs, the Fountains at Pretoria and the many towns ending with --fontein'. In over 90% of the surface of South Africa, groundwater occurs in hard rocks in faults, fractures and joints and in dolomite and limestone, in dissolved openings called fissures (http://rava.qsens.net/themes/groundwater).

Groundwater assessment is done using various methods and the most basic is measuring groundwater level and quality. Groundwater levels are measured using piezometer tubes and dip meters. Wells for domestic or agricultural purposes can be used for measuring groundwater levels. Groundwater recharge can also be determined using isotopes, for example carbon-14, chloride and the water balance methods. Groundwater quality monitoring is also done to check for chemicals, environmental isotopes, trace and radioactive elements, and for microbiological analysis.

Remote sensing data used for groundwater exploration include Landsat, ASTER, MODIS, NOAA-AVHRR, SPOT and SRTM and IRS-LISS-II (Linear Imaging Self-scanning Sensor) among others. These sensors are used to identify surficial (topographic or mineralogical) features associated with groundwater processes, sites of recharge and/or discharge and spatial and temporal changes in vegetation health and abundance, soil moisture / soil water and surface water (Brunner et al., 2007; Hoffmann & Sander, 2007; Meijerink, 1996; Srivastava & Bhattacharya, 2006). The twin GRACE satellites launched by NASA in 2002 measure changes in the gravity field and the variations in terrestrial water storage at a very coarse spatial resolution of 200-300 km and monthly temporal resolution. The change in distance and speed between the two satellites is in principle a result of the change in gravity field caused by change in terrestrial water storage (soil moisture / soil water, groundwater, wetlands, surface water, snow and ice) on Earth, mass changes of the ice sheets and glaciers, and air and water vapour mass change within the atmosphere (Tapley et al., 2004a). Therefore, to estimate groundwater storage and changes, the contribution of other water components to gravity has to be subtracted by incorporating other data sources and models (Crowley et al., 2006; Scanlon et al., 2012; Strassberg et al., 2009).

### *4.4.1 In situ data sources*

The Department of Water Affairs is the custodian of the National Groundwater Data Base (NGDB) where all the groundwater information from the network of monitoring boreholes is kept and the National Groundwater Information System (NGIS). These include:

- The National Groundwater Archive (NGA): a web enabled database system that allows capturing, viewing, modifying and extracting groundwater related data by registered users (***Figure 8***). Currently, its main focus is on point data known as geosites (boreholes, dug wells, seepage ponds, springs, etc.), with plans of including line and polygon data in future. There are about 258 400 geosites currently registered in the archive (http://www3.dwa.gov.za/NGANet/Security/WebLoginForm.aspx)
- CHART: an integrated hydrogeological analysis and reporting solution aimed at assisting hydrogeologists and hydrogeochemists in decision-making during analysis and assessment of hydrogeological and hydrogeochemical data. It also assists hydrogeologists with implementation and management of monitoring programmes and networks
- Geohydrological Reports System: a database that contains groundwater related technical reports, with approximately 2 600 technical reports in the library at the DWA National Office. These reports reflect the hydrogeological investigations done by DWA officials or consultants. Enquiries can be made on the website http://www.dwa.gov.za/ghreport.

Other groundwater related documents and 1:500 000 hydrogeological maps and brochures are also available on request. The maps compilation started in 1990, using GIS (Arc/INFO 7.1.1) techniques (Jonck & Meyer, 2002). The map depicts aquifer types (of which there are four, namely Intergranular Aquifers, Fractured Aquifers, Karstic Aquifers and Intergranular and Fractured Aquifers) and their expected immediate borehole yields (of which there are five yield categories). Provision was also made for multi-layered aquifers. The yield maps were compiled by using the lithology background and analyses of borehole data as the basis for determining the different groundwater units and for resolving yield categories. An overlay of the yield data in terms of different-coloured yield category data points onto the lithology map was provided by GIS. The distribution of these data points also allowed for the identification of areas of sparse information. The median method of data analyses was applied, where the number of data points within a groundwater unit was calculated to determine a median value. Figure 8 shows the distribution of the boreholes countrywide.

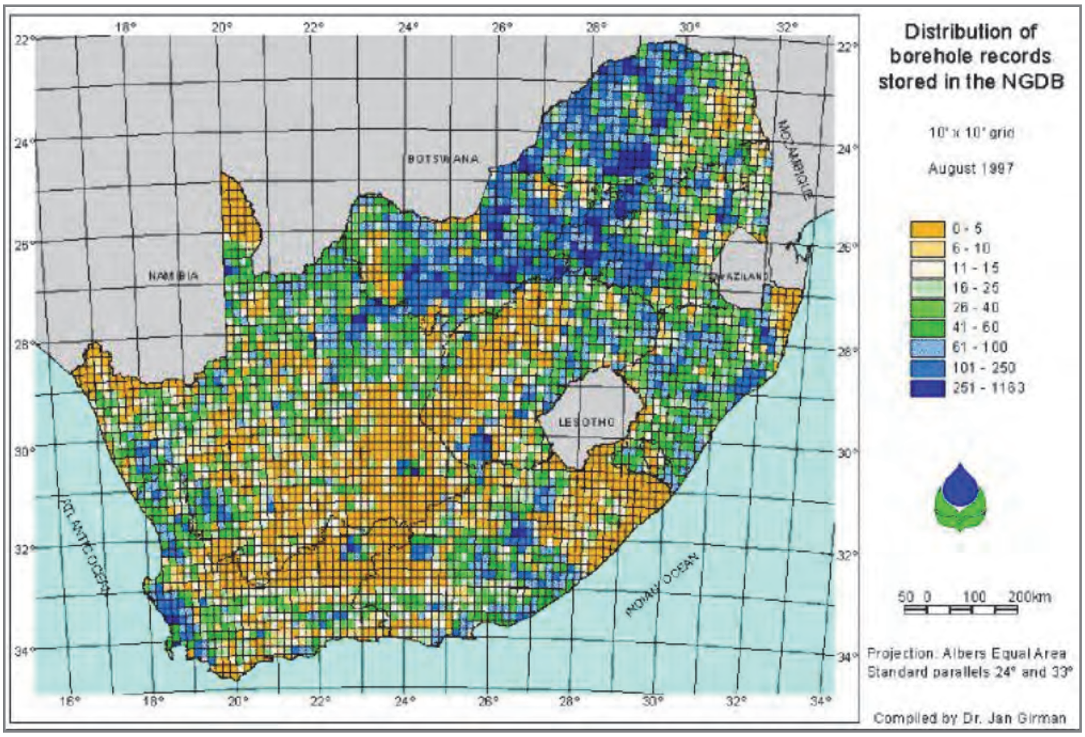


*Figure 8: Distribution of borehole records stored in the NGDB (Source:* **http://www.dwaf.gov.za/geohydrology/Maps/bor_distribution.asp***)*

### *4.4.2 Remote sensing data sources*

Unfortunately there are no remote sensing based products for groundwater monitoring.

## 4.5 Water Quality

Water quality is a very important parameter in water resource management and the standard depends on an intended purpose, for instance domestic, farming, mining or industrial purposes, or its suitability to maintain a healthy ecosystem (Biswas & Tortajada, 2011). Water quality is affected by both natural processes and human activities, for example agricultural activities, urban and industrial development, mining and recreation (http://www.dwaf.gov.za/Dir_WQM/wqmFrame.htm).

In situ water quality assessments and standards depend on the intended use of the water, and measurements include chemical, physical and biological characteristics (Chapman, 1996). Although in situ collection and measurement of water samples, and the subsequent analyses, are quite accurate in space and time, they do not give that spatiotemporal view of water quality needed for the accurate assessment and management of water bodies. Hence, remote sensing techniques, have been developed to monitor water quality through the estimation of optically active water constituents like suspended particulate matter (SPM), non-algal particles (NAP), chlorophyll pigments (Chl *a*) (a proxy for eutrophication and primary production), coloured dissolved matter (CDOM), and temperature. A number of satellite remote sensors are suitable for retrieving water quality parameters, for example NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the European Space Agency's Medium Resolution Imaging Spectrometer (MERIS) and the follow up OLCI mission with the Sentinel 3 satellite series.

### *4.5.1 In situ data sources*

The DWA's Resource Quality Services houses the Water Management System Water Quality database for rivers, dams and lakes, from the various water quality programmes that are run by the department and these include:

- The National Chemical Monitoring Programme provides data and information on the surface inorganic chemical water quality of South Africa's surface water resources.
- The National Eutrophication Monitoring Programme: 80 impoundments have been monitored in the country thus far.
- The National Microbiological Monitoring Programme for Surface Water provides information on the status and trends of the extent of faecal pollution, in terms of the microbial quality of surface water resources in priority areas. The information is available in the form of bi-monthly reports for each water management agency, as well as a map of all the hotspots.
- The National Aquatic Ecosystem Health Monitoring Programme's River Health Programme uses biological indicators (for example fish communities, riparian vegetation and aquatic invertebrate fauna) to assess the health of rivers so as to provide information on the ecological state of river ecosystems in South Africa. This information is available in the form of reports.
- The National Toxicity Monitoring Programme measures, assesses and regularly reports on the status and trends of the nature and extent of potentially toxic substances in South African water resources (watercourses, groundwater and estuaries), and the potential for toxic effects to selected organisms.

There is also a large dataset hosted by different institutions that conduct water quality research. For instance, the CSIR has designed and used a pencil buoy to collect radiometric data in inland and coastal waters to estimate their eutrophication statuses, together with remote sensing techniques.

### *4.5.2 Remote sensing data sources*

There are no readily accessible global water quality products for inland and coastal waters. These data are only available for oceans and seas. Intensive research is underway to be able to provide for inland and coastal waters under different programmes globally, for example ChloroGIN (http://www.chlorogin.org/).

South Africa is making headway with developing state of the art remote sensing techniques to monitor eutrophication and water quality of inland and coastal waters under the CSIR, in collaboration with academic institutions such as the University of Cape Town (UCT). They produced the Maximum peak-height Chl *a* product for some South African lakes until April 2012 from MERIS Full Resolution (www.afro-sea.org.za). However, this product is no longer operational. Projects are underway, such as Globolakes (Maberly, 2012; Politi, 2012) and ESA Diversity II (http://www.diversity2.info/), which plan to produce and test global inland water quality products.

## 4.6 Surface water level / extent

Surface water measurement is the characterisation of surface water bodies (extent and water level), including streams, rivers, lakes and wetlands. In situ surface water level measurement can be done using non-recording (graduated vertical staff gauge; ramp or inclined gauge; wire-weight gauge installed on a structure above the stream; and graduated rod, tape, wire or point gauge for measuring the distance to the water surface) and recording gauges (hydrostatic gauges, bubble gauges), and non-contact gauges (radar and ultrasonic). In South Africa, Schoeman and Partners, a consultancy firm, has done some validation and verification projects of surface water levels on behalf of the DWAF, using various formulae to calculate the amount of water stored in dams based on the dams' characteristics. These formulae take factors such as wall length, water depth, backwater and surface area into account and in most cases make use of aerial photography.

Radar altimetry and thermal remote sensing is being used to map water surface level / extent, in some instances in combination with topographical data (Alsdorf et al., 2001; C. Birkett, 2000; L. C. Smith, 1997; Wdowinski et al., 2008). A programme was launched to monitor the changing water levels of selected large lakes around the world using data from the NASA/CNES TOPEX/POSEIDON (T/P) and Jason-1 satellites, with the follow-up Jason-2 (or OSTM) mission continuing the programme (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/product_history.htm). Lake level variations are measured for 350 of the world's largest lakes at 10 day intervals with high levels of accuracy – 10 cm for the larger lakes. ESA and De Montfort University (DMU-UK) also developed a system to estimate river and lake heights from ERS and Envisat data. De Montfort University developed an automated system to produce two types of products called River Lake Hydrology product (RLH) and River Lake Altimetry product (RLA). However, South African lakes are too small to be mapped using these systems.

### *4.6.1 In situ data sources*

The Hydrological Services division of the DWA stores surface water data (http://www.dwaf.gov.za/hydrology/), which includes:

- Verified average daily flow, monthly volume, flow / capacity for reservoirs, rivers, lakes, canals and pipelines;
- Unverified near real time, daily and weekly flows for 400 + stations across the country; and
- Weekly flow of about 180.

### *4.6.2 Remote sensing products*

A number of remote sensing products of surface water level / extent are available. These are summarized in Tbale 26 below. The Global Reservoir and Lake Elevation Database uses near real time radar altimeter data over inland water bodies in a semi-operational manner. The Global inundation product is generated from several sensors: passive microwave (SSM/I), scatterometer (ERS), and visible and near-IR (AVHRR) for improved detection of surface water.

*Table 26: Global water bodies datasets*

| Product | Period of coverage | Resolution | | Spatial coverage | Source | Reference |
|---|---|---|---|---|---|---|
| | | **Spatial** | **Temporal** | | | |
| **Global Reservoir and Lake Elevation Database** | 1992-date | inland water bodies > 100 km$^2$ | 10 days | Global | http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir | Birkett & Mason (1995) |
| World Lake Database | 2005-date | | | | http://wldb.ilec.or.jp/ | Crétaux et al. (2011) |
| Waterbodies | 1999-date | 1/112° | 10 days | Africa | http://www.vgt4africa.org/ViewContent.do?pageId=31 | Gond et al. (2004) |
| Waterbodies | 1999-date | 1/112° | 3 days | Global | http://land.copernicus.eu/global/products/WB | Pekel et al. (2011) |
| Global inundation product | 1993-date | 100 m$^2$ | | | http://crest.ccny.cuny.edu/rscg/Products/Extent/index.html | Prient et al. (2007; 2001) |
| Global Lakes and Wetlands Database | | ≥ 0.1 km$^2$ | | Global | http://worldwildlife.org/pages/global-lakes-and-wetlands-database | Lehner & Döll, (2004) |

## 4.7 Surface runoff / Stream flow

Stream flow (the flow of water in streams, rivers and other channels) is a temporally lagged, spatial integral of runoff over a river basin. Over time, runoff is equal to the difference between precipitation and evapotranspiration and, hence, an important part of the water cycle. Surface runoff, on the other hand, is the water flow that occurs when the soil is saturated and excess water from rain or other sources flows over the land surface. Measuring stream flow is done through stream gauging. This involves obtaining a continuous record of stage, making periodic discharge measurements, establishing and maintaining a relation between the stage and discharge, and applying the stage-discharge relation to the stage record to obtain a continuous record of discharge. River discharge is computed by multiplying the area of water in a channel cross section by the average velocity of the water in that cross section; where the mechanical current-meter and Acoustic Doppler Current Profiler (ADCP) measure the velocity. There are currently no direct methods of estimating runoff / stream flow / river discharge using remote sensing techniques. Only techniques to infer these parameters are being used. Liebe et al. (2009), for example in West Africa used small reservoirs as runoff gauges by estimating their water storage changes using ASAR data and established that there is a relationship between surface area covered by water and water volume and related this to surface runoff.

### *4.7.1 In situ data sources*

Like surface water level data, stream flow data are available at the Hydrological Services division of the DWA. It stores surface water data (http://www.dwaf.gov.za/hydrology/), and includes:

- Verified average daily flow, monthly volume, flow / capacity for reservoirs, rivers, lakes, canals and pipelines; and
- Unverified near real time, daily and weekly flows for 400 + stations across the country and weekly flow for about 180 stations.

## 4.8 Land use / Land cover

Land cover refers to different features covering the earth's surface, like forests, wetlands, impervious surfaces and other land and water types. Land use shows how people use the landscape, be it for agriculture, development, conservation, or mixed uses. Land use land cover changes (LULC) have a critical effect on the hydrology of a region and on the availability of water and quality of water resource. Hence, LULC data plays an important part in water resource management.

Land use changes, for example, impact on water availability as different land uses different amounts of water. Land cover is a useful indicator of efficient water use and distinguishes between productive water use (for instance from crop lands) and non-productive water use (for instance evaporation from bare or eroded soil). Land cover is an important parameter in water accounting as a water use allocation can be coupled to various land cover classes. Changes in land cover, tracked by regular satellite imagery, allows quantification of the beneficial and non-beneficial uses of water (Bastiaanse, 2009).

### *4.8.1 Remote sensing products*

The first South African National Land Cover map (NLC 94) was published in 1996, and produced from 1:250 000 scale hard copy Landsat images acquired in 1994-1995. This map had 31 land cover classes captured as a digital vector dataset (Fairbanks et al., 2000). The recorded overall classification accuracy of this map was 79.4%. The follow-up South African NLC map (NLC 2000) was published in 2005 and generated from 2000-2001 Landsat and SPOT imagery. This map was captured as a digital raster data set containing 45 land cover classes, with an overall accuracy of 65.8% (Van den Berg et al., 2008). No official new NLC map has been released since 2005. However, an update of the NLC maps was released by SANBI in 2009 using a mosaic of provincial LC products generated between 2005 and2008 using Landsat and SPOT imagery, as well as thematic products generated by the ARC, DWAF, and ESKOM, such as plantations and informal settlements (Schoeman et al., 2013). The reported mapping accuracies for these datasets were between 80% and 83%.

Global land cover products are also available from different sources, and these are highlighted in Table 27 below.

*Table 27: Land cover products available online*

| Product | Period of record | Resolution | | Spatial coverage (longitude, latitude) | Source | Reference |
|---|---|---|---|---|---|---|
| | | Temporal | Spatial | | | |
| International Geosphere-Biosphere Programme Data and Information<br>System Cover (IGBP-DISCover) | 1993 | Once-off | 1 km | Global | www.landcover.org | Townshend (1994a) |
| MODIS MCD12Q1/Q2 | To date | Yearly / monthly | 500 m/ 1 km | Global | Data access through different portals via<br>https://lpdaac.usgs.gov/data_access | Friedl et al. (2010) |
| Landsat FROM-GLC (Finer Resolution Observation and Monitoring of Global Land Cover) | 1990, 2010 | Updated in 2010 | 30 m | | http://data.ess.tsinghua.edu.cn/landsat_pathList_fromglcseg_0_1.html | |
| MERIS GlobCover | 2009 | Bimonthly | 300 m | Global | http://due.esrin.esa.int/globcover/LandCover2009/Globcover2009_V2.3_Global_.zip | Arino et al. (2007) |
| University of Maryland (UMD) | 1993 | Once-off | 1 km | Global | http://glcf.umd.edu/data/landcover/ | Hansen et al. (2000) |
| Global Land Cover 2000 (GLC2000) | 2000 | Once-off | 1 km | Global | | Bartholome & Belward (2005) |
| NLC 1994 | 1994 | Once-off | 1:250 000 | SA, Lesotho & Swaziland | ARC-ISCW | Fairbanks et al. (2000) |
| NLC 2000 | 2000 | Once-off | 1:50 000 | SA | ARC-ISCW | Schoeman et al. (2013) |
| NLC 2009 | 2009 | Once-off | 30 m | SA | SANBI | SANBI (2009) |

## 4.9 Land Surface Temperature

Land surface temperature is one of the key parameters in the physical processes of surface energy and water balance at local to global scales, since it is a driving force in the exchange of long wave radiation and turbulent heat fluxes at the surface-atmosphere interface. Knowledge of LST provides information on the spatiotemporal variations of the surface equilibrium state and is critical in many water applications, including evapotranspiration, climate change, the hydrological cycle and more generally urban and environmental studies (Anderson et al., 2008; Elhag et al., 2011; Karnieli et al., 2010; Timmermans et al., 2007; Van der Kwast & De Jong, 2004). It has been recognised as one of the high priority parameters by the International Geosphere and Biosphere Program (IGBP) (Townshend, 1994; Townshend et al., 1994b). Globally, the in situ network of LST measurements is very sparse, with the main data source being the flux towers and air temperature measurements from meteorological stations. Satellite remote sensing technology in the thermal range provides the possibility to derive maps of LST and emissivity (Kerr et al., 1992; Sobrino et al., 2004; Wan, 2008).

### *4.9.1 In situ data sources*

There are no records of in situ surface temperature in South Africa, except meteorological data from the SAWS, ARC, other research and academic institutes, and agricultural organisations.

### *4.9.2 Remote sensing data sources*

**Table 28** below summarises the remote sensing based LST products that are available on the web. Although some sensors have the thermal bands, they do not yet have the operational LST product available.

*Table 28: Remote sensing based LST products that can be accessed on the web*

| **Product** | **Period of Record** | **Resolution** | | **Spatial coverage (longitude, latitude)** | **Source** | **Reference** |
|---|---|---|---|---|---|---|
| | | **Temporal** | **Spatial** | | | |
| MODIS LST | 1993 to date | Monthly | 1 km | Global | https://lpdaac.usgs.gov/data_access | |
| MSG-SEVIRI LST | 2004 to date | 15 minutes | 3 km | Global | Contact helpdesk helpdesk.landsaf@ipma.pt | Caselles et al. (1997), Wan et al. (1996) |
| AVHRR LST | 1989 to date | Daily | 1 km | Global | http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.AVHRR-LST/ | Dech et al. (1998) |
| ASTER LST | 2000 to date | 16 days | 90 m | Global | https://lpdaac.usgs.gov/data_access | (Gillespie et al. 1998) |
| AATSR LST | Up to 2012 | 2-3 days | 1 km | Global | https://earth.esa.int/web/guest/data-access | |

## 4.10 Elevation / Topography

The elevation of a geographic location is its height above a fixed reference point, most commonly a reference geoid. Two fundamental elevation representations are the elevation of the ground, the digital elevation model (DEM), and of the surface, digital surface model (DSM). In some instances, elevation is measured using the centre of the Earth as the reference point. A topographical map is used to depict elevation, often through use of contour lines. Different instruments are available to measure elevation, including the theodolite, total station, GPS to measure distances and elevations. Remote sensing is also used to determine surface elevation. Photogrammetry, lidar, active radar and sonar remote sensing systems have been used to process DEMs or DSMs (http://resources.arcgis.com/en/help/main/10.1/index.html#//009t0000023w000000). These data are crucial in hydrological modelling.

### *4.10.1 In situ data sources*

**Figure 9** illustrates the coverage of contour data that is used for topographic mapping in South Africa. These data and spot height data are available from the Chief Directorate: National GeoSpatial Information (CD: NGI) at 5 and 20 m vertical intervals from 1:10 000 and 1:50 000 orthophoto map series. This data set currently covers 43% of the country. DEMs are available from CD: NGI at 25 m and 50 m intervals with partial coverage of South Africa (Els, 2011). Table 29 also summarises the land surface elevation datasets that are in use in South Africa.

### *4.10.2 Remote sensing data sources*

There is a variety of remote sensing based DEM data available globally and specifically developed mainly for South Africa. The WRC recently appointed the ARC to develop a hydrologically improved 30 m DEM of South Africa based on the 90 m SRTM DEM (Weepener et al., 2012). The SRTM voids were filled with elevation values interpolated from 20 m (1:50000 scale) vertical interval contours. There is also the Stellenbosch University 5 m DEM (SUDEM) product, which was developed by combining the 1:10 000 contour and spot heights maps, with the 1:50 000 used for gap filling and SRTM DEM (Van Niekerk, 2012). Global products include the shuttle radar topographic mission (SRTM) 90 m DEM and the advanced spaceborne thermal emission and reflection radiometer (ASTER) global digital elevation model 30 m (GDEM), as shown in Table 30.

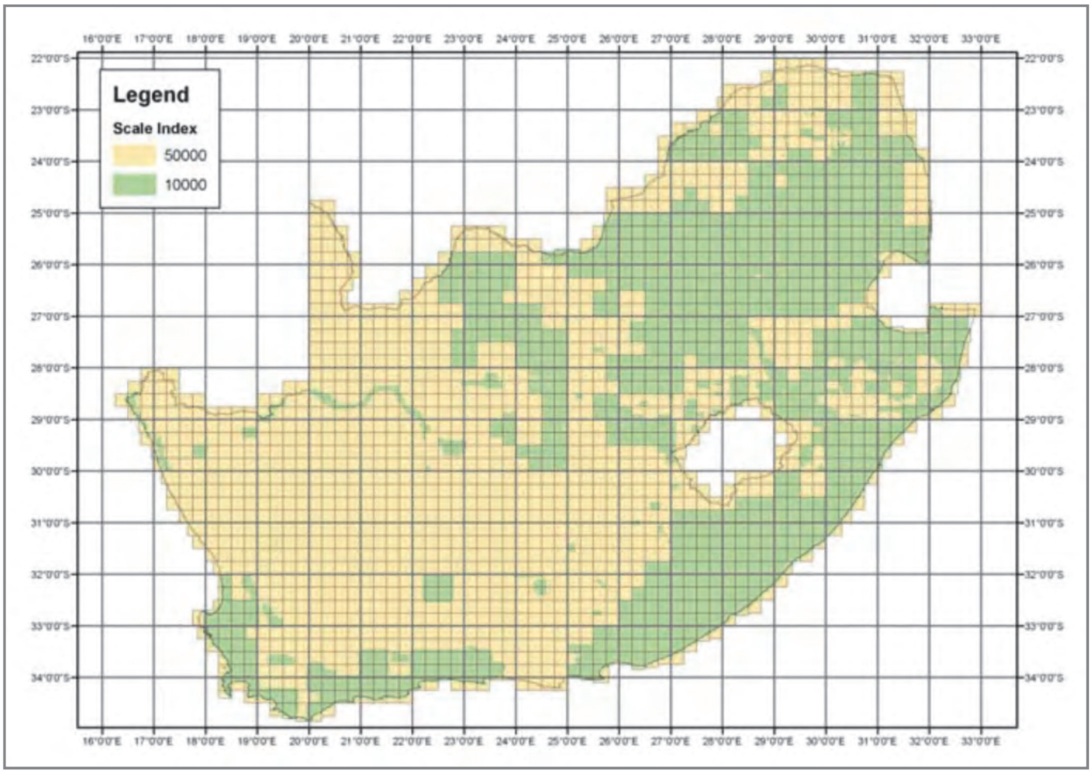


*Figure 9: Areas for which 1:10 000 and 1:50 000 contour data is available (Source: Van Niekerk, 2012)*

*Table 29: South African topography datasets*

| **Type** | **Dataset** | **Resolution/ interval** | **Coverage** | **Source** |
|---|---|---|---|---|
| Contour | 1: 10 000 contours | 5-20 m | South Africa (partial coverage) | CD:NGI |
| | 1: 50 000 contours | 20 m | South Africa | |
| DEM | 25 m DEM | 25 m | South Africa (partial coverage) | CD:NGI |
| | 50 m DEM | 50 m | South Africa (partial coverage) | CD:NGI |

*Table 30: Digital Elevation Model products available in SA and globally*

| **Product** | **Period of record** | **Resolution** | | **Spatial coverage (longitude, latitude)** | **Source** | **Reference** |
|---|---|---|---|---|---|---|
| | | **Temporal** | **Spatial** | | | |
| WRC DEM | 2008 | Once off | 30 m | South Africa | | Weepener et al.(2012) |
| SUDEM | 2011 | | 3 km | South Africa | | van Niekerk, (2012) |
| SRTM DEM | 2011 | | 90 m, 250 m | Global | https://hc.box.net/shared/1yidaheouv | Breit et al. (2002)<br>Smith & Sandwell (2003) |
| ASTER GDEM | 2008 | | 30 m | Global | http://gdem.ersdac.jspacesystems.or.jp/ | Hirano et al. (2003) |
| Global 30 Arc-Second Elevation data set (GTOPO 30) | Up to 2012 | | 1 km | Global | http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=10003 | Hastings & Dunbar (1998) |
| WorldDEM™ | To be available in 2014 | | 12 m | Global | http://www.astrium-geo.com/en/168-tandem-x-global-dem | |

## 4.11 Satellite data and their potential in water resources management

Remote sensing data are also available, not only as processed products, but as raw data to retrieve different water cycle components that can be used in water resource management. These sensors are summarised in Tabl 31 below, highlighting their potential application.

*Table 31: Satellite remote sensors and their potential application in water resource management*

| **Satellite** | **Sensors onboard** | **Period of record** | **Spatial Resolution** | **Temporal Resolution** | **Spectral bands** | **Data access** | **Precipitation** | **Evapotranspiration** | **Soil moisture / soil water** | **Surface water level/ extent** | **water quality** | **Land cover** | **LST/ SST** | **Groundwater** | **surface elevation** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ERS-1/ 2 (European Remote Sensing) | Imaging Synthetic Aperture Radar | 1991/ 95 - 2000/ 11 | 30 m | 35 days | C band | https://earth.esa.int/web/guest/data-access | | | x | x | | | | | |
| | Along-Track Scanning Radiometer | | | | IR, MW | | | | | | | | X | | |
| | Radar Altimeter | | | | Ku band | | | | | x | | | | | |
| Envisat | Advanced Along Track Scanning Radiometer (AATSR) | 2000 - 2012 | 1 km | 35 days | VIS - NIR, SWIR, MWIR, TIR | https://earth.esa.int/web/guest/data-access | X | X | | X | | | | | |

| MetOp-A/ B |  | Meteosat |  |  |  |  |
|---|---|---|---|---|---|---|
| ASCAT - Advanced SCATterometer | AMSU-A1/A2 - Advanced Microwave Sounding Units | 3rd generation to be launched in 2017 | Meteosat Visible and Infrared Imager (MVIRI) | Spinning Enhanced Visible and Infrared Imager (SEVIRI) | Medium Resolution Imaging Spectrometer (MERIS) | Advanced Synthetic Aperture Radar (ASAR) |
| 2006/ 2012 -date |  | 1977 - date |  |  |  |  |
| 25/ 50 km | 40 km | 3 km |  |  | 300 m/ 1 km | 30 m/ 150 m/ 1 km |
| 2 days |  | 15 min |  |  | 3 days | 35 days |
| C band | MW | VNIR, TIR |  |  | VIS-NIR | C band |
| http://navigator.eumetsat.int/discovery/Start/Explore/Quick.do |  | http://www.eumetsat.int/website/home/Data/Products/MeteosatDataCollectionServices/index.html |  |  |  |  |
|  | x | X |  |  |  |  |
|  |  | X |  |  |  |  |
| x |  | X |  |  |  | x |
|  |  | X |  |  |  | x |
|  |  | X |  |  | x |  |
|  |  |  |  |  | x |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |

| Sentinel 2 | Sentinel 1 | CryoSat | GOCE (Gravity Field and Steady-State Ocean Explorer) | Proba-1/ V (PRoject for OnBoard Autonomy) | | |
|---|---|---|---|---|---|---|
| MSI (Multi-Spectral Imager) | SAR | SIRAL-2 (SAR/Interferometric Radar Altimeters) | EGG (Electrostatic Gravity Gradiometer) | HRC (High Resolution Camera) | CHRIS (Compact High Resolution Imaging Spectrometer) | AVHRR (Advanced Very High Resolution Radiometer) |
| to be launched in 2014 | to be launched in 2014 | 2010- date | 2009 - date | 2001 - date | 2001 - date | |
| 10, 20, 30 m | 20 m | 250 m, 5 km | 100 km | 10 m | 20 m | 1 km |
| 5 days | 5 days | weekly | | 7 days | 7 days | daily |
| VIS, NIR, SWIR | C band | | Gravity | | 415 - 1050 nm | VNIR |
| | | https://earth.esa.int/web/guest/data-access | https://earth.esa.int/web/guest/-/goce-data-access-7219 | | | |
| | | | | | | |
| x | | | | | x | x |
| x | x | x | | | | x |
| | x | x | | | x | |
| x | | | | | x | x |
| x | | | | x | | x |
| | | | | x | | X |
| | | | x | | | |
| | | x | x | | | |

| ALOS/Daichi (Advanced Land Observation Satellite) | | Radarsat 1/ 2 | Sentinel 3 | | | |
|---|---|---|---|---|---|---|
| PRISM (Panchromatic Remote-sensing Instrument of Stereo Mapping) | PALSAR (Phased Array type L-band Synthetic Aperture Radar) | SAR | MWR (Microwave Radiometer) | SRAL (SAR Altimeter) | OLCI (Ocean and Land Colour Instrument) | SLSTR (Sea and Land Surface Temperature Radiometer) |
| 2006 – 2011 | | 1995/ 2007 – 2013/ date | to be launched in 2014 | | | |
| 2.5 m | 30 m | 5 - 100 m | 300/ 500 m/ 1 km | | | |
| 2 days | | 24 days | 2 - 4 days | | | |
| 0.52 - 0.77 µm | L band | C band | 200 MHz | C and Ku band | 21 bands (400 - 1020 nm) | VIS, SWIR, MWIR, TIR |
| Apply for data access http://jda.jaxa.jp/en/service.php#application | | http://gs.mdacorporation.com/products/sensor/radarsat/rs1_pric | | | | |
| | | | | | | |
| | | | | | x | x |
| | x | x | x | x | | x |
| | x | x | | x | | |
| | | | | | x | |
| | | | | | x | |
| | | | | | | x |
| | | | | | | |
| x | | | x | | | |

| Landsat 1 – 8 | IRS-P6 (RESOURCESAT-1/ 2) | | IKONOS | GCOM-C | GCOM-W | |
|---|---|---|---|---|---|---|
| RBV, MSS, TM, ETM, ETM+, OLI, TIRS | Advanced Wide Field Sensor (AWiFS) | Linear Imaging Self Scanner (LISS-4) | Multispectral and Panchromatic | SGLI (Second Generation Global Imager) | AMSR2 (Advanced Microwave Scanning Radiometer 2) | AVNIR-2 (Advanced Visible and Near Infrared Radiometer type-2) |
| 1972 - date | 2003/ 2011 - date | | 1999 – date | 2012 - date | | |
| 15, 30 60, 120 m | 5.8, 23.5, 56 m | | 1 m, 4 m | 250, 500 m/ 1 km | 5 - 50 km | 10 m |
| 16 days | 5 days | | 3 - 5 days | | 2 days | |
| VNIR, TIR, SWIR, Panchromatic | VNIR, SWIR, TIR | | Panchromatic, VIS, NIR | VIS, NIS, SWIR, TIR | | VNIR |
| http://glcf.umd.edu/data/landsat/ | for pricing visit https://earth.esa.int/web/guest/data-access | | for pricing visit http://www.satimagingcorp.com/pricing.html | https://earth.esa.int/web/guest/data-access | | |
| | | | | | x | |
| x | | | | X | | |
| x | | | | X | x | |
| x | | | | | | |
| x | | | | X | | |
| x | | X | | | | x |
| x | | | | X | x | |
| | | | | | | |
| | | | x | | | |

| SPOT 1 – 7 (Satellite Pour l'Observation de la Terre) |  |  | Terra/ Aqua (EOS AM-1/ PM-1) (2002 – date) | Orbview- 2/ 3 |  | NOAA (National Oceanic and Atmospheric Administration) |
|---|---|---|---|---|---|---|
| SPOT Vegetation | Proba-V | ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) | MODIS (Moderate Resolution Imaging Spectroradiometer) | MSI, Panchromatic | SeaWIFS (Sea-viewing Wide Field-of-view) | AVHRR (Advanced Very High Resolution Radiometer) |
| 1998 - date | 2013 to date | 1999 - date | 1999/ 2002 - date | 1997 -date | 1997 - date | 1978 - date |
| 1 km | 100 / 300 m | 15 m/ 30 m/ 90 m | 250 m, 500 m/ 1 km | 1/ 4 m | 1 km | 1 km |
| daily | daily | 1 - 2 days | 1 - 2 days | <3 days | daily | daily |
| VNIR, SWIR | VNIR | VNIR, SWIR, TIR | 0.4-3.0 µm, 3-14.5 µm | VNIR, Panchromatic | VNIR | NVIR, TIR |
| http://www.spot-vegetation.com/pages/policy.html | data not yet accessible on the site | https://earth.esa.int/web/guest/data-access | https://earth.esa.int/web/guest/data-access | - | https://earth.esa.int/web/guest/data-access | web/guest/data-access, http://earthexplorer.u |
|  |  |  |  |  |  |  |
| x | x |  | x |  |  | x |
| x |  |  | x |  |  | x |
|  |  |  |  | x |  | x |
|  |  | x | x |  | x | x |
| x | x | x | x | x |  | x |
|  |  |  | x |  |  | x |
|  |  |  |  |  |  |  |
|  |  |  |  | x |  |  |

| COSMO-Skymed | TerraSAR | CBERS 1 - 4 | WorldView 1/ 2 | RapidEye | Quickbird | |
|---|---|---|---|---|---|---|
| SpotLight, StripMap, ScanSAR | High Resolution SpotLight, SpotLight, StripMap, ScanSAR | Infrared Multispectral Scanner Camera (IRMSS), Advanced Wide Field Imager | Multi-spectral Imager | Multispectral Imager | Multispectral and Panchromatic | HRV (High Resolution Visible) imaging, high resolution geometrical (HRG) |
| 2007 - date | 2007 to date | 1999 - date | 2007/ 2009 – date | 2008 –date | 2001 – date | 1996 – date |
| 1 - 100 m | 1 - 18 m | 2.7 - 260 m | 1.8 m | 5 m | 60 cm, 2.4 m | 1.5 - 20 m |
| 16 days | 2.5 - 11 days | 3/ 26 days | ~3 days | daily | 1 - 3 days | 1 -5 days |
| X band | X band | Panchromatic, VIS, NIR | VNIR | VNIR | VNIR, Panchromatic | VNIR, Panchromatic |
| http://www.e-geos.it/products/pdf/prices.pdf | http://www.astrium-geo.com/en/122-price-lists | http://www.dgi.inpe.br/CDSR/ | http://www.e-geos.it/products/pdf/prices.pdf | https://earth.esa.int/web/guest/-/rapideye-products | http://glcf.umd.edu/data/quickbird/ | http://www2.astrium-geo.com/files/pmedia/public/r146_9_priceli |
| | | | | | | |
| | | | | | | |
| x | x | | | | | |
| x | x | x | x | x | x | x |
| | | x | | | | x |
| | | x | x | x | x | x |
| | | | | | | |
| | | | | | | |
| x | x | x | x | x | x | x |

| JERS 1 | OceanSat-1/ 2 | Topex/Poseidon | Jason-1 / OSTM/ Jason-2 | GRACE | Pléiades 1A/1B | GeoEye-1 |
|---|---|---|---|---|---|---|
| synthetic aperture radar (SAR), optical camera (OPS), optical camera (AVNIR) | (OCM), Multi-frequently Scanning Microwave Radiometer (MSMR), Scanning | Radar Altimeter, Microwave Radiometer | Microwave Radiometer (JMR), Poseidon-3 radar altimeter; Advanced Microwave | Microwave Ranging System, Accelerometer, GPS | MSI (Multi-Spectral Imager), Pan | MSI (Multi-Spectral Imager), Pan |
| 1992 - 1998 | 1999 - date | 1992 - 2002 | 2002 - 2008/ 2008 - date | 2002 - date | 2011 - date | 2008 - date |
| 18 m | 360 m/ 1, 4 km/ 50 km | | 8 km | 200 - 300 km | 70 cm/ 2 m | 34 cm - 1.65 m |
| 44 days | 2 days | 10 days | 10 days | monthly | | daily |
| L band, VNIR | VNIR, Ku-band | C, Ku bands | C, Ku bands | K band | VNIR, Panchromatic | VNIR, Panchromatic |
| 1&selectedEarthTopicTag=&selectedMissionTag=jers- | http://218.248.0.134:8080/OCMWebSCAT/html/controller.jsp | http://podaac.jpl.nasa.gov/datasetlist?search=TOPEX/Poseidon | =JASON-1, http://podaac.jpl.nasa.gov/datasetlist?ids=Pl | http://grace.jpl.nasa.gov/data/, http://isdc.gfz-potsdam.de/ | http://www.geoimage.com.au/contact-us/quote-query-form | http://www.geoimage.com.au/contact-us/quote-query-form |
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| | | | | | x | x |
| | | | | | | |
| | | | | x | | |
| x | | x | x | x | x | x |

## 4.12 Challenges and opportunities for water resources related data sources in South Africa

In situ data are crucial for the calibration and validation (Cal/Val) of remote sensing algorithms and/or products. However, data scarcity, together with poor quality of available data proves a challenge in most countries, including South Africa. Data scarcity and poor quality data also affects the planning and management process.

There is a serious gap in the in situ data network for hydrological measurements. For instance, there are no recorded soil moisture / soil water data. Available ground data, recorded by private organisations for specific purposes is not easily accessible for research purposes. The Skukuza and Malopeni flux tower stations that are used for ET measurement are both located in the Kruger National Park, a savanna biome. Discontinuous historical in situ data for ET are however available from a few continuous collection sites at Skukuza and Malopeni). South Africa is a very diverse country in terms of climate and vegetation, ranging from the Karoo, grassland to forest and savanna. This diversity is not well covered with observations and there is thus a serious gap in data for cal/val of remote sensing products in the country. In other cases, the in situ networks are in decline, as evidenced by reports that there is a declining rain gauge network in the country to date.

The global remote sensing products that are freely accessible to the public are usually without validation in South Africa, which poses a challenge in using these products for decision-making. An established, large, in situ data network for different components of the hydrological cycle, at different locations around the country is essential for a various reasons. Firstly, to provide data that would be easily accessible to the water resource managers for informed decision-making, and for research purposes. Easily accessible and good quality data would also make it possible to develop country and/or region specific products that are more accurate and can be used for further informed decision-making in water resource management.

# 5 EARTH OBSERVATION AND REMOTE SENSING SYSTEMS FOR WATER RESOURCE MANAGEMENT: R&D REQUIREMENTS AND CAPACITY BUILDING NEEDS

Sustainable water resource management is one of the key development goals and challenges of the 21st century. Water resource issues such as floods, water scarcity, droughts, water quality, soil-water-climate interactions are often complex and require large amounts of data. Earth observation has been recognised as a key tool for providing data about the earth surface processes at adequate temporal and spatial scales to aid water resource management and decisions. The use of EO technologies, such as satellite based monitoring, can provide a cost-effective means of replacing or complimenting field data collection. There is growing awareness of the need for local capacity building across all nations in the application of satellite remote sensing and Earth observation (Cassells et al., 2011).

Political leaders at the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg recognised the need for better environmental information and called for urgent action on Earth observation. EO summits in Washington, Tokyo and Brussels and declarations by three of the annual Group of Eight (G8) built on this momentum. Acting on a clear international consensus, ministers established the intergovernmental Group on Earth Observations (GEO) in 2005 with a mandate to build a Global Earth Observation System of Systems, or GEOSS (GEO, 2010). Today, capacity building in the field of Earth observation is largely guided by GEO that foresees a world where a spectrum of global citizens including scientists, decision-makers and individuals have the ability to access and use Earth observations to make decisions. The GEO sponsored effort to build a GEOSS calls for the development of a capacity building strategy based on existing efforts and best practices (GEO, 2006). GEO has nine societal benefit areas for the application of Earth observation, of which one of them is ‘water management’. The other eight include agriculture, biodiversity, climate, disasters, ecosystems, energy, health, and weather forecasting.

At the GEO Ministerial Summit in Geneva, Switzerland, on 17 January 2014, GEO received unanimous endorsement to continue its efforts of increasing the availability of open data for a second decade. GEO's mandate is to drive the interoperability of the many space based, airborne and in situ Earth observations around the globe. Without concerted efforts to coordinate across diverse observations, these separate systems often yield just snapshot assessments, leading to gaps in scientific understanding and hampering data fusion in support of better capacity building and decision making for society. GEO aims to fill such gaps by providing a comprehensive, more integrated picture of our changing Earth. GEO is accomplishing this by establishing GEOSS and a portal through which data and other information can easily be accessed at little or no cost. South Africa's Minister of Science and Technology, Mr Derek Hanekom said, "This new initiative gives us the necessary framework to support informed decisions about a range of priorities, including food security, access to clean water and sanitation, natural resources and coastal and disaster management." (GEO, 2014)

Similarly to GEO, in response to the urgent need for action in Africa expressed at the WSSD in Johannesburg in 2002, ESA launched the TIGER initiative to promote the use of Earth observation for improved Integrated Water Resources Management in Africa. Since its launch, TIGER has become one of the most successful EO capacity building initiatives. The TIGER initiative will be discussed in this report together with other capacity building networks and initiatives.

The objectives of this section are to:

- Review the current South African state of knowledge on the application of Earth observation and remote sensing technologies in water management in South Africa (including the identification of knowledge gaps and potential applications); and
- Make recommendations on harnessing collective knowledge on Earth observation and remote sensing systems, R&D requirements, and capacity building needs to obtain the information required.

## 5.1 Background for capacity building

### *5.1.1 Capacity building definitions*

Capacity building is defined as an activity which involves strengthening particular scientific or technical abilities and resources in individuals, institutions or infrastructure (Wignaraja, 2009). Some authors and institutions support the use of the expression 'capacity development' in recognition of the existing knowledge or infrastructure available (Wignaraja & Yocarini, 2008; Cassells et al., 2011).

The term 'capacity building' in this report is based on the GEO definition formulated at the 1992 United Nations Conference on Environment and Development (UNCED) that encompasses human, scientific, technological, organisational and institutional resources and capabilities. UNCED recognised that a fundamental goal of capacity building is to enhance the abilities of stakeholders to evaluate and address crucial questions related to policy choices and different options for development. Considering the definition of capacity building, three elements of relevance to Earth observation are: human, institutional and infrastructure capacity (GEO, 2006).

- Human capacity building refers to the education and training of individuals to be aware of access to and use and development of Earth observation data and products.
- Institutional capacity building is focused on developing and fostering an environment for the use of Earth observations to enhance decision-making. This includes building policies, programmes and organisational structures in governments and organisations aimed at enhancing understanding of the value of Earth observation data and products.
- Infrastructure capacity building is related to the hardware, software and other technology required to access, use and develop Earth observation data and products for decision-making.

The success of Earth observation related capacity development depends on the building of capacity in all (not only one) of the three dimensions: human, institutional and infrastructural. Capacity and performance is a result of the interactions within and between these dimensions (GEO, 2006; Cassells et al., 2011).

## 5.2 The GEO approach and vision to capacity building

GEO's approach to capacity building seeks to coordinate and build upon existing efforts worldwide to increase the efficient use of limited resources, rather than creating new Earth observation capacity building efforts. Such coordination can bring additional institutions into the GEO community and can help fill gaps in current Earth observation capacity. This coordination also increases access to Earth observation data and products and seeks to encourage decision-makers worldwide to use these tools to guide their decisions in sustainable development planning and policymaking (GEO, 2006). The guiding principles in GEO's approach to capacity building include:

- Building on existing efforts and best practices;
- Focusing on user needs;
- Fostering collaboration and partnership, especially with and between developing countries, at the local, national, regional and global level;

- Concentrating on end-to-end Earth observation needs, including user requirements, data access, collection, archiving and analysis, and product development and exchange; and
- Enhancing the sustainability of existing and future Earth observation capacity building efforts by building awareness amongst decision-makers in developing countries and facilitating the development of comprehensive, sustainable capacity building efforts that address infrastructure capacity needs, education and training, and build local institutional capacity.

## 5.3 Current Status of Earth Observation Capacity Building Initiatives For Water Resource Management

The availability of EO data and products, especially in developing countries, has until recently not been sufficient to support environmental decision-making and thereby hampered capacity building efforts in EO (GEO, 2006). However, more recently, the GEOSS Common Infrastructure and the GEO technical interoperability standards and formats have made it possible to integrate and disseminate data sets produced by diverse systems and instruments. The GEO Web Portal, complemented by a growing number of community portals, has given users comprehensive access to a wide range of data and services available through GEOSS. The GEOSS Data Sharing Principles, which advocate for the full and open access to data and were first agreed upon in the GEOSS 10-Year Implementation Plan, were reconfirmed by the 2007 Cape Town Ministerial Summit. This led directly to decisions by major satellite operators to provide unrestricted access, often free-of-charge, to remotely sensed data. These data, together with the information products and services made possible by in situ data providers, modellers, and analysts, are already empowering decision-makers and managers as they confront complex and interlinked challenges (GEO, 2010). Today, there are a number of EO capacity building initiatives and capacity building has become an important mandate of many organisations that conduct EO research including the WRC, CSIR, SANSA, TIGER and WaterNet.

## 5.4 Enabling capacity building through the GEO Web Portal

The GEO Portal (http://www.geowebportal.org) is a central Portal that provides access to Geospatial and EO data and allows users to discover, browse, edit, create and save geospatial information from GEO members around the globe. The GEO Portal facilitates the discovery of EO data from thousands of services, instruments, collections, libraries and catalogues worldwide, transforming the data collected into vital information for society. The GEO Web Portal is an important tool for focusing the capacity building efforts in areas where capacity is needed most in each of the nine societal benefit areas. It provides a mechanism to facilitate human, institutional and infrastructure development by:

- Enabling information exchange and knowledge development;
- Promoting coordination and synergy;
- Providing access to resources for capacity building;
- Promoting networking; and
- Conducting outreach.

## 5.5 Enabling sustainable infrastructure capacity building efforts through GEONETCast

GEONETCast is a global network of satellite based dissemination systems that provides near real time environmental data and products to a worldwide user community. The current partners within the GEONETCast initiative include the China Meteorological Administration (CMA), the National Oceanic and Atmospheric Administration (NOAA), the World Meteorological Organization (WMO) and EUMETSAT, as well as many prospective data provider partners. The Faculty of Geo-Information Science and EO of ITC, Twente University in The Netherlands is partnering with GEONETCast to provide training and capacity building to potential users in Africa. ITC have also developed the GEONETCast Toolbox which is a plug-in to the open source ILWIS remote sensing software which offers a set of utilities that facilitates the easy import of various satellite and environmental data / products that are disseminated via GEONETCast into a common GIS environment (ITC, 2011). GEONETCast has significant potential to enhance access to a wide range of EO data in all societal benefit areas to users who may not have previously had access to such resources, especially developing country users with limited access to high speed Internet (GEO, 2006).

GEONETCast is designed to put a vast range of essential environmental data within easy access of users around the globe. It is a user driven, user friendly and low cost information dissemination service that aims to provide global information as a basis for sound decision-making in a number of critical areas, including public health, energy, agriculture, weather, water, climate, natural disasters and ecosystems. Accessing and sharing such a range of vital data will yield societal benefits through improved human health and wellbeing, environment management and economic growth.

The following products and services are available to the GEONETCast user community:

- Meteosat image data
- GOES East and West image data
- FY-2 image data
- Land and Ocean Sea Ice Satellite Application Facility (SAF) products
- EUMETSAT meteorological products
- NOAA-NESDIS meteorological products
- NOAA-NESDIS Ocean colour and sea surface temperature products
- VEGETATION products from VITO
- MODIS Ocean colour products
- In situ and observational data

## 5.6 Capacity building and Earth Observation in South Africa

The use of Earth observation in water related research is increasing and is considered an essential tool for future policy and decision making. Capacity building has become a key mandate of many institutions and the emphasis on capacity building in the field of Earth observation is increasing. Some of the institutions and initiatives involved in EO capacity building will be briefly discussed in the subsequent section.

### *5.6.1 TIGER Initiative*

To improve IWRM in Africa, the ESA launched the TIGER initiative to assist water authorities at the national and basin scale in Africa with setting up prototype information systems and services. The Tiger Initiative was launched in response to the urgent need for action in Africa expressed at the WSSD in Johannesburg in 2002. In the period 2002-2004 the founding members of the TIGER initiative, including the ESA, UNESCO (IHP), the Canadian Space Agency (CSA) and the CSIR (South Africa), started a consultation process in collaboration with African water authorities, technical centres and other stakeholders in both the water and the EO sectors. Four workshops were held to collect and define the institutional, technical, economic and social needs of the water sector in Africa, which helped to develop the TIGER strategy. AMCOW endorsed the initiative that in the timeframe 2005-2007 attracted further new key partners such as the African Development Bank and the United Nations Economic Commission for Africa (UN-ECA). By 2007 some 150 African institutions (water authorities, universities and technical centres) were involved in TIGER through projects and training activities. Up to now, activities have involved more than 30 African water authorities. TIGER follows a Develop-Demonstrate-Transfer approach aimed at empowering African users to take the lead in managing the transition to an operational phase and ensuring sustainability in the long term. Under the TIGER initiative Phase 2, launched in March 2009, 20 projects in 14 countries, involving African scientists and technical centres in collaboration with water authorities, have been selected for implementation and are supported via the ITC of the Netherlands (GEO, 2010).

The objective of the TIGER initiative is to assist African countries to overcome problems faced in the collection, analysis and use of water related geo-information. The aim is to fill existing information gaps relevant for effective and sustainable water resource management at the national to regional scale in thus helping to mitigate the widespread water scarcity in Africa.

TIGER has been endorsed by AMCOW and official recommendations towards its continuation were received by African stakeholders during the First African Week in 2008 and with the El Jadida declaration, released by the community attending the African Association of Remote Sensing of the Environment (AARSE) conference in Morocco in 2012. The TIGER initiative is being guided by an international Steering Committee which includes:

- African Union Commission
- African Water Facility
- African Ministers Council on Water
- Canadian Space Agency
- European Space Agency
- Ramsar
- South African Department of Water Affairs
- UNESCO
- United Nations Economic Commission for Africa

Since its launch 10 years ago, the TIGER initiative has established and supported capacity building activities and development projects involving some 42 African countries, with a total budget of more than 11 million Euro and reaching more than 150 African water authorities and research institutes.

### *5.6.2 TIGER Training and Capacity Building*

Training and capacity building actions are dedicated to support African partners (water authorities, technical centres, universities) to advance towards independent capacity to exploit EO technology for improving knowledge on water resources and climate change. Such activities aim to support the consolidation of a critical mass of technical centres in Africa with the skills and capabilities to derive and disseminate space based water relevant information for scientific research and management at regional, national and local scales (TIGER, 2013).

Training and capacity building activities within TIGER are organised by the TIGER Capacity Building Facility (TCBF), led by the ITC. Some 19 training sessions have been organised focused on both the needs of the different research projects and the requirements of the water authorities and end users involved in TIGER projects. The TCBF further currently provides scientific support to 20 research projects lead and conducted by African scientists. Almost 200 individuals from 26 different African countries, including South Africa, have been involved in actions performed by the TCBF.

On the basis of the specific information needs and requirements of the users community, EO based water information services are developed, demonstrated and validated. The objective of the TIGER initiative is to develop EO services in collaboration with African stakeholders and to transfer the services to mandated national and trans-boundary water authorities for operation under their leadership. Such a transfer is a long term process involving capacity building and local adaptations of EO services and information systems.

Over the years, TIGER developments have resulted in a solid and validated EO service portfolio including among others:

- Catchment characterisation and base mapping;
- Water quality monitoring;
- Soil moisture / soil water services;
- Surface water extent (floods, water bodies) and height monitoring;
- Support to ground water management and exploration; and
- Hydro (meteo-geo) logic modelling.

### *5.6.3 Water Network (WaterNet)*

WaterNet is a regional network of university departments and research and training institutes specialising in water. The network aims to build regional institutional and human capacity in IWRM through training, education, research and outreach by harnessing the complementary strengths of member institutions in the region and elsewhere (WaterNet, 2013). WaterNet member institutions have expertise in various aspects of water resource management and are based in Southern and East Africa. The University of KwaZulu-Natal hosts the EO specialisation modules for the WaterNet Master's Degree in Integrated Water Resources Management through the Centre for Water Resources Research (CWRR).

The four modules include:

i. Spatial analysis for water resources management

The aim of this course is to introduce the students to advanced spatial modelling skills used in water resource assessment, planning and management through:

- The application of specific decision support systems in water resources management;
- The establishment of linkages between GIS and decision support systems;
- Undertaking spatial analysis for water resource management of both surface and ground water and
- Application of multi-criteria analysis techniques.

ii. Earth observation for hydrological analysis

This course aims to enable students to identify and utilise sources of EO data and information available for catchment level hydrological analysis. The content includes the use of satellite based EO techniques for the identification of sources of rainfall, soil moisture / soil water, evaporation, surface and groundwater fluxes and other water resources related data and information.

iii. Advanced GIS

This course aims to provide insight into the applications of GIS in a southern African context. The students will gain an understanding of spatial information science as well as the ability to analyse spatially related problems facing the IWRM practitioner. The students will also gain an understanding of advanced concepts of applied GIS.

iv. EO Project

The EO project aims to consolidate the skills obtained in the three specialisation modules through the application and practical selection of GIS and EO tools for a catchment based study applied to a water resource management problem.

On completion of this specialisation, students are able to apply Earth observation and GIS to many water related scenarios. Initiatives such as WaterNet are therefore valuable in ensuring effective knowledge transfer of EO skills in the implementation of IWRM in Africa.

### *5.6.4 Council for Scientific and Industrial Research (CSIR)*

The CSIR has been instrumental in EO capacity building in South Africa for many years and was a key role-player in the establishment of the TIGER initiative. The CSIR has three defined remote sensing entities, Ecosystems Earth Observations (EEO), the CSIR Meraka Institute and the CSIR Satellite Application Centre (SAC), and is well positioned to provide broad leadership in applications research, research integration and research implementation (CSIR, 2010).

The importance of capacity building is emphasised in the vision of the EO research group as they aim to be a world-class natural resources remote sensing unit that:

- Actively contributes to the national human capacity development in terms of remote sensing and general spatial technology expertise;
- Provides comprehensive spatial data (remote sensing and GIS) support, specifically in terms of hyperspectral, structural, and multi-temporal sensing, as well as spatial modelling support, to the CSIR NRE and the broader CSIR to address institutional strategic research initiatives;
- Plays a leading role in directing remote sensing research at the CSIR and tailoring current institutional environmental research efforts to cutting-edge initiatives in terms of remote sensing strategic thinking;
- Provides remote sensing research leadership and promotes the science at the national level; and
- Continuously strives to deliver high impact peer reviewed research outputs.

### *5.6.5 Water Research Commission (WRC)*

Since its establishment in 1971 in terms of the Water Research Act (Act No 34 of 1971), the WRC has been instrumental in funding water related research in South Africa. South Africa is currently still at risk of having insufficient water, while water quality and availability issues are also becoming more acute. However, the country is much better prepared to deal with this problem owing to the WRC's meaningful contribution to the capacity building of the water sector through its continued commitment to direct and fund research on critical issues (WRC, 2013). The first WRC funded project that utilised Earth observation was in 1996 and since then, the Commission has funded many EO related projects and the number of such projects is increasing annually. An important outcome of all WRC funded projects is both institutional and human capacity building and the benefits thereof is evident in the increase in expertise in Earth observation in South Africa.

Currently the WRC is supporting the project 'Wide-scale modelling of water use and water availability with earth observations / satellite imagery' led by the University of Stellenbosch. This project applies satellite imagery for determining areas irrigated, crops cultivated and water use of selected agricultural crops in South Africa. The project will build the capacity and capability for water accounting in the country.

The WRC is also supporting a project that will develop a monitoring system, based on Earth observations that will monitor the status of water logging and salt effected soils on selected irrigation schemes in South Africa.

The WRC collaborates with other partners including with UNDP Capacity building network programme (Cap-Net), SANSA, the DWA and the ESA to facilitate capacity building training workshops. In November 2013, the WRC hosted a training-of-trainers workshop on land cover mapping for water resource management, which was attended by 35 trainees from various African countries. The objective of these training-of-trainers workshops, which are facilitated by the TCBF, is to ensure that "upon training on this tool, participants should be able to use the material to deliver further training to remote sensing practitioners or water management professionals in their own regions." (Moseki, 2013) After a workshop such as this, the participants are equipped with the material to teach others EO techniques including:

- Data acquisition strategies and techniques;
- Water quality monitoring;
- Flood mapping;
- Vegetation monitoring;

- Evapotranspiration estimation;
- Crop monitoring; and
- Irrigation and land cover mapping.

### *5.6.6 South African National Space Agency (SANSA)*

SANSA was established in December 2010 after the South African National Space Agency Act (Act No36 of 2008), mandated the establishment of a national space agency with the intent to converge and optimise resources and maximise the benefits of space services and applications to society. SANSA was created to promote the use of space and cooperation in space related activities while fostering research in space science, advancing scientific engineering through developing human capacity and providing support to industrial development in space technologies.

SANSA has six thematic focus areas including:

- Earth Observation
- Space Operations
- Space Science
- Space Engineering
- Scientific Advancement and Public Engagement
- Human Capital Development

Of relevance to this report are the two thematic focus areas of human capital development and Earth observation. Under the focus area of human capital development, SANSA aims to train South Africans in key areas of national importance, develop scarce and transferable skills and contribute to the transformation of the country to a knowledge based economy. As part of SANSA's human capacity building, it also offers bursaries for postgraduate research in Earth observation under the EO focus area. SANSA aims to collect, process and distribute EO data to support South Africa's policy-making, decision-making, planning, disaster management, resource and environmental management, economic growth and sustainable development initiatives.

# 6 RESEARCH AND DEVELOPMENT FOCUS FOR WATER RESOURCE MANAGEMENT AND MONITORING VARIABLES IN SOUTH AFRICA

## 6.1 Rainfall

Rainfall is generally a challenging atmospheric parameter to determine and it is often the limiting factor in modelling studies (Clark & Smithers, 2008). The quality, density and coverage of gauge networks vary significantly across South Africa and alternate solutions to rainfall estimation and validation are required (De Coning & Poolman, 2011). The use of satellite based rainfall estimates through remote sensing is an emerging science, which in recent times has seen a rapid evolution within its field, since it is a powerful tool for obtaining valuable weather information (Duan & Bastiaansen, 2013). In South Africa, a few research projects have investigated the use of remotely sensed rainfall in hydrological studies. Operationally only a few projects make use of remotely sensed rainfall information

A study by Terblanche et al. (2001) provides an overview of weather radar related developments in South Africa with a specific aim at hydrological research and operations. Hydrometeorological applications of weather radar have their roots in the country's long-standing research effort on rainfall enhancement from summertime convective storms. An overview of a programme which has developed the necessary infrastructure, expertise and related hardware and software to collect and archive high quality radar data, analyse the information and conduct comparisons with conventional measurements on catchment scales, is described. The two case studies highlight the advantages and disadvantages of using radar information. Furthermore, a strategy to optimise the use of the radar infrastructure is highlighted with specific reference to the radar networking system and how radar rainfall estimates might be integrated with satellite rainfall estimates and measurements by conventional gauges.

A preliminary analysis of the potential for using satellite derived rainfall data through a comparison with available gauge data for four basins in the southern Africa region was reported by Hughes (2006). The study investigated the potential for using rainfall data from satellites for hydrological modelling in the Okavango River basin, the Kafue basin, Thukela River basin and the Kat River basin. The Global Precipitation Climatology Project (GPCP) 1DD dataset (Huffman et al., 2001) and the PERSIANN dataset (Sorooshian et al., 2000) were used in the research study. Hughes (2006) concluded that the GPCP and PERSIANN datasets cannot be used without modifications and require some form of local calibration to represent topographical influences and make them compatible with available rain gauge data. However, Hughes (2006) points out that one problem when attempting to calibrate satellite data is that the datasets are currently too short to represent the variability of rainfall runoff responses that typically occur within southern Africa. The study highlights the prospects of applying relatively straightforward adjustments to satellite derived rainfall estimates and indicates that further assessments appear to be justified.

Sawunyama and Hughes (2008) evaluated the use of a frequency of the exceedance curve algorithm to merge rain gauge and high resolution (0.1°) satellite rainfall estimates, such that the merged rainfall datasets are statistically compatible with the rain gauge datasets. They used the Climate Prediction Centre African Daily Precipitation Climatology (CPCAPC) (Love et al., 2004) gridded daily rainfall totals at 0.1° spatial resolution for Africa. The study evaluated the technique in 20 catchments across South Africa by using the rainfall estimates as an input to the revised groundwater version of the Pitman model and compared simulated stream flow time series.

A study by Gibson et al. (2009) aimed to quantify all components of the water balance to produce a water account. Gibson et al. (2009) conducted a study investigating the use of remote sensing technologies to quantify the water balance components for quaternary catchment G10K in the Piketberg region of the Western Cape to produce a water account. Rainfall grids with a 1 km resolution created by the ARC-ISCW by interpolation using rainfall data from about 550 automatic stations and satellite rainfall estimates were used in the study.

Sinclair and Pegram (2010) estimated soil moisture / soil water over South Africa using the TOPKAPI hydrological model. The purpose of their study was to provide an automated modelling system to estimate soil moisture / soil water at a three hour time step for a 0.125° spatial grid over South Africa, for use by the SAWS in their national FFG system. Rainfall and ET were the two main forcing variables required to run the TOPKAPI model. Rainfall estimates were obtained from the TRMM 3B42RT real time rainfall product. Continuing the work reported by Sinclair and Pegram (2010), Sinclair and Pegram (2013) report that the TOPKAPI hydrological model was extended through the inclusion of a Green-Ampt infiltration module to produce the PyTOPKAPI version of the model. Sinclair and Pegram (2013) then investigated the sensitivity of PyTOPKAPI to systematic bias in the rainfall and ET input variables and to the soil properties used and found that improving rainfall estimates and the parameters used to describe soil moisture / soil water storage would result in the best estimates of soil moisture / soil water.

Cohen Liechti et al. (2012) evaluated a sparse gauging network for rainfall monitoring and observations from spaceborne instrumentation in order to produce rainfall data for a large part of a basin. Three operational high resolution satellite derived estimates: the Tropical Rainfall Measuring Mission product 3B42 (TRMM 3B42), the Famine Early Warning System product 2.0 (FEWS RFE2.0) and the National Oceanic and Atmospheric Administration / Climate Prediction Centre (NOAA/CPC) morphing technique (CMORPH) were analysed in terms of spatial and temporal repartition of the precipitations. The satellite derived estimates were compared to ground data for the wet seasons of the years 2003 to 2009 on a point to pixel basis at daily, 10 daily and monthly time steps and on a pixel to pixel basis for the wet seasons of the years 2003 to 2007 at monthly time steps. Bangira (2013) used ARC2, MPE, CMORPH and TRMM 3B42 remotely sensed rainfall estimates and ASCAT soil moisture / soil water observations in a study that mapped areas of high flash flood potential in the Western in South Africa.

As part of a WRC project K5/1935 (RISKOMAN: A Management Tool for the Inkomati Basin with focus on Improved Hydrological Understanding for Risk-based Operational Water Management), a study was undertaken to investigate rainfall estimates using remote sensing. The study involved a comparison and evaluation of the TRMM and FEWS in the Kaap sub-catchment of the Inkomati catchment. The study showed that overall, when compared to observed gauge data, TRMM exhibited more satisfactory rainfall estimates compared to FEWS, for the Kaap sub-catchment. However, both satellite products provided adequately representative trends relative to the rain gauge data.

The most significant limitation in satellite rainfall estimation is the scale mismatch issue. This issue refers to the assumption that a point (rain gauge) can be representative of the rainfall for an entire area (625 km2, for a satellite with 0.25° spatial resolution) (Duan &Bastiaanssen, 2013).

There is a need for advancement of techniques to address the main challenges that satellite rainfall estimation and research should focus on (Dinku et al., 2011). These include:

- Development of hybrid solutions to combine the benefits of satellites and ground observations (for instance ground radars and gauge networks) in order to improve the benefit of both;
- Development of advanced multi-spectral algorithms to improve the accuracy and spatial resolution of satellite precipitation estimates (providing high resolution data relevant to various applications);

- Improving computational efficiency and accuracy of precipitation now-casting algorithms including those dependent on cloud tracking;
- Improving the accuracy of downscaling algorithms, especially over complex terrain, for hydrological applications; and
- Real time bias adjustment of heterogeneous airborne and ground based rainfall products.

Collaboration among water users, policy-makers and research teams (such as engineers, hydrologists and ecologists) is crucial to address these challenges and to ensure that the capability of remote sensing is fully harnessed (Sorooshian, 2000). Programmes, such as GEOSS, have been initiated to provide a monitoring system and ultimately improve hydrological predictions. This initiative improved the general understanding of the hydrological system and has brought about significant advancements in remote sensing (Dinku et al., 2011). However, despite the wide availability of satellite rainfall estimation products, further research and validation is required, which need to be conducted at a range of scales across differing climates (Sawunyama & Hughes, 2008).

## 6.2 Total evaporation (ET)

The estimation of total evaporation (ET), which includes evaporation from land and water surfaces and transpiration by vegetation, is one of the most important processes in the determination of the exchanges of energy and mass between the hydrosphere, atmosphere and biosphere (Sellers et al., 1996). In agriculture, ET is a major consumptive use of irrigation water and precipitation on agricultural land (Gowda et al., 2007a). A comprehensive review of different methods used to estimate ET is discussed in detail by Verstraeten et al. (2008). Remote sensing based ET models can provide representative measurements of several physical parameters at scales from field (local) catchments, to regional catchments and are better suited for estimating water use of different vegetation surfaces (Allen et al., 2007).

Over the years numerous remote sensing based models that vary in complexity have been developed for estimating regional ET. The complexity of these different methods depends on the balance between the empirical and physically based modules used (Courault et al., 2005). Some of the empirical / statistical techniques have been used operationally with satellite data for computing daily ET at regional scales. The more complex numerical simulation models require detailed input parameters that may limit their application to regions containing a large database of soils and vegetation properties. Current efforts are being directed towards simplifying the parameter requirements of these models. A number of these models have been used in South Africa in research and some operational projects presented below.

### 6.2.1 Current & Recent Research Projects

Ahmad et al. (2005b) used SEBAL to assess actual ET across a range of land uses in the middle part of the Olifants Basin in South Africa. They used a Landsat7 ETM+ image during the rainy season for the analysis. The target area contained diverse land uses, including rainfed agriculture, irrigated agriculture (centre pivot, sprinkler and drip irrigation systems), orchards and rangelands. Their major finding was that SEBAL results showed that 24% of ET is from agricultural use, compared to 75% from non-agricultural land use classes (predominantly forest) and only 1% from water bodies. Although irrigation accounts for roughly half of diverted stream flow in the basin, it contributes only about 4% of basin scale daily ET at the time of assessment.

Kongo and Jewitt (2006) used SEBAL to estimate ET from the Potshini catchment in the Thukela River basin using cloud free Landsat7 ETM image. They compared SEBAL ET estimates with ETo from a weather station on the same pixel. They found that SEBAL over estimated ET by 1.3 mm/day, with the weather station reading being 7.2 mm/day for a point in the same pixel. Hellegers et al. (2011) used SEBAL at the Inkomati Basin to analyse the variability in crop water productivity (CWP) on the basis of actual water consumption and associated biomass production. They used Landsat and MODIS images for ET estimations.

Three surface energy balance models were evaluated by Jarmain et al. (2009a) for different land covers and geographical regions in South Africa using Lansat5 TM and Landsat7 ETM+ images. SEBAL, METRIC and SEBS were evaluated over a compartment planted with *Acacia mearnsii* trees at Seven Oaks (KwaZulu-Natal), Midmar Dam (KwaZulu-Natal), a swamp forest, grassland and a sedges wetland at iSimangaliso Wetland Park, close to St Lucia (KwaZulu-Natal), and an area with Spekboom thicket and degraded veld near Kirkwood (Eastern Cape). The daily evaporation rates measured compared favourably to the simulated evaporation rates using these three different remote sensing based models.

A study was undertaken by the Working for Water (WfW) programme to assess the actual water consumption (ET) of Alien Invasive Plants (AIPs). The water consumption of AIPs for three selected years (dry, wet and average) were analysed using SEBAL (Jarmain & Meijninger, 2012), in combination with MODIS images. The ET rates obtained from SEBAL showed that the annual water consumption of AIP infested areas is similar to forest plantations and higher than most of the indigenous vegetation biomes. Gibson et al. (2009) used the SEBS model to calculate annual

ET for a quaternary catchment in the Western Cape to assess the compliance of water users to water use legislation. The results of the study were inconclusive as the estimated annual catchment ET significantly exceeded the estimated annual catchment rainfall.

WaterWatch executed a study on the water use efficiency of table and wine grapes in the Western Cape, South Africa (Klaasse et al., 2008). SEBAL was applied in conjunction with Landsat satellite imagery to estimate water consumption and water use efficiencies of vineyards. The results of this study showed that SEBAL can be used to estimate water consumption, yield and thus water use efficiency without any knowledge on soil type, cultivar, irrigation system and supply and plant condition.

The Satellite Applications and Hydrology Group (SAHG) of the University of KwaZulu-Natal (UKZN) used the HYLARSMET model over Southern Africa using remote sensing and meteorological data (Sinclair & Pegram, 2013). The project was a follow-on to a previous project – 'Soil moisture / soil water from Satellites – Daily Maps over RSA' – funded by the WRC. The aim of the project was to provide the best available estimate of soil moisture / soil water (SM) and ET over the entire country in near real time, in as much detail as was feasible and freely accessible on the web. Another WRC funded project was initiated to provide a spatially explicit validation procedure for the 1 km grid of SM and ET produced by the SAHG UKZN (Sinclair & Pegram, 2013) and other global change models. The aims of the project were to provide data for the continued support of soil moisture / soil water modelling of South Africa using a hydrologically consistent Land Surface Model (follow-on project proposed from K5/1683) and to provide accurate field and satellite estimates of ET and SM for the calibration of Hydrometeorological models (Mengistu et al., 2014). The SEBS remote sensing model was used for spatial ET and SM estimates. MODIS TERRA, Landsat 7 ETM+ and Landsat 8 images were used in SEBS for ET and SM maps.

The RISKOMAN (Risk-based Operational Water Management) project aims to assist water managers and stakeholders in identifying, implementing and continuously adjusting efficient allocation policies in a dynamic and uncertain hydrological environment. The project partners are UNESCO-IHE, Universidade Eduardo Mondlane (Mozambique), University of KwaZulu-Natal and the Komati Basin Authority. The WRC funded project 'A Management Tool for the Inkomati Basin with focus on Improved Hydrological understanding for Risk-based Operational Water Management', is also part of the RISKOMAN project aimed to improve the hydrological scene-setting and decision-making requirements for water managers and stakeholders within the Inkomati Basin. The project uses remotely sensed SEBAL ET estimates, rainfall and soil moisture / soil water data for operational decision-making, particularly for real time hydrological modelling of the system.

### 6.2.2 Operational Projects

GrapeLook was a project designed to improve water use efficiency of vineyards in South Africa. The project was funded by the Department of Agriculture: Western Cape (supported by the Department of Agriculture, Forestry and Fisheries and the Dutch Embassy) and ESA. The objective of this project was to assist grape farmers and governmental authorities with the management of scarce irrigation water resources and on-farm nitrogen applications in order to promote sustainable optimal resource utilisation, reduce input costs, protect the environment and ultimately increase water use efficiency by means of operational satellite technologies. The project used existing terrestrial and space based elements which were integrated into an end-to-end service directly applicable to vineyards in South Africa. Satellite EO data used to run the existing energy balance and water balance algorithms was undertaken by WaterWatch (http://www.grapelook.co.za/).

FruitLook was the successor of GrapeLook, which was similar to FruitLook, but covered a larger area and included deciduous fruit trees. FruitLook was a demonstration project showing the ability of satellite observations to assist farmers in their daily farm management. The FruitLook project was funded by the Department of Agriculture: Western Cape with the support of the Department of Agriculture, Forestry and Fisheries (DAFF), HortGro and the Integrated Applications Promotion programme of ESA. The project was executed by eLEAF Competence Centre (previously WaterWatch BV), the Netherlands, and the UKZN, South Africa (http://www.fruitlook.co.za).

The WRC and the DAFF are co-funding a project 'Water use efficiency of irrigated agricultural crops determined with satellite imagery' which started on 1 April 2011 and will run until 31 of March 2014. This project was intended to build on research conducted in South Africa in recent years where the accuracy of models that use remote sensing data to estimate ET were evaluated and use of spatially explicit data products generated with the SEBAL model have been evaluated. The project was intended to illustrate how spatially explicit information provided at frequent intervals can be used to assess and potentially improve the water use efficiency (WUE) of irrigated agriculture, through two case studies. In the first case study the focus is on irrigated sugarcane (SugarcaneLook) produced in parts of the Inkomati Basin and in the second case study the focus is on grain crops (GrainLook) produced in parts of the Vaal and Orange River catchments. A number of institutions are contributing to this project, including the University of

KwaZulu-Natal, eLeaf (formerly WaterWatch), the South African Sugarcane Research Institute, the University of Pretoria, the University of the Free State, Stellenbosch University and Griekwaland-Wes Korporatief.

Operational Monitoring product for Planning and Water Allocation in the International Incomati Basin (WATPLAN) was a collaborative project of the European Community's Seventh Framework programme funded by the European Union. The WATPLAN project focused on water resources allocation, the identification of current water use and high resolution monitoring of several water resource indicators (ET, rainfall, ET deficit and rain ET). Data for the entire Inkomati Basin was disseminated weekly using an Internet based portal – an operational monitoring website (www.watplan.com). Information provided through WATPLAN was integrated with the operational water resource management system of the Inkomati Catchment Management Agency (CMA).

The operational projects presented in this section use the SEBAL model which has been validated in different environments worldwide. The SEBAL model is owned by the company eLeaf (formerly WaterWatch) and is protected by intellectual property law and is therefore not freely available for research. Therefore, other models such as the SEBS model which is freely available in ILWIS (GIS and remote sensing software) should be investigated and be used for research and training purposes.

A number of freely downloadable ET data products exist, for example the MODIS 16 ET product and Landsaf data (LSA-SAF ET). The MODIS Science Team, in 2011, released a MODIS ET data product (MOD16) available freely for download. The MOD16 ET products are regular 1 km$^2$ global land surface ET datasets for vegetated land areas at eight day and monthly intervals (Mu et al., 2011). The validation of MOD16 ET is required in South Africa to determine the potential use of the product.

## 6.3 Soil Moisture / Soil Water

Soil moisture / soil water is an important hydrological parameter and has numerous implications on agriculture, water management and environmental monitoring and modelling. Due to the heterogeneity of soil moisture / soil water even at small scales it is expensive and difficult to have continuous records; therefore remote sensing is seen as a promising technique which incorporates the spatial and temporal characteristics of soil moisture / soil water. However, very few studies exist on the use of remote sensing for estimating soil moisture / soil water in South Africa.

A study by Pfeffer (2008) evaluated three satellite soil moisture / soil water products for hydrological applications over South Africa. The products used in this study were the NSIDC and VUA NASA, which are derived from the AMSR and the ENVISAT product derived from the ASAR.

Gibson et al. (2009) conducted a study investigating the use of remote sensing technologies to quantify the water balance components for quaternary catchment G10K in the Piketberg region of the Western Cape to produce a water account. Estimates of surface soil moisture / soil water using two soil moisture / soil water quantification algorithms with data from two different sources of SAR data, Envisat ASAR and Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) were used in the study.

Sinclair and Pegram (2010) estimated soil moisture / soil water over South Africa using the TOPKAPI hydrological model. The purpose of their study was to provide an automated modelling system to estimate soil moisture / soil water at a three hour time step for a 0.125° spatial grid over South Africa, for use by SAWS in their national FFG system. Rainfall and ET were the two main forcing variables required to run the TOPKAPI model. Simulations were run at a three hour time step to estimate the SSI which is defined as the percentage of soil void space taken up by water. Sinclair and Pegram (2013) report that the TOPKAPI hydrological model was extended through the inclusion of a Green-Ampt infiltration module to produce the PyTOPKAPI version of the model. Sinclair and Pegram (2013) then investigated the sensitivity of PyTOPKAPI to systematic bias in the rainfall and ET input variables and to the soil properties used and found that improving rainfall estimates and the parameters used to describe soil moisture / soil water storage would result in the best estimates of soil moisture / soil water.

Bangira (2013) used ARC2, MPE, CMORPH and TRMM 3B42 remotely sensed rainfall estimates and ASCAT soil moisture / soil water observations in a study that mapped areas of high flash flood potential in the Western Cape in South Africa. As part of the RISKOMAN project (WRC Project K5/1935) a comparison of AMSR-E, SMOS and ECV remote sensing soil moisture / soil water products and SAHG land surface model soil moisture / soil water product against ground based measurements at two sites within the Inkomati catchment was undertaken. The objective of the research was to compare and evaluate the ability of satellite based soil moisture / soil water products to reliably measure and monitor the soil moisture / soil water status of a catchment. The study also investigated the variation in the accuracy of soil moisture / soil water estimation in relation to season (summer and winter) and the limitations and problems associated with the current satellite soil moisture / soil water estimates.

A WRC funded project was initiated to provide a spatially explicit validation procedure for the 1 km grid of soil moisture / soil water and ET produced by the SAHG UKZN (Sinclair & Pegram, 2013) and other hydrological models. The aims of the project were to provide data for the continued support of soil moisture / soil water modelling of South Africa using a hydrologically consistent Land Surface Model and to provide accurate field and satellite estimates of ET and soil moisture / soil water for the calibration of Hydrometeorological models (Mengistu et al., 2014).

Currently the only operational remotely sensed soil moisture / soil water product in South Africa is the SAGH SWI product by Pegram and Sinclair. Many other products developed internationally have been used in comparative studies which indicate that there are other products available for use. Remotely sensed soil moisture / soil water is a valuable input parameter to many hydrological applications and will aid prediction in ungauged catchments (Chetty et al., 2013). The establishment of soil moisture / soil water networks is needed in South Africa and any available data should be made available through sites such as the International Soil Moisture / Soil Water Network which can be used in the calibration of products and improvement in soil moisture / soil water estimates.

## 6.4 Ground Water

The application of satellite remote sensing to groundwater studies presents many challenges. UNESCO and ESA, through their different applications and education programmes, support the development and promotion of good practices in the use of Earth observation technology to overcome the water information gap that exists in many developing countries. The AQUIFER project of ESA, for example, is developing different information products based on data from the ENVISAT EO missions to improve management of internationally shared water resources and aquifers and to build up local capacity for service provision of Earth observation based information products in support of aquifer management. UNESCO's International Hydrological Programme (IHP) is providing methodological and technical advice for the better management of these groundwater resources through a series of projects. UNESCO's International Geoscience Programme is contributing to capacity building efforts for the application of satellite information (Meijerink, 2007).

The WRC published two national scale map sheets of the groundwater resources of South Africa (Vegter, 1995a, 1995b), namely: Sheet 1 – Borehole Prospects map; Sheet 2 – Saturated Indices map, with inset maps of Mean Annual Recharge, Groundwater Component of River-flow (Baseflow), Depth to Groundwater Level, Groundwater Quality and Hydrochemical Types.

Baron et al. (1998) developed the groundwater Harvest Potential map of the Republic of South Africa which was a derivative of the set of maps produced by Vegter (1995b). The Harvest Potential provides an estimate of the maximum volume of groundwater that may be abstracted per square kilometre per annum, without depleting the aquifers. It represents a synthesis of the amount of groundwater in storage in an aquifer system, the recharge and the time span between these recharge events. This information forms the basis of General Authorizations for groundwater use under the provisions of the National Water Act (Act No 36 of 1998.

A GIS based experimental methodology (Conrad & Van Der Voort, 1999) introduced the concept of anthropogenic, ecological and cost parameters into assessment of groundwater resources to determine the so-called 'Sustainable Utilisable Potential' or SUP. The SUP was defined as the "volume of groundwater that can be abstracted on a sustainable basis after the requirements of the reserve have been met". It was the first methodology designed to be applied on a quaternary catchment scale and that is also aligned with the principles of the National Water Act (Act No 36 of 1998).

Woodford (1999) used a GIS raster based approach to assess the groundwater situation of the T60 tertiary drainage basin in the Eastern Cape. According to Woodford (1999), sustainable groundwater abstraction depends on adequate recharge to replace the water being removed from the aquifer system. Haupt (2001) used existing available information, mainly the Harvest Potential (HP), to evaluate the groundwater resources of South Africa. The HP is derived from Vegter's (1995a) assessments of limited existing information on recharge and a much generalised assessment of aquifer storage capacity, as well as drought periods.

A WRC report on the DAGEOS Project (Umvoto Africa, 2005) outlines a design strategy for the monitoring of changes in continental water storage (surface and subsurface) and the remote-sensing of the hydromechanical structure and properties of the deep confined fractured rock aquifer systems of the Western Cape by land and space based systems, with particular reference to the application of new Earth observation technologies. The report's focus is an experimental system using a combination of land based microgravity and Global Positioning System (GPS) observations, complemented by satellite gravity and satellite radar methods for monitoring deep aquifer storage changes and determining fundamental hydromechanical properties of the aquifer such as its bulk compressibility.

The recent WRC project 'Development and Application of Global Navigational Satellite Systems (GNSS) Methodology for Groundwater Resource Assessment' (GEOSS, 2011), has the following aims: 1) To demonstrate the use of high precision GNSS technology as a tool for groundwater resource monitoring and assessment; 2) To develop the methodology for relating GNSS measurements of natural or abstraction induced surface deformation and conjunctive hydrogeological data in order to derive the in situ, bulk elastic properties (for instance skeletal compressibility) of an underlying confined fractured rock aquifer; 3) To build South African capacity to establish the technical infrastructure (for instance, data telemetry) and implement the data processing methods required for a pilot GNSS for Groundwater scheme at the Gateway Wellfield, Hermanus.

There are few physical remotely sensed measurements (temperature, backscatter of active microwaves from saturated zones) of direct relevance to groundwater studies, and if so they pertain to specific conditions and thus have limited application as yet. The general application of remote sensing in hydrogeology has been, and still is, in the domain of image interpretation, whereby interaction takes place between what can be observed on the imagery and what is expected on the basis of a conceptual model of the hydrogeology of a given environment, in particular groundwater flow systems (Meijerink, 1997). The interest of hydrogeologists in remote sensing is shifting to the dynamic aspects of water balances and contamination, for which the appropriate instrument is provided by combining image processing, GIS procedures and numerical modelling (Meijerink, 1997). There is need for further development of simple and robust methods to transform the interpreted physiographical or geomorphological units in distributed parameters. A challenge is the development of affordable, physically based use of satellite data with a high temporal resolution for monitoring recharge and emergence of groundwater driven by flow systems (Meijerink, 1997).

## 6.5 Runoff/ Stream Flow

Runoff or stream flow, which is an accumulation of runoff, is typically measured using weirs and other physical flow measurement structures. However, despite advances in the science of remote sensing it is still not really feasible to reliably measure runoff using remote sensing techniques. Runoff is the accumulated result of many other hydrological drivers and processes, such as precipitation, interception, total evaporation and infiltration. Where flow measurements are not available, runoff is estimated using hydrological models of various types and degrees of complexity. Hydrological models require input parameters such as rainfall, potential evaporation, total evaporation, land cover, antecedent soil moisture / soil water and temperature, which can all be estimated with varying degrees of accuracy using remote sensing techniques. Some examples from South Africa in which hydrological models have been used together with remotely sensed inputs to estimate runoff or flooding potential, are provided below.

A study by Hughes (2006) investigated the potential for using rainfall data from satellites for hydrological modelling in the Okavango River basin, the Kafue basin, Thukela River basin and the Kat River basin. Hughes (2006) used the GPCP 1DD dataset (Huffman et al., 2001) and the PERSIANN dataset (Sorooshian et al., 2000).

Sawunyama and Hughes (2008) evaluated the use of a frequency of exceedance curve algorithm to merge rain gauge and high resolution (0.1°) satellite rainfall estimates, such that the merged rainfall datasets are statistically compatible with the rain gauge datasets. Sawunyama and Hughes (2008) used the CPCAPC (Love et al., 2004) gridded daily rainfall totals at 0.1° spatial resolution for Africa.

Gibson et al. (2009) conducted a study investigating the use of remote sensing technologies to quantify the water balance components for quaternary catchment G10K in the Piketberg region of the Western Cape to produce a water account. Sinclair and Pegram (2010) estimated soil moisture / soil water over South Africa using the TOPKAPI hydrological model. The purpose of their study was to provide an automated modelling system to estimate soil moisture / soil water at a three hour time step for a 0.125° spatial grid over South Africa, for use by the SAWS in their national FFG system.

Bangira (2013) used ARC2, MPE, CMORPH and TRMM 3B42 remotely sensed rainfall estimates and ASCAT soil moisture / soil water observations in a study that mapped areas of high flash flood potential in the Western Cape in South Africa. A current WRC funded project aims to assess methodologies for quantifying water use, integrate appropriate sources of data, information and methodologies into the water use quantification and accounting system. As not all components of the water balance can be measured directly or indirectly (through remote sensing techniques), the proposed methodology is to use the ACRU agro-hydrological model together with directly measured and remote sensing estimates of inputs such as rainfall, temperature and reference ET.

The SAFFG system uses hourly input from rain gauges, radar rainfall and satellite rainfall. This information is combined with runoff and hydrology in catchments to determine a measure of bank full stage. The SAFFG system is part of the WMO initiative aimed at providing flash flood guidance to developing countries.

The use of remote sensing for the operational estimation of runoff for flood forecasting and water availability and food security assessments appears to be an area where there is still considerable scope for research in South Africa. Recent developments in remote sensing and data dissemination present both opportunities and challenges for hydrologists to improve currently used flood forecasting systems since remote sensing offers a means to provide frequent global coverage of such critical hydrological data as precipitation and soil moisture / soil water (Entekhabi et al., 1999). One of the potential applications of Earth observation is the use of satellite images to detect the amount of impervious surfaces in catchments to assess runoff potential.

## 6.6 Other applications

Earth observation and remote sensing can be used for a wide range of other applications, including wetland mapping, land use and land cover mapping, and water quality monitoring. Wetland mapping using high resolution satellite imagery includes: wetland delineation and characterisation, wetland inventory, mapping species composition, understanding hydrology and development of management plans.

A study by Dini (2003) examined a pilot application in KwaZulu-Natal (uKhahlamba Drakensberg) that was useful for developing the proposed methodology for the South Africa National Wetlands Inventory. The objectives of the study were to:

- Prepare an inventory of the wetlands of the uKhahlamba Drakensberg Park according to the Ramsar wetland descriptors; evaluate the effectiveness of using satellite imagery as a preliminary mapping tool to determine the location, the extent and the features or characteristics of the wetlands;
- Investigate the feasibility of classifying wetlands based on satellite imagery; and
- Develop a mapping, inventory and monitoring procedure for the wetlands of the uKhahlamba Drakensberg Park that would be applicable on a national scale in the context of a national wetlands inventory.

A study on the detection of wetlands using remote sensing was also undertaken by Gibson (2003) to establish the possibilities of mapping wetlands in Qoqodala, Eastern Cape, South Africa, using Landsat and/or Aster imagery. The methodology for mapping wetlands using Landsat imagery, proposed by Thompson et al. (2002) was adapted and applied to the study area.

A multi-purpose wetland inventory is being developed and promoted through partnerships (Ramsar Convention on Wetlands) and specific analyses at different scales in response to past uncertainties and gaps in inventory coverage using remote sensing and GIS (Rebelo et al., 2009). As part of the global inventory project, a broad scale wetlands used for agriculture was mapped and assessed through Earth observation in southern Africa. The aims were to assess the manner in which local communities use wetlands for multiple purposes, both then and in the future, and to put in place or enhance mechanisms that minimise the degradation of wetlands in order to optimise the livelihood benefits that are generated (Darradi et al., 2006).

In remote sensing, water quality parameters are estimated by measuring changes in the optical properties of water caused by the presence of the contaminants. Water quality parameters that have been successfully extracted using remote sensing techniques include chlorophyll content, turbidity, secchi depth, total suspended solids; coloured dissolved organic matter and trip-ton. In addition, thermal remote sensing methods have been widely used to estimate the water surface temperature in lakes and estuaries (Kumar & Reshmidevi, 2013).

A study by Majozi et al. (2013) was undertaken to assess water quality of Lake Naivasha, Kenya, using MERIS satellite images. The purpose of the study was to investigate the possibility of using Earth observation techniques to map the euphotic zone depth of the Lake. Majozi et al. (2013) concluded that there is a gap in the application of remote sensing to monitor environmental conditions and strong in situ networks need to be established to develop more robust algorithms suitable for African waters.

Through research directed towards the development of local in situ monitoring systems and Earth observation products, continued progress is being made towards a South African national operational near real time satellite eutrophication and cyanobacterial bloom monitoring system by the CSIR and the UCT-MRSU. Near real time trophic status monitoring products for a selection of South African reservoirs are now available using data from MERIS via the ESA Data Dissemination System, and systematic data processing chains developed at the UCT-MRSU (see http://www.afrosea.org.za/php/damSearch.php). There is an increasing need for routine observations of water quality, allowing improvement of knowledge and risk management and quantitative assessment of the extent of eutrophication. There is currently insufficient knowledge and information on the status and trends of water quality and eutrophication and substantial gaps in available data archives (Matthews et al., 2012).

# 7. CONCLUSION AND RECOMMENDATIONS

Earth observation and remote sensing techniques have become valuable tools in supplying data necessary for water resource management and are gaining impetus due to their capability of providing better spatial and temporal information. Remote sensing techniques have been widely used to estimate meteorological and hydrological variables (such as temperature, precipitation and soil moisture / soil water), to estimate fluxes such as total evaporation, and to delineate water bodies.

The most challenging aspect concerning the practical use of Earth observation data in Africa is the derivation of useful geospatial information products and their successful adaptation into a national or regional information infrastructure (Canadian Space Agency, 2004). The lack of qualified specialists to exploit these new capacities is recognised as a major constraint to the successful implementation of remote sensing applications programmes, particularly in developing countries. Therefore, there is a pressing need to facilitate knowledge and technology transfers, especially to Africa, where in many areas the lack of water is a serious constraint to development and scarce information limits proper management of the resource (Meijerink et al., 2007).

While great efforts have been made in increasing capacity building in Earth observation in South Africa, there are still many challenges. Some of these challenges were highlighted in a survey conducted by GEO (2006) and are not only applicable to South Africa, but to most developing countries. Many of the challenges that were raised are however continuously being minimised as technology rapidly advances. While the area of greatest concern is a lack of trained scientists and educators, there is also a need for further educational resources and technology, including in situ data collection systems and infrastructure. Although there are several Earth observation capacity building initiatives in South Africa and globally that are focused on human resources, ranging from short workshops to internationally recognised higher education programmes, the number of trainees are still limited, when considering the substantial need for trained Earth observation scientists and practitioners to be able to translate satellite oriented data and products into relevant end-user geo-information.

Another issue is a lack of funds. This is not only a limiting factor in human capacity building, but also in infrastructure capacity building and without proper infrastructure, human capacity building becomes compromised. Typical infrastructural shortcomings such as a lack of up-to-date equipment and software, limited possibility for combined use of in situ, satellite and ground based observational data, poor access to cost effective bandwidth, intra-national networks and the limited number of databases enabling free data access and exchange are common in developing countries. Factors that contribute to scientific capacity include the national infrastructure, the pool of scientists, laboratories, other research facilities and academic institutions. Besides current technological and capacity development in developing countries, there is a need for close collaboration between countries to strengthen institutions and infrastructures. However, many developing countries, including South Africa, are still reliant on collaboration with developed countries for capacity building. One of the reasons for the reliance of developing countries is the so called 'brain drain', which entails many of the best Earth observation practitioners leaving their country of origin or work place in search of better professional options, either in developed countries or in the private sector, thus leaving a void in the number of educators (GEO, 2006).

The need for capacity building in the field of Earth observation is well recognised in South Africa and continues to grow. South Africa has been instrumental in developing capacity building initiatives such as TIGER, which has not only benefited South Africans, but many other African countries too. This is largely due to the funding, expertise and infrastructure provided by the WRC, the CSIR, SANSA and higher education institutions but is still reliant on the assistance of developed countries to provide software, data, trainers and funding. Even with the increase in capacity building in Earth observation, the number of trainees is still limited, when considering the substantial need for trained Earth observation scientists and practitioners to be able to translate satellite oriented data and products into relevant end-user geo-information for environmental and water resources management.

This study has illustrated the manifold advantages of using Earth observation and remote sensing in managing the countries water resources. It illustrates the current uses and applications as well as the many sources of data that can be exploited. The need for capacity, competencies and infrastructure required to fully utilise the potential of Earth observations and remote sensing is discussed.

In recommendation:

- The opportunity to capitalise on international experience and knowledge through active participation in GEO, GEO tasks and contributions to GEOSS, through the establishment of a vibrant SA-GEO water community of practice should be considered. Discovery of and access to Earth observation data (satellite, aerial and in situ) is critical to successful operational use of these technologies in water resource management. This needs to be made possible through support and use of SAEOSS.

- The development of a resourced (funded) research agenda and capacity building programme will ensure that the country optimises the use of Earth observation and remote sensing technologies for the sustainable management of the countries water resources, so ensuring the informed use of this scarce resource in the development of the country and its people. The WRC should consider focussed research on the use and development of integrated operational observation systems that will supply the required observations of variables essential for informed water resource management decisions. A research agenda should be developed with the Earth observation water community and should be revised periodically as technologies change.
- In anticipation of South Africa's first operational earth observing satellite being developed over the next five years, the opportunity to conduct research that will ensure the water community is ready and prepared to fully utilise this capability, will require significant investment in Earth observation and remote sensing research over the next few years.
- Finally, in order to keep this report 'alive and current' it is recommended that the report becomes the basis of a web based Wikipedia. An appropriate host will need to be identified that is readily accessible to the Earth observation water community of practice and that has the capacity to maintain the system. Possible candidates would include the SAEOSS portal, SAEON or the SA-GEO website. Community participants would then be able to add current information at any time and an annual edited report could be generated as an authoritative reference document for the community.

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