A MANAGEMENT TOOL FOR THE INKOMATI BASIN WITH FOCUS ON IMPROVED HYDROLOGICAL UNDERSTANDING FOR RISK-BASED OPERATIONAL WATER MANAGEMENT

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

There is a need in modern water resources management, particularly in river basins that are said to be *closing* to use new approaches to reconcile the often contrasting requirements of diverse stakeholders, geo-politics and the environmental constraints of that basin. There is a particular need to focus attention to non-structural approaches, since the addition of traditional (*infra-*)structural approaches are often costly providing only small increments in water yield.

The range of non-structural approaches varies enormously, but often integrate a variety of solutions from implementing alternative engineering approaches, new river modelling techniques, water conservation & water demand management to inclusive social interaction and formalised adaptation strategies. However all these require that water resource managers become more familiar with the emergent physical properties of a river basin and knowledge of its inherent uncertainties, and thereto integrate this into their decision-making frameworks.

The Incomati River Basin is extremely important as a water resource shared between South Africa, Swaziland and Mozambique and it too is a rapidly closing river basin. In South Africa, the Inkomati catchment forms a Water Management Area (WMA) with the country's first Catchment Management Agency, the Inkomati Catchment Management Agency (ICMA). The ICMA applied the non-structural framework of Strategic Adaptive Management (SAM) as its *modus operandi.* The cornerstone of SAM is to generate management decisions that take cognizance of a systems variability, and that are reached through consensus which is strategic, adaptive to change and also creative. This is to provide a partnership in the management of the resource that is inclusive of both science and society (Rogers et al., 2000). The ICMA applies SAM at the water resources management level, but also utilises its principles at the level of governance and oversight and thus, requires information systems that are reflective and applicable to this approach.

Two major limitations to this goal were identified:

1. The hydrological basis for the development of the proposed RISKOMAN tools at the scale of the Inkomati Basin is inadequate.
2. There is a need to develop and, through an interactive social learning process aligned with SAM, embed a catchment level information utility in the tools of the decisions maker.

Thus the aims of this project were:

1. To improve the hydrological basis for the development of decision support tools that will assist the ICMA to achieve its mandate at the scale of the Incomati Basin.
2. To develop through an interactive social learning process a tool for the decision maker in the ICMA that facilitates both their everyday operations as well as the governance

requirements (oversight). Specifically the utility is intended to be used by members of the Board of the South African Inkomati CMA, in order for them to engage with information specifically tailored to suit their decision making needs.

Three key points provided by the project Reference Group directed the project into its final form. These were that the proposed RISKOMAN tools should:

- **NOT** be aimed specifically at the ICMA Governing Board in a way that by-passes the managers (decision-makers/Executive), but rather should be aimed at **information bridging** between these two groups within the ICMA, so that governing board members who represent a wide group of stakeholder interests whose disciplinary understanding of water resources management may be limited, may be more fully acquainted with the decision-making actions of the ICMA managing executive, and vice-versa.
- Not replicate decision-support and modelling tools already in place in the Incomati, rather the RISKOMAN tools should find synergy between the tools already acquired or in development by the ICMA and other projects.
- Include remote sensing aspects and improved hydrological understanding which could provide data and information to wide a range of existing initiatives including the information systems in use by the ICMA.

1. Improved Hydrological Understanding

i. Through hydrochemistry

Hydrochemical analysis of the Incomati basin conducted through spatial snapshots were used to characterize dry and wet season basin hydrology between 2011 and 2013. This revealed that distinct trends could be observed in river basin profiles with increasing concentrations of the analysed parameters from upstream to downstream. The Crocodile and Komati sub-catchments of the basin had higher EC (average 278±105 and 131±65 μS/cm, respectively) than compared to the Sabie-Sand (average 63±19 μS/cm). In terms of stable isotopes δ^2H showed an increase from -14‰ in the headwaters to -4‰ downstream particularly along the Crocodile and Sabie rivers during high flows. δ^{18}O had smaller variations (-2.9±0.9‰), but also tended to be slightly higher downstream in the Crocodile. In both high and low flow seasons the Komati waters were more enriched in heavy isotopes than the Crocodile, suggesting a greater evaporative enrichment from irrigation return flows and storage. The Sabie appears to also have the most isotopically depleted waters suggesting that evaporative enrichment as a result of land-use activities in this catchment is of low significance.

ii. Through Earth Observation/Remote Sensing

New earth observation technologies can now provide the water resources manager with new catchment information as well as augment and improve key parameters used in hydrological modelling. Particular satellite-based datasets providing spatio-temporal information on evapotranspiration, rainfall and soil moisture were assessed in terms of their incorporation into hydrological modelling. This is significant because these datasets have the potential to fill many gaps in the deteriorating ground-based observation and gauging networks.

Evapotranspiration (ETa) estimates from the energy balance models SEBS showed reasonable potential to be used as a data source for land-use information and modelling. This was determined by comparison with ground-based Surface Renewal measurements in sugarcane at Komatipoort in the Inkomati basin. SEBS estimates were able to follow similar trends and capture the seasonal differences in ETa. SEBS performed best in seasons where water is less limited such that the average daily relative volume error between ground-based measures and SEBS estimates for December 2011-January 2012 was <16%, whilst February 2012 was < 21%. Poor relationships in certain time periods indicate the need to further investigate the application of SEBS in South African catchments.

The Advanced Microwave Scanning Radiometer (AMSR-E), Soil Moisture and Ocean Salinity (SMOS), Essential Climate Variable (ECV) and the SAHG land surface model were compared and evaluated against ground-based measurements at Craigieburn and White River in the Inkomati Catchment. Results demonstrated that the satellite-based products captured the variations of soil moisture according to season and depth. In particular the SAHG product estimates are most reliable for soil moisture in the wetter months (10-32% error in January and 5-10% error in October), however they do underestimate when rainfall is limited in the winter months (55-60% error in July). Meanhwile ECV data showed 45-55% error in January, 30 to 60% in July and -5 to 30% in October. The AMSR-E data showed 20 to 55% error in January, 18 to 24% in July and 20 to 32% in October. The SMOS consistently underestimated the soil moisture with large percent errors ranging from 40 to 90% in January, 60 to 96% in July and 1 to 41% in October. However, more research is required at broader time scales to assess the validity of using satellite-based soil moisture estimation in hydrological modelling.

Satellite rainfall estimates using the TRMM and FEWS products were tested for performance by pioneering their integration with the ACRU model. Both these products generally under-estimated rainfall when compared to gauges, the FEWS dataset underestimated the most. As a result model simulations indicated that the streamflows produced from TRMM rainfall correlated (R^2=0.55) much better to the gauged streamflow in Quinary X23C (Kaap sub-catchment), than with the FEWS inputs (R^2=0.34). The processing and incorporation of satellite datasets into hydrological models did prove challenging however and this is presently a limitation in capacity and processing terms, for bringing such open-source satellite information into operational water resources management tools.

2. Tools for the Decision Maker

It was recognised early on during the study that whilst a tool may be developed to provision information to assist water resource governance, it should also build on the operational tools emerging from the ICMA. To this end the project built on the emerging working frameworks that allow SAM to be practiced in terms of operational water resources management (OWRM) with respect to river management and stakeholder interaction. Thereafter a formal framework for a tool was developed that couples the information needs, and aspirations or, the water management discourse at the managerial level with the broader *vision* for the Inkomati Water Management Area (WMA). This was achieved by placing the principles upon which the ICMA developed its Catchment Management Strategy (CMS) and merging these with its Strategic Objectives that guide the ICMA's business function.

The end result is a platform that should allow a clear transmission of information from managers to governing board members and vice-versa in a way that is dynamic, flexible and reflexive such that it embodies SAM, but at the same time can be used operationally as a reporting or self-auditing tool for the ICMA to use. The final form of this framework was developed into a prototype web-based geographic platform, called the Adaptive Operational Governance Dashboard (AOGD). This is a hierarchical information system, which at first point of entry displays key visual indicators using a traffic light system. The indicators are based on STEEP[1] criteria toward which the *vision* of the Inkomati WMA should be achieved moving forward.

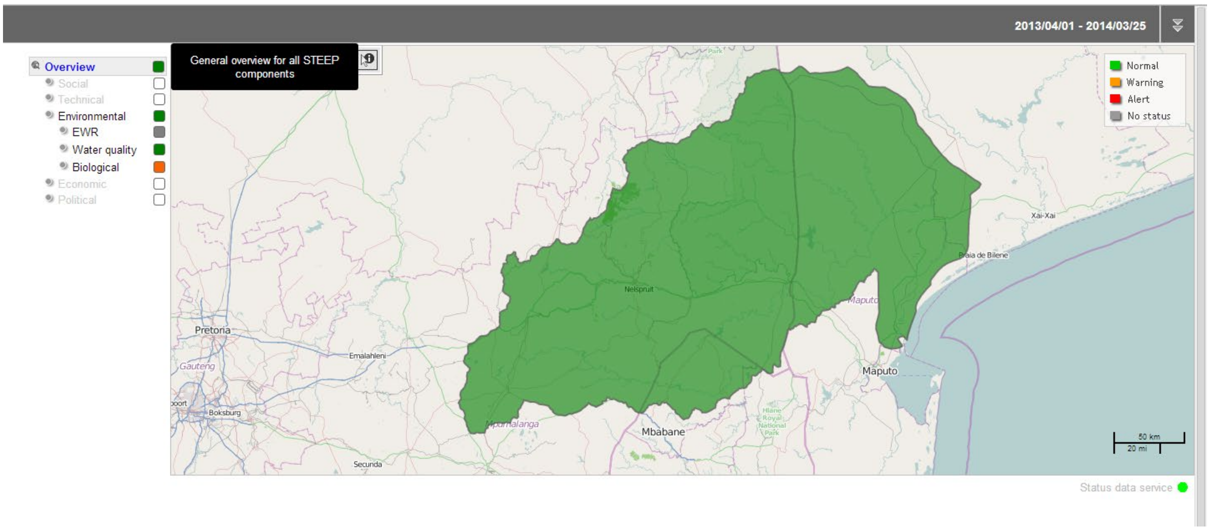

Figure i: The AOGD for the Inkomati Water Management Area using the STEEP framework

The AOGD is described with a conceptual background and technical description. It is intended that with continued investment by both the ICMA, funders and informatics service providers that the AOGD will assist the transfer of SAM principles from one term of office of each governing board to the next, and furthermore will provide useful context and a practical utility for emerging CMAs in the country.

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[1] Social, Technical, Environmental, Economic, Political

ACKNOWLEDGEMENTS

The research in this solicited project was initiated, managed and funded by the Water Research Commission, for whose assistance we are sincerely grateful. The project would also not have been possible had it not been for the logistical and operational support of the Inkomati Catchment Management Agency (ICMA) and the Komati Basin Water Authority (KOBWA).

The project team is also extremely grateful to the financial support provided by Waterschap Groot Salland, The Netherlands to the development of the Operational Governance Dashboard Prototype, and also to HydroLogic, The Netherlands for the software engineering support to that prototype.

We are pleased to have worked in close partnership with colleagues from UNESCO Institute of Higher Education (UNESCO-IHE) on this project, in particular Prof P van der Zaag, Prof S Uhlenbrook, and Dr I Masih. The Project team appreciates the valuable guidance of the following reference committee members:

Ms E Karar (Chairperson)	Water Research Commission
Mr W Nomquphu	Water Research Commission (Acting Chairperson for the first and fourth meeting)
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ACRONYMS

ACRU	Agricultural Catchments Research Unit
AMSR-E	Advanced Microwave Scanning Radiometer
AOWRMF	Adaptive Operational Water Resources Management Framework
CIU	Catchment Information Utility
CMS	Catchment Management Strategy
CROCOC	Crocodile River Operations Committee
DSS	Decision Support System
DWA	Department of Water Affairs
ECV	Essential Climate Variable
ET	Evapotranspiration
EWR	Environmental Water Requirement
FEWS	Famine Early Warning System
ICMA	Inkomati Catchment Management Agency
IWRM	Integrated Water Resources Management
KNP	Kruger National Park
KOBWA	Komati Basin Water Authority
M.ASL	Metres above sea level
MANCO	Management Committee
MAP	Mean Annual Precipitation
NWA	National Water Act
OWRM	Operational Water Resources Management
SAM	Strategic Adaptive Management
SEBS	Surface Energy Balance System
SM	Soil Moisture
SMOS	Soil Moisture and Ocean Salinity
STEEP	Social, Technical, Environmental, Economic, Political (values)
TRMM	Tropical Rainfall Measuring Mission
WRC	Water Research Commission
WUA	Water User Association

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1. INTRODUCTION: SETTING THE SCENE

The Incomati[2] River Basin is extremely important as a water resource shared between South Africa, Swaziland and Mozambique. In South Africa, the Inkomati catchment forms a Water Management Area (WMA) and the legislated movement towards Catchment Management Agencies (CMA) is most advanced in this WMA. The Inkomati Catchment Management Agency (ICMA) was "operationalised" in September 2005.

In July 2008, an interdisciplinary research project partnered by UNESCO-IHE Institute for Water Education (Delft, The Netherlands), Eduardo Mondlane University, University of KwaZulu-Natal and the Komati Basin Water Authority was approved for funding by the UNESCO-IHE Partnership Research Fund (UPaRF), The title of the project was "*Risk-based operational water management for the Incomati River Basin (RISKOMAN)*", with a focus on the operational water management across the three nation states. This project was then supplemented with support from the Water Research Commission (WRC) under project K5/1935 with a primary focus of the South African portion of the basin, working closely with the ICMA.

1.1. The RISKOMAN Project

In heavily committed basins with many different water use(r)s located in different riparian countries strong interdependencies exist, whereby water allocation decisions have important economic, social, environmental and political consequences. Decision-making and decision support tools consider difficult trade-offs, and are frequently based on optimising an economic objective function subject to constraints representing, among other things, hydrological processes. Large variability of rainfall, both within and between years, leads to even larger variations in river flow and adds uncertainty to the water allocation equation.

The stated aim of the RISKOMAN research was to assist water managers and stakeholders in identifying, implementing and continuously adjusting efficient allocation policies in a dynamic and uncertain hydrologic environment. This was to be achieved through the development of an innovative policy support system which integrates the **physical**, **social** and **economical** dimensions of the allocation problem while explicitly investigating the hydrologic and climate uncertainties. This policy support system is intended to improve the quality of information upon which managers can develop hedging strategies in order to reduce the risk exposure of the various water users.

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[2] Incomati – spelt with a 'c' rather than a 'k' to represent the whole Incomati basin to incorporate broader interaction with stakeholders in Mozambique, Swaziland as well as South Africa.

The Water Research Commission identified an opportunity for collaboration with this project and committed funding to address two major gaps in the originally proposed RISKOMAN, i.e.

1. To develop and, through an interactive social learning process, embed a catchment level information utility (CIU) in the tools of the decisions maker. This was to be specifically targeted at members of the Governing Board of the South African Inkomati CMA, in order for them to be able to engage with information specifically tailored to suit their decision making processes.

2. To improve the hydrological basis for the development of the proposed RISKOMAN tools at the scale of the Incomati Basin. The basis for this was to provide key sources of spatial information and interpretation for decision makers. Over the past decade, improved Earth Observation and allied spatial methodologies have matured as utilities which are extremely useful in basin level decision making. Key contributions to the current state of knowledge as regards best practice in applying hydrological understanding in river and basin management would be the development of tools in which direct estimates of precipitation, evaporative water use (often termed "green water"), soil moisture and catchment topography through remote sensing and their consideration in the water resources planning process.

This was initiated through the erstwhile School of Bioresources Engineering and Environmental Hydrology and later Centre for Water Resources Research at University of KwaZulu-Natal which was awarded a project, i.e. K5/1935 – A Management Tool For The Inkomati Basin With Focus On Improved Hydrological Understanding For Risk-Based Operational Water Management: Whilst the overall approach was generally accepted by the inaugural project steering committee for K5/1935 in November 2010 at the Komati Basin Water Authority (KOBWA) offices at Driekoppies Dam. There were three key points of consensus from the steering committee that directed the project into its final form. These were that the proposed RISKOMAN tools should:

- **NOT** be aimed specifically at the ICMA Governing Board in a way that by-passes the managers (decision-makers/Executive), but rather should be aimed at **information bridging** between these two groups within the ICMA, so that governing board members who represent a wide group of stakeholder interests and whose disciplinary understanding of water resources management may be limited, may be more fully acquainted with the decision-making actions of the ICMA managing executive, and vice-versa.
- Not replicate decision-support and modelling tools already in place in the Incomati, rather the RISKOMAN tools should find synergy between the tools already acquired or in development by the ICMA and other projects.
- Include remote sensing aspects and improved hydrological understanding which could provide data and information to wide a range of existing initiatives including the information systems in use by the ICMA.

1.2. RISKOMAN – WRC and UNESCO-IHE partnership: identification of roles and outputs

1.2.1. Alignment of objectives

The interaction of the RISKOMAN research partners, the University of KwaZulu-Natal (Water Research Commission) and UNESCO-IHE (UPaRF) following the first steering committee meeting required that a joint concept statement be developed for the project, as follows:

'The establishment of an improved hydrological understanding of the Incomati Basin, with the identification of variability in the systems hydrological and managerial drivers. Through this, the project will determine the present and future decision making requirements for optimal management of the basin's water resources given devolved responsibilities in the RSA. Furthermore the project will use these findings to integrate with the transboundary water sharing initiatives between RSA, Mozambique and Swaziland. These objectives will be achieved through:

i. Identification of hydrological information requirements to the water resource managers in the basin, such as the ICMA and other parties.
ii. Contributing to an improved hydrological understanding of the Incomati Basin, through a focus on the identification of variability in the systems hydrological and managerial drivers.
iii. Establish tools in support of water resources decision making which are geographically explicit, effective, robust and user-friendly and transferable to other catchments, i.e. a catchment information utility.

Subthemes are:

- Given devolved responsibilities for water resources management being passed on from central government in the Incomati, the project will identify the present and future decision making requirements for optimal management of the basin's water resources in a multi-lateral management setting.
- How can short term forecasting of key hydrological drivers improve decision making?
- Identify key knowledge gaps in the management of the systems water resources and address those within the scope of the project team.

Specific outcomes include the absolute quantifications of water demands in the system, such as actual land-use based water uses and losses, rather than relying on estimates, using new innovative technologies (e.g. Earth Observation & Remote Sensing, hydrochemistry), and the development of innovative ways that these can be used in scientifically and politically justifiable water allocation policies, through temporally variable forecasting (e.g. weeks to months) and economic trade-offs (and associated policy instruments), in order to manage the system in the most optimal fashion (e.g. STEEP[3] & SAM[4]) i.e. in such a way that water users are able to maintain an acceptable assurance of supply under hydrological and climatic variability and change (i.e. Risk).'

Figure 1.1 displays schematically the focus areas of research by collaborators within the RISKOMAN project. Further details on the UNESCO-IHE components may be found at http://www.unesco-ihe.org/RISKOMAN, and abstracts of completed research reports in Appendix I of this report.

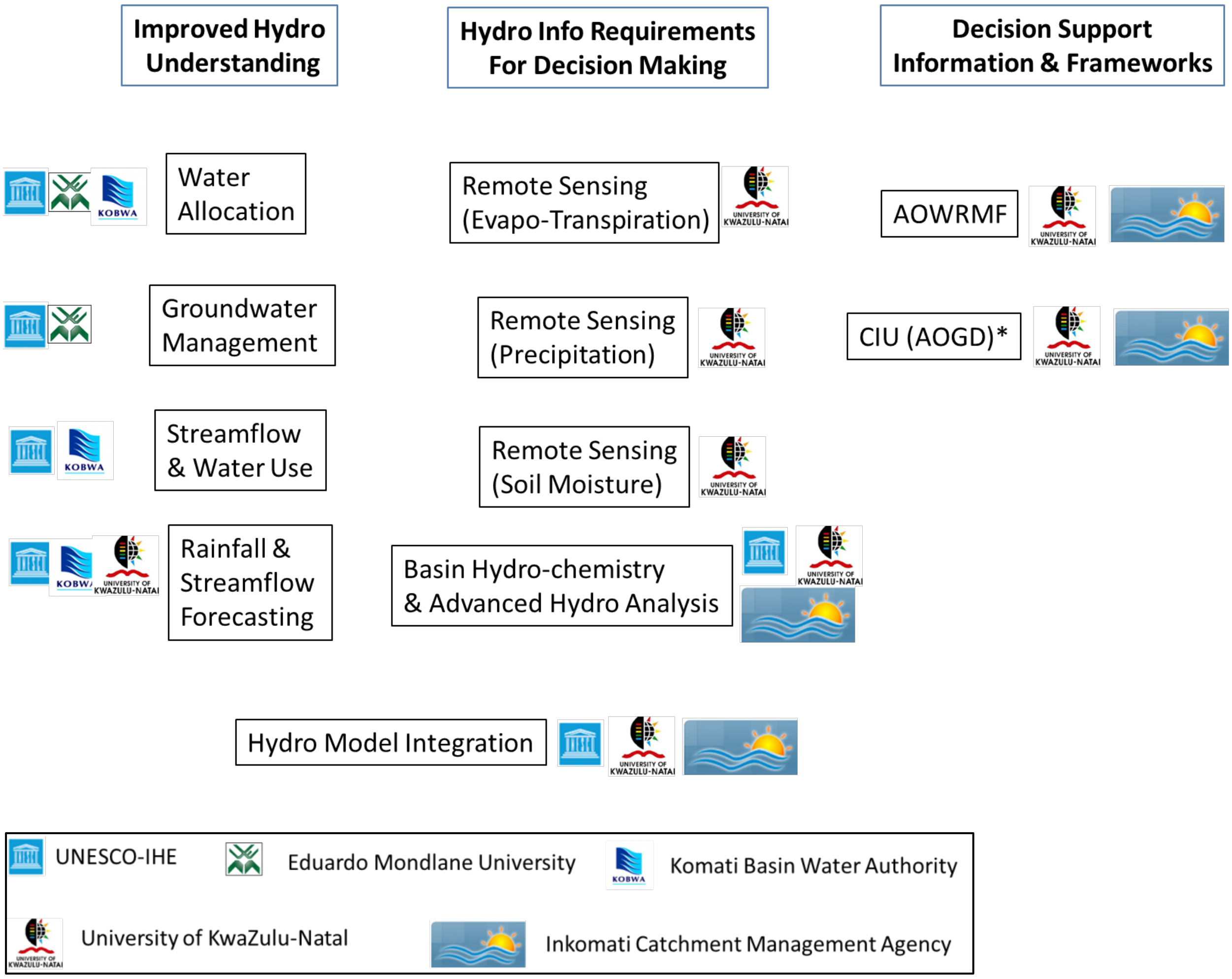

Figure 1.1: Overview of roles and partnerships in the RISKOMAN Project (*The development of the CIU was augmented with significant inputs from DHI-South Africa, HydroLogic and Waterschap Groot Salland (The Netherlands)). Over time, the CIU has become known as the

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[3] STEEP – Social, Technical, Environmental, Economic and Political factors that influence the IWRM status-quo

[4] SAM – Strategic Adaptive Management

Adaptive Operational Governance Dashboard (AOGD) and is referred to as such throughout this report.

The products emanating from project K5/1935 (as in Figure 1.1) are as follows:

1. Hydrological information requirements for decision-making

Remote sensing (RS) products have developed significantly in recent years to the point that many products have both high spatial and temporal resolution, and often these are also open-source. Thus, the study focused on the comparison, evaluation and application of open source RS products of rainfall, evapotranspiration (ET) and soil moisture as potential sources of hydrological information and data for use in operational water resource management in the Inkomati catchment. In addition spatial hydro-chemical techniques have also developed to the point that they can be implement in operational water management from the perspective of identifying the sources and pathways of water in a basin, to assessing anthropogenic impacts on the resource and to calibrate existing water resource management models.

- Remote Sensing: Evapotranspiration:
  The Surface Energy Balance System (SEBS) model was used to generate daily actual ET estimates in the Inkomati catchment. The actual ET estimates generated by SEBS were compared against observed historical daily actual ET estimates for an irrigated sugarcane field situated in Komatipoort. The surface renewal technique was used to obtain the historical daily actual ET estimates.

- Remote Sensing: Precipitation:
  A comparison and evaluation of the Tropical Rainfall Measuring Mission (TRMM) and Famine Early Warning System (FEWS) rainfall satellite products was undertaken in the Kaap sub-catchment of the Inkomati catchment

- Remote Sensing: Soil Moisture:
  The Advanced Microwave Scanning Radiometer (AMSR-E), Soil Moisture and Ocean Salinity (SMOS), Essential Climate Variable (ECV) and SAHG land surface model were acquired, processed and then compared and evaluated against ground-based measurements at selected research catchments in the Inkomati Catchment.

- Basin Hydro-chemistry
  Hydro-chemical analysis using conservative tracers (Stable Isotopes) and a variety of water quality parameters were used to improve the hydrological processes understanding of the Incomati river basin to inform for better water management and planning. The products allowed for a spatio-temporal isotopic profile of rivers of Incomati and insights into main hydrological and dominating runoff generation processes.

2. Decision Support Information and Frameworks

- An Adaptive Operational Water Resources Management Framework (AOWRMF):

  Recognising the need for an integrated approach to water resources management and that river catchments are complex STEEP (Social, Technological, Economic, Environmental, Political) systems. This aspect developed the metrics to test the performance of an adaptive and operational framework that had been established for operational river management on the Crocodile River. One outcome was the establishment of the Crocodile River Operations Committee (CROCOC) which allowed for managers, stakeholders and researchers to engage in consensus-driven decision-making and cooperative action towards shared objectives in river operations, in a catchment bound by international flow regulation treaties and a significant environmental lobby. This used Strategic Adaptive Management (SAM) as a guiding framework. This was assessed against the progressive implementation of the ecological reserve for the lower reaches of the Crocodile River in the Inkomati basin.

- An Adaptive Operational Governance Dashboard (AOGD):

  Building upon the development of operational water resource management tools and decision support frameworks, the ICMA is also an institution that adopts SAM into its' water resources governance philosophy (see ICMA, 2010). The AOGD has the explicit aim of engendering a transparent and mutually informative exchange between the ICMA's managing executive and governing board, in order to truly effect both Adaptive and Operational[5] Governance decision making and intuition. The research in this report translates the conceptual approach developed through this project into a working generic geographic dashboard (web-based) prototype that can be installed at the ICMA and, with further development, also be used at other CMAs in the future.

The AOWRMF is a framework that has evolved following significant investment by various individuals and institutions (as acknowledged by the author of section 3.1) prior to, and during, project K5/1935. Notably the drawing together of diverse facets of the AOWRMF's development and deriving a metric to assess its implementation was required. This is in order to provide a coherent conceptual framework that is both grounded in science and

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[5] Operational Governance is the application of Corporate Governance in practice. Corporate Governance refers broadly to the rules, processes, or laws by which business is operated, regulated and controlled. The application of this in practice should enable effective implementation of the legislative mandate of the institution without hindering that implementation. Operational governance thus refers to the interface between the governance and the operations or implementation of the functions of the institution to enable effective implementation of the legal mandates and function within the legislative environment.

management but importantly also provides a distinct example of progressive and now formalized practice that the ICMA has developed in recent years. This represents a clear product at an operational level that can link to the governance-oversight functions expressed in the form of an AOGD in section 3.2.

1.3. Structure of the Report

The remainder of Section 1 gives an overview of the Inkomati Water Management Area (Chapter 1.2), institutional set-up of the Inkomati Catchment Management Agency (Chapter 1.3), and the anticipated need for catchment information utilities at the ICMA (Chapter 1.4). Thereafter the report is divided into two sections:

- Section 2 gives a summary of the detailed research into hydrological processes understanding of the Inkomati river basin through hydrochemistry (Chapter 2.1) and remote sensing (Chapter 2.2). (The detailed results of both of these are found in reports 1 and 2 in the accompanying CD).

- Section 3 then gives the detail related to decision-support tool frameworks that emanated from the project. The first of these is a decision-support framework implemented for river operations in the Crocodile River through consensus-based approaches, to formalize adaptive operations (Chapter 3.1). The second describes the conceptual framework and prototype development of a catchment-based tool to facilitate adaptive-operational governance within the ICMA (Chapter 3.2).

1.4. Inkomati Water Management Area and ICMA overview

1.4.1. Location of the Inkomati

The Incomati River Basin is located in the eastern region of southern Africa (Figure 1.2) and has a catchment area of 46,800 km^2. In the north-east of South Africa its headwaters lie in the south-western highveld/western Transvaal plateau area of Mpumalanga province at some 2000 m above sea level. The Komati River, as it is known in that region, then flows into northern-western Swaziland where it descends rapidly down from the Great Escarpment through to the middleveld (above 600 m.asl) and into the lowveld and re-enters RSA in the south-east of Mpumalanga at Swaziland’s northern border at some 200 m above sea level. Thereafter the Komati is joined by a significant tributary, the Lomati at which point it is still known as the Komati and flows in a north-easterly direction. Adjacent to the town of Komatipoort the Komati is fed by a major tributary from the west, the Crocodile River, becoming the Inkomati before flowing across the Lebombo mountains and into Mozambique where it is joined by the Sabie River from the north and is thereafter known as the Incomati River. The Incomati River then follows a “horse-shoe” course across the coastal plain and flows into the Indian Ocean a short distance north of Maputo. The Incomati also contains three significant ephemeral tributaries, i.e. the Massintonto and Uanetze that rise in the semi-arid plains of the Kruger National Park, and the Mazimechope, all of which join the main stem as the river flows through southern Mozambique. Respective catchment areas for the three countries within the Incomati are 61.4%, 33.2% and 5.4% for South Africa, Mozambique and Swaziland.

In South Africa the basin is managed as a Water Management Area (WMA) called the Inkomati WMA, the operational area of which is effectively the national primary drainage region, X.

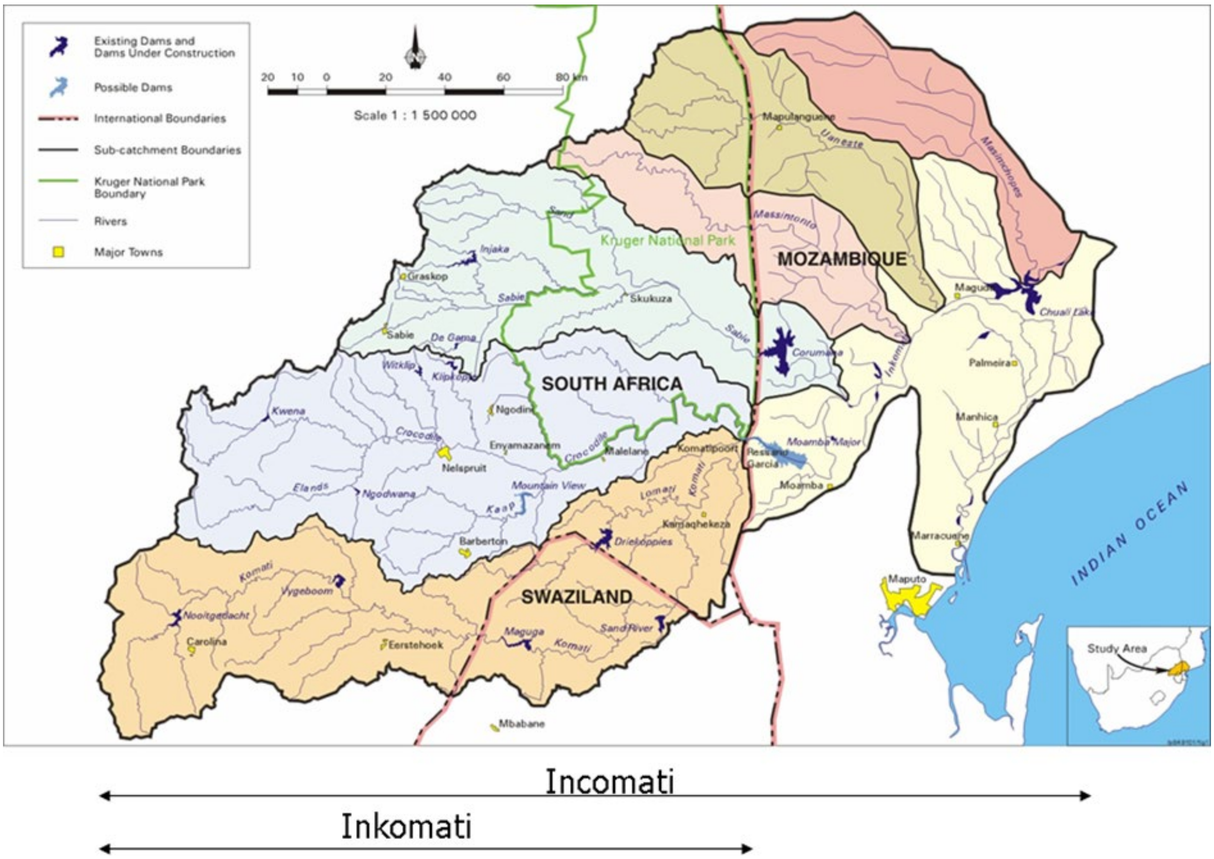

Figure 1.2: The Inkomati Water Management Area within the Incomati basin (adapted from, JIBS, 2001)

1.4.2. Climate

The Incomati catchment is situated within the sub-tropics and lies within the summer rainfall region of southern Africa (October-March). The weather patterns are governed by the seasonal shift in the South Indian Anticyclone, part of a subtropical anticyclone belt centered on 30°S, bringing with it moist air from the south-east (Ross et al., 2001). The Incomati basin as a whole has an average rainfall of 740 mm.a^{-1} (Sengo et al., 2005) and is characterized by mesic rainfalls in the high altitude western region with a Mean Annual Precipitation (MAP) between 800-1000 mm.a^{-1}. Along the escarpment area this MAP can reach up to 1400-1800 mm.a^{-1} and then drops rapidly as one moves further east away from the escarpment down to as little as 300-400 mm on the western side of the Lebombo range. Tropical cyclones emanating from the Mozambique channel frequently cause flooding in the Incomati basin between January and March.

Temperatures vary greatly between the hot humid summers and mild winters where the mean annual temperature is 17°C, whilst the hottest month of January averages 21°C and the coldest month of June averages 11.5°C. Frosts do occur during winter months within the South African part of the basin, except for the extreme east of the catchment.

Catchment average potential evaporation is some 1900 $mm.a^{-1}$ and decreases from east to west, which results in an increase in the water deficit from west to east and consequent irrigation demand in that direction also (Sengo et al., 2005).

1.4.3. Population & Land-use

The Inkomati WMA of the RSA had a population during 2007 of 2.2 million, being approximately around 4.5% of the national population (ICMA, 2010) of which 33%, 31% and 36% live in the Komati, Crocodile and Sabie-Sand sub-catchments respectively. Of these, the Crocodile sub-catchment has the largest urban population. For the total WMA, 67% of the population is classed as rural, although due to the increase in the provision of services since 2007. A large proportion of this rural population may now be classed as urban (ICMA, 2010) since the bulk of these areas are former homeland areas containing dense peri-urban dwellings. The Bushbuckridge area of the Sabie-Sand sub-catchment has one of the highest population densities in the South Africa (ICMA, 2010). The large population of the Inkomati WMA also means that there is a high domestic water use demand as well as other competing demands for water allocation.

Apart from the large conservation areas that include the Kruger National Park (KNP), the Inkomati WMA has a significant proportion of forestry in the central escarpment region and a small but significant area of irrigated sugarcane and fruit in the eastern regions of the Crocodile and Komati sub-catchments. There are also large extents of subsistence farming and residential areas in the east that form the former homeland areas in the basin. The Inkomati WMA has many commercial farmers but also has the largest number of previously disadvantaged and emerging farmers in the country (ICMA, 2010).

The main water intensive industries in the Inkomati WMA include: paper and pulp production; sugar mills; and ferrochrome smelting. There are also various industries linked to municipal water use.

1.4.4. Catchment Infrastructure

The Incomati basin has a large variety of water related infrastructure developments including over 90 dams with a supply capacity greater than 50000 m^3. The main dams being: Maguga dam (in Swaziland), Driekoppies, Nooitgedacht, Vygeboom in the Komati sub-basin; Kwena dam in the Crocodile sub-basin; and Inyaka dam, and Corumana (in Mozambique) in the Sabie-Sand sub-basin.

1.4.5. Economy

The economy of the Inkomati WMA is quite varied and it is estimated that the catchment alone contributes 1.3% of RSAs gross domestic product, which is significant given that it is one of the smaller WMAs in the country (DWAF, 2003b). The largest economic sectors (in 1997) in this WMA in terms of GDP, were: Manufacturing (24.6%); Agriculture (18.6%); Government (6.4%); and Trade (13.4%). Although it is classed as a secondary sector tourism also has a significant contribution to local GDP.

(Further details are found in report 1 in the accompanying CD)

1.4.6. The Inkomati Catchment Management Agency (ICMA)

The 1998 NWA required the implementation of devolved management and distribution of water to the benefit of all in the RSA. Through this measure it was proposed that water management powers be progressively transferred to Catchment Management Agencies (CMA) from the central water management authority at the time, the Department of Water Affairs and Forestry (DWAF, now DWA). The framework for this approach was to establish these institutions around the large, 'primary' catchments in the country, at that time there were 19 (now 9), including the X primary drainage region of the Inkomati.

The Inkomati CMA[6] (ICMA) was the first CMA established in the Republic of South Africa (March 2004), the founding principles of which are (ICMA, 2009):

Sustainability
In order to ensure ecological and socio-economic sustainability for the future of the nation, water resources have to be carefully managed.

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[6] ICMA is defined as a schedule 3 (a) public entity in accordance with the Public Finance Management Act No 29 of 1999.

Equity

Ensuring that water is equally distributed to all citizens of RSA beginning with those that were historically denied of this basic human need while taking into account the needs of neighbouring countries sharing the same rivers with us.

Efficiency

Ensuring that the national scarce commodity of water is allocated to a broad effective use in order to support a diverse, robust and stable economy.

In terms of the NWA each CMA would have initial functions:

- To investigate and advise on the protection, use, development, conservation, management and control of the water resources in its water management area.
- To develop a catchment management strategy (CMS).
- To co-ordinate the activities of water users and water management institutions within its water management area.
- To promote co-ordination between implementation of its CMS with the implementation of water services development plans by water services authorities
- To promote community participation in the protection, use, development, conservation, management, and control of water resources in its water management area.

Central to the on-going direction and successful implementation of these functions is achieving the desired future state for 'Water for all in the Inkomati' (ICMA, 2008). By achieving this vision the ICMA strives for seven outcomes as set-out in its mission statement, to:

- manage water according to the NWA
- manage all water uses to promote equity and efficiency
- protect the water resources to support biodiversity and local use by communities
- involve stakeholders in water resource decision making
- facilitate co-operation between water related institutions to promote political credibility within the Inkomati WMA
- Contribute towards social and economic development in the WMA
- Support the cooperative management of the Inkomati basin as an internationally shared watercourse

In order to deal with extreme complexities of IWRM in the Inkomati WMA the ICMA manages the catchment according to the principles of Strategic Adaptive Management, or SAM (Rogers et al., 2000). In summary, the requirements of SAM are that management of the environmental resource, which in this case happens to be water, has to be adaptive in order to be able to account for variations in the state of the resource. The most obvious causes for these state changes are climatic changes, but more broadly can also include social, technical, environmental, economic and political changes, these are generally termed STEEP factors. Given the complexities that are associated with managing in an uncertain STEEP environment, requires ways to deal with changing circumstances in a way that incorporates (Biggs, as cited in Pollard et al., 2008):

- getting as many people as possible thinking holistically about the system and events (biophysical, socio-economic and institutional)
- scenario-based planning (aided by mathematical and computer-based simulation) can help one plan and account for random events
- be prudent when making decisions ensuring that there are buffers to absorb surprises
- employ adaptive management which seeks a 'learn-by-doing' so direction can be adapted as new information becomes available
- recognize that in complex systems there are a number of ways to arrive at the same end-point

Moreover SAM incorporates this thinking by generating management decisions that are reached through consensus which is strategic, adaptive and also creative, so that a there is a partnership in the management of the resource that is inclusive of science and society (Rogers et al., 2000).

Based on these concepts the ICMA has developed 5 strategic objectives (Box 1.1). The ICMA incorporates these objectives into its collective thinking, i.e. to constantly improve their understanding of the Inkomati catchment, and fulfil its social obligations by way of achieving the shared vision for a desired future state of the catchment. The aforementioned STEEP factors are the principle assessment by which this vision is meant to be achieved and the cornerstones of the ICMA's Catchment Management Strategy (CMS). This is discussed in greater depth in Section 1.5 and Section 3.

Box 1.1: The ICMA's 5 Strategic Objectives (ICMA, 2010)

- adaptively develop/implement participative systems for authorization, compliance, monitoring and enforcement that aim to balance resource use and protection in ways that ensure reform and promote socio-economic development
- adaptively stimulate/develop/implement co-operative governance that promotes co-ordination of river operating systems, spatial planning and development to protect the resource and catchment
- set and pursue the agenda for international negotiations that reflect local conditions/needs
- become an internationally recognized hub for participative IRWM by adaptively coordinating, generating and distributing data, knowledge and, skills and management systems
- adaptively develop/implement institutional structures and services within the ICMA to create an enabling environment that supports achievement of the above objectives as they aim to meet changing circumstances.

The ICMA is structured in such a way that there are two tiers one for management and another tier for governance (Figure 1.3). The first tier is that which falls under the CEOs office and includes 4 sub-water resource management divisions plus corporate services. The tier that is governance is achieved through 'co-operative' governance which is seen as being critical to the engagement of a wide variety of sectors who would have previously not interacted, for example white commercial farmers with black emerging farmers (e.g. Colvin et al., 2008). This co-operative governance is achieved through an inclusive governing board and collaborating CEO. Specifically the bringing together of such diverse stakeholder groups to oversee the direction of the ICMA is seen as crucial for participatory engagement at each level in the management hierarchy of the resource and is constitutionally mandatory in RSA. Moreover since the ICMA is the first of its kind in the country the role of an effective and inclusive governing board is seen as being essential to set the trend for the remaining CMAs in the country (ICMA, 2009).

Figure 1.3: Organogramme for structure of the Inkomati CMA, (ICMA, 2014, http://www.inkomaticma.co.za/)

The original governing board of the ICMA had 13 members and the CEO was an ex-officio member as stipulated by the NWA. The members of the first governing board were representatives from:

- Local Government Water Services, SALGA
- Industry, mining and power generation
- Commercial Agriculture

- Office of the Premier, Mpumalanga Province
- Existing Agriculture by Historically Disadvantaged Individuals (HDIs)
- Productive use of water by the poor
- Civil Society – SANGOCO
- Traditional Leaders
- Potential agriculture use by HDIs
- Stream flow reduction (forestry)
- Conservation
- Local Government Integrated Planning, SALGA
- Tourism and Recreation

In addition to the governing board there is also an auditing board which consists of three governing board members and three independent members. Facilitating the governing of the ICMA the board then manifests itself as seven other committees with various representatives from the board, these committees are as follows:

- Chairpersons Working Committee – an operational committee of the governing board
- Finance and Risk Committee
- Remuneration and Human Resources Committee
- Technical Committee
- Water Committee
- Marketing and Communications Committee
- Executive Committee

Whilst it is important to note that the governing board should have a 5 year term of office, the first board remained in office until 2014 beyond its original term of office ending 31 December 2009[7]. The next governing board is to be appointed by The Minister of Water and Environmental Affairs based on an advisory committee for the appointment of governing board members, which was advertised during January 2014. It must also be stated that the Governing Board is, in terms of the Public Finance Management Act (1999) the accounting authority of the ICMA and has to take all decisions of the ICMA. The Governing Board is accountable to The Minister and must submit a proposed strategic plan and budget for the following financial year annually each September (*pers com* Adv Boshoff, J. ICMA Board Secretary July 2010).

Emphasis must also be placed at this point that there was a capacity building program directed at the ICMA Governing Board to familiarize the ICMA's mandate as per the NWA as well as inducting them on their fiduciary duties and responsibilities. This process was facilitated by a partnership with Waterschap Groot-Salland (http://www.wgs.nl/) to capacitate the board in cooperative governance, who also provided support for the development of the AOGD prototype (Section 3) to further this process.

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[7] This was extended from the original 31 May 2008 term of office

1.5. Assessment of CMA needs

Interacting with some of the members of the ICMA's Governing Board and the MANCO during the project helped the team to understand why a catchment information dissemination tool, i.e. the AOGD, might be essential for adaptive decision-making, but also brought to the fore how such a tool will be of benefit to the ICMA. This section summarises the findings of the interactions with the staff at the ICMA and describes the operational governance gaps that the AOGD could fulfil. The views expressed in this part are derived from discussions with the members of the ICMA's Governing Board and MANCO (Further details are found in Reports 4 and 5 in the accompanying CD

1.5.1. Interaction with some of the members of the Governing Board and MANCO of the ICMA

Decision-making and accountability patterns are quite distinctive in the ICMA. At the outset, decision-making takes two different forms. On the one hand, the Governing Board engages in policy decision-making, determines the rules and makes available resources to be used for achieving the mandate of the ICMA. On the other, the MANCO engages in operational decision-making, implements its mandate by utilizing the available resources and functions within the rules established by the Governing Board. The MANCO is in effect accountable to the Governing Board, and the Governing Board to the National Minister for Water and Environmental Affairs.

Given the accountability pattern, it was identified that the role the AOGD could fulfil would be to provide a self-auditing system for the MANCO, whilst at the same time provide a reporting mechanism to the Governing Board. The Governing Board could in turn consider it as a performance monitoring/evaluation tool to assess the functioning of the MANCO. Furthermore it could alleviate the cumbersome process involved in the conventional reporting style that requires one to wade through large reports as the AOGD is also intended to provide information on various facets of catchment management in a geographically relevant platform would also be visually appealing. Additionally, it could, at a glance, highlight the areas that need attention, particularly in relation to vSTEEP criteria upon which the ICMA sets it vision (see section 1.4.6). These criteria would otherwise remain hidden in a normal reporting mechanism.

Through the discussions it became evident that meaningful accountability to the stakeholders occurs through 'informal channels' in the form of catchment management forums. However, due to weak communication and reporting channels within the ICMA, the members of the Governing Board and the ICMA have scarce information about what proceeds in these forums, much to their chagrin. It was therefore proposed that the AOGD could also help bridge this gap by providing information from, and to, these local catchment forums. This information sharing will enable building trust amongst the staff members of the ICMA and between the ICMA and the stakeholders. Dynamic information flows mapped in such a tool could help usher in transparency in the functioning of the ICMA and provide an easier guide for the stakeholders to measure the performance of the ICMA with regard to its mandate derived from the National Water Act (1998). Finally, it was felt that a tool could be used to instantly follow-up to examine whether areas of concern have been adequately addressed, thus engendering resilience in the system (given of course adequate human and technical resources).

1.5.2. Key Benefits of an AOGD to the *vision* of the ICMA

The above discussion has indicated how the AOGD could be of benefit to the ICMA as well as various structures within the ICMA, including its governing board. An attempt is now made to identify at 3 key benefits of the AOGD:

First, the ICMA through its CMS described one of its goals to also be a learning organisation. This was described by (Roux et al., 2010) as a goal to allow an organisation to maintain and improve high standards of service (single-loop thinking), reflecting on core assumptions (double-loop thinking) and the underlying values/paradigms (triple-loop thinking) enables the prioritization of incoming knowledge and doing things differently. It is believed that the AOGD will facilitate this through enabling dynamic information flows through the organisational structure of the ICMA and follow-up actions being undertaken. Thus the AOGD will provide the platform for iterative management and thereby embody fully well the concept of single-, double- and triple-loop thinking and learning for adaptive decision-making.

Second, the background knowledge for such a tool would be locally borne out of the South African experience and encapsulate the stakeholder values (vSTEEP) required for decentralised water resource management. Importantly, the AOGD would also have to be flexible enough in its structure to easily adapt to suit changing demands.

Finally, it is hoped that the generic principles structured within the AOGD – that is, the necessary but not sufficient conditions, could be utilized by existing and potential catchment management agencies in other regions of South Africa, depending on their specific contingencies.

The conceptual development and prototype development of this tool is discussed in detail in section 3.2.

2. IMPROVED HYDROLOGICAL UNDERSTANDING OF THE INCOMATI RIVER BASIN

Providing sound information for water resources management and planning decisions remains a challenge in most southern Africa catchments. The Incomati is no exception. Despite the relatively good data and information available for the Inkomati and some of its tributaries, there are many aspects where improved understanding of the hydrological functioning of the catchment and improved and new sources of catchment data can provide better information to decision makes and planners (Figure 1.1). To this end, the project has incorporated two sub-projects; i.e. i) an attempt to provide better understanding of the hydrological processes which control the movement of water through the catchment, and ii) an investigation of the availability and usefulness of remote sensing sourced estimates of rainfall, evapotranspiration and soil moisture.

2.1. Quantification of hydrological processes through water quality parameters and environmental isotopes

Saraiva Okello, A.M.L., Riddell, E, Uhlenbrook, S., Masih, I, Jewitt, G.P.W. van der Zaag, P. and Lorentz, S.A.

Understanding hydrological processes in a catchment is very important, as these provide information on the primary controls on the water cycle, influencing, water quality and water quantity as well as their spatial and temporal dynamics. The understanding of these processes becomes especially important for the prediction of floods, erosion, and solute and contaminant transport, particularly as hydrological systems often show threshold behaviour. In the context of ongoing and future climate and land use changes, simple statistical methods or models calibrated to the status quo are inadequate for prediction, highlighting the importance of detailed understanding of the processes underlying the observed phenomena. For example, detailed understanding of the runoff generation process is needed in order that the effects of global changes can be better modelled, ultimately leading to more responsible management of natural resources as well as risks. Thus, a good understanding of the hydrology of the basin constitutes the basis for good assessment of current and future water availability in the basin. Many models (JIBS, 2001; Nkomo and Van der Zaag, 2004) have been set-up for hydrological and water resources assessment of the Incomati, but some limitations have been recognized in their representation of hydrological processes, particularly during low flows. Large variability of rainfall, both within and between years, leads to even larger variations in river flow and adds uncertainty to the water allocation process.

This component of the research project aimed to improve the hydrological understanding of the river basin, with the intent to provide improved hydrological input to water resources allocations tools. This was achieved through intensive field work campaigns, application of tracer methods, remote sensing data and hydrologic modelling.

2.1.1. Study Area

The research was conducted over the entire Incomati river basin. Figure 2.1 shows the Incomati river basin, the main sub catchments and location of the sampling points. The geology of the basin comprises sedimentary, volcanic, granitic, and dolomitic rocks, and quaternary and recent deposits. The basin is characterized by a wide variety of natural vegetation types. These vary between beaches and recent dunes, tropical bush and forest, and different types of savannah and grassveld. The entire Incomati river basin lies within the summer (October-March) rainfall region, with a mean annual precipitation of about 740 mm/a, which generally increases from east to west. The highest precipitation occurs in the upper Sabie catchment (around 1200 mm/a). The mean annual potential evaporation for the basin as a whole is about 1900 mm/a, which generally decreases from east to west.

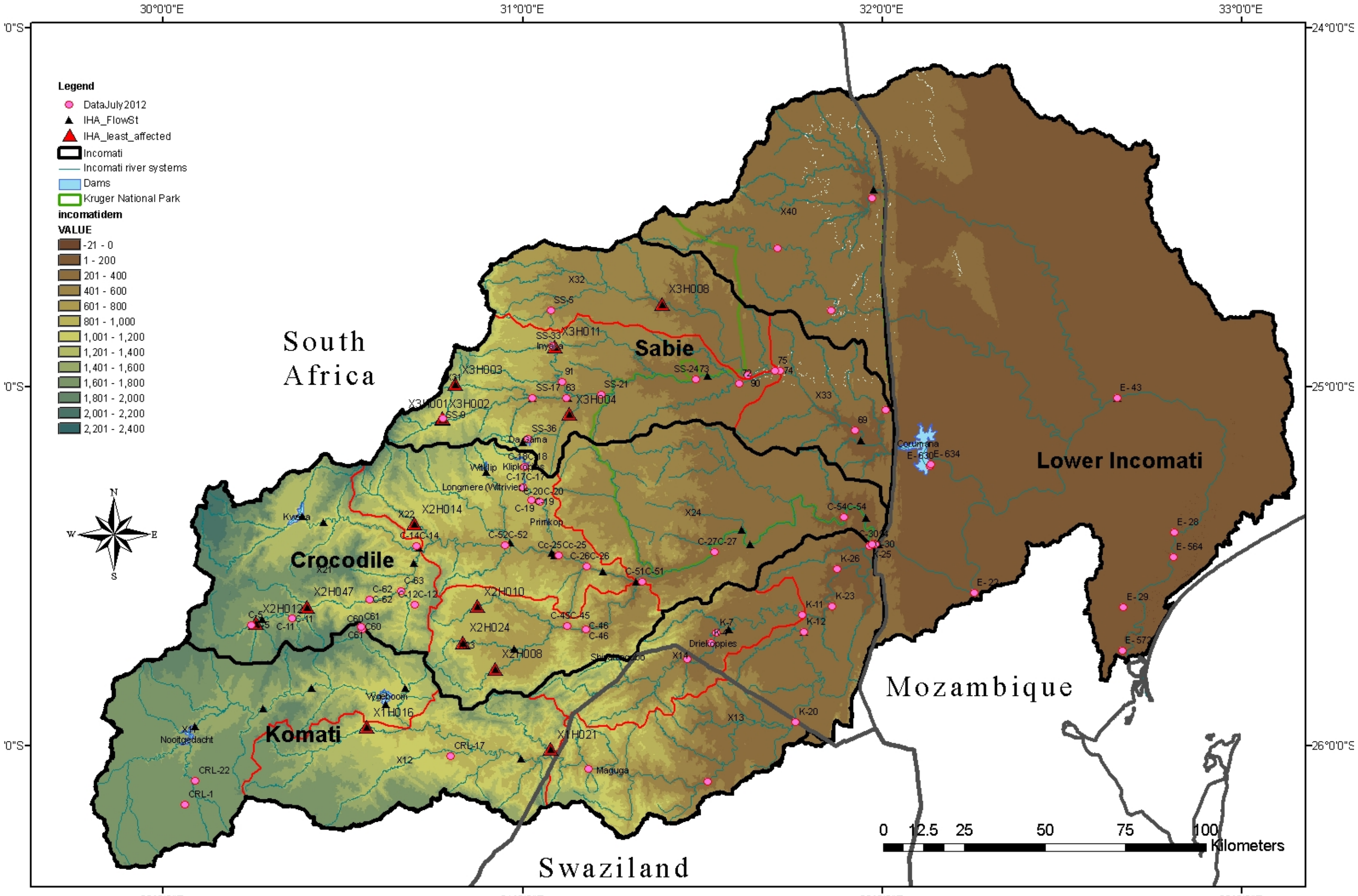


Figure 2.1: The Incomati river basin, main sub-catchments, sampling locations and flow gauges

2.1.1. Methods

2.1.1.1. Spatial snapshot and parameters analysed

Spatial snapshot sampling was conducted in the Incomati river basin at the end of the wet season (February 2011 and 2012) and during stable low flows (July 2011, 2012). From March 2012 to April 2013 sampling of key locations was conducted monthly in conjunction with ICMA and KNP, as part of their monthly regular monitoring programs. From November 2013 an automatic water sampler was installed at the outlet of Kaap sub-catchment, to sample water at finer temporal scale and capture events.

The aim was to develop a hydro-chemical and isotope map of the catchment, in order to identify sources, pathways and response times of components of discharge contributing to upstream water flow. The parameters analysed include:

- EC, Temperature, pH, ORP – measured in situ with Multi-sensor;
- Alkalinity measured in situ by Gran titration method;
- Cations: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} – measured in Chemistry laboratory University of KwaZulu-Natal (UKZN) and at UNESCO-IHE, the Netherlands;
- Anions: HCO_3^-, NO_3^-, SO_4^{2-}, – measured in Chemistry laboratory UKZN and at UNESCO-IHE;
- Oxygen 18 and Deuterium – measured in isotope laboratory UKZN and at UNESCO-IHE.

Sampling locations (see Figure 2.1) were chosen from the water quality database of the Department of Water Affairs (DWA) in South Africa, and based on the water quality study conducted by JIBS (2001). They represent locations close to dams, DWA weirs, and main river confluences. Geology and land use were also considered. Where there was a significant change of geology and/or land uses, a greater number of samples were collected to capture the influence of these.

Tracer methods provide an excellent means of examining hydrological processes, particularly runoff generation processes. The use of natural tracers such as isotopes or geochemical tracers provides valuable information about runoff components and their formation and dynamics at the catchment scale. This means that the entire hydrological system of the catchment can be investigated. Environmental tracers are useful because of their conservative behaviour. Stable water isotopes are natural tracers of water movement. Isotopes ratios of hydrogen (2H) and oxygen (18O) within water molecules themselves are particularly useful, as comparison of stream waters with precipitation can indicate the nature and timing of catchment flow paths (Tetzlaff et al., 2007; Wissmeier and Uhlenbrook, 2007). They can also provide useful information to quantify and understand the partition of evaporation, transpiration and soil water (Yepez et al., 2003). The separation of baseflow from direct runoff in a hydrograph is important to hydrologists, planners, and engineers, as it aids in determining the influence of different hydrologic processes on discharge from the catchment. Because the timing, magnitude, and duration of groundwater return flow differs so greatly from that of direct runoff, separating and understanding the influence of these distinct processes is key to analysing and simulating the likely hydrologic effects of various land use, water use, weather, and climate conditions and changes (Buttle and McDonnel, 2004; Klaus and McDonnell, 2013).

2.1.1.2. Collection and analysis of samples

Sampling was mainly done at bridges which allowed access to free-flowing water in the main river channel. Water was collected from the river using a bottle with weights and a rope. Sample bottles were washed twice before the final sample was retained *In-situ* measurements were also taken. All the samples were clearly and uniquely labelled and kept in a cooler box. From the cooler box, the samples were kept in a fridge. Analysis for isotopes, cations and anions was completed within a week from collection. Oxygen and hydrogen isotopic ratios were measured using the Liquid-Water Isotope Analyzer manufactured by Los Gatos Research (LGR) at the UKZN Laboratory. Oxygen and hydrogen compositions were reported as delta values (δ). The measurement is based on high-resolution laser absorption spectroscopy. Total Alkalinity was measured by potentiometric titration. Cations were measured using *Varion 700* ICP Optical Emission Spectrometer. Anions were measured using Ion Chromatography.

2.1.1.3. Hydrograph separation

Hydrograph separation is the process where the storm hydrograph is separated into baseflow components and surface runoff components. The principle of hydrograph separation using stable isotopes is based on a contrast in the isotopic composition of the basin groundwater and that of a given storm. The groundwater in the basin will have an isotopic composition which reflects the long-term averaged input value whereas the storm will have a discrete value falling somewhere within the range of the mean annual value. If the two end-members have a distinct difference in their geochemistry or isotopic signature, the stormflow hydrograph can be separated to their component contributions based on a mass balance approach. More details on the method can be found in (Uhlenbrook et al., 2002; Buttle and McDonnell, 2004). Dissolved solids, represented by electrical conductivity (E.C.) or chloride can also be expected to vary with the ratio of baseflow to storm runoff and provide additional information for baseflow separation.

2.1.2. Results

2.1.2.1. Spatial overview of water quality

The main observations that can be drawn from the sampling exercises and set the benchmark for the catchment hydro-chemical status are presented below (Table 2.1, Figures 2.2-2.5). In both low and high flow seasons, the Crocodile and Komati rivers had higher EC (average 278±105 and 131±65 μS/cm, respectively) than Sabie-Sand (average 63±19 μS/cm). Major ions followed a similar trend, but the Lower Incomati (within Mozambique) registered the higher concentration of alkalinity, Calcium, Magnesium, Sodium and Silica. pH did not register a significant variation; temperature was lower during the low flows, which occur in winter and ORP was higher for the same period, but with no significant variation.

Table 2.1: Summary of the results indicating mean values of the studied variables and their variation (Standard deviation given in parenthesis) in the Incomati basin.

Parameter		**Komati**	**Crocodile**	**Sand-Sabie**	**Lower Incomati**	**Incomati Basin**
EC [μS/cm]	February	277.7 *(105.1)*	131.1 *(65)*	63.3 *(18.9)*	na na	132.4 *(85)*
	July	100.7 *(49.4)*	107.8 *(69.3)*	72.1 *(27.4)*	177.6 *(103.7)*	99.1 *(61.2)*
Temperature [^{o}C]	February	27.4 *(0.2)*	24.7 *(1.3)*	25.9 *(1.2)*	na na	25.3 *(1.5)*
	July	15.6 *(3.1)*	13.7 *(2.5)*	16.7 *(2.7)*	20.2 *(0.6)*	15.6 *(3.1)*
ORP [mV]	February	134.0 *(12.7)*	127.2 *(24.1)*	147.0 *(25.6)*	na na	132.6 *(23.8)*
	July	223.3 *(32)*	218.7 *(50.9)*	104.9 *(70)*	na na	170.7 *(86.4)*
pH [-]	February	7.8 *(0.1)*	8.0 *(0.2)*	7.7 *(0.1)*	na na	7.9 *(0.2)*
	July	6.3 *(0.5)*	6.6 *(1.5)*	7.2 *(0.5)*	7.5 *(0.3)*	6.7 *(1)*
δ^{2}H [‰]	February	-6.10 *(0.88)*	-9.84 *(1.38)*	-9.14 *(1.63)*	na na	-9.23 *(1.79)*
	July	-6.19 *(3.42)*	-8.39 *(4.53)*	-8.57 *(4.62)*	-2.38 *(2.79)*	-7.49 *(4.45)*
δ^{18}O [‰]	February	-2.22 *(0.02)*	-2.85 *(0.27)*	-3.37 *(0.42)*	na na	-2.90 *(0.44)*
	July	-2.68 *(0.74)*	-2.92 *(0.88)*	-2.95 *(0.87)*	-1.73 *(0.33)*	-2.79 *(0.86)*
Alkalinity [mg/L]		81.5 *(34.7)*	67.9 *(34.3)*	46.3 *(69.6)*	87.2 *(26.5)*	65.9 *(49.4)*
Calcium [mg/L]		9.2 *(4.3)*	11.1 *(6.4)*	8.6 *(9.3)*	18.3 *(3.7)*	10.3 *(7.2)*
Magnesium [mg/L]		7.8 *(3.7)*	9.1 *(6.5)*	5.5 *(8.1)*	13.4 *(3.3)*	7.9 *(6.6)*
Sodium [mg/L]		10.2 *(7)*	11.3 *(8.4)*	18.3 *(49.7)*	29.7 *(4.7)*	14.3 *(28.6)*
Potassium [mg/L]		0.2 *(0.1)*	0.2 *(0)*	0.2 *(0.1)*	0.3 *(0)*	0.2 *(0.1)*
Silica [mg/L]		7.7 *(1.8)*	8.1 *(2.9)*	7.2 *(2.5)*	10.2 *(2.6)*	7.9 *(2.6)*
Nitrate [mg/L]		0.0 *(0)*	1.4 *(1.3)*	1.1 *(1.2)*	2.6 *(2.3)*	1.0 *(1.3)*

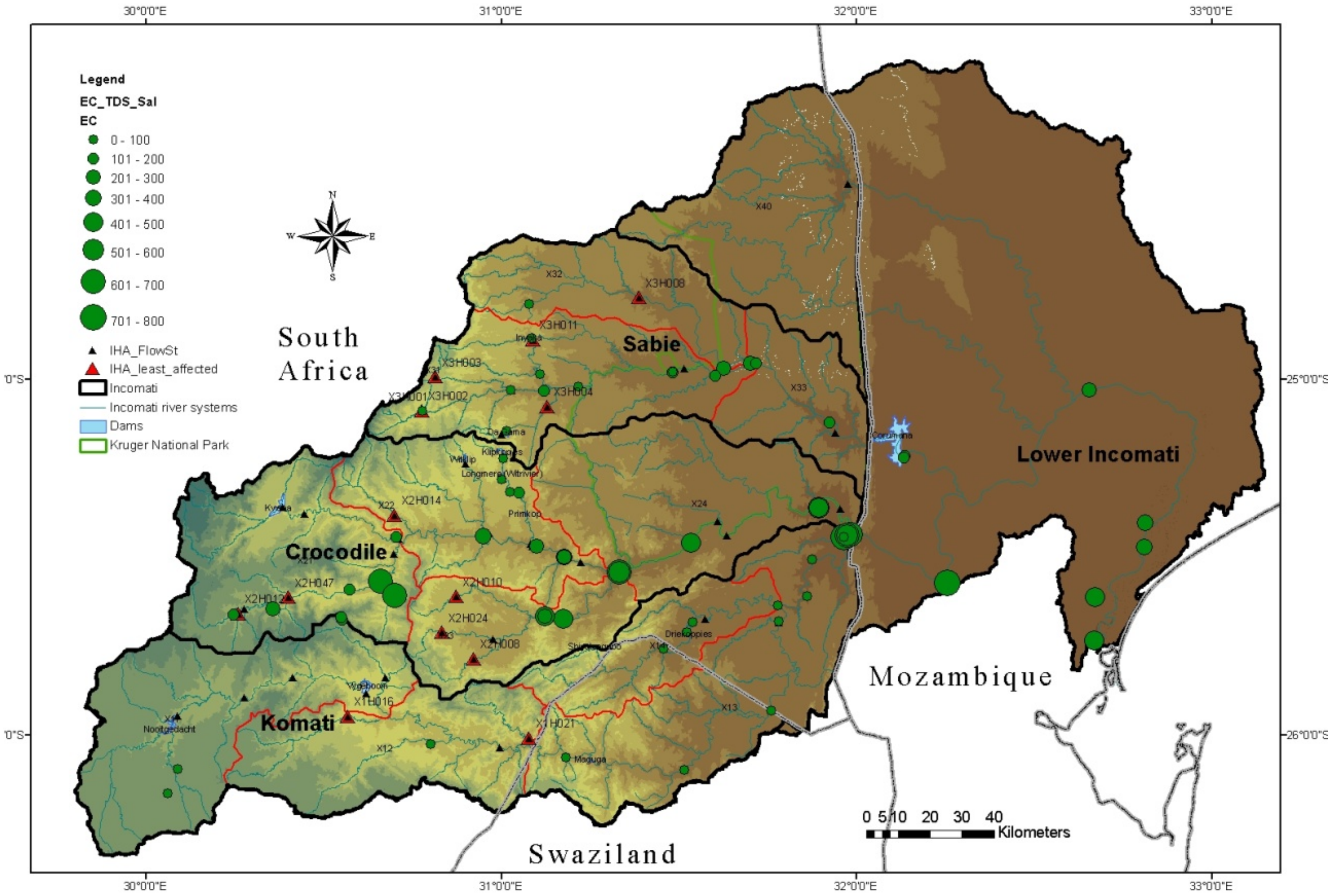


Figure 2.2: Electrical conductivity in the Incomati Basin

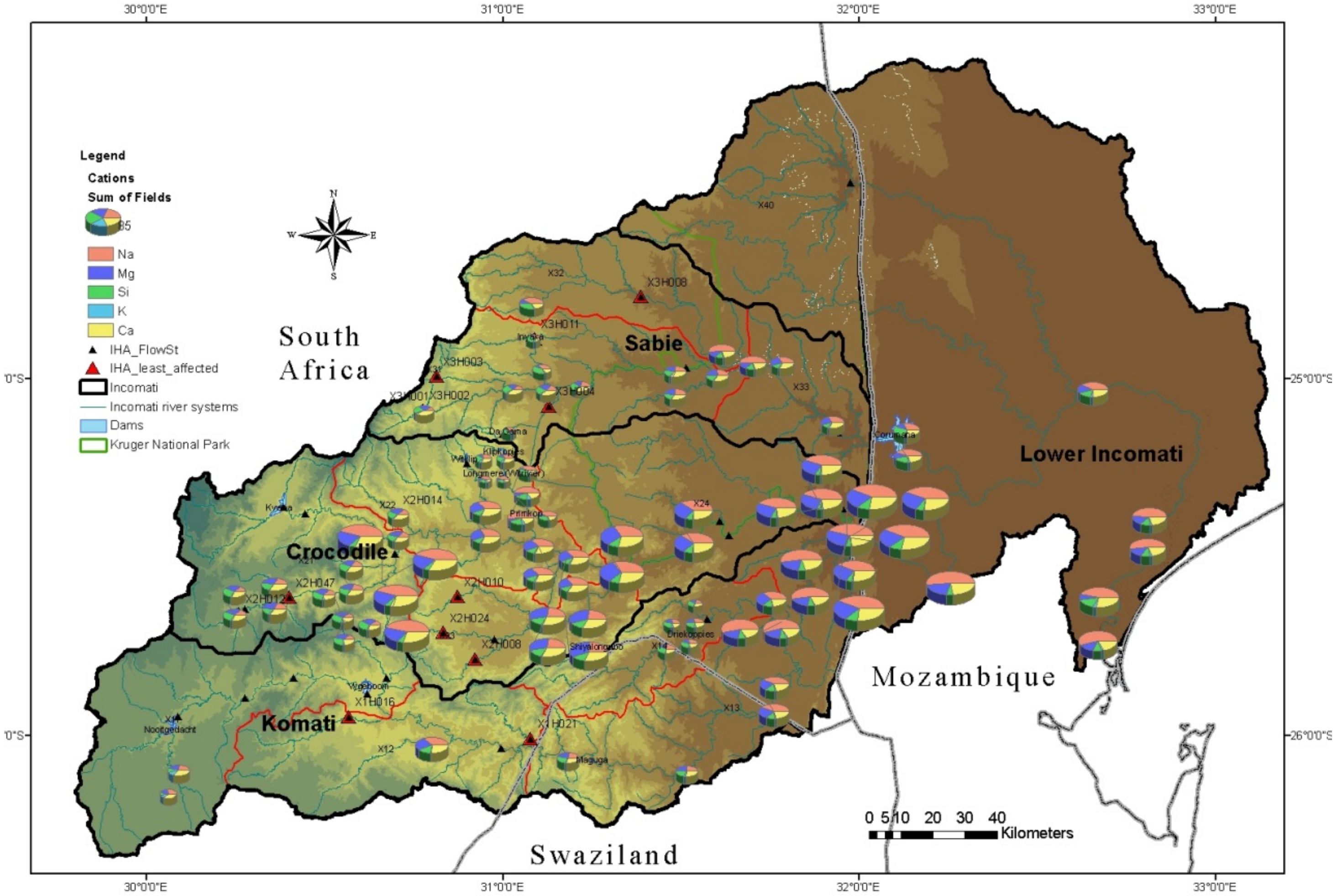


Figure 2.3: Major cations (Sodium Na, Magnesium Mg, Silica Si, Potassium K and Calcium Ca) in the Incomati Basin

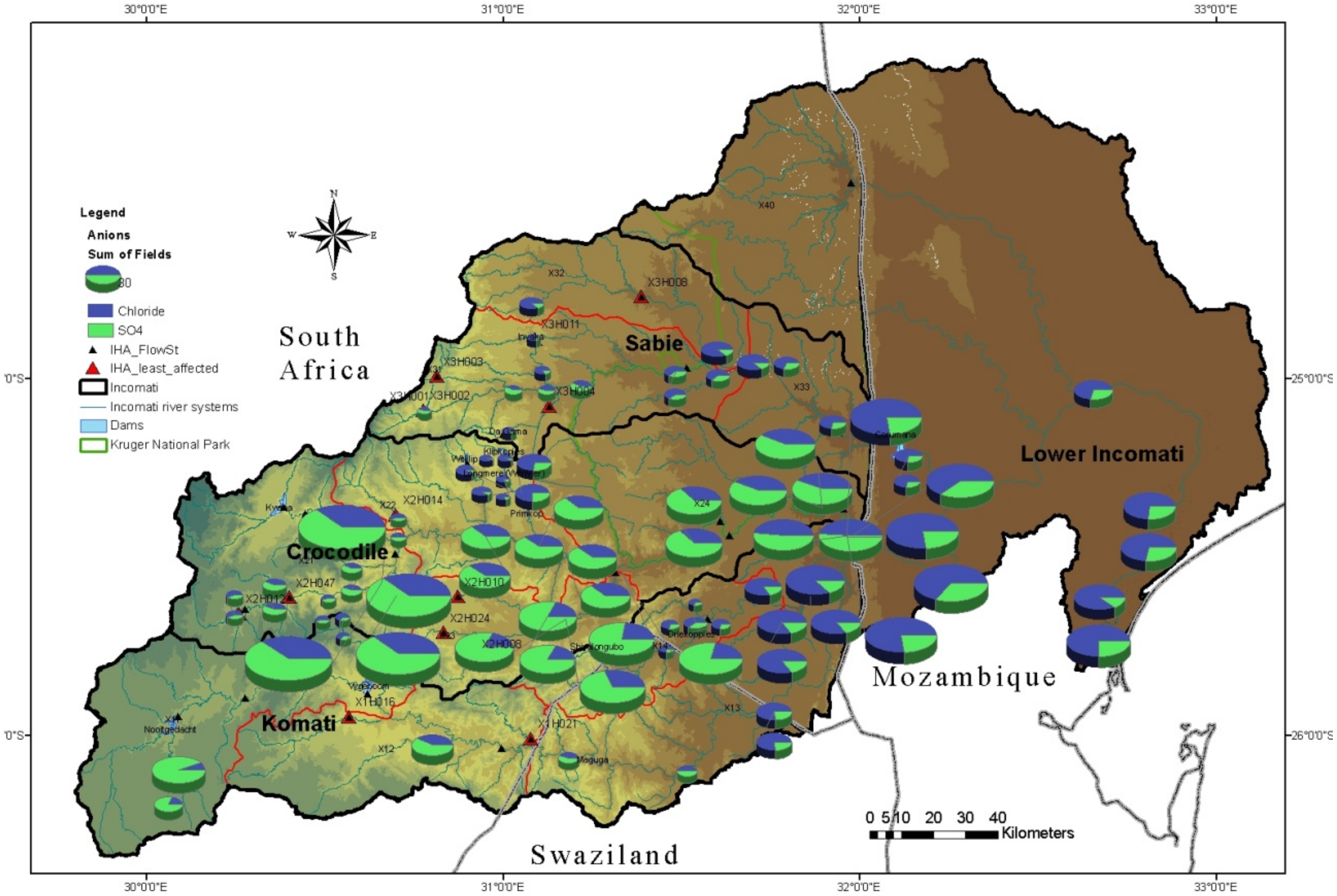


Figure 2.4: Major anions (Chloride Cl and Sulfate SO_4) in the Incomati Basin

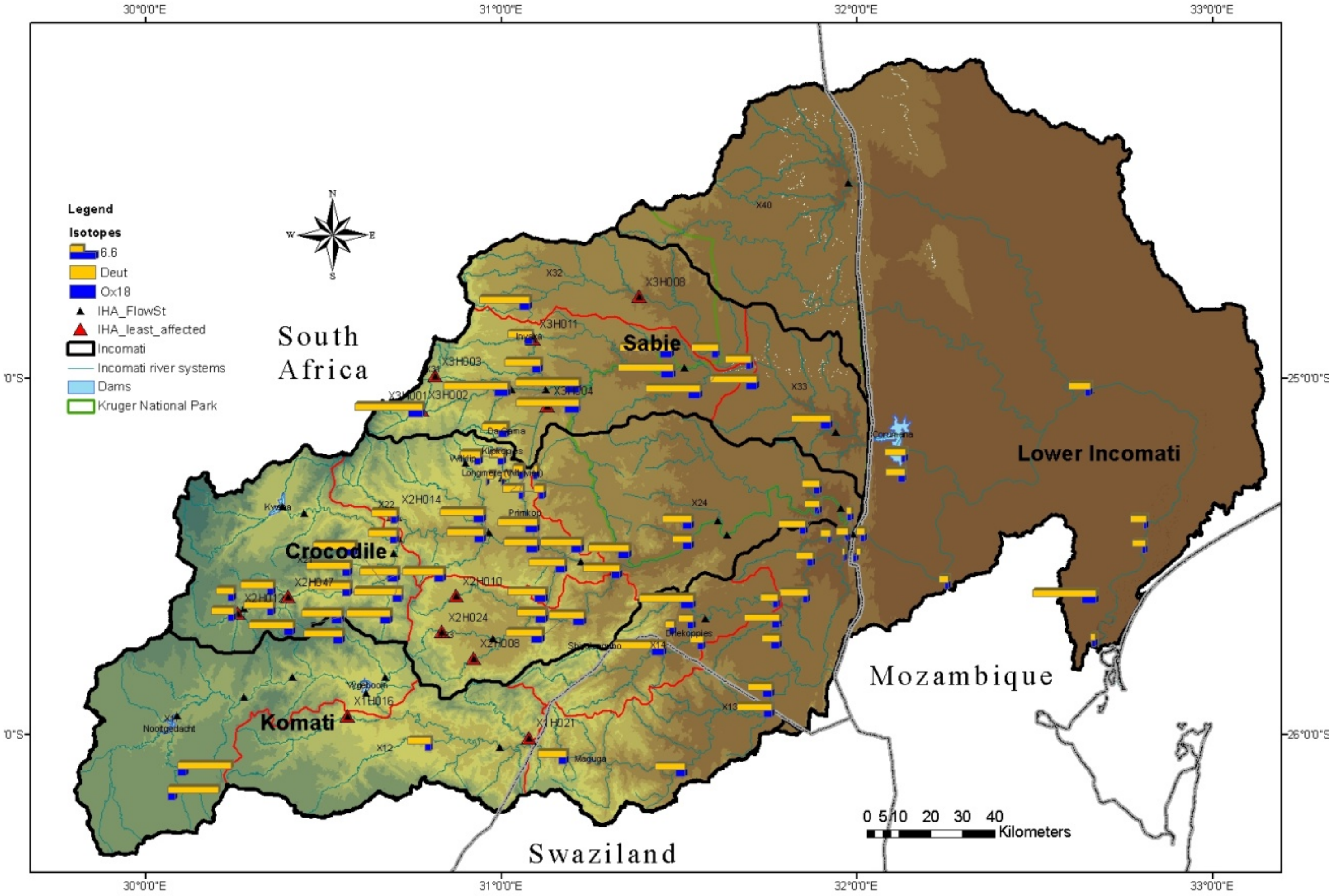


Figure 2.5: Stable isotopes Deuterium and Oxygen-18 in the Incomati Basin

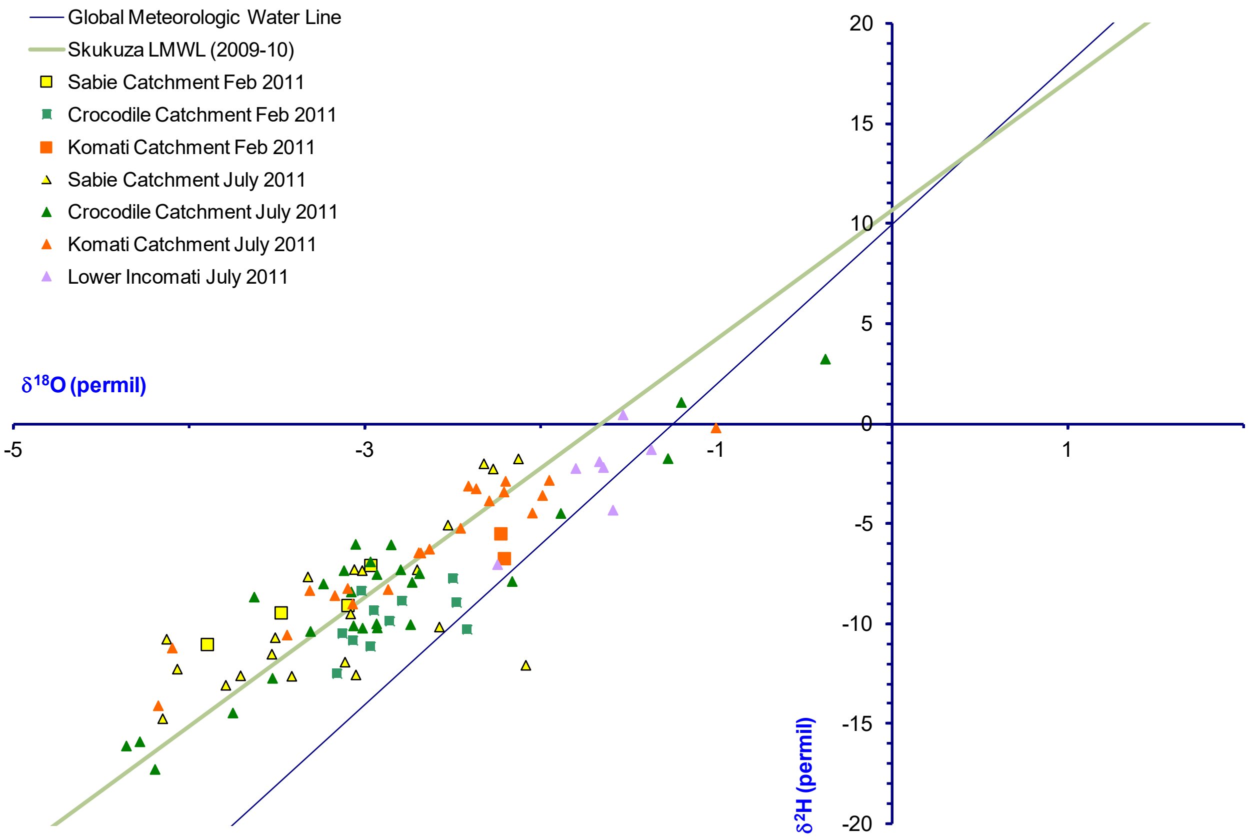


Figure 2.6: Stable Isotope distributions plotted per sub-catchment of the Incomati for 2011

In terms of stable isotopes, Deuterium (^{2}H) seemed to increase from -14‰ in the headwaters to -4‰ downstream particularly along the Crocodile and Sabie rivers during high flows. Oxygen 18 (^{18}O) had smaller variations (-2.9±0.9‰), but also tends to be slightly higher downstream in the Crocodile. In both high and low flow seasons the Komati waters seem to be more enriched in heavy isotopes than the Crocodile, suggesting a greater evaporative enrichment, probably from irrigation return flows and storage. The Sabie River appears to have the most isotope depleted waters suggesting that evaporative enrichment as a result of land-use activities in this catchment, is of low significance and/or that there are stronger baseflows from groundwater arising from direct recharge. The general grouping for the low flows in the Crocodile is suggestive of a sustained relatively undistributed water source, which would be explained by the river course traversing dolomite regions with direct contact with groundwater, in its middle reaches. A local meteoric water line was derived for Skukuza (24°59′24″S, 31°34′58″E) Figure 2.6 illustrates that the majority of the samples plot close this line.

2.1.2.2. Temporal variation of water quality

Over the monitoring period, it could be observed that the water quality followed a pattern of dilution during the rainy season, and increased concentrations in the dry season, with highest concentrations in August/September (see Figure 2.7-2.8). In the case of the Crocodile catchment, an interesting observation is that some tributaries, i.e. the Kaap and Elands rivers, have higher EC than the main river.

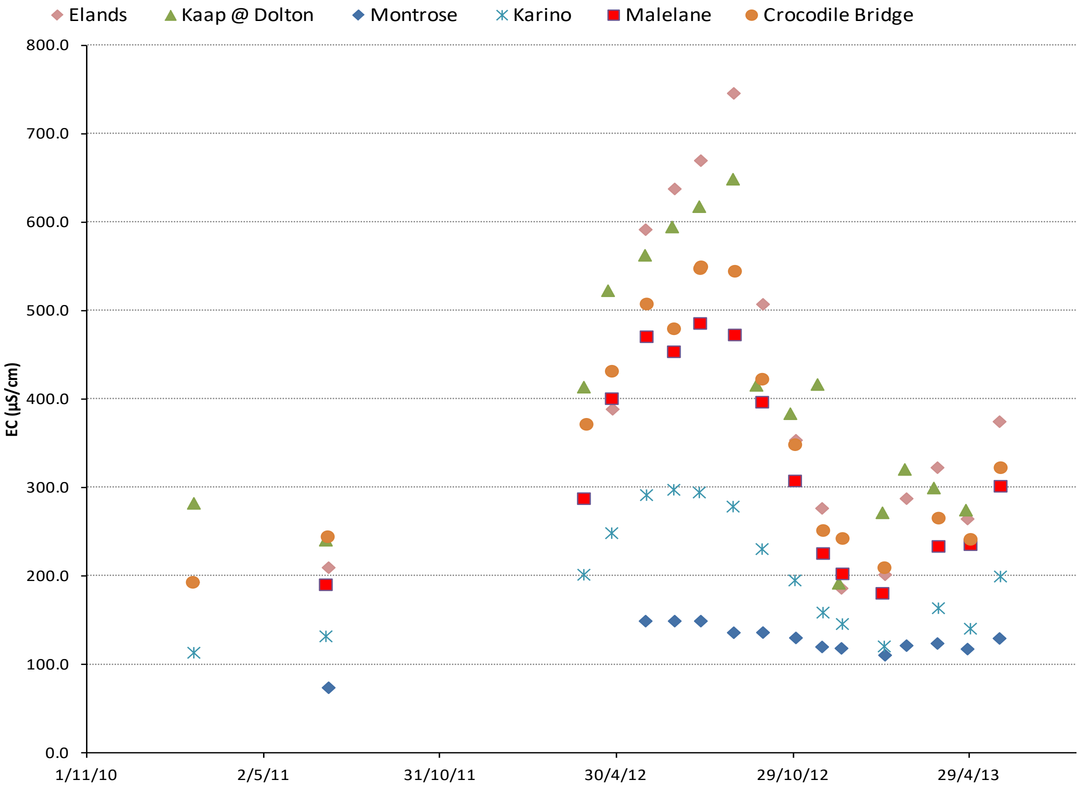


Figure 2.7: Temporal variation of Electrical conductivity (EC) for major tributaries and locations in the Crocodile Catchment, during the monitoring period of February 2011 to May 2013.

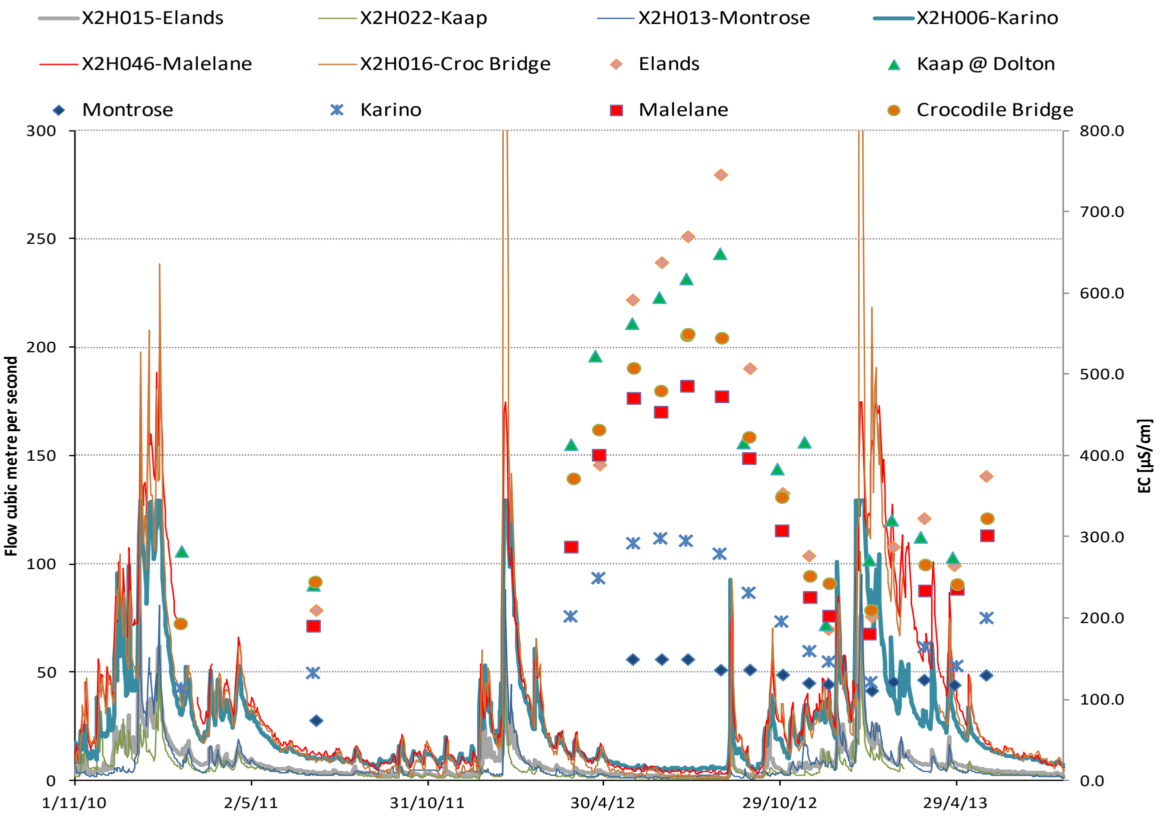


Figure 2.8: Streamflow and EC for selected locations of the Crocodile River and tributaries.

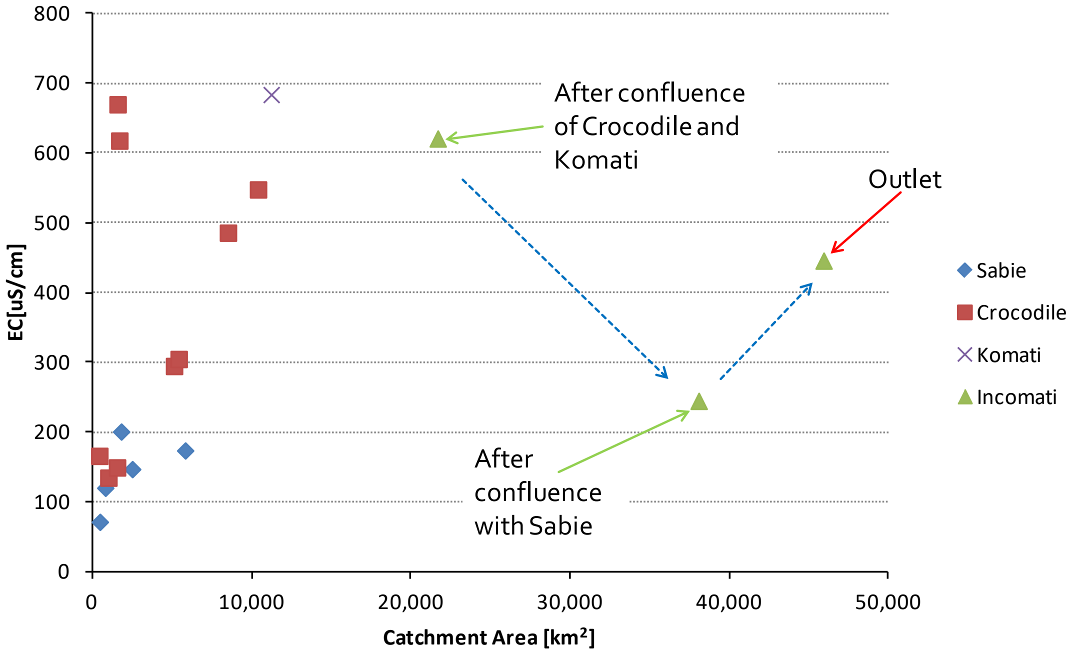


Figure 2.9: Scaling effects of EC in function of the drainage area, for the main sub-catchments of the Incomati

Another relevant finding is the effect of scale on the water quality (Figure 2.9), and the impact of dilution of inflow from the Sabie River to the Incomati. The Sabie's waters are much more pristine than the Komati and Crocodile Rivers, so after the confluence with these the overall EC of Incomati reduces, as a result of the mixing and dilution.

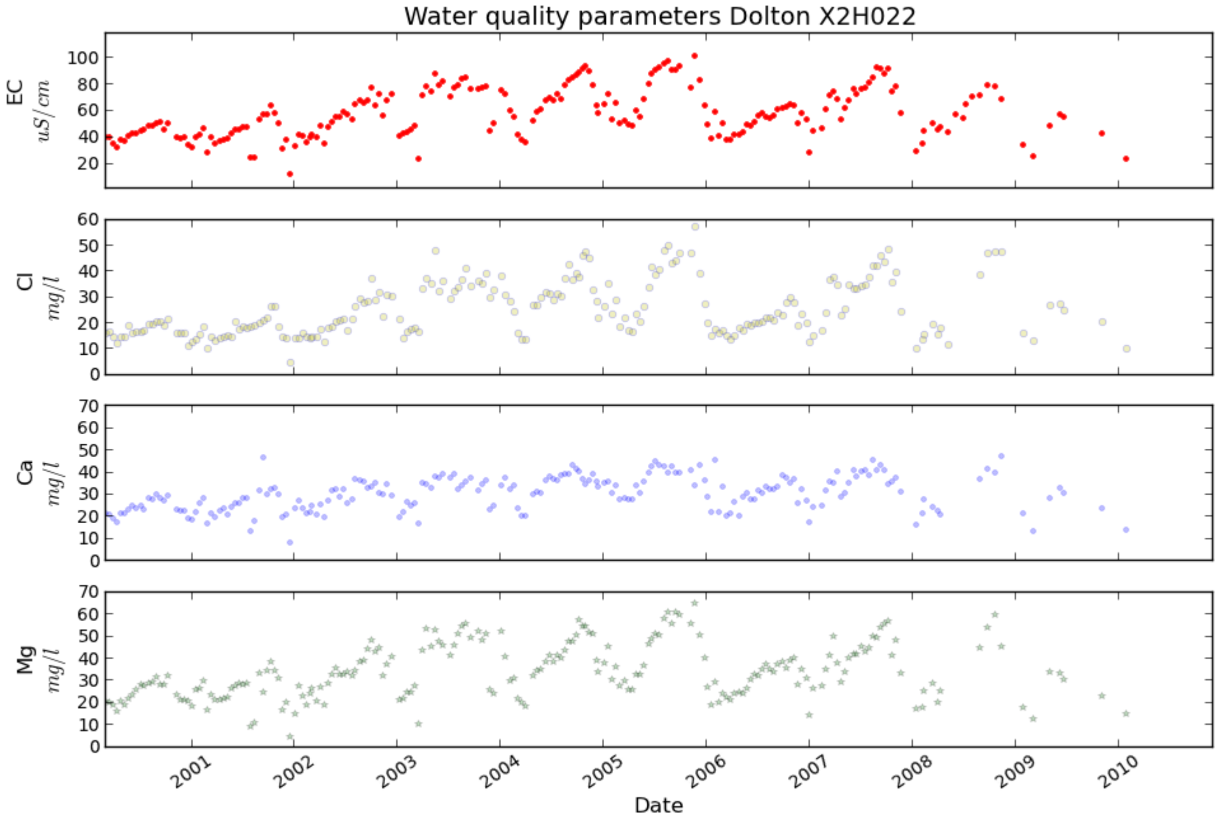


Figure 2.10: Long term variation of water quality parameters at the Kaap outlet

2.1.2.3. Long term temporal variation of water quality in the Kaap Catchment

Figure 2.10 illustrates the seasonal variation of water quality over several years, based on historical data. Wet years tend to have smaller water quality variations than dry years. All the parameters follow similar patterns of EC, and there is a strong correlation of EC with most anions and cations. Thus, it can be concluded that EC is a useful indicator of overall water quality in the basin.

2.1.2.4. Hydrograph separation

Hydrograph separation at a seasonal scale was performed using analysis of Electrical Conductivity (Figure 2.11), Chloride, Silica, Calcium and Magnesium for the Kaap River outlet and 3 nested catchments within the Kaap catchment, to identify and quantify the main runoff components. Electrical conductivity was found to be the most useful parameter, because of consistency in the data available. Preliminary results of a classical two component hydrograph separation indicate the dominance of the groundwater component in the low flow regime, with a contribution of 90% of the total flow. However, during wet seasons deep groundwater accounts for 50% of total flow, and a third component, soil water (or shallow groundwater) appears to play an important role, particularly after a sequence of wet years. Therefore, a three component hydrograph separation is most relevant at a seasonal scale. The inter-annual temporal variability of runoff components is larger than intra-annual, meaning that the definition of end members needs to be done carefully.

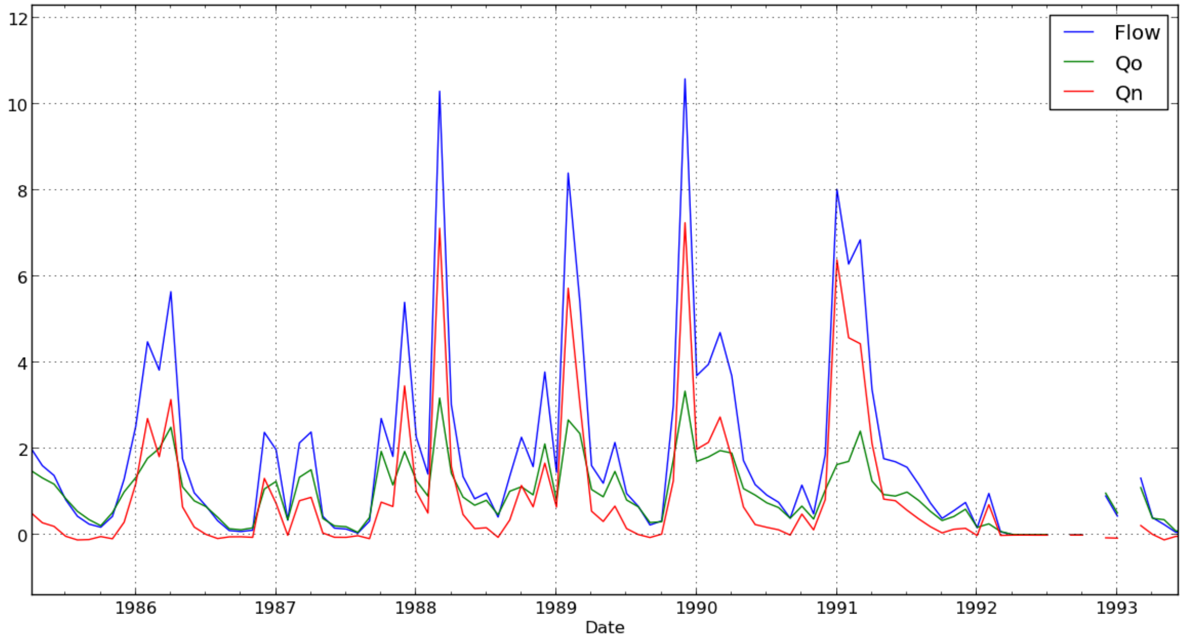


Figure 2.11: Two-component Hydrograph Separation using EC as tracer. The end members are Old water, or groundwater (Qo) and New water or event water (Qn).

2.1.3. Key findings

- Electrical Conductivity (EC) should be a good and significant indicator of the status of water quality in the Incomati system.
- There is a general trend of increasing major cations, anions, and EC from upstream headwaters to downstream in the Incomati Basin.
- Isotopes also indicate more depleted water in headwaters (resembling the frontal rain inputs from oceanic water) and more enriched water downstream, particularly in the Crocodile and Komati systems.

- The Sabie River has better water quality than the Komati and Crocodile Rivers which are more impacted by land use activities.
- In the Crocodile system in particular, the particularly during low flows (May to September).
- The signal of irrigation return flows can be traced by elevated EC, high Sodium (Na^+) and enrichment of isotopes.
- The impact of reservoirs can be traced through enrichment of isotopes, due to the process of evaporation.
- Flow from the Crocodile River plays an important role in diluting water quality from its tributaries; the Sabie River appears to play a very important role by providing input of good quality water which dilutes the entire Incomati system.
- The Kaap catchment relies on large groundwater storage, but it also responds quite rapidly to rainfall events. This process may be occurring in several other catchments in the Incomati, particularly those similar to the Kaap.

2.2. Analysis of Spatial and Temporal Variability of Streamflow in the Incomati River Basin

Saraiva Okello, A.M.L., Masih, I, Uhlenbrook, S., Jewitt, G.P.W. van der Zaag, P. and Riddell, E

The level of water abstraction in the Incomati River has increased markedly over the past few decades and the actual water demand is projected to increase in the future as a result of further economic development and population growth (Nkomo and Van der Zaag, 2004; LeMarie et al., 2006; Pollard et al., 2011). Consumptive use of surface water amounts to more than 1,880 Mm^3/a, which represents 51% of the average amount of surface water generated in the basin (Van der Zaag and Vaz, 2003). The major water consumers (see Figure 2.12 and Table 2.2), accounting for 91% of all consumptive water uses, are the irrigation and afforestation (forest plantation) sectors, followed by inter-basin water transfers to the Umbeluzi basin and Olifants catchment in the Limpopo basin (Van der Zaag and Vaz, 2003; DWAF, 2009d; Aurecon, 2010).

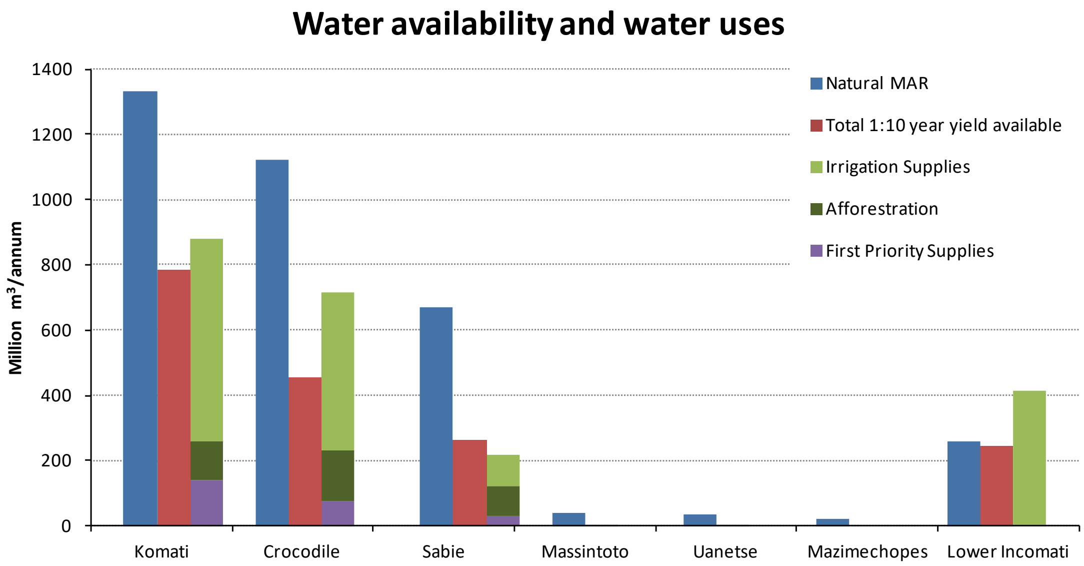


Figure 2.12: Water availability in terms of natural mean annual runoff (mar), water yield 1:10 year and water uses. The first priority uses include domestic, industrial, mining and water transfers. Source: adapted from Aurecon (2010)

Table 2.2: Summary of estimated natural streamflow, water demands in the Incomati basin in million m^3/annum (Aurecon, 2010) and major dams (> 10 million m^3) (Van der Zaag and Vaz, 2003)

	Natural MAR	First Priority Supplies	Irrigation Supplies	Afforestration	Total Water Use
Komati	1332	141.5	621	117	879.5
Crocodile	1124	74.7	482	158	714.7
Sabie	668	30	98	90	218
Massintoto	41	0.3	0	0	0.3
Uanetse	33	0.3	0	0	0.3
Mazimechopes	20	0	0	0	0
Lower Incomati	258	1.5	412.8	0	414.3
Mozambique	325		412.8		
South Africa	2663		961		
Swaziland	488		240		
Total	3476	248	1614	365	2227

Tributary	**Country**	**Major dam**	**Year commissioned**	**Storage capacity ($10^6 m^3$)**
Komati	South Africa	Nooitgedacht	1962	81
Komati	South Africa	Vygeboom	1971	84
Komati	Swaziland	Maguga	2002	332
Komati	Swaziland	Sand river	1966	49
Lomati	South Africa	Driekoppies	1998	251
Crocodile	South Africa	Kwena	1984	155
Crocodile	South Africa	Witklip	1979	12
Crocodile	South Africa	Klipkopje	1979	12
Sabie	South Africa	Da Gama	1979	14
Sabie	South Africa	Injaka	2001	120
Sabie	Mozambique	Corumana	1988	879

Since the 1950s the area of irrigated agriculture and forestry has increased steadily, particularly in the Komati and Crocodile systems, as can be seen from Table 2.3.

Table 2.3 land use and water use change from 1950s to 2004 in Komati, Crocodile and Sabie subcatchments. Source adapted from AURECON (2010)

		1950s	**1970s**	**1996**	**2004**
Komati	Irrigation area (km^2)	17.6	144.1	385.1	512.4
	Afforested area (km^2)	247	377	661	801
	Domestic water use (million m^3/a)	0.5	7.7	15.5	19.7
	Industrial and mining water use (million m^3/a)	0	0	0.5	0.5
	Water Transfers out (million m^3/a):				
	To Power stations in South Africa	3.4	103	98.1	104.7
	To irrigation in Swaziland	0	111.8	122.2	121.8
1. Crocodile	Irrigation area (km^2)	92.8	365.8	427	510.7
	Afforested area (km^2)	375	1550	1811	1941
	Domestic water use (million m^3/a)	3	12.2	33.6	52.4
	Industrial and mining water use (million m^3/a)	0.1	7.5	19.8	22.3
2. Sabie	Irrigation area (km^2)	27.7	68.4	113.4	127.6
	Afforested area (km^2)	428	729	708	853
	Domestic water use (million m^3/a)	2.4	5.3	13	26.7
	Industrial and mining water use (million m^3/a)	0	0	0	0

This chapter presents an analysis of long term rainfall and streamflow records. The goal of this analysis was to determine whether or not there have been significant changes in rainfall and streamflow during the time of record, and what the implications of such changes for water resources management are. The main research questions are:

- Does analysis of precipitation and streamflow records reveal any persistent trends?
- What are the drivers of these trends?
- What are the implications of these trends for water management?

The variability and changes of rainfall and streamflow records were analysed; and possible drivers of changes identified from the literature and further analysis of reports of water resources assessments previously conducted in the area. Spatial variation of trends in streamflow and their possible linkages with the main drivers are analysed. Based on the findings, approaches and alternatives for improved water resources management and planning are proposed.

2.2.1. Methodology

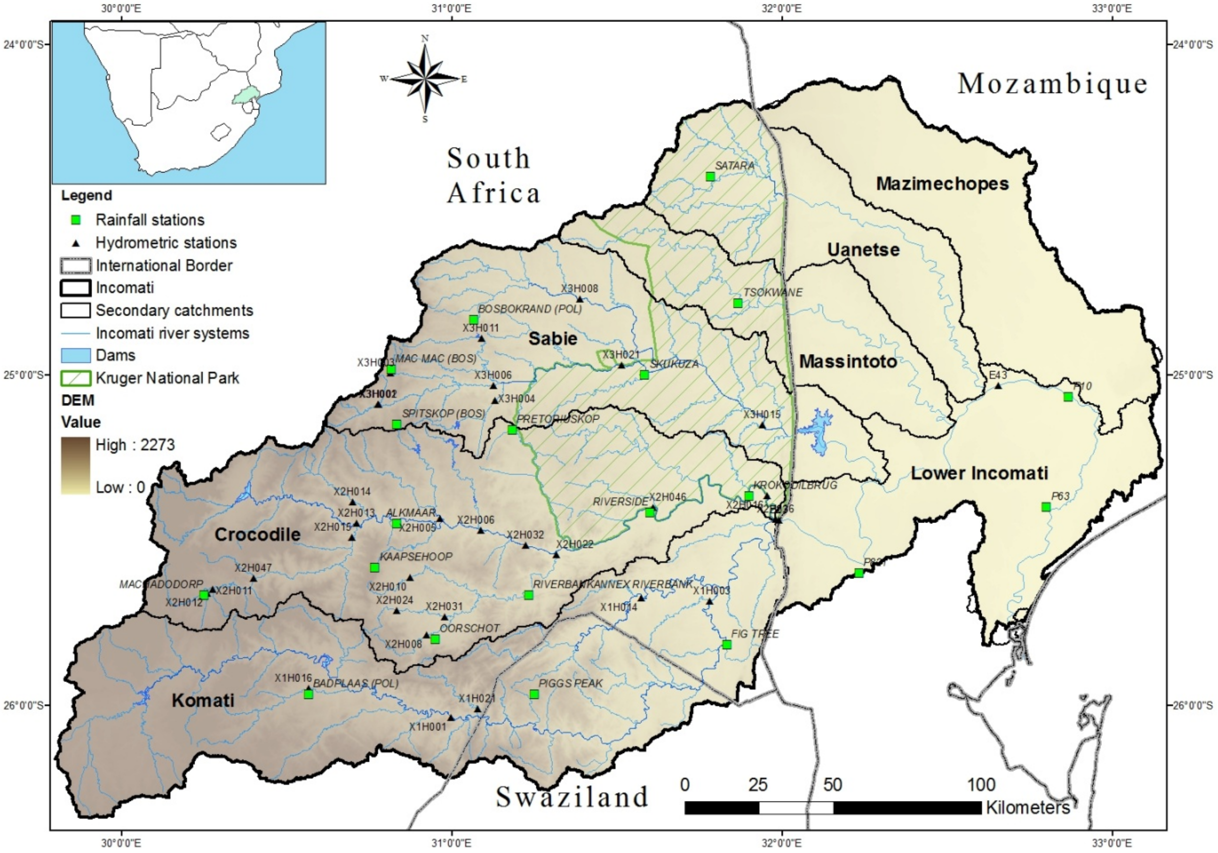


Figure 2.13: Map of location of the study area, illustrating the main sub catchments, the hydrometric and rainfall stations analysed, and the basin topography and dams

2.2.2. Data and Analysis

2.2.2.1. Rainfall

Rainfall data was extracted from the Lynch (2003) database of annual, monthly and daily rainfall for Southern Africa for the period of 1905 to 2000. Twenty stations with the best quality data (evaluated by the percentage of reliable data indicated on the database) and providing a representative spatial coverage of the catchment were selected for detailed analysis (Figure 2.13). Some of the time series were extended using new data collected from the South Africa Weather Service (SAWS). The spatial and temporal heterogeneity in rainfall across the study area was characterised using statistical analysis and investigation of annual anomalies. The time series of annual and monthly rainfall from each station was subjected to the Spearman test in order to identify any trends, for the period of 1950-2000 and 1950-2011. The Pettitt Test (Pettitt, 1979) was also used to identify break points in the time series. The annual time series were also analysed for the presence of serial correlation.

2.2.2.2. Discharge: Indicators of Hydrologic Alteration

The US Nature Conservancy developed a statistical method known as the "Indicators of Hydrologic Alteration" (IHA), for assessing the degree to which human activities have changed flow regimes. The IHA method (Richter et al., 1996; Richter et al., 2003; Richter and Thomas, 2007) is based upon the concept that hydrologic regimes can be characterized by five ecologically-relevant attributes: (1) magnitude of monthly flow conditions; (2) magnitude and duration of extreme flow events (e.g. high and low flows); (3) the timing of extreme flow events; (4) frequency and duration of high low flow pulses; and (5) the rate and frequency of changes in flows. Table 2.4 shows the hydrological parameters analysed within each indicator group. Analyses are based on availability of daily flow data, so selected gauges within the Incomati basin were analysed with this method. Many studies have successfully applied the IHA methodology in order to access impacts on streamflow caused by anthropogenic drivers (Maingi and Marsh, 2002; Taylor et al., 2003; Mathews and Richter, 2007; De Winnaar and Jewitt, 2010; Masih et al., 2011). In the case of the present study, the indicators of magnitude of monthly water conditions, magnitude and duration of extreme water conditions, as well as timing were analysed for the same period (1970-2011), to assess whether consistent trends of increase or decrease of means and variations of the flow metrics were present.

Table 2.4: Hydrologic parameters used in Range of Variability Approach (Richter et al., 1996)

IHA Group	**Regime Characteristics**	**Hydrological parameters**
Group 1: Magnitude of monthly water conditions	Magnitude timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude duration	Annual minima and maxima based on one, three, seven, thirty and ninety day(s) mean
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day maximum and minimum
Group 4: Frequency and duration of high/low pulses	Frequency and duration	No. of high and low pulses each year Mean duration of high and low pulses within each year (days)
Group 5: Rate/Frequency of water condition changes	Rates of change of frequency	Means of all positive and negative differences between consecutive daily values No. of rises and falls

The IHA software was used to identify linear trends of the streamflow time series, based on the regression of least squares. This trend is evaluated with the P value, and only trends with $p \leq 0.05$ were considered significant trends. The value of the slope of the trend line indicated whether the trend was increasing or decreasing.

In the Incomati Basin, 104 gauging stations operated by DWA in South Africa and 2 operated by ARA-Sul in Mozambique were selected for this analysis. This discharge data with time-series lengths ranging from 1909 to 2012 was then screened. Based on the quality of data, time series length, influence of infrastructure (dams, canals) and spatial distribution, 33 stations were selected for detailed analysis (see Table 2.5 and Figure 2.14). As this catchment is highly modified very few stations could be considered to have low impact by human interventions. Analysis of the 33 indicators of hydrologic alteration were conducted and summarized, to identify patterns and trends of the streamflow record (single period analysis for the entire time series and for the period of 1970-2011), as well as to assess the impact of infrastructure on the streamflow (2 periods analysis).

Table 2.5: Hydrometric and rainfall stations analysed, location, catchment area, data length and missing data

	Station	Latitude	Longitude	Place	Catchment Area (km^2)	Data Available	Years	Period analysed for trends	Missing Data
Komati	X1H001	-26.0362	30.9976	Komati River @ Hooggenoeg	5499	1909-10-01 2012-05-08	102	1970-2011 (42 years)	8.0%
	X1H003	-25.6823	31.7819	Komati River @ Tonga	8614	1939-10-04 2012-05-15	72	1970-2011 (42 years)	6.8%
	X1H014	-25.6739	31.5753	Mlumati River @ Lomati	1119	1968-08-02 2012-04-17	43	1978-2011 (34 years)	0.5%
	X1H016	-25.9479	30.5687	Buffelspruit @ Doornpoort	581	1970-08-21 2012-06-06	41	1970-2011 (42 years)	3.4%
	X1H021	-26.0094	31.0797	Mtsoli River @ Diepgezet	295	1975-10-08 2012-05-08	36	1976-2011 (36 years)	2.7%
Crocodile	X2H005	-25.4325	30.9658	Nels River @ Boschrand	642	1929-07-04 2012-05-17	82	1970-2011 (42 years)	0.8%
	X2H006	-25.4698	31.0881	Krokodil River @ Karino	5097	1929-10-02 2012-06-04	82	1970-2011 (42 years)	0.1%
	X2H008	-25.7860	30.9243	Queens River @ Sassenheim	180	1948-02-01 2012-05-10	63	1970-2011 (42 years)	0.5%
	X2H010	-25.6111	30.8749	Noordkaap River @ Bellevue	126	1948-02-11 2012-05-10	63	1970-2011 (42 years)	5.7%
	X2H011	-25.6464	30.2775	Elands River @ Geluk	402	1956-10-01 1999-12-11	42	1957-1999 (43 years)	0.9%
	X2H012	-25.6586	30.2605	Dawsons Spruit @ Geluk	91	1956-10-03 2012-05-08	55	1970-2011 (42 years)	0.3%
	X2H013	-25.4486	30.7118	Krokodil River @ Montrose	1518	1959-01-21 2012-06-05	52	1970-2011 (42 years)	1.6%
	X2H014	-25.3824	30.7015	Houtbosloop @ Sudwalaskraal	250	1958-12-17 2012-08-01	53	1970-2011 (42 years)	5.1%
	X2H015	-25.4904	30.6986	Elands River @ Lindenau	1554	1959-07-23 2012-06-27	52	1970-2011 (42 years)	3.1%
	X2H016	-25.3639	31.9557	Krokodil River @ Tenbosch	10365	1960-08-24 2012-07-13	51	1970-2011 (42 years)	5.6%
	X2H022	-25.5432	31.3167	Kaap River @ Dolton	1639	1960-08-31 2012-06-28	51	1970-2011 (42 years)	5.7%
	X2H024	-25.7118	30.8350	Suidkaap River @ Glenthorpe	80	1964-09-25 2012-06-28	47	1970-2011 (42 years)	1.7%
	X2H031	-25.7303	30.9784	Suidkaap River @ Bornmans Drift	262	1966-06-23 2012-06-28	45	1966-2011 (46 years)	5.0%
	X2H032	-25.5142	31.2245	Krokodil River @ Weltevrede	5397	1968-09-15 2012-06-28	43	1970-2011 (42 years)	2.4%
	X2H036	-25.4366	31.9824	Komati River @ Komatipoort	21481	1982-10-20 2012-07-13	29	1983-2011 (28 years)	4.1%
	X2H046	-25.3989	31.6106	Krokodil River @ Riverside	8473	1985-09-04 2012-06-20	26	1986-2011 (26 years)	2.0%
	X2H047	-25.6131	30.4016	Swartkoppiesspruit @ Kindergoed	110	1985-10-24 2012-06-27	26	1986-2011 (26 years)	2.2%
Sabie	X3H001	-25.0890	30.7779	Sabie River @ Sabie	174	1948-03-15 2012-03-08	63	1970-2011 (42 years)	0.8%
	X3H002	-25.0880	30.7783	Klein Sabie River @ Sabie	55	1963-11-08 2012-04-11	48	1970-2011 (42 years)	0.4%
	X3H003	-24.9933	30.8144	Mac-Mac River @ Geelhoutboom	52	1948-03-16 2012-05-17	63	1970-2011 (42 years)	0.5%
	X3H004	-25.0762	31.1305	Noordsand River @ De Rust	200	1948-02-21 2012-04-11	63	1970-2011 (42 years)	3.9%
	X3H006	-25.0306	31.1265	Sabie River @ Perry's Farm	766	1958-09-04 2000-01-19	41	1970-1999 (30 years)	2.6%
	X3H008	-24.7700	31.3886	Sand River @ Exeter	1064	1967-09-01 2011-10-26	43	1968-2011 (43 years)	15.5%
	X3H011	-24.8881	31.0912	Marite River @ Injaka	212	1978-11-28 2012-04-18	33	1979-2011 (32 years)	7.6%
	X3H015	-25.1495	31.9407	Sabie River @ Lower Sabie Rest Camp	5713.88	1986-12-09 2012-04-19	25	1988-2011 (24 years)	8.2%
	X3H021	-24.9685	31.5154	Sabie River @ Kruger Gate	2407.2	1990-11-15 2012-04-18	21	1991-2011 (21 years)	10.8%
Lower Incomati	E23	-25.4375	31.9906	Incomati River @ Ressano Garcia	21200	1948-10-31 2011-09-06	62	1970-2011 (42 years)	9.0%
	E43	-25.0306	32.6547	Incomati River @ Magude	37500	1952-11-01 2011-08-31	58	1970-2011 (42 years)	3.5%

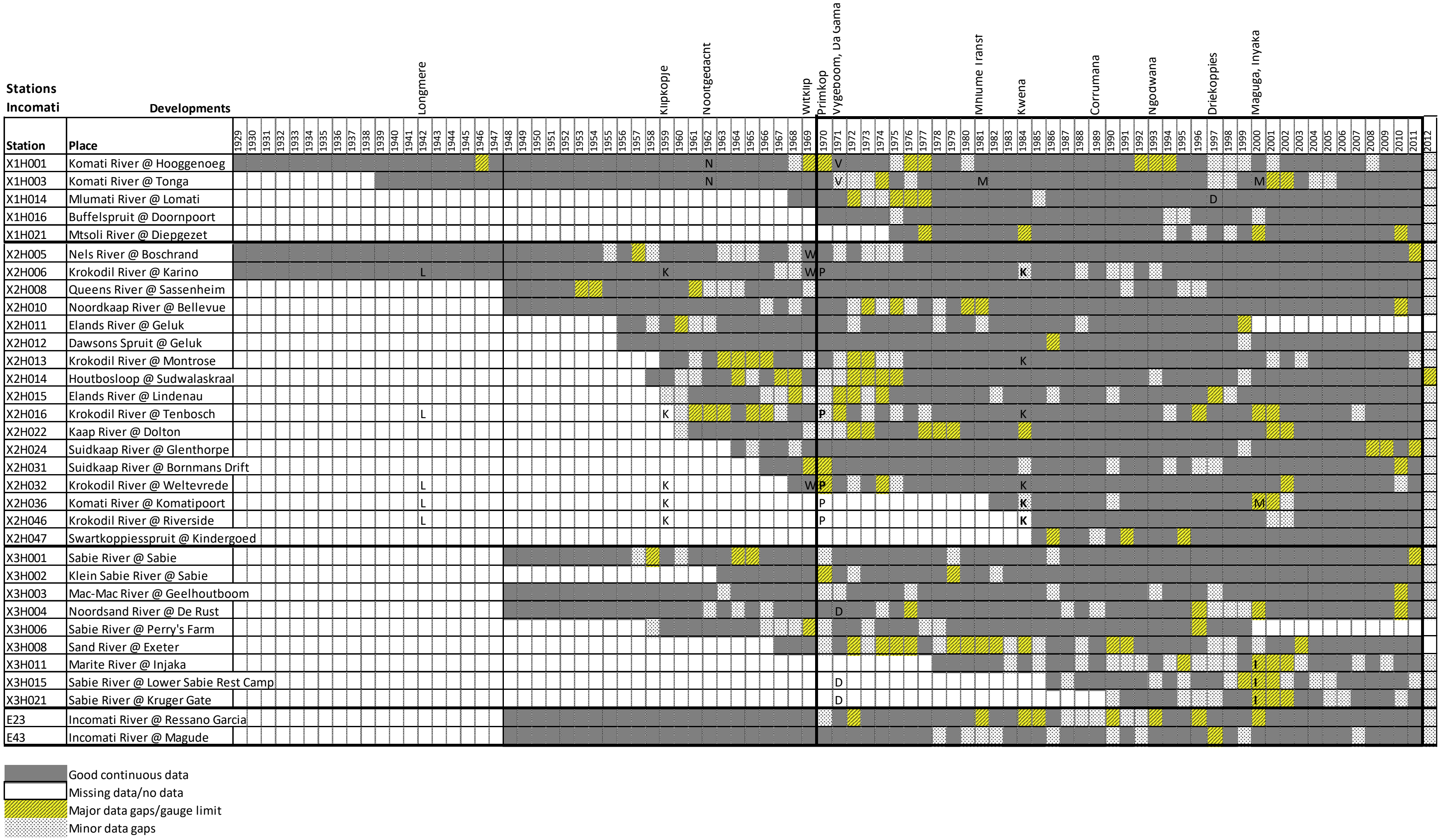


Figure 2.14: Streamflow data used on this study, with indication of time series length, data quality, missing data. Major developments in the basin, such as dams, are on the top horizontal line on the year they were commissioned; indication is made of the gauges affected by the developments.

2.2.2.3. Land use analysis

Land use analysis was conducted based on secondary data, as remote sensing maps are available only from a period when most of the current forestry plantations were already established. A map of current land use (courtesy of ICMA, 2011) and land use of 2004 where visually compared with the maps of trends of IHA. Where occurrence of trends in flow regime was consistent with changes in land use, this was further investigated, by looking at temporal evolution on the land use change.

2.2.3. Results

2.2.3.1. Rainfall

Statistical analysis was conducted on the 20 rainfall stations described in Table 2.6, for the period of 1950 to 2011. The variability of rainfall across the basin was confirmed to be high, both intra and inter-annually, with a wide range between years. It is interesting to note that this variability is higher for the stations located on the escarpment, due to the elevation gradient. The variability across the basin is also significant, as illustrated by the box plot of Figure 2.15.

The investigation of trends on the annual time series revealed no significant trends on most stations using the Spearman trend test, at a 95% confidence level. The existence of serial correlation on annual and monthly time series was also investigated, but was not to be found present. Some change points were identified using Pettitt test but the changes were not significant. Figure 2.16 shows for example the anomalies of annual rainfall and the moving average for the stations of Machadodorp and Alkmaar. Annual and monthly rainfall also does not exhibit any clear trend of increase or decrease in most of the stations. This is consistent with the larger scale analyses conducted by Schulze (2012) and Shongwe et al. (2009).

Table 2.6: Description of rainfall stations analysed for trends, also the long term Mean Annual Precipitation (MAP) in mm/a, the standard variation, and detection of trend (confidence level of 95% using Spearman test) and occurrence change point (using Pettitt test)

							Analysis for the period 1950 to 2011			
Name	**Station ID**	**Latitude**	**Longitude**	**Altitude [MASL]**	**MAP [mm]**	**P Reliable [%]**	**Mean [mm/a]**	**St.Dev. [mm/a]**	**Trend Spearman**	**Pettitt**
MACHADODORP	0517430 W	-25.667	30.250	1563	781	79.6	773	134		
BADPLAAS (POL)	0518088 W	-25.967	30.567	1165	829	90.6	817	153		
KAAPSEHOOP	0518455 W	-25.583	30.767	1564	1443	78.5	1461	286		yes
MAC MAC (BOS)	0594539 W	-24.983	30.817	1295	1463	75.1	1501	287		
SPITSKOP (BOS)	0555579 W	-25.150	30.833	1395	1161	68.5	1197	266	yes	yes
ALKMAAR	0555567 W	-25.450	30.833	715	830	95.2	874	172		
OORSCHOT	0518859 W	-25.800	30.950	796	787	92.2	775	185		
BOSBOKRAND (POL)	0595110 W	-24.833	31.067	778	982	82.4	919	297		yes
PRETORIUSKOP	0556460 W	-25.167	31.183	625	707	60.0	734	188		
RIVERBANKANNEX RIVERBANK	0519310 W	-25.667	31.233	583	683	70.5	782	163		yes
PIGGS PEAK	0519448 A	-25.967	31.250	1029	1024	40.1	1075	315	yes	yes
SKUKUZA	0596179 W	-25.000	31.583	300	560	63.1	566	140		
RIVERSIDE	0557115 W	-25.417	31.600	315	547	66.5	520	187		
SATARA	0639504 W	-24.400	31.783	257	568	42.1	602	151		yes
FIG TREE	0520589 W	-25.817	31.833	256	591	63.4	594	145	yes	yes
TSOKWANE	0596647 W	-24.783	31.867	262	540	66.1	544	134		yes
KROKODILBRUG	0557712 W	-25.367	31.900	192	584	62.9	590	147		
MOAMBA	P821 M	-25.600	32.233	108	632	63.9	633	185		
XINAVANE	P10 M	-25.067	32.867	18	853	76.2	773	241		
MANHICA	P63 M	-25.400	32.800	33	883	86.2	903	275		yes

Explanatory Note: MAP is the Mean Annual Precipitation, and P reliable is the percentage of reliable data for the gauge, as assessed by Lynch (2003). The mean refers to the average of total annual precipitation for the period of 1950 to 2011. On the column trend Spearman only gauges that had trends significant at 95% confidence level are indicated with "yes". On the column Pettitt the "yes" indicates occurrence of some change points on the time series.

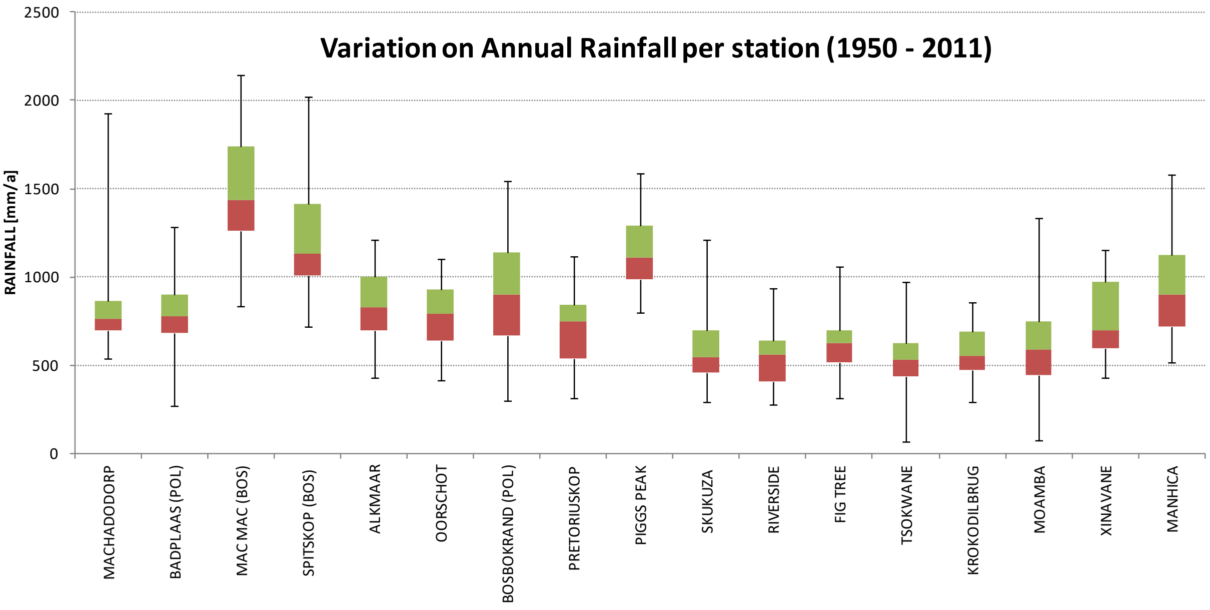


Figure 2.15: Box plot illustrating the spatial variation of annual rainfall across the Incomati basin (median, 25%, 75% are shown by the green and red boxes. The lines illustrate the range). The stations are presented from west to east, along basin profile.

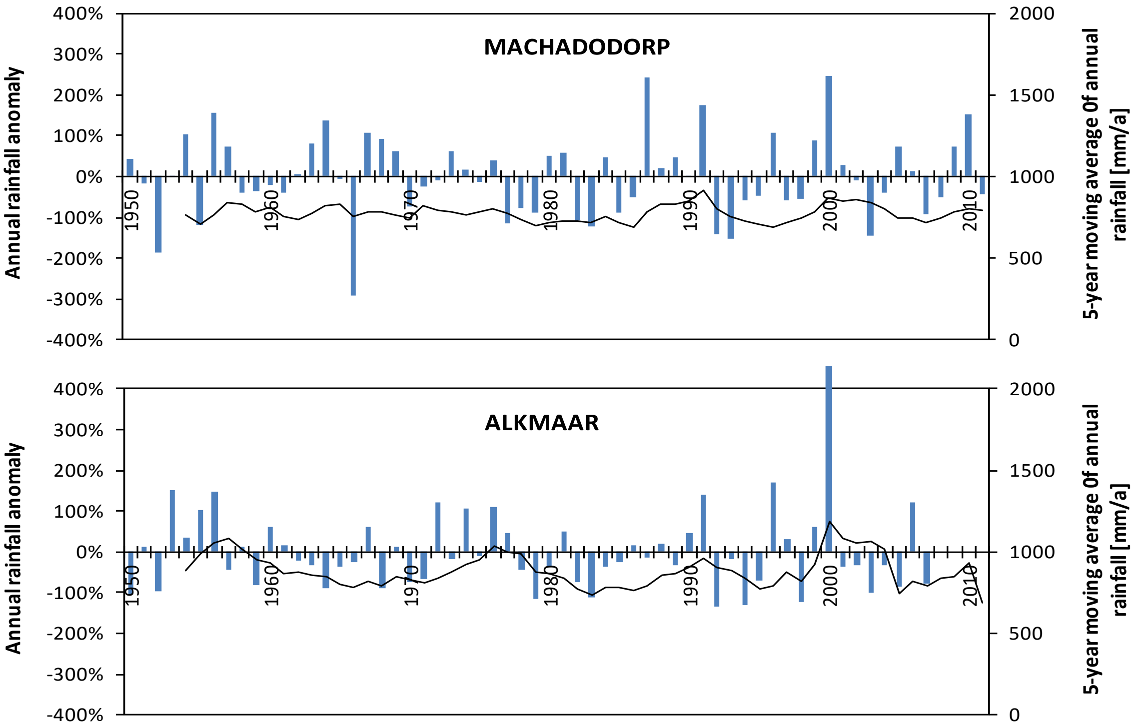


Figure 2.16: Annual rainfall anomalies (blue bars), computed as the deviation from the long term average 1950-2010 and 5 year moving of annual rainfall (black line, legend on the right).

Variability of streamflow

The metrics of the different hydrologic indicators were compiled as an output of IHA analysis. The results for the gauging stations located at the outlet (or the most downstream) of each main sub catchment are presented on Table 2.7. The variability is described using non-parametric statistics (median and coefficient of dispersion), because the hydrological time series are not normally distributed, but positively skewed; the mean (average) is much higher than the median (See Tables in Aurecon, 2010). The coefficient of dispersion (CD) is defined as CD = (75th percentile-25th percentile)/50th percentile. The higher the CD, the higher will be the variation of the parameter.

Table 2.7: Hydrological indicators of main sub catchments

		KOMATI		CROCODILE		INCOMATI		SABIE		INCOMATI	
STREAMFLOW INDICATORS	UNITS	X1H003 - TONGA		X2H016 - TENBOSH		X2H036 - KOMATIPOORT		X3H015 - LOWER SABIE		E43 - MAGUDE	
Period of Analysis:		1970-2011 (42 years)		1970-2011 (42 years)		1983-2011 (28 years)		1988-2011 (24 years)		1970-2011 (42 years)	
Drainage area	km^2	8,614		10,365		21,481		5,714		37,500	
		Median	*CD*	Median	*CD*	Median	*CD*	Median	*CD*	Median	*CD*
Annual*	**m^3/s**	**16.94**	***2.14***	**21.35**	***1.97***	**34.28**	***2.11***	**17.35**	***2.31***	**47.44**	***2.01***
October	m^3/s	3.95	*1.47*	2.54	*1.88*	2.24	*1.87*	3.08	*0.92*	8.72	*1.21*
November	m^3/s	5.72	*1.94*	5.75	*2.35*	7.09	*3.88*	4.81	*1.09*	16.14	*1.49*
December	m^3/s	11.46	*2.09*	15.07	*1.48*	18.79	*2.63*	10.83	*1.49*	22.91	*2.90*
January	m^3/s	17.26	*1.82*	20.68	*1.47*	34.47	*1.52*	18.52	*1.35*	37.96	*1.35*
February	m^3/s	25.09	*1.95*	31.37	*2.01*	29.77	*2.80*	16.33	*1.84*	45.09	*3.21*
March	m^3/s	18.33	*1.74*	27.15	*1.63*	42.15	*1.90*	19.51	*2.30*	51.75	*2.32*
April	m^3/s	11.64	*1.74*	19.82	*1.37*	24.10	*2.13*	13.69	*1.13*	34.90	*2.03*
May	m^3/s	8.03	*1.41*	9.11	*1.68*	9.98	*2.16*	7.04	*1.64*	17.85	*1.86*
June	m^3/s	4.96	*1.90*	5.66	*1.62*	7.10	*2.45*	5.64	*1.25*	14.04	*1.44*
July	m^3/s	3.77	*1.98*	4.56	*1.48*	4.72	*2.28*	3.79	*1.18*	10.41	*1.47*
August	m^3/s	2.67	*1.63*	2.63	*1.71*	2.51	*1.35*	3.40	*1.08*	8.46	*1.41*
September	m^3/s	2.43	*1.47*	2.08	*1.81*	2.24	*1.51*	2.69	*1.15*	7.06	*1.11*
1-day minimum	m^3/s	0.31	*4.04*	0.24	*2.64*	0.14	*5.29*	1.45	*1.13*	2.49	*1.48*
3-day minimum	m^3/s	0.38	*3.38*	0.32	*2.16*	0.25	*3.76*	1.53	*1.08*	2.71	*1.76*
7-day minimum	m^3/s	0.59	*2.55*	0.40	*2.88*	0.33	*4.35*	1.60	*1.16*	3.01	*1.61*
30-day minimum	m^3/s	1.46	*2.13*	1.52	*1.79*	1.29	*2.08*	2.01	*1.12*	4.84	*1.37*
90-day minimum	m^3/s	3.69	*1.47*	3.45	*1.34*	3.17	*2.09*	3.02	*1.23*	8.14	*1.38*
1-day maximum	m^3/s	134.4	*1.26*	142.2	*1.38*	274.3	*1.00*	113	*2.51*	381.5	*1.80*
3-day maximum	m^3/s	102.9	*1.50*	126.9	*1.33*	232.9	*1.15*	87.62	*2.60*	344.1	*1.74*
7-day maximum	m^3/s	81.79	*1.59*	107.4	*1.20*	201.4	*1.13*	62.55	*2.27*	273.7	*1.56*
30-day maximum	m^3/s	54.39	*1.45*	76.98	*1.28*	109.6	*1.33*	37.66	*1.93*	156.7	*1.45*
90-day maximum	m^3/s	39.19	*1.33*	45.08	*1.16*	68.69	*1.71*	28.06	*1.47*	102	*1.32*
Date of minimum	Julian Date	275	*0.10*	274	*0.12*	281.5	*0.15*	278.5	*0.06*	290.5	*0.21*
Date of maximum	Julian Date	38.5	*0.16*	33	*0.11*	35.5	*0.19*	20.5	*0.17*	39.5	*0.14*
Low pulse count	No	6	*1.63*	4	*1.63*	5	*1.55*	4	*1.00*	3	*1.33*
Low pulse duration	Days	5.5	*1.41*	5	*1.60*	3.5	*0.71*	6.5	*1.69*	6.75	*2.09*
High pulse count	No	6	*0.75*	4	*1.25*	5	*0.95*	4	*0.69*	4	*0.75*
High pulse duration	Days	4	*1.31*	4	*2.13*	4.5	*1.28*	5	*2.10*	8.5	*1.03*
Rise rate	m^3/s	0.7095	*1.39*	0.64	*0.98*	1.161	*1.38*	0.404	*1.12*	1.058	*1.43*
Fall rate	m^3/s	-0.7295	*-0.98*	-0.61	*-0.78*	-1.38	*-1.28*	-0.2398	*-1.10*	-0.6278	*-2.31*
Number of reversals	No	111.5	*0.26*	113	*0.42*	121	*0.18*	95	*0.29*	86	*0.49*

* On the annual statistics mean and coefficient of variation were used

The flow patterns are consistent with the summer rainfall regime with highest flow and rainfall events associated with tropical cyclone activity in January-March. At the E43-Magude station on the Lower Incomati, the median monthly flows range from 7 to 52 m^3/s.

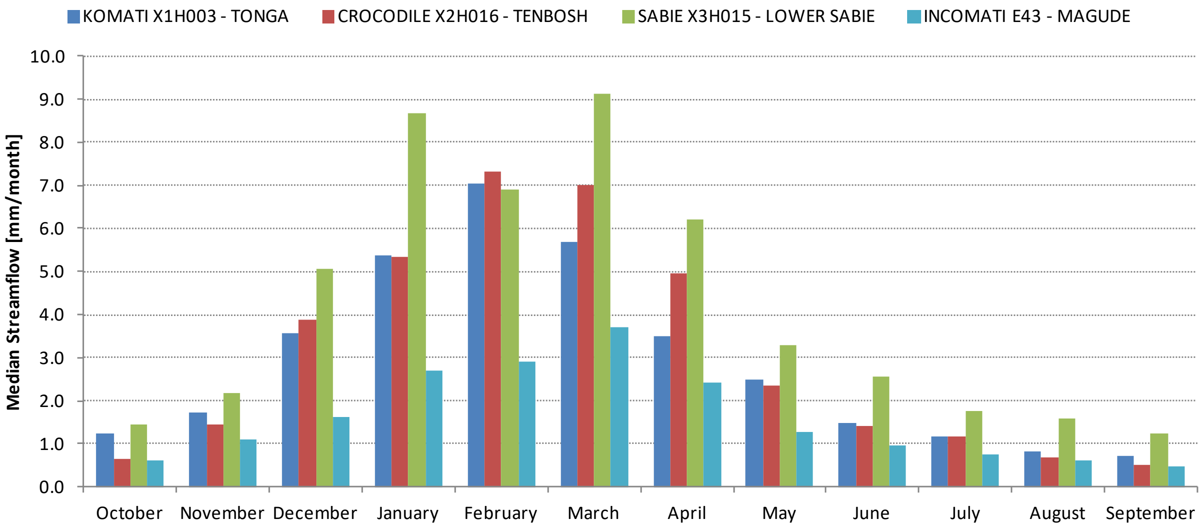


Figure 2.17: Median of observed daily streamflow for the gauges located at the outlet of major sub-catchments Komati, Crocodile, Lower Sabie and Incomati (based on daily time series from 1970 to 2011)

The comparison of the flow normalized by area (Figure 2.17) for the main sub-catchments reveals that the Sabie yields a higher runoff than Komati and Crocodile. This is the case because the observed streamflows include the impact of water abstractions and streamflow reduction activities which are more intense in the Komati and Crocodile catchments (Hughes and Mallory, 2008; Mallory and Hughes, 2012).

Another aspect to note is that the flows during February are likely to be higher than observed records, but are buffered due to flow regulation, and/or because high streamflow extremes are not fully captured by the current monitoring network.

Trends in streamflow

In Figure 2.18, the plot of trends indicated by the slope of the trend line is presented per selected hydrological indicator. For comparison, the same indicators are plotted for the periods 1970-2011 and for 1950-2011. The significant trends are highlighted with a circle. Table 2.8 presents the slope of the trend lines and P values for the gauges located at the outlet or most downstream point of each main sub-catchment.

The first observation is a significant trend of decreasing mean flow in October in almost all stations, especially the ones located on the main stem of Crocodile and Komati. This means that along the entire basin October is the month with greatest water stress. This is explained by the fact that this is the month of start of the rainy season, when the dam's levels are lowest and irrigation water requirements are highest (DWAF, 2009b; ICMA, 2010).

This trend is consistent with the decreasing trends of minimum flows, as exemplified by the 7-day minimum. In contrast, we can see that the count of low pulses increased significantly in many gauges, which indicates more frequent occurrence of low flows. Another striking trend is the significant increase of number of reversals of almost all stations, indicating the effect of flow regulation and water abstractions (reversals occur when the flow trend changes from increasing to decreasing).

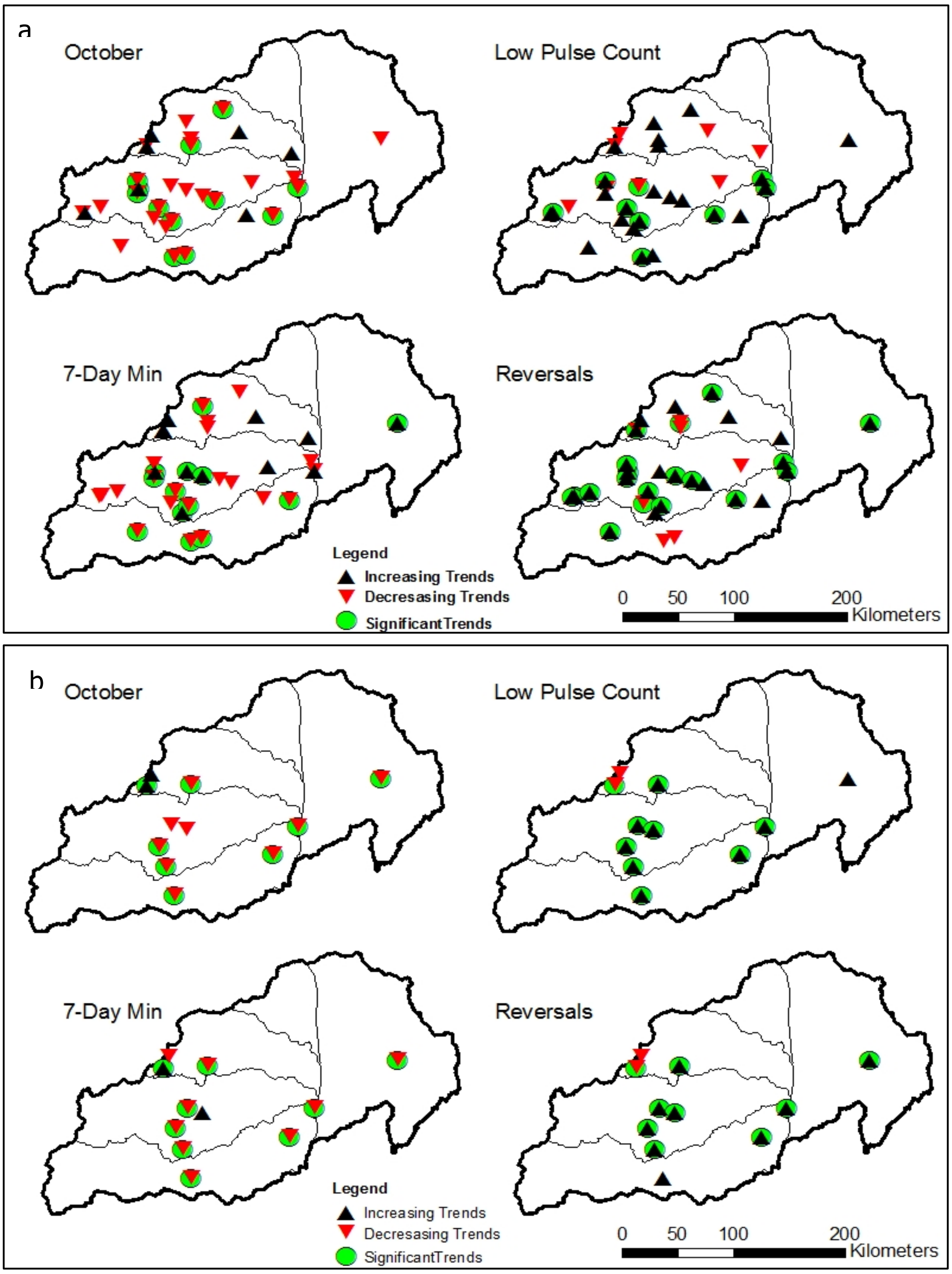


Figure 2.18: Trends of different indicators of streamflow: a) for period 1970-2011; b) for period 1950-2011

The significant trends (95% confidence level) occurring on the various indicators were counted per station and plotted on the map in Figure 2.19. The salient pattern on the map is that more significant decreasing trends occur in the Komati and Crocodile systems, which are also the most stressed sub-catchments. Another interesting aspect is that some of the trends cross-compensate each other. So some of the positive trends occurring on tributaries of the Crocodile, for example the October Median Flow and baseflow, are cancelled as we move downstream the main stem.

This phenomenon can also be observed at basin scale on the Sabie, where the trends of decreasing flows are not so frequent or significant. It is likely that this occurs because the majority of the Sabie falls under the conservation area of the Kruger National Park (KNP) and therefore no major abstractions occur here. Table 2.8 illustrates that many of the trends observed in the Sabie catchment are contrary to those observed on Komati and Crocodile. Thus, it is likely that the trends observed in downstream E43 – Magude, in Mozambique, are as a result of a combination of the positive effect of conservation approach of KNP on Sabie, and negative effect of flow reductions in Crocodile and Komati.

Table 2.8: Trends of the hydrological indicators for the period 1970-2011. In bold are significant trends at 95% confidence level.

	KOMATI		CROCODILE		SABIE		INCOMATI		INCOMATI	
STREAMFLOW INDICATORS	X1H003 - TONGA		X2H016 - TENBOSH		X3H015 - LOWER SABIE		X2H036 - KOMATIPOORT		E43 - MAGUDE	
Period of Analysis:	1970-2011 (42 years)		1970-2011 (42 years)		1988-2011 (24 years)		1983-2011 (28 years)		1970-2011 (42 years)	
Drainage area [km^2]	8,614		10,365		5,714		21,481		37,500	
	Slope	*Pvalue*	Slope	*Pvalue*	Slope	*Pvalue*	Slope	*Pvalue*	Slope	*Pvalue*
October	**-0.285**	***0.05***	-0.052	*0.5*	0.017	*0.5*	-0.017	*0.5*	-0.313	*0.25*
November	-0.254	*0.1*	-0.006	*0.5*	0.263	*0.5*	0.020	*0.5*	-0.165	*0.5*
December	-0.194	*0.5*	-0.090	*0.5*	0.199	*0.5*	0.783	*0.5*	-0.087	*0.5*
January	-0.437	*0.5*	-0.023	*0.5*	1.493	*0.25*	1.979	*0.25*	-0.960	*0.5*
February	-1.027	*0.1*	-0.927	*0.25*	0.544	*0.5*	-0.486	*0.5*	**-2.847**	***0.05***
March	-0.360	*0.5*	-0.397	*0.5*	0.390	*0.5*	-0.112	*0.5*	-1.346	*0.5*
April	-0.082	*0.5*	-0.007	*0.5*	0.899	*0.25*	1.532	*0.25*	-0.195	*0.5*
May	-0.225	*0.1*	-0.045	*0.5*	0.416	*0.5*	0.788	*0.5*	-0.365	*0.5*
June	**-0.215**	***0.025***	0.059	*0.5*	0.270	*0.5*	0.470	*0.5*	-0.045	*0.5*
July	**-0.179**	***0.005***	0.060	*0.5*	0.219	*0.5*	0.171	*0.5*	-0.039	*0.5*
August	-0.074	*0.1*	0.105	*0.5*	0.134	*0.25*	0.312	*0.5*	0.090	*0.5*
September	-0.029	*0.5*	0.134	*0.5*	0.081	*0.5*	0.218	*0.5*	0.166	*0.25*
1-day minimum	**-0.027**	***0.025***	-0.015	*0.25*	0.061	*0.1*	0.003	*0.5*	**0.139**	***0.001***
3-day minimum	**-0.029**	***0.025***	-0.015	*0.25*	0.061	*0.1*	0.004	*0.5*	**0.127**	***0.005***
7-day minimum	**-0.038**	***0.05***	-0.015	*0.5*	0.064	*0.1*	0.004	*0.5*	0.094	***0.05***
30-day minimum	**-0.069**	***0.025***	-0.025	*0.25*	0.058	*0.25*	0.033	*0.5*	0.054	*0.5*
90-day minimum	**-0.115**	***0.01***	-0.059	*0.25*	0.131	*0.1*	0.038	*0.5*	-0.054	*0.5*
1-day maximum	-5.143	*0.25*	-5.425	*0.25*	-2.743	*0.5*	-12.070	*0.25*	**-10.580**	***0.025***
3-day maximum	-3.749	*0.25*	-3.670	*0.25*	-1.379	*0.5*	-8.171	*0.5*	**-9.254**	***0.025***
7-day maximum	-2.361	*0.25*	-2.427	*0.25*	0.014	*0.5*	-3.742	*0.5*	**-6.722**	***0.05***
30-day maximum	-1.022	*0.25*	-1.023	*0.25*	0.662	*0.5*	0.092	*0.5*	-3.400	*0.1*
90-day maximum	-0.671	*0.25*	-0.576	*0.5*	0.789	*0.5*	0.934	*0.5*	-2.147	*0.25*
Date of minimum	-0.686	*0.5*	0.354	*0.5*	0.548	*0.5*	-0.420	*0.5*	1.374	*0.5*
Date of maximum	0.817	*0.5*	0.347	*0.5*	-3.222	*0.5*	0.288	*0.5*	0.617	*0.5*
Low pulse count	0.132	*0.1*	**0.238**	***0.001***	-0.045	*0.5*	0.185	*0.5*	0.043	*0.25*
Low pulse duration	0.068	*0.5*	-0.140	*0.5*	-0.669	*0.1*	-0.297	*0.25*	-0.602	*0.5*
High pulse count	**-0.127**	***0.005***	0.007	*0.5*	-0.023	*0.5*	-0.096	*0.25*	-0.068	***0.05***
High pulse duration	0.029	*0.5*	**-1.263**	***0.01***	1.081	*0.25*	0.144	*0.5*	-0.103	*0.5*
Rise rate	-0.007	*0.5*	-0.008	*0.5*	0.005	*0.5*	0.017	*0.5*	**-0.034**	***0.05***
Fall rate	0.003	*0.5*	**-0.013**	***0.05***	-0.007	*0.5*	-0.012	*0.5*	-0.007	*0.5*
Number of reversals	0.574	*0.1*	**1.083**	***0.01***	0.723	*0.5*	0.560	*0.5*	**0.764**	***0.005***

From Table 2.8 it can be seen that the Komati (Tonga gauge) sub-catchment is where most negative trends occur, particularly during the months of October, June and July. In the Crocodile (Tenbosch gauge) the trends are not visible, because a lot of cross-compensations have already occurred; The Kaap and Elands tributaries of the Crocodile River have significant decreasing trends in their mean monthly flows, as well as low flows. On the other hand, the Kwena dam, which is located on the main stem of the Crocodile, is managed in a way to augment the flows during the dry season. This results in increasing flows during the low flow months.

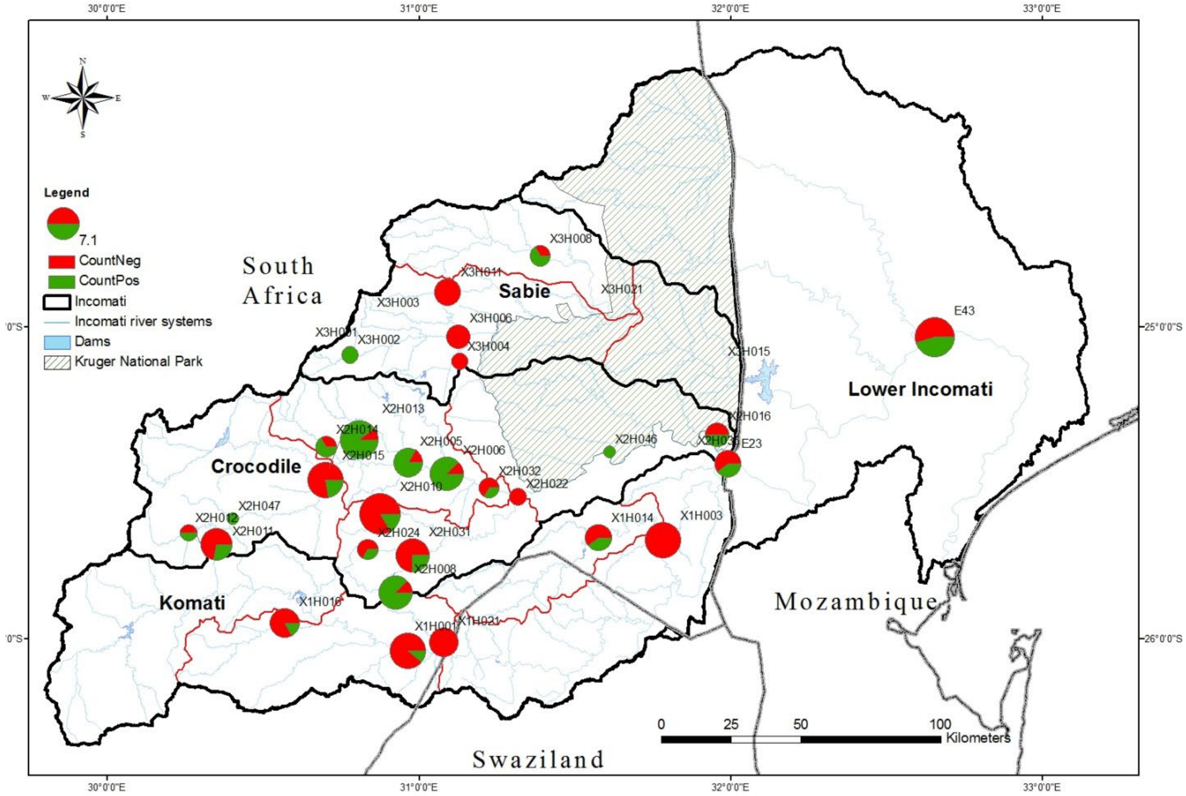


Figure 2.19: Count of significant trends. Declining trends in red and increasing trends in green. The size of the pie is proportional to the total number of significant trends

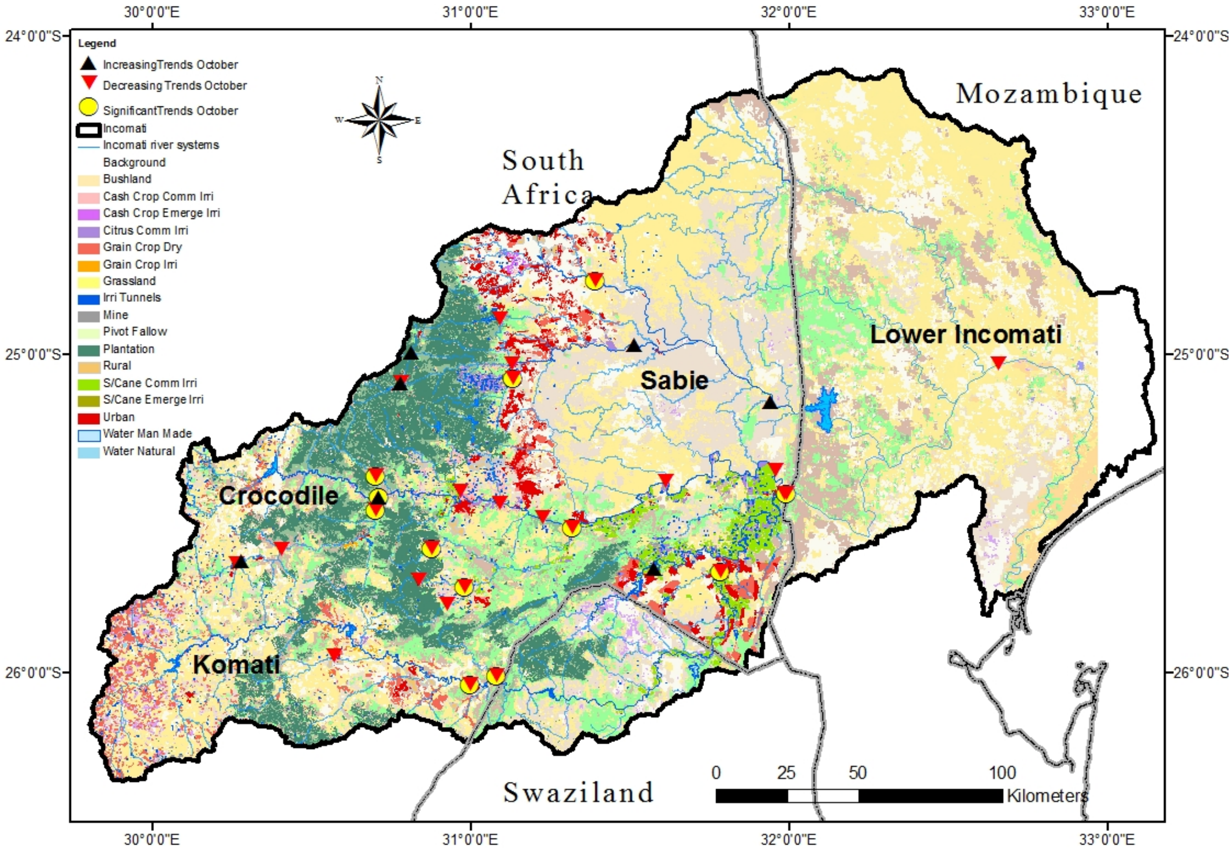


Figure 2.20: Land use-land cover map of Incomati (Aurecon, 2010; ICMA, 2010) and streamflow trends in the month of October.

It is important to note that these trends are even more pronounced when longer time series are considered. Below two examples from the Crocodile Basin are presented.

Example of decreasing trends: Noord Kaap X2H010

The Noord Kaap gauge showed the most intriguing trends. Out of the 33 IHA indicators this gauge had 12 significant trends, 10 of them negative, which indicates a major shift in flow regime over the period of analysis. However, there is no record of dam or major infrastructure being constructed (DWAF, 2009a), which suggests this could be the impact of land use change, namely forestry and irrigation. The decreasing trends occur in all months, are more pronounced during low flow months, particularly September (Figure 2.21) and October. There is a significant decrease of high flow and small floods and an increase of extreme low flows. The annual flow duration curve for the periods 1949-1974 and 1978-2011 show a dramatic decrease on annual flows. Figure 2.22 illustrates the comparison of median monthly flows for the 2 periods, including the range of variability of flow for the period of 1949-1974; From analysis of land use changes over time we can see that the sharp decrease of mean monthly flows during the 1960s coincides with the increase of area under irrigated agriculture; During the 1970s there was also a great increase of area under forestry, namely Eucalyptus (DWAF, 2009b). The commercial forestry consumes more water through evaporation than the native vegetation it replaces, and under the South African NWA, must be licensed as water user, as a Streamflow Reduction Activity (SFRA) (Jewitt, 2002; Jewitt, 2006b)

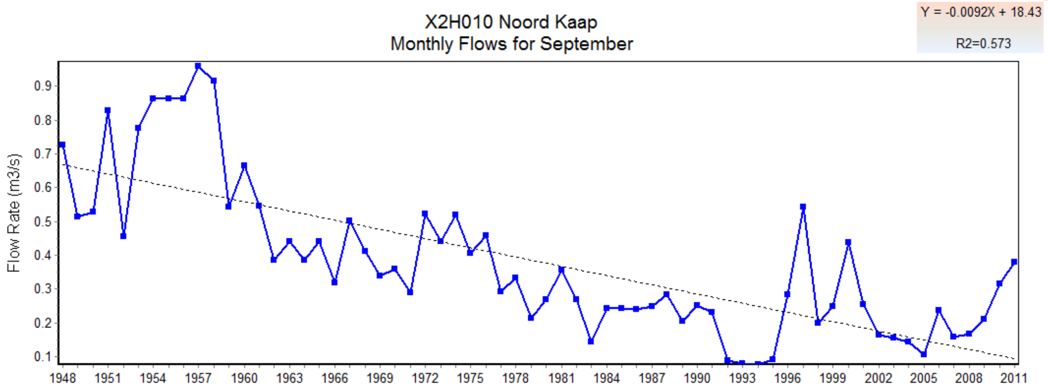


Figure 2.21: Plot of median monthly flows for September for the entire time series (1949-2011) on the Noordkaap gauge, located on the Crocodile sub-catchment.

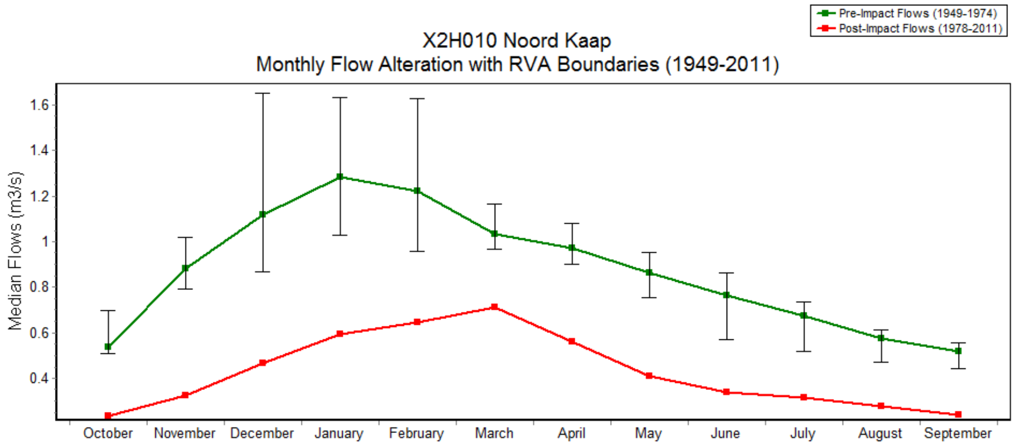


Figure 2.22: Plot of median monthly flows for 2 periods (1949-1974 and 1978-2011) on the Noordkaap gauge, located on the Crocodile Sub catchment.

2.2.3.2. Impact of Kwena dam (1984) on streamflows of the Crocodile River, Montrose gauge X2H013

Kwena dam is the main reservoir on the Crocodile system, located upstream in the catchment. The dam is used to improve assurance of supply of water for irrigation purposes in the catchment. The Montrose gauge is located a few kilometres downstream of this dam. The 2 period (1959-1984 and 1986-2011) analyses illustrated the main impacts of Kwena dam on the river flow regime, which are: reversed seasonality, dampening of peak flows and an increase on low flow and base flow indexes. These results are consistent with the analysis conducted by Riddell et al. (2014) which found significant alterations of natural flow regime on the Crocodile basin over the past 40 years. They developed a methodology to assess historical compliance with environmental water allocations, and reported that there is high incidence of non-compliance, reduction of low flows and some homogenisation of the flow regime as a result of dam operations. Similar impacts were found in studies in different parts of the world (Richter et al., 1998; Bunn and Arthington, 2002; Maingi and Marsh, 2002; Birkel et al., 2013).

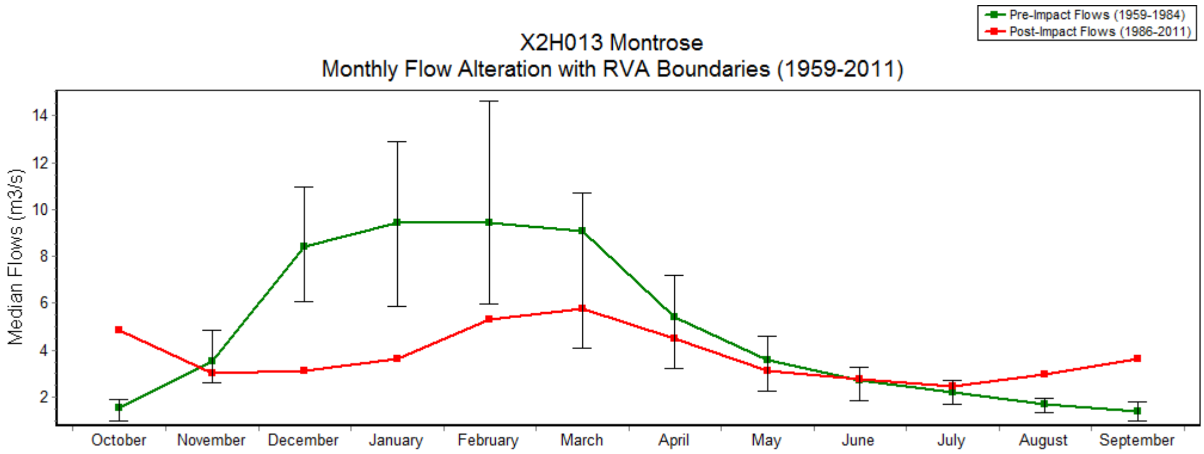


Figure 2.23: Impact of Kwena dam (1984) on streamflows of the Crocodile River, Montrose gauge X2H013

One can see that this reservoir is managed primarily to augment low flows whilst unintentionally attenuating headwater floods. This change in the flow regime influences the streamflow along the main stem of the Crocodile River, but as tributaries join it, and water is abstracted, the effect is reduced.

Impact of anthropogenic actions

As can be seen from water use information, the impacts of land-use change and waters abstractions are the main drivers of changes in the flow regime on the Incomati. However, the situation is variable along the catchment. For the Sabie system, in spite of significant areas of commercial forestry in the headwaters, the indicators of mean, annual and low flows do not show significant trends of decrease. This can be explained by the fact that most of the forestry area was already established during the period of analysis for trends (1970-2011) (DWAF, 2009c). When the entire time-series for some of the headwaters in the Sabie is considered, some decreasing trends can be found. The fact that a large proportion of the Sabie catchment is under conservation land-use (KNP, game reserves) also plays an important role in maintaining the natural flow regime.

On the Crocodile however, irrigated agriculture, forestry, mining and urbanization were the most important anthropogenic drivers. They affect the streamflow regime, the water quantity and likely the water quality as well. This has important implications when environmental flow requirements and minimum cross-border flows need to be adhered to. Pollard and du Toit (2011) and Riddell et al. (2014) have demonstrated that the Crocodile river is not complying to environmental flow requirements during most of the dry season.

Whilst in the Komati, the strategic water uses, which have first priority (such as water transfer to ESKOM plants in the Olifants catchment and to irrigation in the Umbeluzi) (Nkomo and Van der Zaag, 2004; DWAF, 2009d) have a high impact on streamflows. Because of other water requirements, for irrigation, forestry and other industries, the flow is already over allocated, and steady trends of decreasing flows could be identified. This is another system where the environmental flows and cross-border requirements are generally not met during the dry season (Pollard and du Toit, 2011).

2.2.4. Discussion

2.2.4.1. Limitations of this study

The available data series had some gaps, especially during high flow periods. Because of this the analysis of high flow extremes is limited. There was almost no data from gauges in completely pristine areas. For the trend analysis, the period of common data followed the construction of several impoundments and other developments.

Another challenge is the disparity of data availability across the different riparian countries. In Mozambique only two gauges had reliable flow data for this analysis, representing the entire Lower Incomati system. There is definitely a need to strengthen hydrometric monitoring network on the Mozambican part of the basin, as well as on the tributaries starting in the Kruger National Park.

Some gauges are from nested catchments. A lot of trends and alterations counter-balance each other, as can be seen clearly in the Crocodile system. However, some cases of contradictory trends that occurred could likely be explained by the change of measurement equipment and adjustment of the flow rating curves. Analysis of best quality stations and a number of stations in the same system was conducted to avoid this pitfall.

2.2.4.2. What are the most striking trends and where do they occur?

The analysis resulted in identification of major trends such as:

- Significant decreasing trends of the magnitude of monthly flow (particularly low flow months June to October), minimum flow (1-, 3-, 7-, 30 and 90-day minimum) and occurrence of high flow pulses;
- Significant increasing trends of the magnitude of monthly flow (August and September) in some locations in the Crocodile and Sabie, and on the occurrence of flow reversals basin wide;
- Some gauges showed no significant change or no clear pattern of change on the parameters analysed. These are mainly gauges located on the Sabie, which by 1970 had established the current land-use seen to the present day.

In the Komati system the flow regulation and water abstractions have very strong impacts on streamflow. Most gauges are already severely impacted, and it is quite difficult to characterize natural flow conditions. Flow regulation has highest impacts on low flow and minimum flows. On the Komati, there is significant irrigated agriculture, particularly sugar-cane. Also, the upstream dams of Nooitgedacht and Vygeboom are mainly used to supply cooling water to power stations of ESKOM outside the basin, thus, the water is exported and not used within the basin.

On the Crocodile system the flow regulation, through operation of Kwena Dam for example, has impacted on the attenuation of extreme flow events. The high flows are reduced, and the low flows generally increase, leading to reversed seasonality downstream of Kwena Dam. The dam is used to improve assurance of supply of water for irrigation purposes in the catchment. However, on X2H010 – Noord Kaap there is a significant and dramatic reduction of flows, shown on monthly flow, on flow duration curves and low flow parameters. This change is compared through inference using land-use data; with increase of area under forestry in the sub catchment, as well as with increase in irrigation (electricity was available in that region from 1960s).

In the Sabie system, most gauges did not show significant varied trends. This is most likely due to fewer disturbances: lower water demands, less water abstractions, and larger areas under conservation. During the period from 1970 to 2011, there are no clear impacts of climatic change (in terms of rainfall) on the streamflow.

2.2.4.3. Implications of this findings for water resources management

When analysis of trends is combined with the land-use of the basin (Figure 2.10), it is clear that the majority of gauges with decreasing trends are located in areas where forestry or irrigated agriculture dominate the land use, and where conservation approaches are less prevalent.

For the management of water resources in the basin, it is important to note that there are some clear patterns illustrated by the Sabie, Crocodile, Komati and Noord Kaap systems. For example, Sabie flows generated in upper parts of catchment persist through, whilst in other rivers where Kruger National Park or catchment forums are less of an influence, flows are highly modified. This suggests that the use of the conservation approach of KNP, through Strategic Adaptive Management, can be very beneficial to at least maintain environmental flows in the system. It is important to consider not only the magnitude of flows, but their duration and timing as well.

Dams do provide storage and attenuate floods to some extent in the basin, but have impacts downstream, such us the reduction of mean monthly flows and reversed seasonality, which can hamper the health of ecosystems downstream of the dams. So other possibilities of water storage should be further investigated and adopted in the basin in future, such as aquifer storage, artificial recharge, rainfall harvesting, etc. The design of operation rules for dams should also aim at mimicking the system's natural variability.

Given the likely expansion of water demands due to urbanization and industrial development, it is also important that water demand management and water conservation measures are better implemented in the basin. For example, there could be systems to reward users that use technology to improve their water use efficiency, and to municipalities that encourage their users to have lower water demands.

This study also shows the complexity of water resources availability and variability; this is even more relevant considering that this is a transboundary basin, and that there are international agreements regarding minimum cross-border flows and maximum development levels that have to be adhered to (Nkomo and Van der Zaag, 2004; Pollard and Toit, 2011; Riddell et al., 2012).

There is a great discrepancy of data availability between different riparian countries; it is very important that Mozambique in particular improves their monitoring network, in order to better assess impact of various management activities occurring upstream in other water management states.

A careful assessment of benefits derived from water use should be done, in order to assess if the first priority water uses are indeed the most beneficial basin wide.

The research conducted shows important interactions of the dynamics of streamflow that are complex and intertwined, often working simultaneously within a river basin.

Statistical analysis of rainfall data revealed no significant trend of either an increase or a decrease for the studied period. Although rainfall has a strong correlation with streamflow, this study concludes that land use and flow regulation are larger drivers of temporal changes in the streamflow in the basin. Indeed, over the past 40 years the areas under commercial forestry and irrigated agriculture has increased four-fold, increasing the water use basin wide.

The study therefore recommends that conservation approaches to water management that include strategic adaptive management should be further deployed in the basin. Water demand management and water conservation should be alternative options to the development of dams, and should be further investigated and established in the basin. The land use practices, particularly forestry and agriculture, have significant impact on water quantity and quality of the basin; therefore, stakeholders from these sectors should work closely with the water management institutions, to keep the minimum flow quantity and quality in the system.

2.3. Application of Remote Sensing data sets and information for Hydrological Modelling in the Inkomati catchment

(CHETTY, KT. GOKOOL, S. NAIDOO, P. VATHER, T.)

One of the aims of the RISKOMAN project is to improve understanding of the hydrology of the Inkomati catchment through earth observation (EO), new catchment information and improved hydrological modelling. This section therefore summarises the use of remote sensing data sets and information to improve the hydrological understanding of the Inkomati catchment. This research made use of satellite-based remote sensing of rainfall, evapotranspiration (ET) and soil moisture (SM) products. Full details are provided in Report 2 on the accompanying CD.

There is increasing pressure on the hydrological community to produce water resources information that is up to date and of use to decision makers. In order to meet this objective, reliable data is required at appropriate spatial and temporal scales and to drive hydrological models which are increasingly used in day to day water resources management and planning decision making, such as at the ICMA. Several research studies have assessed the potential or actual use of satellite-based observations in hydrology. A major focus of most of this research has been to develop and modify approaches to estimating hydrometeorological fluxes and states or variables (Schmugge et al., 2002). Land surface temperature, runoff, snow cover, water quality, elevation, landcover variables and surface roughness are some of the variables which can be estimated from remotely sensed data (Schmugge et al., 2002). Important fluxes such as ET, soil moisture and precipitation can also be estimated from remote sensing, many of which are subsequently incorporated into hydrological models. Therefore linking these spatially derived estimates to hydrological models for improved hydrological modelling would be useful and add value to catchment level decision making, thus addressing the project aim of obtaining a better understanding of the hydrology and water use of the Inkomati catchment.

The conceptual structure of the Australian Water Resources Assessment (AWRA) System (Figure 2.24) (Van Dijk and Renzullo, 2011) provides a context and possible starting point for application of satellite-based data as input for hydrological modelling to aid water resources management in South Africa.

This study has focused on the comparison, evaluation and application of remote sensing products of rainfall, evapotranspiration (ET) and soil moisture as a pioneering study to investigate these as potential sources of information and data for hydrological modelling in South Africa, using the Inkomati catchment as a study area. Thus, the overall aim of this study was to evaluate the potential of remote sensing data to provide important information and datasets for application in hydrological models, for the improved understanding of catchment hydrology.

Within this context, the specific objectives of this study are to compare and evaluate remote sensing rainfall products against observed gauge rainfall; evaluate the Surface Energy Balance System (SEBS) model (Su, 2002) for actual ET estimation; compare and evaluate RS soil moisture products against the observed data from sites in the Inkomati catchment; and finally acquire and process TRMM satellite-based rainfall for application in the ACRU hydrological model. The investigations and subsequent conclusions drawn from these studies are summarised in the following sub-sections.

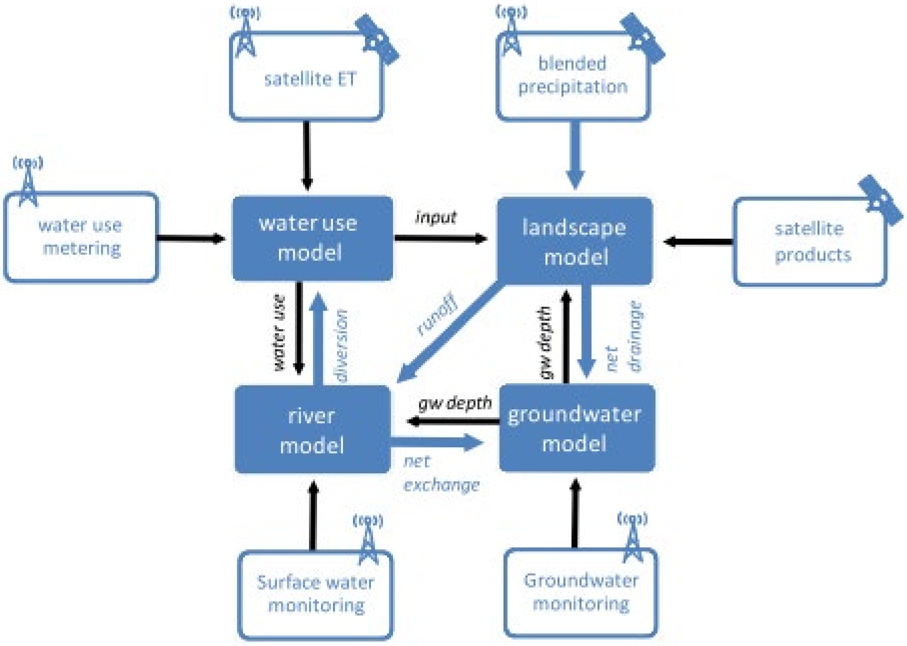


Figure 2.24: Conceptual framework of the AWRA system (Van Djik and Renzullo, 2011)

2.3.1. Remote Sensing Rainfall Products

Rainfall represents a vital component of the hydrological cycle, and is a key input for hydrological models (Sorooshian et al., 2000). Since rainfall is understood to be the driver of the hydrological cycle; accuracy of hydrological modelling predications depends on the quality of observed rainfall intensity, amount, duration and extent (Hughes, 2006). The main source of precipitation measurements for hydrological applications is provided by rain gauge data (De Coning and Poolman, 2011). However, rainfall is variable in space and time, and measurements are often subject to a low spatial resolution, lack of areal representation over land, and data unavailability over the oceans (Sorooshian et al., 2000). Furthermore, the quality, density and coverage of gauge networks vary significantly across the Earth (Huffman, 2006). Even in areas where rain gauge networks exist, there are still several limitations around the quality and length of datasets.

Rainfall amount and distribution is a difficult atmospheric parameter to determine, and it is often the limiting factor in modelling studies (Clark and 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 and 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, and arguably, is rapidly becoming a powerful tool for obtaining valuable weather information (Duan and Bastiaansen, 2013).

A review of literature on remote sensing of rainfall provided insight into the various remotely sensed rainfall products available and applications of these products across the world. The products that have been most extensively researched, globally, are:

- TRMM (Iguchi et al., 1998; Huffman, 2007; Collischonn et al., 2008).
- FEWS (Cohen Liechti et al., 2012);
- GPCP (Hsu et al., 1999; Huffman et al., 2001);
- NOAA (Xie and Arkin, 1996; Hong, 2004) and CMORPH (Joyce et al., 2004);
- PERSIANN (Sorooshian et al., 2000);
- TAMSAT (Grimes et al., 1999);
- TOVS (Susskind et al., 1997);

In this project a comparison and evaluation of the Tropical Rainfall Measuring Mission (TRMM) and Famine Early Warning System (FEWS) was undertaken in the Kaap sub-catchment of the Inkomati catchment. The research questions for this study are:

- Which of these two products is the most suitable for use in South Africa?
    - What are the main challenges associated with the use and application of these satellite-based rainfall products?

- Do satellite-based rainfall estimates compare satisfactorily with estimates from conventional rain gauges?
    - Are these satellite-based estimates within a sufficient range to gauged estimates?
    - How does seasonality influence the trends of rainfall estimates?

2.3.1.1. Method and Study Site

A commonly used validation process involves comparing data from single rain gauges with individual satellite pixels (Collischonn et al., 2008; Almazroui, 2011; Cheng et al., 2011; Duan and Bastiaanssen, 2013). TRMM and FEWS rainfall maps were downloaded from their respective websites, and compared to rain gauge measurements in the Kaap catchment of the Inkomati basin. VISAT 4.7 and ArcGIS 9.3 were used for image processing and creation of output maps, since this software was most accessible, and freely available at most University of KwaZulu-Natal (UKZN) computer LANs. Satellite data was downloaded for the main summer (December and January) and winter months (June and July) between 01/12/2011-31/01/2013. The rain gauge selection criteria were based on reliability and length of record, as well as location within the satellite pixel. After evaluating the attributes and quality of rainfall records for all the rain gauges located within the Kaap sub-catchment of the Inkomati basin, two rain gauges were selected; Roffiekultuus (011017FC) and Nelshoogte (011017FE). Statistical analyses were performed on the output maps and rainfall estimation trends between TRMM, FEWS and rain gauge data, were identified. The resultant trends were evaluated in order to determine how the satellite rainfall estimates compared to observed rainfall, and whether the satellite rainfall estimation products could provide inputs for hydrological modelling.

As seen in Figures 2.25 and 2.26, FEWS satellite data had a greater spatial resolution (0.1°) than TRMM (0.25°). 15 December 2011 was the date chosen to highlight the difference in spatial resolution; since there were rainfall events that led to estimations, from satellite and rain gauge data, which were within a satisfactory range of each other.

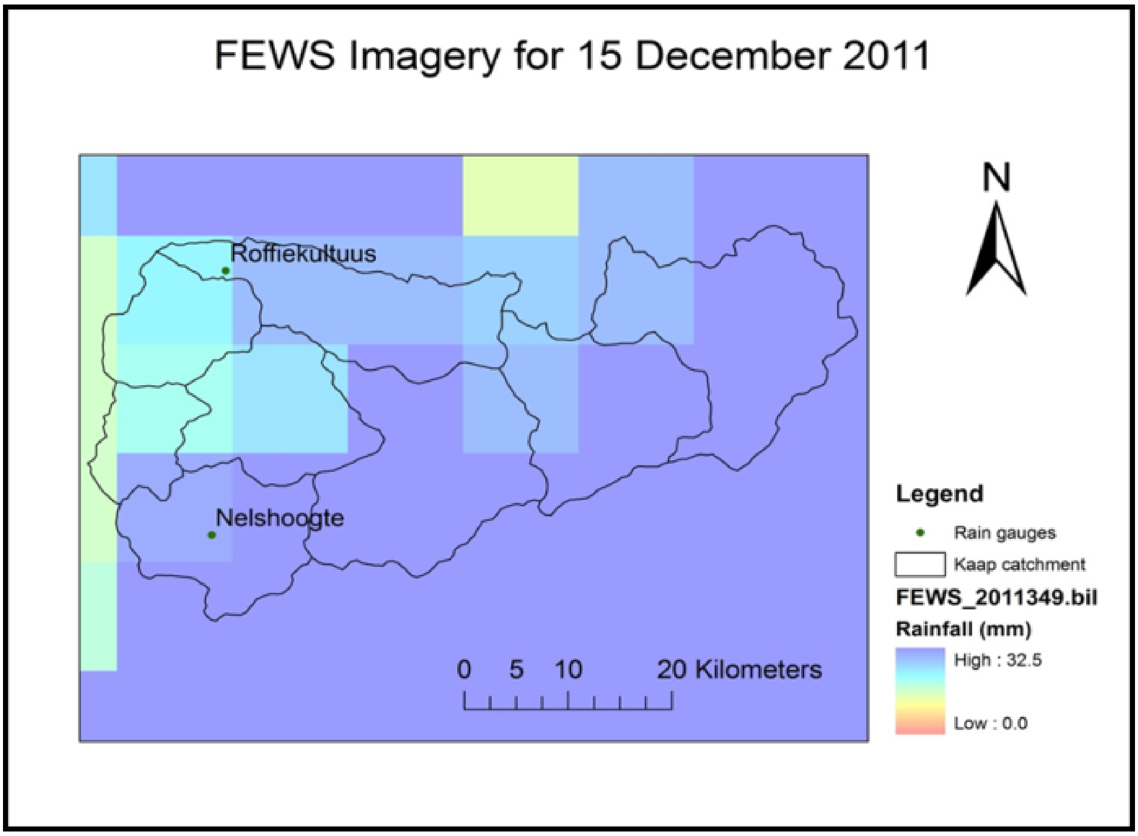


Figure 2.25: FEWS satellite data for Kaap sub-catchment, December 2011

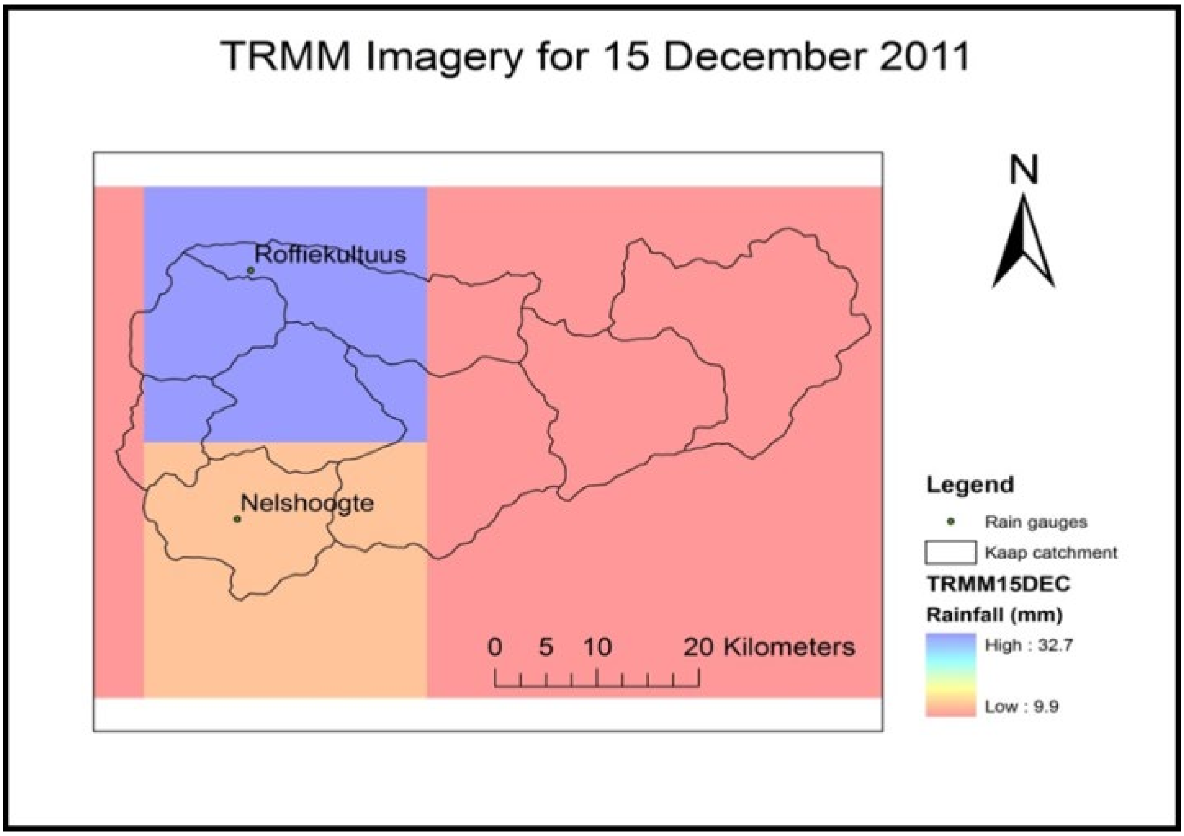


Figure 2.26: TRMM satellite data for Kaap sub-catchment, December 2011

2.3.1.2. Results

As seen in Figure 2.27, both satellite products matched the general trends of the rain gauge, with FEWS exhibiting a greater underestimation than TRMM. After 2nd January 2012, there was a peculiar occurrence of continuously low rain gauge values, coupled with relatively high satellite estimations. This could be due to instrument error or high intensity rainfall events, but this could not be verified in this study. More representative results were seen in Figure 2.28; satellite estimations closely matched the trends of the rain gauge data. However, TRMM rainfall data occasionally predicted rainfall events prior to the rain gauge reading, and on certain days it exhibited significantly higher rainfall values (67.49 mm on 05/01/2012) than FEWS (3 mm) and rain gauge sources (2.8 mm). Table 2.9 shows the performance statistics for TRMM and FEWS data for the different rain gauges and highlights the underestimation of satellite rainfall.

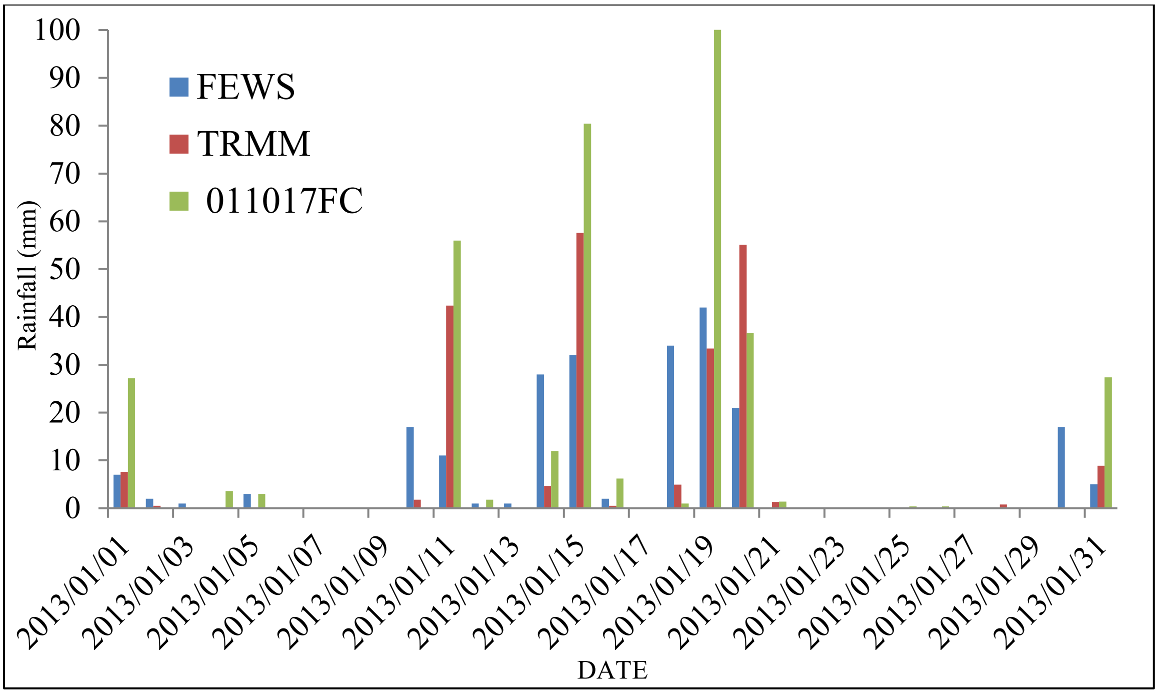


Figure 2.27: FEWS and TRMM rainfall estimations compared to Roffiekultuus (011017FC) rain gauge data, for 1st December 2011 to 31st January 2013

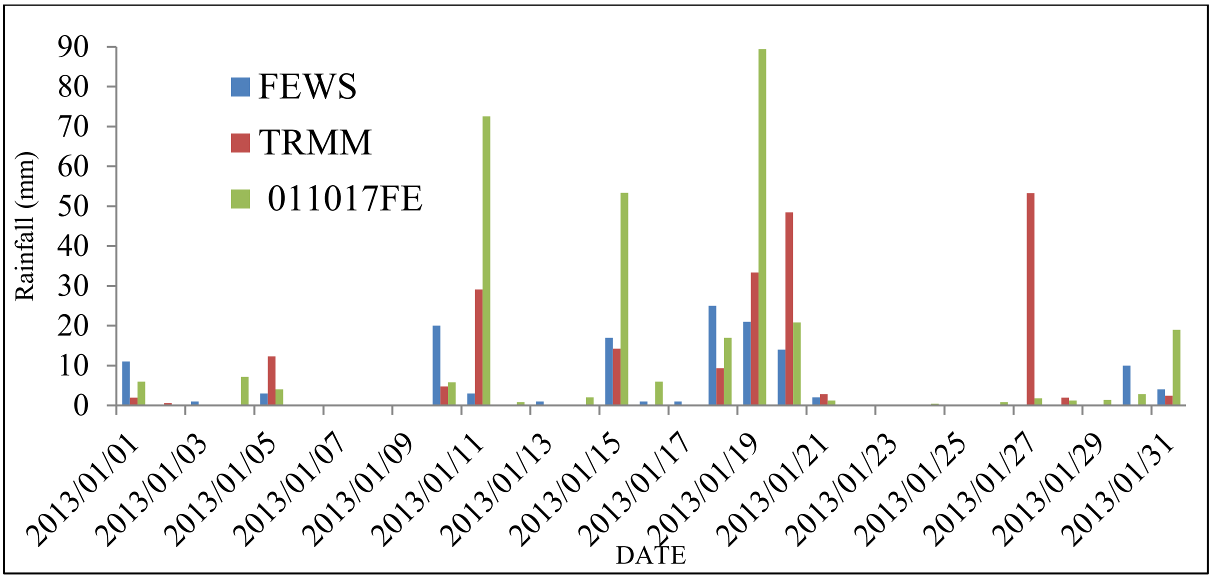


Figure 2.28: FEWS and TRMM rainfall estimations compared to Nelshoogte (011017FE) rain gauge data, for 1st December 2011 to 31st January 2013

Table 2.9: Statistical comparisons for TRMM and FEWS datasets against the selected rainfall stations

COR: Correlation Co-efficient RMSE: Root Mean Square Error

	Roffiekultuus (011017FC)						Nelshoogte (011017FE)					
	COR		RMSE		R Squared		COR		RMSE		R Squared	
DATE	FEWS	TRMM	FEWS	TRMM	TRMM	FEWS	FEWS	TRMM	FEWS	TRMM	TRMM	FEWS
Dec 11-Jan 12	0.158	0.371	12.452	12.495	0.138	0.250	0.702	0.553	9.081	11.580	0.493	0.306
Jun 12-Jul 12	N/A	N/A	0.077	0.077	N/A	N/A	N/A	N/A	0.183	0.183	N/A	N/A
Dec 12-Jan 13	0.798	0.731	16.700	16.938	0.535	0.636	0.575	0.575	13.980	13.837	0.331	0.331

Conclusions drawn from the study indicated that overall, when compared to observed gauge data, TRMM exhibited more satictory rainfall estimates, compared to FEWS, for the Kaap sub-catchment. However, both satellite products provided representation which is considered adequate when compared to the rain gauge data. TRMM, despite having a lower spatial resolution, utilises more advanced and improved algorithms that generate sufficiently accurate and valuable rainfall estimates for a global dataset (Huffman, 2007; Collischonn et al., 2008). FEWS, which provides rainfall estimates for a southern Africa dataset, at a finer resolution is a useful alternative, it is more user-friendly, and provides adequately representative rainfall estimates. The results could be viewed as evidence that the satellite products evaluated could provide the rainfall input required for hydrological modelling, however, this must tempered by the small dataset used in this initial assessment. Therefore, it is concluded that the use of satellite imagery could be beneficial for the modelling of catchments that lack an adequate network of rain gauges. TRMM rainfall estimates, and to a lesser extent, FEWS rainfall estimates, could ultimately improve predictions of hydrological modelling, especially in data sparse or ungauged catchments.

2.3.2. Actual ET Estimation from the Surface Energy Balance System (SEBS)

Within South Africa there is a diverse range of water users, all competing for a share of a limited resource (Jarmain et al., 2009). Consequently, the need to accurately estimate and understand the temporal and spatial variations of total evaporation takes on added significance (Jarmain et al., 2009). An array of techniques have been proposed to estimate total evaporation from the crop surface, however these techniques often prove to be complex to apply, data intensive, and are generally limited to small spatial scales and homogenous land covers (Li et al., 2009). The continued advances in satellite earth observation and geographic information system technologies have provided an invaluable approach to practitioners requiring reliable total evaporation data over large temporal and spatial scales.
Courault et al., 2005 and Verstraeten et al., 2008; identify and discuss in detail, four broad classes of techniques which are based on satellite earth observation and used to estimate

total evaporation. These include techniques based on residual methods of the energy balance, empirical direct methods, deterministic methods, and the vegetation index approach. The estimation of total evaporation as a residual of the shortened energy balance is a commonly applied technique for both operational and scientific research purposes (Jarmain et al., 2009).

Some of the commonly applied techniques include; the Surface Energy Balance Index (SEBI), The Surface Energy Balance Algorithm for Land (SEBAL), The Surface Energy Balance System (SEBS), Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC), and The MODIS evaporation product (MOD 16).

The research outlined in this section forms part of the broader RISKOMAN project by providing a review of satellite earth observation techniques and an application to generate a total evaporation time series which can be incorporated into a hydrological model. After a detailed review of the available literature on the use of satellite earth observation techniques to estimate total evaporation, the SEBS model was selected for application. The SEBS model, developed by Su (2002) is a single sourced surface energy balance model which can be utilized to estimate turbulent fluxes within the atmosphere or to determine the evaporative fraction through the use of remote sensing and meteorological data for both local and regional scales (Su, 2002; Jin, 2005; Hailegiogis, 2006; Badola, 2009; Jarmain et al*.,* 2009; Li et al., 2009; Van de Kwaast, 2009; Gibson et al., 2011; Ma, 2011; Ma, 2012; Muhammed, 2012; Abelrady, 2013).

The SEBS model permits the use of data obtained from a variety of satellite sensors, this data is available at varying spatial, temporal, and spectral resolutions. A number of utilities are available within the model to integrate meteorological data and satellite earth observation data to estimate daily total evaporation (Su, 2002). According to Su (2002) there are three primary sets of data required by SEBS to estimate the daily total evaporation for any region. This data is obtained from two sources, i.e. through satellite earth observation systems measuring spectral reflectances and radiances of the land surface, and meteorological stations.

2.3.2.1. Methodology

The methodology adopted in this study was aimed at assessing the usefulness of remote sensing in the estimation of daily total evaporation and how this can be used in hydrological modeling studies. The approach was tested at a research site in Komatipoort in order to compare the daily total evaporation estimates from SEBS against historical daily total evaporation estimates, obtained from a field site where the Surface Renewal technique, was being applied. The study covered the period 01st December 2011 to 25th November 2012. The Surface renewal dataset was compiled in a separate study WRC K5/2079/4 by Dr Caren Jarmain and the system was set up on a sugarcane field in Komatipoort (co-ordinates: 25 35'

40" S and 31 53' 33" E) . The aims of this study are to validate the SEBS model against historic observed surface renewal data and, to identify a suitable infilling technique which can be used to provide missing data in a total evaporation time series.

Performance statistics were used to analyze the results from the comparisons between the total evaporation estimates from the SEBS model and the historical total evaporation estimates obtained from the surface renewal system. The statistics used in this study were the mean, median, standard deviation, relative volume error and a two sample t-test. The relative volume error was determined by comparing the SEBS total evaporation estimate against the corresponding historical total evaporation estimates obtained from the surface renewal system. These statistics have been used in a variety of studies in which satellite earth observation data is used to estimate total evaporation (Su, 2002; Badola, 2009; Jarmain, 2009; Yang, 2010; Elhag, 2011; Gibson et al., 2011; Rwasoka et al., 2011; Gokool et al., 2012; Muhammed, 2012). The two sample t-test was conducted to assess if there was any significant difference between the means of the historical total evaporation estimates obtained from the surface renewal system and the total evaporation estimates from the SEBS model.

Infilling techniques used to create a continuous daily total evaporation time series

The linear interpolation technique and the Kc_{act} technique were applied in this study. These techniques were selected based on their relative ease of application, simplicity and the data requirements of the technique. Muhammed (2012) applied a simplistic linear interpolation technique to infill missing data in a total evaporation time series, which could be attributed to presence of clouds cover, error in data collection, or the temporal resolution of the satellite sensor.

The linear interpolation technique described in Muhammed (2012) is given as

$$ET_2 = [(ET_3-ET_1)/X_3-X_1)]\ (X_2-X_1) + ET_1$$

Where ET_2 = The unknown daily total evaporation value (mm/day)
ET_1 = The first known daily total evaporation value (mm/day)
ET_3 = The next known daily total evaporation value (mm/day)
X_1 = The Julian day for ET_1
X_2 = The Julian day for ET_2
X_3 = The Julian day for ET_3

The Kc_{act} technique derived and discussed in Santos et al. (2008) was used to incorporate total evaporation estimates derived from a satellite-based remote sensing technique, i.e. Mapping Evapotranspiration with high Resolution and Internalized Calibration (METRIC), into a Water Balance model, with the aim of improving irrigation scheduling in the Genil Cabra Irrigation Scheme, Spain. Santos et al. (2008) describe Kc_{act} as the ratio between total evaporation and the reference evaporation which is determined using the standardized Penman-Monteith technique (ASCE-EWRI, 2005). It is important to note that the Kc_{act} differs from the Kc described by Allen et al. (1998), (Santos et al., 2008).

$Kc_{act} = AET/ET_0$

Where Kc_{act} = Actual Kc
AET = Total evaporation
ET_0 = Reference evaporation

In order to assess which technique would be most suitable to infill potential missing data in the SEBS total evaporation time series to be created for this study, a preliminary investigation involving two tests was undertaken. A time period of 6 months, i.e. from 01st Jan 2012-30th Jun 2012 was used to conduct the preliminary investigation.

The first test made use of the observed historical daily total evaporation record from surface renewal system, which was obtained for studies undertaken by Jarmain (2012) and Jarmain et al. (2013). Forty five known total evaporation values obtained from the surface renewal system were hidden for the aforementioned time period. These values were treated as missing data. The linear interpolation technique and the Kc_{act} technique were then applied to these forty five days to infill the missing data records. The forty five days were selected randomly and of these 45 days, the maximum number of consecutive days which required infilling was preset as 3 days. The rationale behind a 3 day selection period was because the 3 days were the maximum number of consecutive days in which a SEBS total evaporation estimate could not be produced.

In the second test, SEBS daily total evaporation estimates generated for the period 01st Jan 2012-30th Jun 2012 were utilised. Forty five random days of known SEBS estimates were hidden. Both the linear interpolation technique and the Kc_{act} technique were then applied to infill the (hidden) missing data records.

Results from Test 1:

The linear interpolation technique and Kc_{act} technique were applied to the observed data set. Tables 2.10, 2.11 and 2.12 indicate the results of the investigations. The use of the linear infilling technique to estimate missing daily total evaporation values yielded positive results, producing an average relative volume error of less than 20%, a root mean square error of 0.90 and a R^2 value of 0.67. The results of the t-test indicate a fairly good agreement between the known surface renewal values and the linear in-filled surface renewal values and show no significant difference between their means. The use of the Kc_{act} technique to estimate missing daily total evaporation values yielded positive results, producing an average relative volume error of less than 10%, a root mean square error of 0.6 and a R^2 value of 0.84. These statistics as well as the results of the t-test indicate a good agreement between the known surface renewal values and the Kc_{act} in-filled surface renewal values and show no significant difference between their means.

Both the techniques appear to be in fairly good agreement with the observed data for the forty five random days and they are able to capture the trends of the observed data. The results of the t-tests shown in Table 2.5 indicate that the null hypothesis can be accepted for both the techniques at the 95% confidence interval. However it must be noted, on average the two techniques marginally over-simulate the daily total evaporation that would be expected for the forty five days. This can be noted in Tables 2.3 and 2.4 by the negative value for the average relative volume error.

Table 2.10: Statistical comparison between observed total evaporation vs infilled total evaporation using linear interpolation for 45 random days during the period 01st Jan 2012 to 30th Jun 2012.

	Surface Renewal ET	Surface Renewal ET (Infilled)	Relative Volume error (%)
Total (mm)	122.16	124.33	-1.78
Average (mm/day)	2.71	2.76	-18.56
Median (mm/day)	2.76	2.56	
Variance	2.47	2.06	
Standard Deviation (mm/day)	1.57	1.43	
Max (mm/day)	6.07	6.00	
Min (mm/day)	0.42	0.63	
RMSE (mm/day)	0.90		
R^2	0.67		

Table 2.11: Statistical comparison of observed total evaporation vs infilled total evaporation using Kc_{act} for 45 random days during the period 01st Jan 2012 to 30th Jun 2012.

	Reference ET	Surface Renewal ET (Infilled)	Surface Renewal ET	Relative Volume Error (%)
Total (mm)	163.70	121.17	122.16	0.81
Average (mm/day)	3.64	2.69	2.71	-9.21
Median (mm/day)	3.50	2.49	2.76	
Variance	1.75	2.19	2.47	
Std Dev (mm/day)	1.32	1.48	1.57	
Max (mm/day)	6.70	6.03	6.07	
Min (mm/day)	1.60	0.65	0.42	
RMSE (mm/day)	0.60			
R^2	0.85			

Table 2.12: Two sample t-test for the difference between means, comparison of linear infilling and observed data as well as Kc_{act} and observed data.

Technique	Df	T-test (p-value)	Rejection region for null hypothesis (95% confidence)	T-statistic	Rejection region for null hypothesis (95% confidence)	Accept/Reject
Linear Int	44	1	$p < 0.05$	0.15	$1.96 < T < -1.96$	Accept
Kcact	44	0.95	$p < 0.05$	0.07	$1.96 < T < -1.96$	Accept

Results from Test 2:

The linear interpolation technique and Kc_{act} technique were applied to the hidden days in the SEBS data set. Tables 2.13, 2.14 and 2.15 indicate the results of the investigation. The use of the linear in-filling technique to estimate missing daily total evaporation values yielded poor results, producing an average relative volume error of less than 20%, a root mean square error of 1.54 and an R^2 value of 0.27. These statistics as well as the results of the t-test indicate a satisfactory agreement between the known SEBS values and the linear in-filled SEBS values and show no significant difference between their means.

Table 2.13: Statistical comparison of SEBS total evaporation vs infilled total evaporation using linear interpolation for 45 random days during the period 01st Jan 2012 to 30th Jun 2012.

	Surface Renewal ET	Surface Renewal ET (Infilled)	Relative volume error (%)
Total (mm)	201.12	195.49	2.80
Average (mm/day)	4.47	4.34	-19.78
Median (mm/day)	4.34	4.07	
Variance	3.24	1.40	
Std Dev (mm/day)	1.80	1.18	
Max (mm/day)	8.75	8.15	
Min (mm/day)	0.00	2.09	
RMSE (mm/day)	1.54		
R^2	0.27		

The use of the Kc_{act} technique to estimate missing daily total evaporation values yielded poor results as well, producing a root mean square error of 1.96 and an R^2 value of 0.37. These statistics as well as the results of the t-test indicate a poor agreement between the known SEBS values and the Kc_{act} in-filled SEBS values and show a significant difference between their means. Although the technique produced an average relative volume error of 21%, this result alone was not enough to justify that the technique performed well.

Table 2.14: Comparison of SEBS total evaporation vs In-filled ET using Kc_{act} for 45 random days during the period 01st Jan 2012 to 30th Jun 2012.

	Reference ET	Surface Renewal ET (Infilled)	Surface Renewal ET	Relative volume error (%)
	201.12	163.70	141.68	29.55
Total (mm)	4.47	3.64	3.15	21.69
Average (mm/day)	4.34	3.50	3.05	
Median (mm/day)	3.24	1.75	1.99	
Variance	1.80	1.32	1.41	
Standard Deviation (mm/day)	8.75	6.70	5.85	
Max (mm/day)	0.00	1.60	1.33	
Min (mm/day)	1.96			
RMSE (mm/day)	0.27			
R^2				

Table 2.15: Two sample t-test for the difference between means, comparison of linear in-filling and SEBS data as well as Kc_{act} and SEBS data.

Technique	Df	T-test (p-value)	Rejection region for null hypothesis (95% confidence)	T-statistic	Rejection region for null hypothesis (95% confidence)	Accept/Reject
Linear Int	44	0.7	$p < 0.05$	0.39	$1.96 < T < -1.96$	Accept
Kcact	44	0	$p < 0.05$	4.04	$1.96 < T < -1.96$	Reject

Both techniques have been shown to perform poorly on the known SEBS data set. The two techniques appear to roughly follow the same trend as the SEBS data. On average, the linear interpolation technique over-simulates the total evaporation value for a specific day whilst on average the Kc_{act} technique under-simulates the total evaporation value, which is generated by SEBS.

The results of the t-test shown in Table 2.8 indicate that the null hypothesis for the linear interpolation technique can be accepted at the 95% confidence interval, whilst for the Kc_{act} technique the null hypothesis will be rejected at the 95% confidence interval.

Taking into consideration the results obtained for each of the scenarios, the linear interpolation technique was chosen to infill the missing data in the SEBS daily total evaporation time series which was to be generated. The effects of cloud coverage within the MODIS level1_B images resulted in no daily total evaporation values being generated for twenty eight days of the entire SEBS time series. The linear infilling technique was applied to these days in order to create a complete time series.

Comparison of SEBS daily total evaporation estimates against observed historical daily total evaporation

The daily total evaporation estimates generated by SEBS for the time period 01st December 2011-25th November 2012 were compared with observed historical surface renewal estimates for the corresponding time period. The comparison between the SEBS daily total evaporation estimates and the Surface Renewal daily total evaporation estimates show considerable variations over the entire time period. The average daily relative volume error during the months of December and January is less than 16%, whilst February is less than 21% which indicates a fairly good agreement between the SEBS daily total evaporation estimates and the observed data.

The poor correlation between the observed data and the SEBS daily total evaporation estimates begins from the month of March onwards up until September. With the exception of the month of March, the average relative volume error is close to a 100% or exceeds a 100%. This indicates that the estimates generated by SEBS are close to double that of the total evaporation which is observed. The correlation between the observed data and the SEBS daily total evaporation estimates then begins to improve from October onwards.

The monthly comparisons between the SEBS estimates and the observed data indicate that the SEBS model has a consistent bias when estimating daily total evaporation for the study area. The model has a tendency to perform better during the warmer parts of the study period. A two sample t-test was conducted for the time period 01st December 2011-25th November 2012. The results of the t-test presented in table 11 further serve to confirm the observation that the SEBS model has a consistent bias when estimating daily total evaporation. The null hypothesis is accepted during the warmer periods of the time series, i.e. December, January, February and March at the 95% confidence level indicating that there is no significant difference between the means between the surface renewal total evaporation estimates and the SEBS total evaporation estimates.

However during the colder periods of the time series, i.e. from April to August, the null hypothesis is rejected at both the 95% confidence level indicating a significant difference between the means between the surface renewal total evaporation estimates and the SEBS total evaporation estimates. This trend can also be seen in the time series comparison between SEBS and the Surface Renewal technique illustrated in Figure 2.29. Although the null hypothesis has been rejected at the 95% confidence interval for the months of September and November the SEBS model was found to have performed considerably better in these months as opposed to the months of the colder period.

Although there is a poor correlation between the observed data and the SEBS daily total evaporation estimates, the seasonal trends which are displayed in the observed data set are captured within the SEBS daily total evaporation time series. Overall, the comparison between the SEBS daily total evaporation estimates and the surface renewal total evaporation estimates for the entire duration of time period indicates a very poor relationship.

The poor relationship between the SEBS estimates and the observed data is attributed to three possible causes, i.e. the difference in the spatial resolution between SEBS and the Surface Renewal technique, the effects of cloud coverage and the infilling of missing data in the observed record. The SEBS estimates are generated through the use of MODIS level 1_B data which is collected at a spatial resolution of 1km whereas the Surface Renewal technique operates at a point scale. According to McCabe and Wood (2006), MODIS has a restricted ability in capturing the spatial variability of energy fluxes at the field level. Coarse resolution satellite earth observation data may be appropriate for the partitioning of energy at the catchment scale however at the field scale, high resolution spatial data is required in order to adequately detect inter-field variations (Gibson et al., 2011). Consequently it is expected that more often than not there will be an unfavorable comparison between the SEBS estimate and the observed data due to the differences in the spatial resolution at which the estimate is produced.

The number of clear sky MODIS level1_B images available for the study area during the period 01st Dec 2011 to 30th Jun 2012 was limited. A large majority of the images possessed a percentage of cloud coverage. As mentioned cloud coverage has a strong influence on the amount of reflected radiation which can be measured from the earth's surface for both the optical and thermal wavelengths. Clouds, just like the earth's surface, reflect radiation. During cloudy conditions both the reflected radiation from the cloud as well as a small percentage of reflected radiation from the earth's surface may be captured by the satellite sensor as opposed to clear sky conditions in which only reflected radiation from the earth's surface is captured. The data captured for the optical and thermal bands are used during the SMAC, albedo, land surface emissivity, and land surface temperature computations within SEBS. These maps are key inputs to the SEBS model. Therefore inaccuracies associated with these inputs will be further exacerbated during the computation of daily total evaporation within SEBS. The excess radiation which is captured during cloudy conditions strongly influences the daily total evaporation estimate generated by SEBS.

The surface renewal time series which was used for the validation component of the study was not a complete record. Approximately 25% of the 361 day record was infilled, this was due to the surface renewal system being removed just prior to harvesting and just after crop re-establishment (30th May 2012-28th July 2012), as well as a short period in Jan 2012 (10th-30th) (Jarmain, 2014).

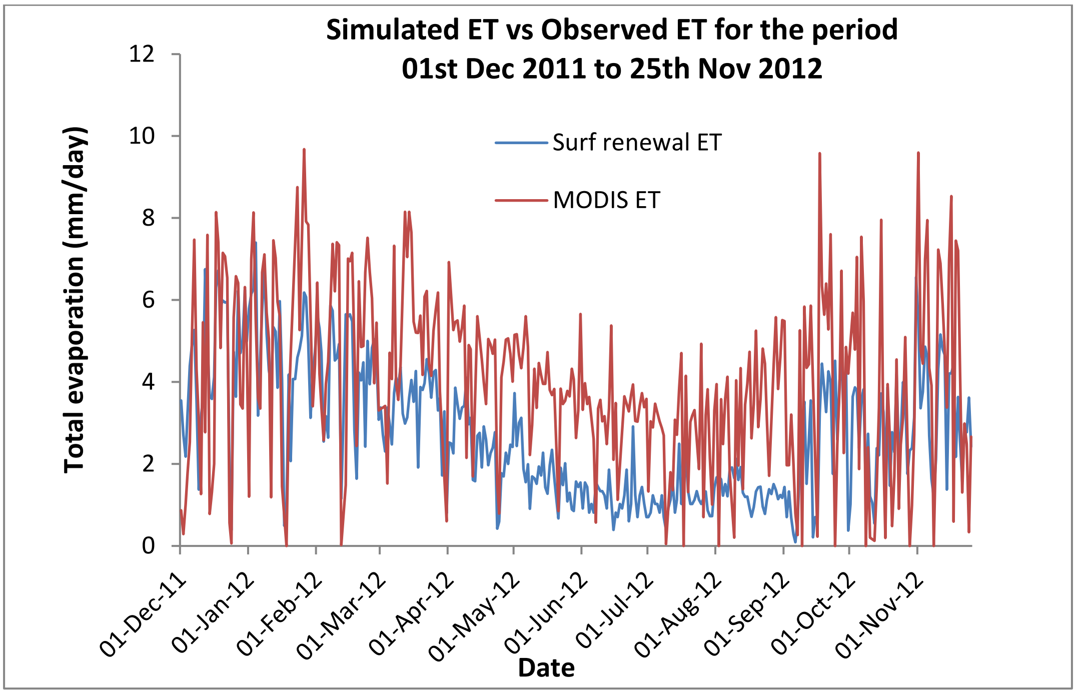


Figure 2.29: Comparison between SEBS daily total evaporation estimates and Surface renewal daily total evaporation estimates

2.3.3. Remote Sensing Soil Moisture Products

Soil moisture can be described as the water, which is contained in the weathered soil layer of the earth's surface (Wagner et al., 2012). Soil moisture is an important hydrological parameter, as it is important for a variety of applications, including flood forecasting, drought monitoring and weather predictions, crop growth monitoring (irrigation) and water management (Qin et al., 2013). Soil moisture can be viewed as an important bio-physical parameter, which is used as an interface linking the land surface and the atmosphere (Lakshmi, 2012; Mekonnen, 2009). Currently, methods of estimating soil moisture include ground-based measurements, which are carried out using field instruments, land surface models, which use meteorological data as inputs at a predefined spatial resolution and remote sensing, which uses sensors on satellites and aircrafts (Qin et al., 2013).

The methods of remote sensing of soil moisture are gamma radiation, near infrared, thermal infrared and microwave radiation. Each method works on its own principles, measures a unique property and has advantages and disadvantages. The microwave radiation remote sensing of soil moisture can be considered the most capable technique of remote sensing, partly due to the limitations of the other techniques (Gruhier et al., 2010; Wagner et al., 2012). This technique is reported to provide a distinctive potential for soil moisture estimation, as the range of electromagnetic wavelengths is largely unaffected by surface solar illumination and cloud cover (Wang and Qu, 2009). However, measurements are limited to areas which contain low vegetation cover (Njoku and Entekhabi, 1996).

According to Wagner (2008) soil moisture may not be a parameter in the land surface energy balance, however it impacts the variables of the land surface energy balance. Soil moisture affects the net radiation, which increases when the soil is wet and soil moisture controls the partitioning of energy between latent and sensible heat (Small and Kurc, 2001). According to Lakhanker (2009) soil moisture is a key component in crop growth. If the soil moisture content is too high, there is a lack of oxygen present in the soil pores (Lakhanker, 2009). Conversely, if the soil moisture is too low, it becomes more difficult for crops to extract water. In both cases, crop growth is greatly affected (Engman, 1991).

Soil moisture is the prime regulator of catchment's response to a rainfall event, as it partitions precipitation into infiltration and runoff, and is a key component in streamflow (Lakhankar, 2009). Soil moisture is a natural storage of water, which is becoming increasingly important due to the depletion in terms of quality and quantity of the other water resources (Lakhankar, 2009). Monitoring the soil moisture status of an area, such as a catchment, can be vital for avoiding and mitigating environmental impacts (Ni-Meister et al., 2005). These impacts include droughts and floods, and may be a result of the non-linear relationship between precipitation and runoff, (Guillem, 2010). Due to the heterogeneity of soil moisture even at small scales it is expensive and impractical to have continuous records; therefore the remote sensing approach to soil moisture estimation is seen as a promising technique which would incorporate the spatial and temporal characteristics of soil moisture.

The objective of this research component was to acquire selected satellite-based remotely sensed soil moisture products, then compare and evaluate the selected satellite-based remotely sensed soil moisture measurements to ground-based measurements at two sites within the Inkomati Catchment.

Methods of soil moisture measurement

Currently, there are several methods for soil moisture measurement *viz.* in-situ or ground-based measurements, remote sensing based measurements and modelling based soil moisture estimates. In-situ soil moisture methods provide measurements, which can be used to validate remote sensing and land surface model estimates. These ground-based measurements require capital, labour and time to monitor an area, even on a small scale, which is a limitation to the establishment of soil moisture networks (Cashion et al*.,* 2005). The major disadvantages of all in-situ methods are that point measurements are obtained. These point measurements are not capable of representing the spatial and temporal characteristics of soil moisture (Pegram and Sinclair, 2007).

Remote sensing can be considered as a promising technique as it has the capability to overcome the spatial and temporal variability of point scale soil moisture measurements. Therefore, large scale estimates of soil moisture can be obtained continuously, and from areas that are inaccessible. There are numerous soil moisture products from active and passive microwave remote sensing techniques, which include Advanced Microwave Scanning Radiometer (AMSR-E), Soil Moisture and Ocean Salinity (SMOS) and the Essential Climate Variable (ECV).

The PyTOPKAPI model, which is used to generate the SAGH landsurface soil moisture product, is an open source operation of the TOPKAPI distributed hydrological model. It is used to investigate the dynamics of soil moisture at a catchment scale (Sinclair et al., 2012). The model is based on meteorological, remote sensing and static data sets. The meteorological data required includes relative humidity, wind speed, temperature at hourly intervals and solar radiation flux (Sinclair et al., 2012). The remote sensing data required are NDVI and rainfall, which are three hourly TRMM rainfall products. One of the benefits of the model is that it is capable of producing soil moisture estimates at three hour intervals (Sinclair et al., 2012). The SAHG product can be considered a satellite-based soil moisture product as most of the model inputs are remotely sensed.

2.3.3.1. Methodology

The research aims to evaluate whether the satellite-based soil moisture techniques could be used in monitoring the soil moisture content of the Inkomati area. For the purpose of this research, satellite soil moisture products were chosen due to their spatial and temporal resolution, the availability of the data sets and processing time required for the data. The soil moisture data sets considered for use in the study are the Advanced Microwave Scanning Radiometer (AMSR-E), Soil Moisture and Ocean Salinity (SMOS), Essential Climate Variable (ECV) and SAHG PyTOPKAPI land surface model-based product (SAGH product) (Table 2.16)

Table 2.16: Spatial and temporal resolution and sources of soil moisture products

Product	AMSR-E	SMOS	ECV	SAHG
Spatial Resolution (Km)	25.00	40.00	25.00	12.50
Temporal Resolution (Days)	2.00	2.00	1.00	0.13
Record Length (Year)	2002-present	2009-present	1978-2010	2008-present
Availability	Free: http://sharaku.eorc.jaxa.jp	Free: http://eopi.esa.int.	Free: www.esa-soilmoisture-cci.org/	Free http:sahg.ukzn.ac.za/soil_moisture

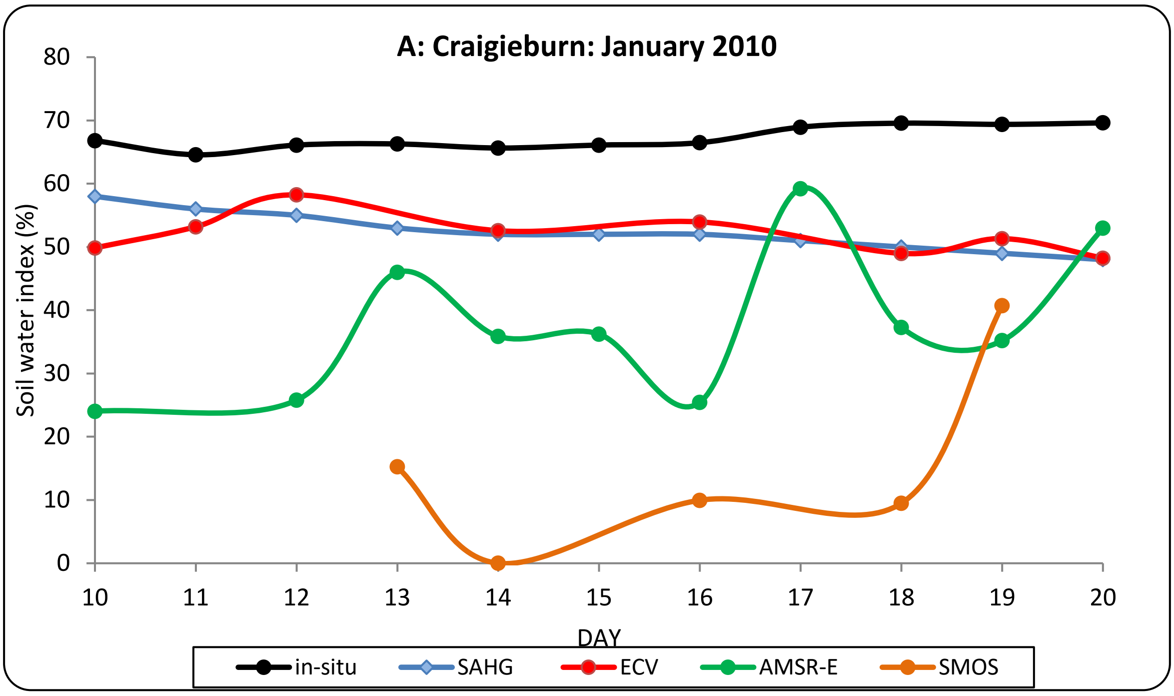
The AMSR-E, SMOS, ECV and SAHG products were acquired, processed and then compared and evaluated against ground-based measurements available for two sites in the Inkomati catchment where soil moisture data are available for the same period. The Craigieburn site (co-ordinates: 24.667 S and 30.974 E) in Bushbuckridge and Macadamia orchard (co-ordinates: 25.26291 S and 31.06257 E) in White River, in the Inkomati Catchment.

2.3.3.2. Results

Figures 2.30, 2.31 and 2.32 show the soil moisture estimates from differing products for January and July at Craigieburn whilst showing October at the Macadamia orchard. It is noted that the SWI is very similar in value over the two periods (January and July). It is expected that the winter period would have a substantially lower SWI compared to the summer period. The reasons for this similar SWI can be that the area has a high water table, which results in a high SWI all year round, the land cover conserves the soil storage and thus the SWI, there was rainfall just before the winter study period which resulted in a high SWI or there were problems with the Watermark^{TM} sensors, such that there were inaccuracies in the measurements.

The SAHG soil moisture measurements compared well to ground-based measurements in the summer months however, it showed poor comparison to ground truth in the winter months. It did however follow the trend of the ground-based soil moisture throughout the July period although it was significantly underestimated. This occurred as rainfall drives the SAHG product, such that a decrease in rainfall will result in lower soil moisture estimates. The SAHG product was expected to perform well as it is a South African product of soil moisture whilst the other measurements are global products. The resolution of SAHG is also favorable as it is a lot finer spatial resolution (12.5 km) than the other products.

The ECV data correlated well to the ground-based soil moisture estimates when compared to the AMSR-E and SMOS data. The EVC data set had many days where the site had no measurement. One of the merged products in the ECV product is AMSR-E; however AMSR-E has a more complete data set of the sites than ECV. The AMSR-E measurements seemed to follow the trend of the ground-based soil moisture measurements although it is greatly underestimated soil moisture. The AMSR-E data varies in the wetter months and is steady in the drier months. Therefore, the AMSR-E data is seen to be dependent on climatic patterns. The SMOS data correlated the least to ground-based soil moisture. It didn’t follow the trend and it underestimated soil moisture the most. The SMOS data was expected to give good results as it was the most recently developed of the products. The poor results however, can be attributed to the fact that it was launched in late 2009 and the data obtained (2010) is from its calibration period. Therefore these values are the measurements to evaluate and improve upon, such that continuous changes and upgrades will occur to improve the reliability and accuracy of the SMOS system. Numerous changes are therefore required, such as the algorithms and technical characteristics of the SMOS system in order to obtain better soil moisture estimates. The SMOS data set also had a high number of missing data for both sites. When processing the data, it was seen that many areas had gaps apart from the gaps between the swaths.



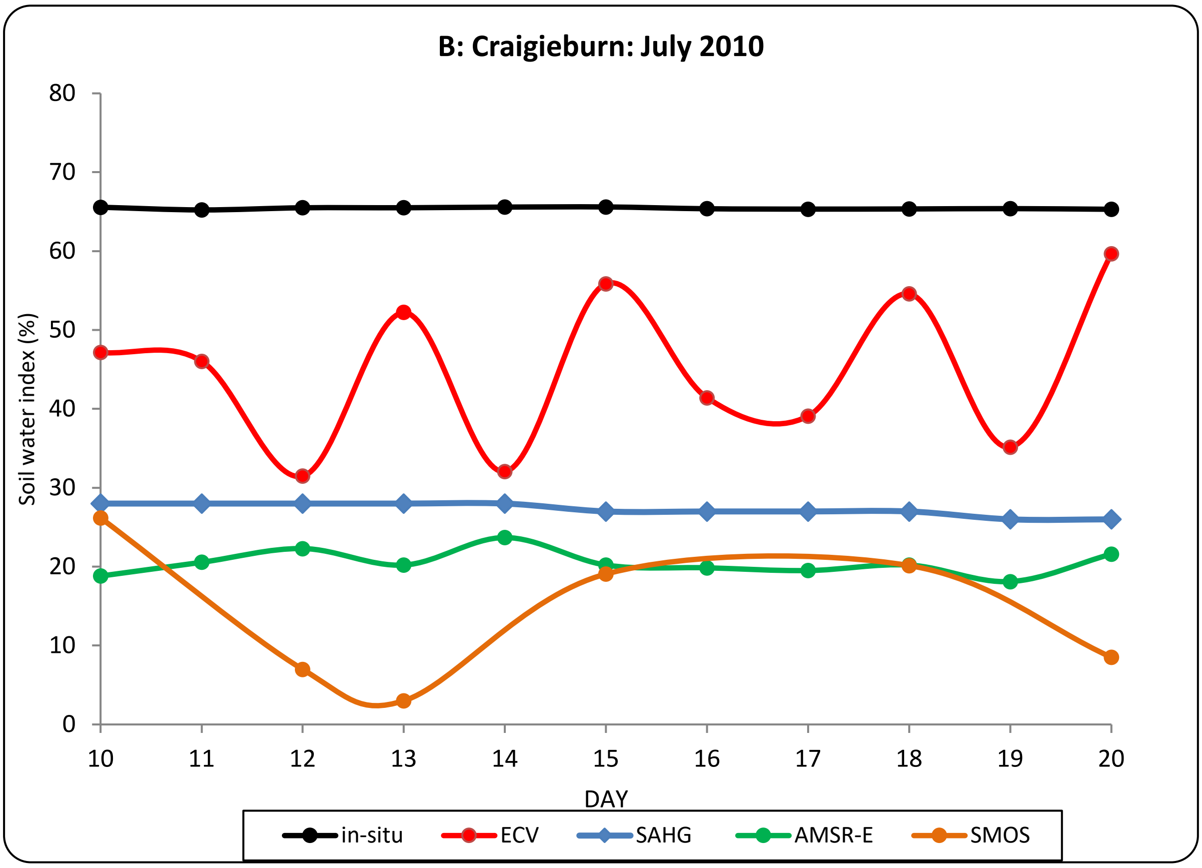


Figure 2.30: A: Soil Moisture Measurements for different products (January 2010); B: Soil Moisture Measurements for different products (July 2010) at Craigieburn.

Results from the study indicated that the satellite-based products captured the variations of soil moisture according to season and depth. The major issue in the validation process is vertical and horizontal scaling The vertical issues arise when comparing ground-based soil moisture at a depth of 15 and 30 cm to a satellite-based soil moisture measurements which represent the top 10 cm of the soil and is affected by the presence of vegetation. Horizontal scaling issues present a major problem for the validation procedure as the validation compares ground-based soil moisture which is a single point measurement, to satellite-based soil moisture measurements, which is a large scale average of an area. Another problem with the validation study was the limited snapshots of time for which the comparisons could take place. This was mainly due to the accessibility and processing time required for larger datasets of the satellite-based products. Ground-based soil moisture estimates are very useful for understanding the temporal characteristics of remotely sensed products; however they are less useful for evaluating large scale spatial patterns.

The percentage error of the satellite-based soil moisture products were then compared to ground-based soil moisture measurements. The percentage error results were tabulated as seen in Table 2.8. From Table 2.17, it can be seen that the percentage error for SAHG for the January period ranges from 10 to 32%, 55 to 60% in july and -5 to 10 percent in October. The ECV data ranges in percentage error from 45 to 55% in January, 30 to 60% in July and -5 to 30% in October. The AMSR-E data ranges in percentage error from 20 to 55% in January, 18 to 24% in July and 20 to 32% in October. SMOS had the highest percentage error and ranged from 40 to 90% in January, 60 to 96% in July and 1 to 41% in October.

Table 2.17: Soil moisture measurements and subsequent percentage error

JANUARY	in-situ	SAHG	% error	AMSR-E	% error	EVC	% error	SMOS	% error
10	66.82	58.00	13.20	24.04	64.02	49.86	25.38	-	-
11	64.57	56.00	13.28	-	-	53.19	17.62	-	-
12	66.10	55.00	16.80	25.78	61.00	58.24	11.90	-	-
13	66.28	53.00	20.04	45.99	30.62	-	-	15.23	77.02
14	65.64	52.00	20.78	35.88	45.33	52.57	19.91	18.87	71.25
15	66.11	52.00	21.34	36.23	45.19	-	-	-	-
16	66.48	52.00	21.78	25.43	61.75	53.96	18.84	9.96	85.02
17	68.94	51.00	26.02	59.22	14.09	-	-	-	-
18	69.56	50.00	28.12	37.28	46.41	48.98	29.59	9.48	86.37
19	69.38	49.00	29.37	35.19	49.28	51.32	26.03	40.74	41.27
20	69.61	48.00	31.05	52.95	23.93	48.24	30.70	-	-
JULY									
10	65.56	28.00	57.29	18.81	71.31	47.15	28.08	26.19	60.05
11	65.22	28.00	57.07	20.55	68.49	46.04	29.41	-	-
12	65.50	28.00	57.25	22.30	65.96	31.48	51.93	6.98	89.34
13	65.50	28.00	57.25	20.21	69.15	52.20	20.30	3.00	95.41
14	65.58	28.00	57.30	23.69	63.88	32.06	51.11	-	-
15	65.60	27.00	58.84	20.21	69.20	55.86	14.85	19.07	70.93

JANUARY	in-situ	SAHG	% error	AMSR-E	% error	EVC	% error	SMOS	% error
16	65.37	27.00	58.70	19.86	69.62	41.41	36.65	-	-
17	65.33	27.00	58.67	19.51	70.14	39.10	40.15	-	-
18	65.35	27.00	58.68	20.21	69.08	54.58	16.47	20.14	69.18
19	65.39	26.00	60.24	18.12	72.29	35.16	46.22	-	-
20	65.30	26.00	60.19	21.60	66.93	59.65	8.65	8.51	86.97
October									
15	41.40	43.00	-3.88	31.36	24.24	46.07	11.29	0.09	21.53
16	43.18	43.00	0.41	26.31	39.06	45.00	-4.22	0.06	14.14
17	43.49	43.00	1.12	21.63	50.27	46.07	-5.94	-	-
18	43.80	43.00	1.82	21.63	50.62	-	-	0.01	1.63
19	44.11	42.00	4.78	24.87	43.61	35.93	18.54	-	-
20	47.67	45.00	5.61	24.15	49.34	61.93	29.90	0.07	16.51
21	47.83	44.00	8.01	18.02	62.32	47.14	1.44	0.08	19.53
22	47.36	44.00	7.10	20.55	56.62	43.93	7.25	-	
23	47.36	44.00	7.10	20.55	56.62	-	-	0.04	9.07
24	46.98	43.00	8.47	20.91	55.50	40.07	14.70	-	-
25	46.12	43.00	6.77	20.55	55.45	-	-	-	-
26	45.50	43.00	5.50	-	-	28.84	36.63	-	-
27	45.04	43.00	4.53	23.07	48.78	42.53	5.56	-	-
28	45.19	45.00	0.43	32.08	29.01	-	-	0.17	40.23
29	45.04	45.00	0.09	27.03	39.97	50.44	12.00	0.11	26.28
30	44.96	47.00	-4.53	20.55	54.30	-	-	0.03	6.74

The land surface model (SAHG product) measurements of soil moisture are reliable in adequately representing soil moisture in the wetter months (January and October). However, the SAHG product soil moisture measurements underestimate soil moisture when rainfall is limited (July). The ECV data set was accurate and reliable compared to the other remotely sensed soil moisture products (AMSR-E and SMOS). It possessed missing data which needs to be addressed, as the product aims to be the most consistent data set. The AMSR-E soil moisture measurements followed the trends in climate rather than that of the ground-based soil moisture. It contained missing values due to the satellite not covering the catchment even if the catchment was located in the band of measurement. The SMOS data was the worst data set used in the study. It consistently underestimated the soil moisture with large percent errors when compared with the observed data and all the products. SMOS and had the most amount of missing data within the study period. The data didn't follow any general trend nor did it show any promise for use in the Inkomati catchment. In conclusion, only the land surface model (SAHG) and ECV data sets showed promise for the measurement of soil moisture within the Inkomati catchment.

However, more research is required at larger time scales with more validation data sets if these products are to be used for soil moisture estimation in hydrological modelling.

2.3.4. Preliminary investigation: Application of satellite derived TRMM and FEWS rainfall datasets in the ACRU hydrological model

Challenges working with remote sensing datasets for operational catchment modelling

The incorporation of remote sensing or satellite-based datasets into operational hydrological modelling though appealing, remains a scarcely explored domain of research. The integration of satellite earth observation products into hydrologic models poses a significant challenge, as the direct use of satellite earth observation data in hydrologic models is still generally not possible (Wagener, 2009). Hydrologic models often require some form of adaptation in order to accommodate satellite earth observation data (Sandholt et al., 1999; Wagener, 2009).

The work undertaken in this study proved a challenge every step of the way. Some of the difficulties experienced include:

- Access to remote sensing data sources and long registration processes and waiting periods.
- Different frameworks, methods and tools used to download data.
- Low speed internet connections made downloading datasets a time consuming task.
- Non-uniformity of product formats, each product usually has to be manipulated and processed for input into common GIS and remote sensing packages.
- Time and expertise required to manipulate and process imagery and to prepare data as input to models.
- Large amounts of disk space and supercomputing facilities to work with remote sensing imagery and associated hydrological modelling.
- Availability of good quality observed data with appropriate lengths of records for validation studies.

These are expanded on below.

2.3.4.1. Application of TRMM and FEWS rainfall datasets in the ACRU Model

This section details the preliminary investigations in applying remotely sensed information and datasets into a hydrological model. The challenges associated with the integration of RS-based datasets into hydrological models are highlighted. A description of the ACRU model, configuration and setup of the model and preparation of the TRMM and FEWS data is also detailed. Preliminary results comparing observed and simulated streamflows are presented.

The Agricultural Catchments Research Unit (ACRU) model was developed by Schulze, 1975 and has been frequently updated since its inception (Schulze, 1995; Jewitt and Schulze, 1999;

Martinez et al., 2001; Warburton, 2010). ACRU has been described as a "multi-purpose and multi-level integrated physical conceptual model that can simulate stream flow, total evaporation, land cover, management and abstraction impacts on water resources at a daily time step" (Jewitt and Schulze, 1999) (Figure 2.31). ACRU makes use of daily rainfall data as the chief input. Monthly values may also be used as inputs to the model for variables which are "cyclic in nature, conservative and less sensitive" (Schulze, 1995). Monthly inputs are converted into daily values within the model through a process known as Fourier analysis (Schulze, 1995). The various catchment components as well as the components of the hydrological cycle maybe simulated in ACRU through the application of sub modules which revolve around daily multi-layer soil water budgeting (Schulze, 1995). The ACRU model has been applied extensively for a variety of purposes some of which include crop yield estimation, irrigation scheduling, as well as climate and land use change impact analysis (Jewitt and Schulze, 1999; Martinez et al., 2001; Schulze, 1995; Warburton, 2010).

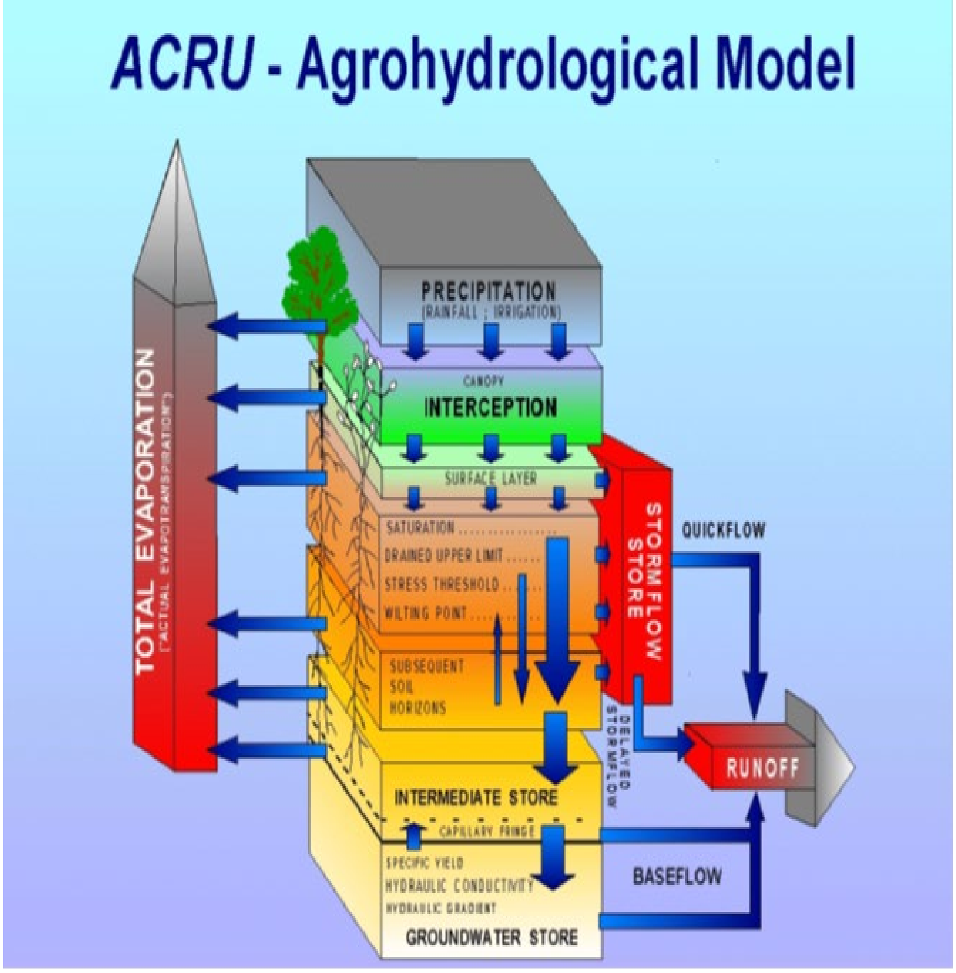


Figure 2.31: Multi-layer soil water budgeting through the partitioning and redistribution of soil water (Schulze, 1995).

Configuration of the ACRU model for Quinary X23C

The ACRU model configuration involves a detailed analysis of the landcover and soils information available, the terrain and the water bodies in the catchment. This enables the user to identify the different land-uses within the catchment, decide on the level of catchment discretization for modeling *viz.* lumped whole catchments/sub-catchments/quinaries or hydrological response units (HRUs) and, derive a flow path for water moving through the catchment.

Quaternary catchment X23C of the Kaap sub-catchment (Figure 2.32A) was selected for this study since it is an upstream catchment, with a suitable gauging weir with good quality streamflow data. Figures 2.32B and 2.32C illustrate the landcover and soils of the Kaap sub-catchment. Land cover information was provided from a recently derived data set by the ICMA. This was compiled by GeoTerraImage (GTI) (Pty Ltd) and has been generated from 2010 high resolution SPOT5 satellite imagery, based on 2.5 metre pixels, and represents detailed land-cover and land-use patterns in the catchment. A combination of single date SPOT5 2.5 m resolution satellite imagery, acquired during 2010, 2009 and 2008 was used to derive the 2010 Inkomati Land-Cover dataset.

This new land-cover dataset which has 83 different land-cover classes, were reclassified into ACRU compatible vegetation classes and assigned corresponding ACRU parameters.

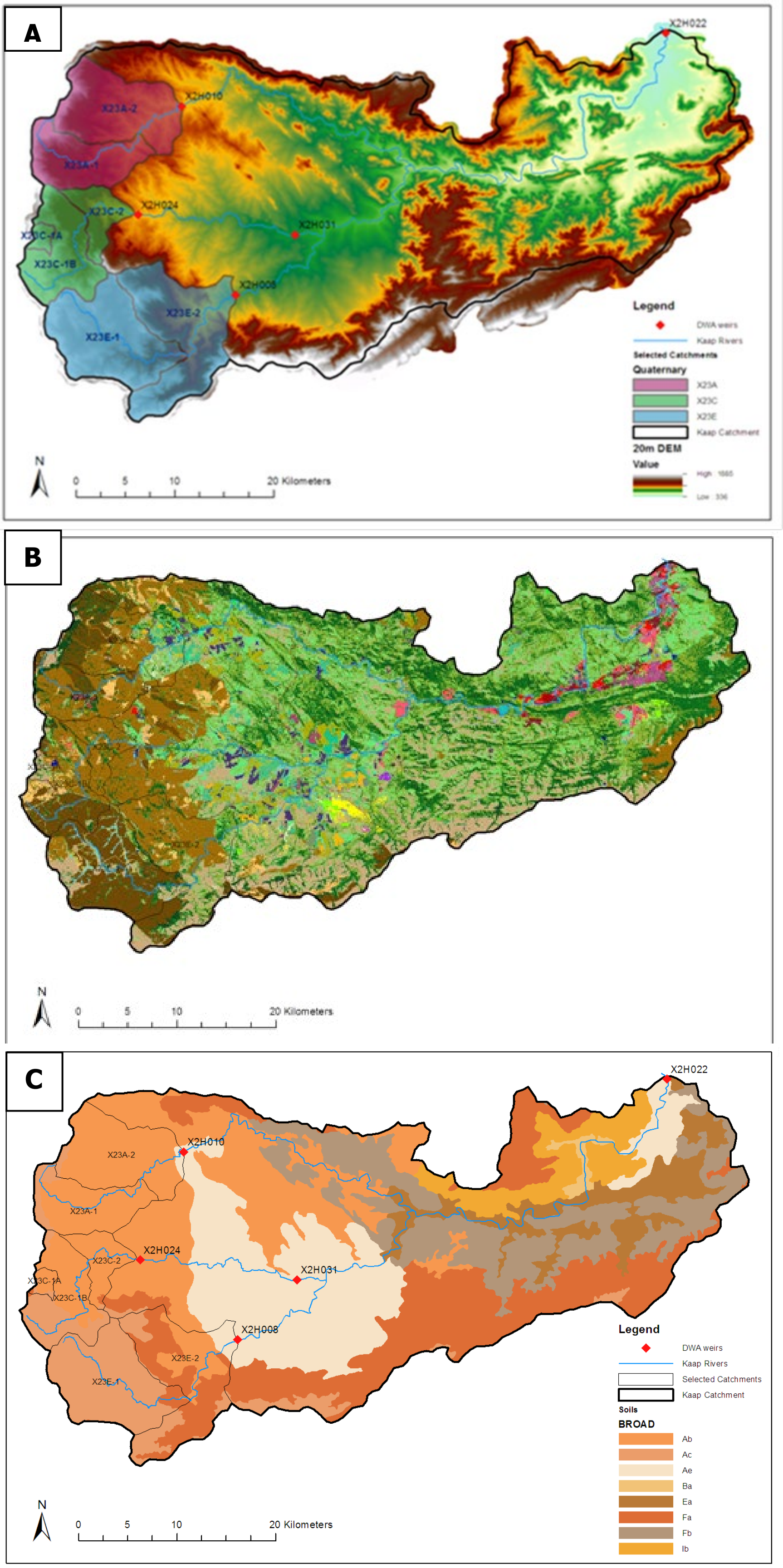


Figure 2.32: The Kaap Catchment (A – quinary catchments with the 20 m DEM; B – Newly derived Landcover; and C – Soils information).

The configuration of Quaternary catchments into land use dependent HRUs was then undertaken. Using the national coverage developed by Schulze et al., 2010, Quinary Catchment boundaries of X23C were obtained and the land cover in each Quinary Catchment is defined and sub-delineated into a basic configuration of 15 land use determined HRUs which are hydrologically inter-connected, as illustrated in Figure 2.33.

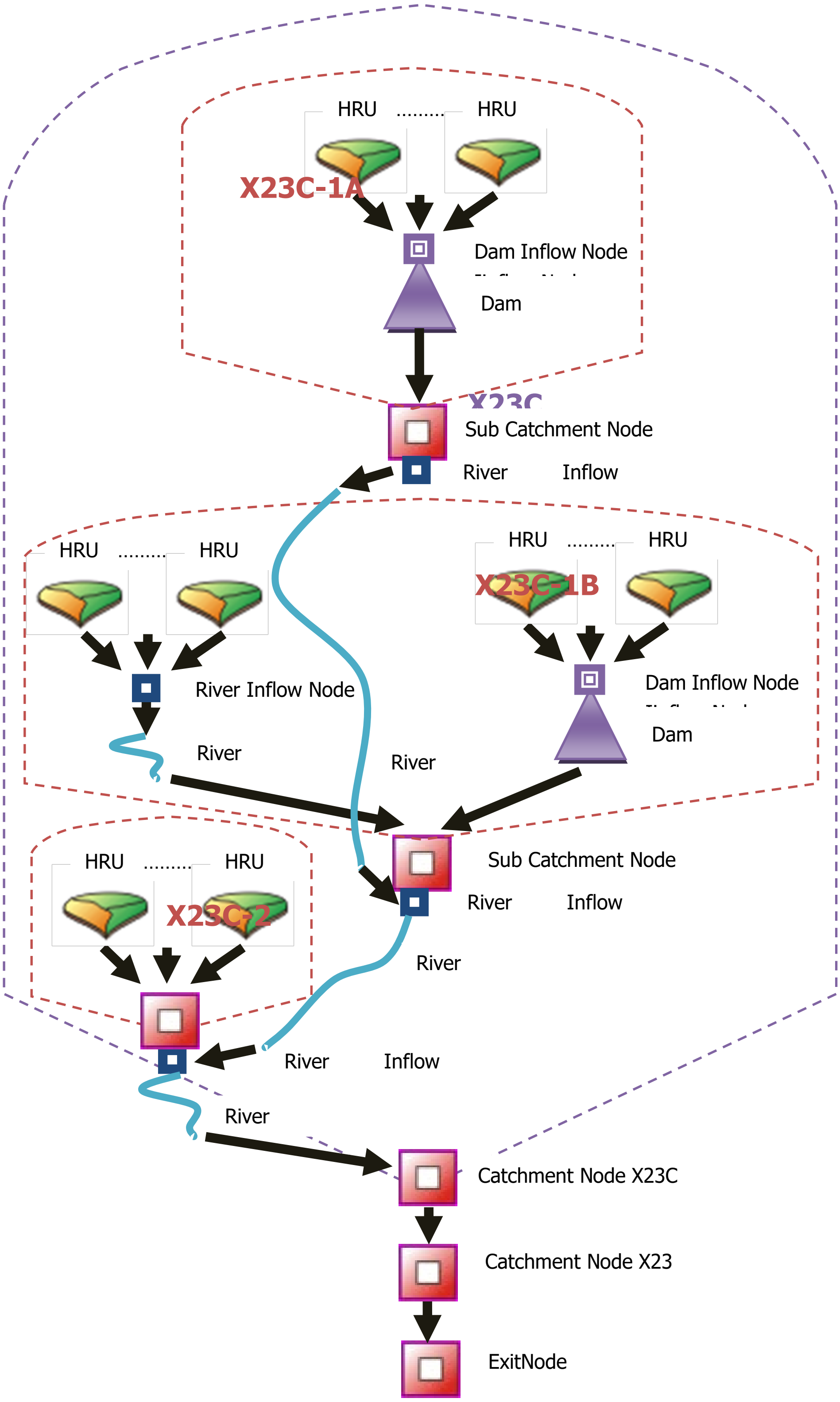


Figure 2.33: Configuration of the ACRU model for quaternary X23C

Raingauge rainfall data was obtained from the ARC for the Moodies Estate, Louws Creek. The dataset extended from September 2006 to September 2013. The TRMM product 3B42 V7 daily rainfall estimates were downloaded from the TOVAS data download portal. The FEWS dataset was obtained from the ICMA data portal. The images were processed in VISAT, converted to GeoTIFF and imported to ArcGIS 9. The TRMM and FEWS images were over-layed onto the Kaap sub-catchment quinary images and pixel values were identified and recorded for each quinary. Selected time periods for satellite-based TRMM and FEWS daily rainfall data were processed into a daily time series of rainfall for input into the ACRU hydrological model to simulate streamflow in upstream quinary, X23C, of the Kaap sub-catchment in the Inkomati catchment. Thus, a daily time series of rainfall in mm/day was setup and incorporated into the ACRU climate files for input into the ACRU model.

The model was run from 2006 to 2013 with a selected driver rainfall station (gauge) within the catchment. The model was also run with a six month TRMM derived rainfall dataset and a six month FEWS derived rainfall dataset (01/01/2010 to 30/06/2010). A comparison between the TRMM, FEWS and raingauge datasets for the six months period indicated that the TRMM and FEWS datasets followed similar trends to the gauged rainfall (Figure 2.34). However there were discrepancies in the low flows and peaks of rainfall. Both the satellite datasets generally under-estimated the rainfall when compared to the raingauge, with the FEWS dataset underestimating the rainfall the most.

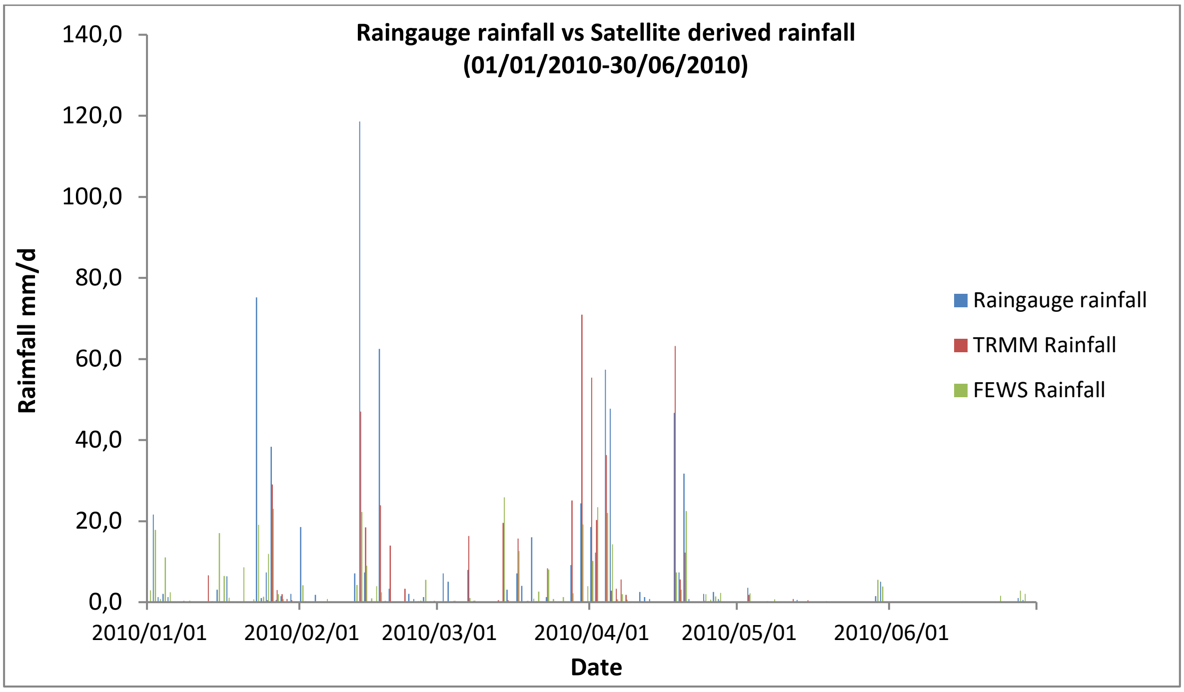


Figure 2.34: Comparison between raingauge, TRMM and FEWS rainfall estimates

The discrepancies between the datasets are also shown in Figure 2.35 and Figure 2.36 which indicates a R^2 value of 0.38 which shows poor correlation, which could be attributed to the analysis of a short dataset which only represents a snapshot in time. The differences between the rainfall products and raingauge could also be attributed to that fact that a raingauge is a point measurement and the satellite represents a spatial average over an area. The TRMM and FEWS rainfall datasets need to be extended such that more in depth analyses can be performed when comparing the rainfall datasets. Methods for correcting satellite rainfall, e.g. bias correction and downscaling should also be investigated. Literature also points towards blending satellite and rain-gauge data to improve areal rainfall estimates over a catchment.

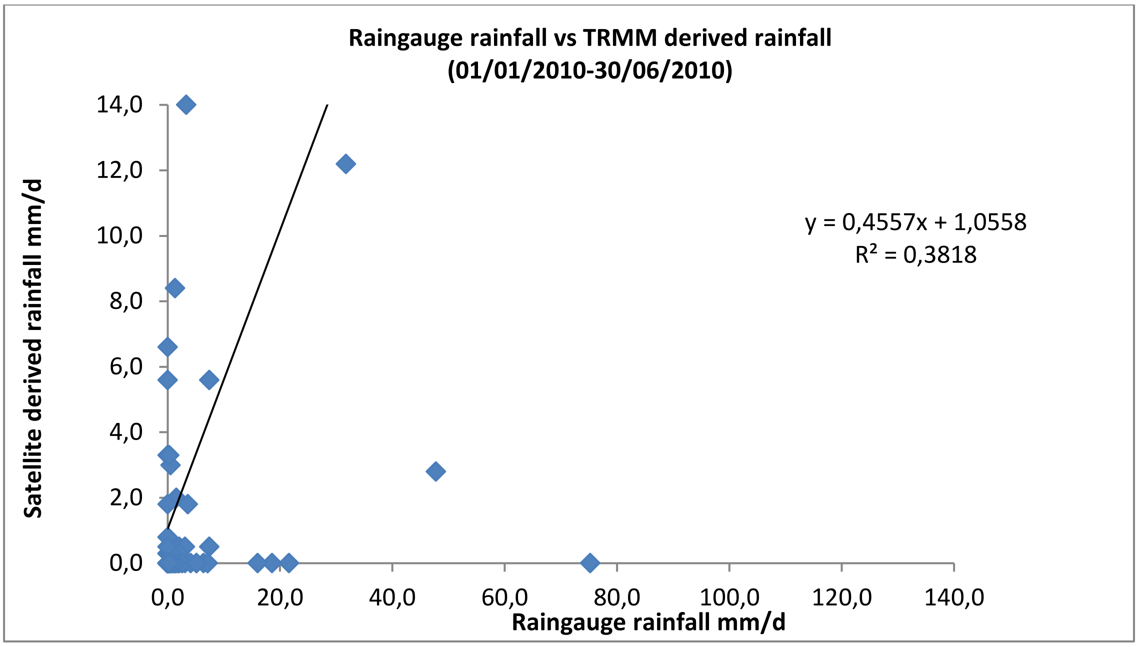


Figure 2.35: R^2 for Raingauge versus TRMM rainfall

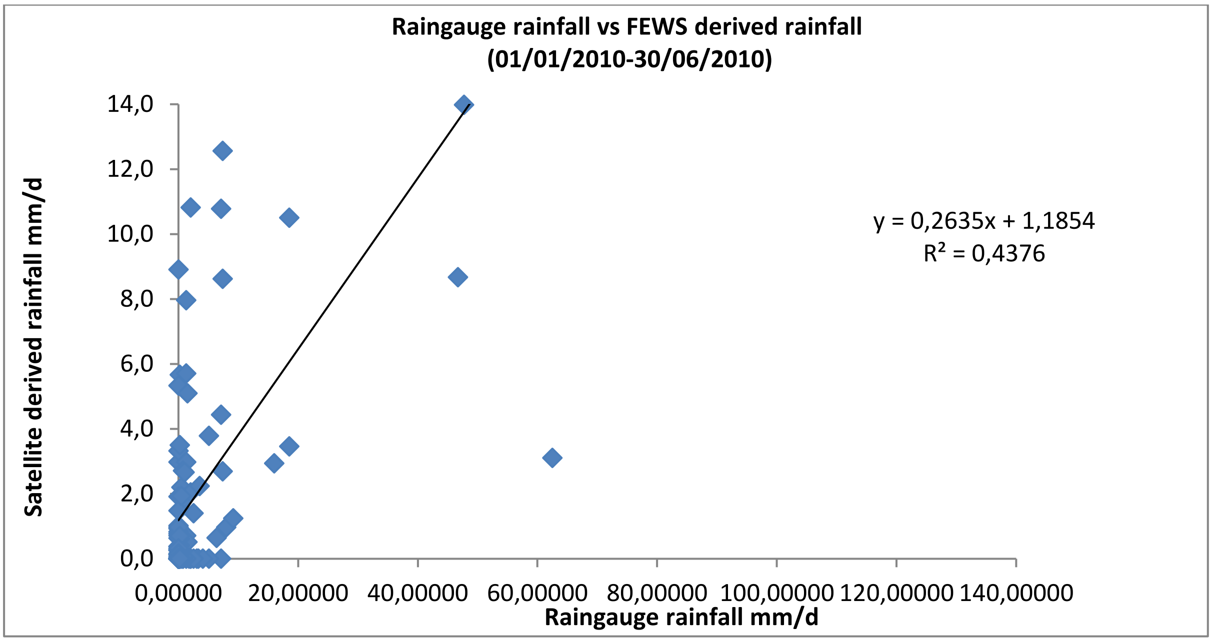


Figure 2.36: R^2 for Raingauge versus FEWS rainfall

The ACRU model under-estimated streamflows from raingauge data when compared to observed streamflow data in quinary X23C. However the simulated streamflow followed the main trends of the observed streamflow data. Streamflows from FEWS was highly under-estimated (Figure 2.37). Simulated streamflows from TRMM data had a better correlation to the observed streamflow data, than streamflows simulated from raingauge data and from FEWS, for quinary X23C (Figures 2.38 and 2.39). Further investigations are necessary on longer datasets and in other quinary catchments to establish the performance of the hydrological model with satellite dataset in the Inkomati catchment. The preliminary investigations indicate the potential for satellite-based datasets and their application in hydrological modelling.

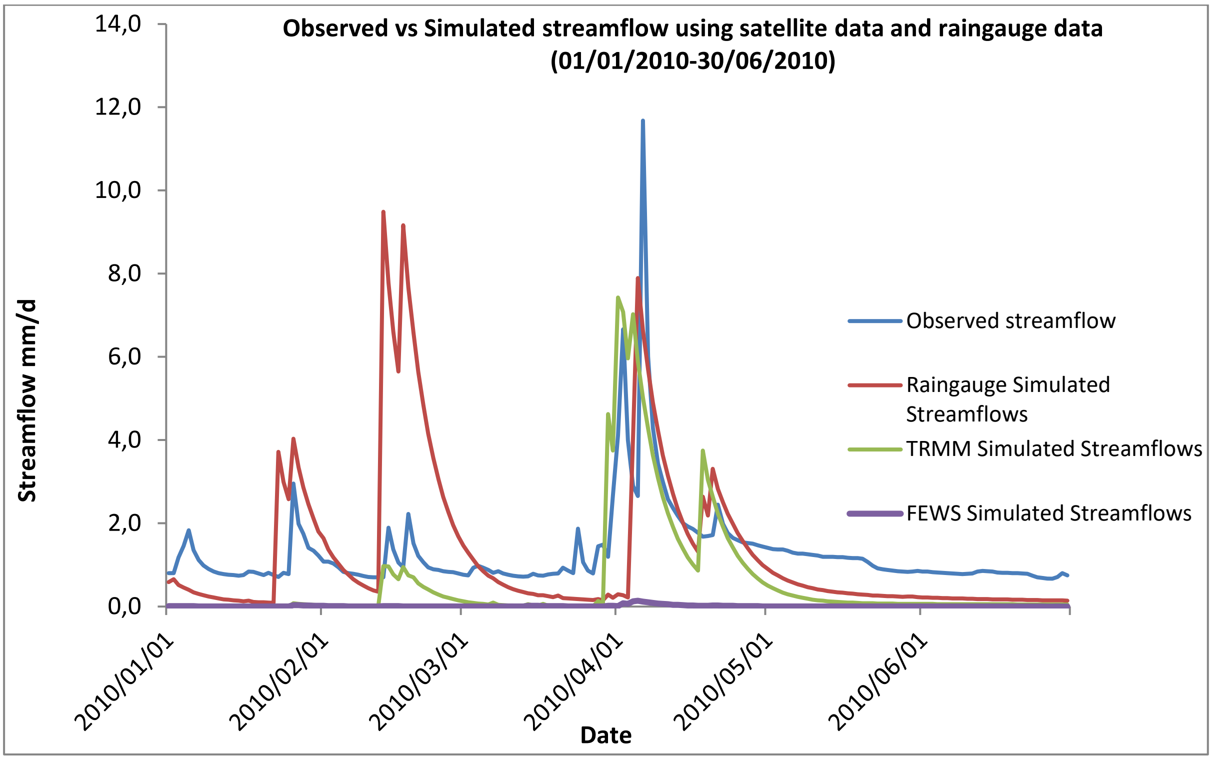


Figure 2.37: Comparison of Simulated streamflows for raingauge, TRMM and FEWS datasets.

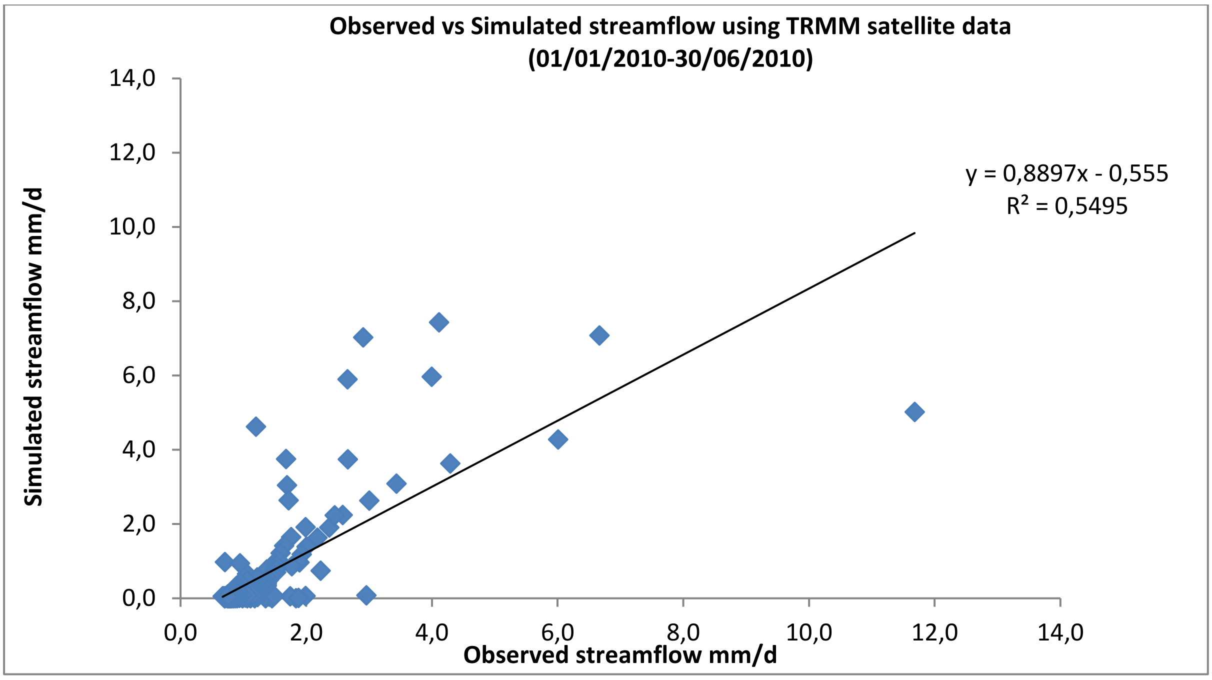


Figure 2.38: Comparison of Simulated streamflows from raingauge versus TRMM datasets.

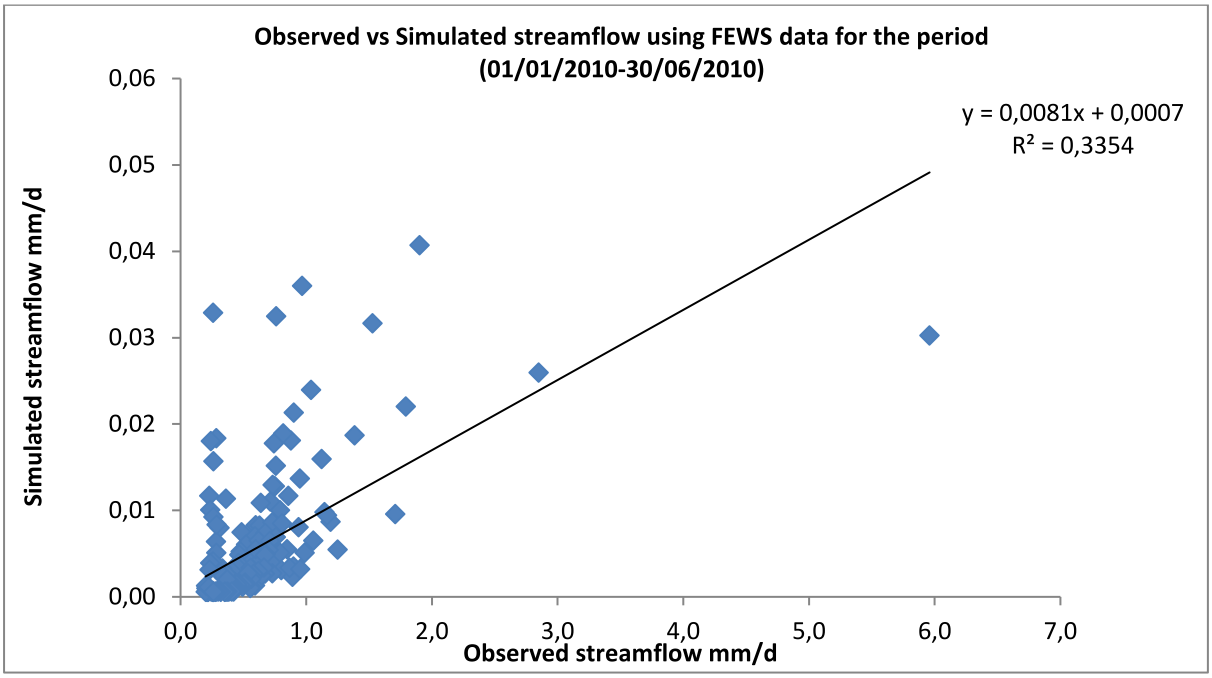


Figure 2.39: Comparison of Simulated streamflows from rain gauge versus FEWS datasets.

2.3.5. Summary

The findings from each of the studies undertaken in this component of the project indicate that earth observation data, in this instance satellite-based datasets and information can play a vital role in hydrological modelling. The datasets have the potential to fill many gaps in the deteriorating observed measurements and gauging networks and can aid predictions and hydrological simulation in ungauged catchments.

Satellite rainfall estimates from both TRMM and FEWS products have followed similar trends to the rainfall estimates from gauges. However, the TRMM dataset performed better than the FEWS when compared to the raingauge directly. These datasets can therefore provide useful rainfall estimates in ungauged catchments and catchments where the quality of the existing datasets is poor. The satellite rainfall datasets have the potential to fill many gaps in the deteriorating observed rainfall measurements network. Further investigations into the relationships between the satellite products spatial representation of rainfall and the rainfall from gauges will be of great value and add to the confidence with which these satellite datasets are used.

Evaporation estimates from energy balance models using satellite derived parameters and inputs have been investigated and show potential to provide acceptable estimates of actual ET at large spatial and finer temporal scales. The SEBS model investigated in this study shows potential to be used as a data source for ETa estimates. SEBS estimates were able to follow similar trends and capture the seasonal differences in ETa. Poor relationships in certain time periods indicate the need to further investigate the application of SEBS in South African catchments. The satellite-based ETa estimates are however, important as these ETa estimates can be further utilised in various ways in water resources studies for example focusing on crop water use, water use efficiency and irrigation scheduling.

The use of TRMM and FEWS satellite rainfall data as input into the ACRU model was pioneered in this study. Preliminary investigations indicate that the streamflows produced from TRMM rainfall correlated much better to the gauged streamflow in Quinary X23C. The processing and incorporation of satellite datasets into hydrological models proved challenging, however ideas and methods for manipulating data and creating long time-series will aid in this process. There is however, much more research required into making the models and datasets compatible for use with each other and to validate the use of these remote sensing based datasets in order to adequately represent the hydrology of a catchment. This includes the incorporation of satellite ETa and SM products into fully integrated remote sensing driven (of course with on-the-ground calibration) operational hydrological models.

According to a review by Van Dijk and Renzullo (2011) the use of satellite observations in hydrological models can be categorized into “soft” or interpretative uses (e.g. mapping, evaluation) as well as “hard” or quantitative uses (as model input or in data assimilation). The use of satellite products for dynamic forcing; parameter estimation; model evaluation and development; and data assimilation is increasing due to advancements in satellite technology and computational capacity. Of course the constraints to their use are consistently being minimised, nevertheless as demonstrated within this study there is considerable need for local capacity development in South Africa for training of local remote sensing technicians and hydrological modellers to implement these advancements in real-time operational water resources models that are becoming increasingly necessary (see section 3.1).

3. DECISION SUPPORT INFORMATION AND FRAMEWORKS

3.1. An Adaptive Operational Water Resources Management Framework to facilitate effective Operational River Management on the Crocodile River

(Jackson, B.)

3.1.1. Operational Water Resources Management (OWRM)

Water resources systems have diverse social, technological, ecological, economic and political (STEEP) characteristics and processes that are interlinked and interdependent (Berkes and Folke, 1998, Berkes et al., 2003; Cilliers et al., 2013)). Complexity is recognised to be highly context and value dependant, having numerous legitimate needs and outcomes, and having various dependencies and feedbacks between the STEEP factors. Semi-arid run-of-river dominated basins[8] exacerbate and enhance the difficulty in achieving IWRM within this complexity. These types of river systems are especially sensitive and susceptible to degradation in closing river basins[9] due to the intrinsic uncertainty and complexity associated with high variability in runoff and lack of storage to manage it with. There is little evidence to show that current institutional arrangements for water resource management have been able to deal with the issues of basin closure.

Typically, studies on IWRM, complexity, adaptive management and basin closure, highlight the current gaps to their fulfilment, but fall short of indicating the further need to improve the short term operations of semi-arid run-of-river dominated catchments, and concentrate more on water resources planning interventions. Although water resource managers are required to perform tasks for both water resources planning and operations, water resource modelling for planning is widely practiced in South Arica, but the use of water resources modelling for operations appears to be less widely practiced. This is an area that requires further development and implementation (Clark and Smithers, 2013).

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[8] River systems in semi-arid regions, such as the lowveld region of South Africa, have highly seasonal flow regimes with a marked pattern of low or zero flow during the dry season.

A run-of-river dominated system can be defined as a river system that has no or little in stream storage available for the management of runoff and is thus dependent on rainfall for runoff generation

[9] Basins are said to be closing When the supply of water falls short of commitments to fulfil demand in terms of water quality and quantity within the basin and at the river mouth, for part or all of the year, (Falkenmark and Molden, 2008; Molle, Wester and Hirsch, 2009).

3.1.2. Importance of making OWRM adaptable

The *dual learning pathways* of science and management are equally important for water resources management, and need to be applied in a *social learning* context to achieve concerted action in complex and uncertain contexts and situations (Ison and Watson, 2007). The facilitation of social learning and the creation of institutions under the adaptive management umbrella are key criteria for the management of complex problem situations (Daniel and Walker, 1996; Jiggins and Roling, 2000). IWRM, including OWRM should thus be developed and implemented in an "adaptive manner" that stimulates scientists and practitioners through the philosophy of "learn by doing", i.e. being informed by practice. The corollary is that in complex systems, the users must be also part of deriving management solutions since this is where and how they learn (Pollard and Du Toit, 2008). If they are excluded, the 'system' does not learn and hence adapt to change and surprise. Traditionally where systems of governance and management meet, they generally do not effectively accommodate the diversity of legitimate stakeholder needs and value-sets.

The ICMA has thus expressly acknowledged that it is a learning organisation (see section 1.5) that has embraced SAM and that it must be able to modify its behaviour to reflect new knowledge. The ICMA uses the SAM implementing framework developed for South Africa (Pollard and Du Toit, 2007), which splits SAM into 3 key phases: *adaptive planning; adaptive management;* and *adaptive evaluation*. The adaptive planning phase has already been conducted by the ICMA during the development of its CMS and strategic plan, but the adaptive management and adaptive evaluation phases have yet to commence.

Water resource managers are required to perform tasks for both water resources planning and operational needs and it is important that these aspects are linked together under a single framework. According to the Global Water Partnership (2013) a DSS for IWRM typically includes a database and processing environment, a knowledge and information system, a modelling and analysis framework, a socioeconomic modelling and analysis framework, and a communication framework. As implied by Sawunyama et al. (2012) the management of scarce water resources requires that a DSS is both flexible and adaptable in design in order to provision accurate real time data, including the hydrological modelling associated with it. Such DSS's provide the requisite level of information upon which OWRM has the ability to become adaptive, since:

- OWRM has historically been dealt with using management (tacit) knowledge rather than scientific knowledge, which implies that learning from management experience is important and that scientific knowledge in the area can be improved.
- River basin operational processes requires support for real time decision making in the short term (coming hours and days) and DSS's support the operator in making these specific decisions (Szylkarski et al., 2013) – and thus adapt to changing conditions.

- Operational DSS's require large amounts of real time data and physics-based models with continual updates based on the most current river/reservoir state, and both short term and long term forecasts need to be included. (Clark and Smithers, 2013; Szylkarski et al., 2013). Modern technology allows for a high level of automation and sophistication in operational information technology.
- Models can be used for real-time catchment management by linking them with data management systems that include forecast data (Labadie et al., 2007). This implies that any real time or operational modelling should be linked to data management systems.

3.1.3. The Crocodile River: A case study for Operational Water Resources Management

The Crocodile River (See Figure 1.2) is one of the main river catchments within the Inkomati WMA, is an excellent example of a semi-arid closing basin that is run-of-river dominated (IWAAS, 2010; Inkomati CMS, 2010b) for the following reasons:

- High water demand versus the available supply.
- Significant variability and seasonality in available water in both time and space.
- Low storage capacity in relation to the water demand in the catchment. The only dam on the main stem, Kwena Dam, only influences about 10% of the mean annual runoff.
- Rainfall areas and main irrigation demand areas are spatially disparate.
- Its a long river (length of approximately 250km), which makes it difficult to manage during low flow periods, when losses can be significant and unpredictable.
- International obligations for water sharing with Mozambique and Swaziland.
- It is ecologically important to the Kruger National Park yet the ecological flow requirements have yet to be implemented (the ICMA indicates that the implementation of the Reserve will result in decreased water availability as well as decreased assurances of supply).

3.1.3.1. Institutional Arrangements: Institutions, Responsibilities, and Communications

The NWA requires CMAs to establish catchment management committees to facilitate stakeholder engagement around IWRM at catchment level. The ICMA has already established a Crocodile River Forum in this regard and a more specific operational committee, the Crocodile River Operations Committee (CROCOC) was established to meet the institutional need in terms of OWRM. The CROCOC now meets quarterly[10].

The NWA also allows for the establishment of Water User Associations (WUA). WUAs are a key mechanism in the NWA for facilitating decentralisation of relevant powers and functions for IWRM to the local level and thus enable effective stakeholder engagement in IWRM at the

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[10] although the CROCOC can convene more frequently as the need arises

local level. Within the Crocodile River, no WUAs have been established. However, Irrigation Boards do exist in terms of the previous Water Act of South Africa, Act 54 of 1956. The Irrigation Boards continue to perform their functions in terms of that act until transformed into WUAs.

The establishment of the CROCOC required the documentation of the institutional arrangements showing roles, responsibilities, forums, committees and decision and communication lines shown in Figure 3.1 below:

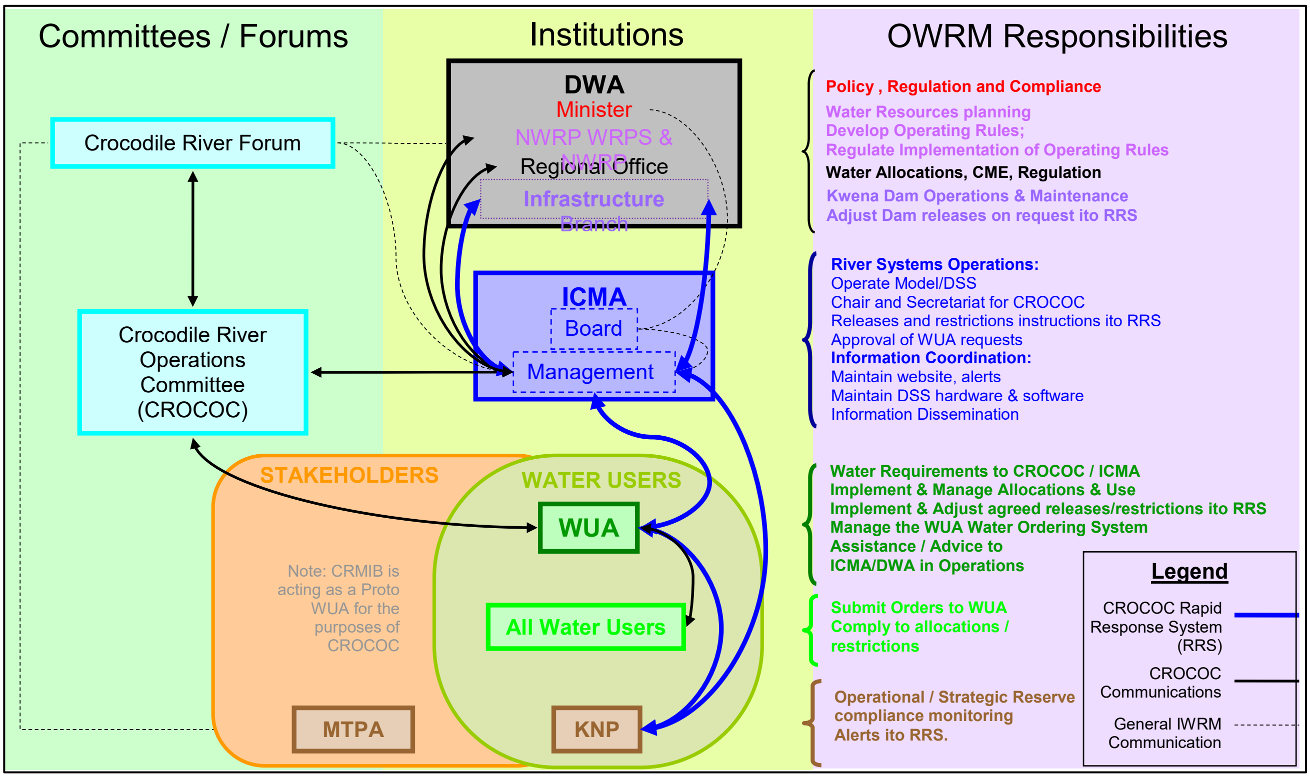

Figure 3.1: Institutional arrangements in the Crocodile River (DWA = Department of Water Affairs; ICMA = Inkomati Catchment Management Agency; NWRP = National Water Resource Planning; WRPS = Water Resource Planning Systems; DSS = Decision Support System; RRS = Rapid Response System; WUA = Water User Association; KNP = Kruger National Park; MTPA = Mpumalanga Tourism and Parks Agency; IWRM = Integrated Water Resource Management; CRMIB = Crocodile River Major Irrigation Board), adapted from ICMA (2010)

3.1.4. Developing an Adaptive Operational Water Resources Management Framework (AOWRMF)

The valuable guidance provided to the ICMA by Professor Kevin Rogers during the development of the CMS reinforced the importance and need for extensive stakeholder involvement and participatory decision in IWRM. His guidance also established the importance of a consensus-based decision making system around IWRM with the ICMA. The CROCOC is perhaps one culmination of this endeavour since it was established to coordinate the stakeholder participation, decision making, action research and strategic adaptive management needs. This led to a vital sense of ownership of decisions and policies linking both technical DSS related data to the more complex social-ecological needs of the Crocodile River, ultimately leading to reduced resistance and even cooperation in implementing management action. The committee operates under a TOR that acts as the mutually acceptable ethical framework for *Adaptive Operational Water Resources Management (AOWRMF)* in the Crocodile River. The CROCOC has now established itself as the central consultative technical advisory body for operational water resources, managed by the ICMA and provides the mechanism for interaction, exchange of operational information and coordination of operational activities and decisions.

The knowledge required to implement an effective AOWRMF were analysed, evaluated, and adjusted (and documented) in the following hierarchy of categories (see Report 3 on accompanying CD for further detail):

• Institutional Arrangements	Social Scientific Learning	Management Learning
• Stakeholder Participation and Decision Making		
• Data and Information	Technical Scientific Learning	
• Modelling and Decision Support Systems		

The evaluation of the efficacy of the AOWRMF within this project had two outputs:

- assess how this is facilitated through the social learning of ICMA and CROCOC (social evaluation)

- assess the implementation of ecological reserve of the Crocodile River using real time operating rules (technical evaluation)

3.1.5. Results of the AOWRMF development

The AOWRMF is thus the outcome of four years (Oct 2009 to Oct 2013) of deliberation, action research and development in collaboration with the CROCOC stakeholders, as documented in King and Pienaar, 2011; McLoughlin et al., 2011; and Pollard and Du Toit, 2011; Jackson et al., 2012. The *vision*, *objectives* and *scoping management options* (adaptive planning aspects of Pollard and du Toit, 2007) in the AOWRMF are shown in final form in Figure 3.2.

3.1.5.1. A Rapid Response System

The Rapid Response System within the AOWRMF has evolved to cater for both operational water resources management and ecological flow implementation and incorporates various aspects of operational river management. It is the necessary prerequisite in which adaptive management is conducted in the Crocodile River and is also the key enabler of short term feedback loops (social transparency). In particular it has evolved to become a core enabler of openness and inclusivity for short term and near real time operations. This is because the CROCOC which meets quarterly thus cannot be used for day to day short term decision making. The committee can thus not ensure that the short term operations meet the social objectives and the rapid response system fills this gap.

The rapid response system includes the following aspects:

- Dissemination of real time rainfall, runoff and dam level information through emails and a web portal.
- Calculation and dissemination of short term forecasted rainfall, runoff and dam levels (weekly, but updated daily).
- Defined monthly alerts for river flows based on international obligations and historical statistics compared to current real time information.
- Defined worry levels around the reserve or ecological flows, linked to management actions.
- Calculation and dissemination of the weekly forecast ecological flows or reserve.
- Automated emails and SMS delivery to relevant stakeholders linked to the alert and worry levels.
- Management log of all alerts and related actions, available for all.
- Linked to longer term aspects of the AOWRMF through the presentation of the logbook and short term monitoring results at CROCOC meetings.

3.1.5.2. Data, Information and dissemination

Water resource managers are required to perform tasks for both water resources planning and operations needs and it is important that these aspects are linked together under a single framework. According to the Global Water Partnership (2013) a DSS for IWRM typically includes a database and processing environment, a knowledge and information system, a modelling and analysis framework, a socioeconomic modelling and analysis framework, and a communication framework.

The DWA Project WP 9429: A Real-Time Operating Decision Support System (DSS) for the Crocodile East River System (Hallowes et al., 2007) and the Inkomati Water Availability Assessment Study (DWA, 2009) sourced the majority of the foundational information used in the Crocodile for water resources planning and operations. The information requirements relate to for instance: dam storages, landcover, hydrology, irrigation boards, WARMS (water use registration), climate forecasts, river health program data, etc. A significant proportion of this data is used to drive the water resource DSS and combined modelling platform (Figure

3.3) upon which the CROCOC predicates its decision-making[11], further details of which can be found in Appendix 0.

Experience in the implementation of the AOWRMF has shown that the real time rainfall and stream flow loggers and water level probes require extensive maintenance. Staff was appointed at the ICMA and a technical support and maintenance contract with the service provider was put in place to ensure the continued reliable operations of the hardware.

Water meters for irrigated water use currently installed are not real time enabled. Enabling them to report water use in real time would improve the short term modelling and flow forecasting.

All of the above data and information is collected and disseminated to stakeholders through the rapid response system and the CROCOC via a combination of, e-mail, web portal and CROCOC presentations. This is managed by a water resources information management database running on the Mike customised DSS.

Whilst the hydrochemical and remote sensing data that was presented in section 2 has not been integrated with the DSS that the CROCOC uses, it nevertheless suggests that in the future this information will be extremely useful in these decision making frameworks in order to:

- provide a quantitative validity to hydrological data integration (particularly in terms of remote sensing data) in models at increasingly finer spatial and temporal resolutions – key to real-time water resources management
- provide qualitative baseline information for a broad array of stakeholders to understand catchment hydrodynamics (water pathways from hydrochemistry; land-use/topographic related water fluxes from remote sensing data), in order to elicit a robust conceptual hydrological platform upon which to predicate decisions at the operational level.

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[11] The TOR of the CROCOC summarises the main information and decision needs at various temporal scales required for operational water resources management of the Crocodile River.

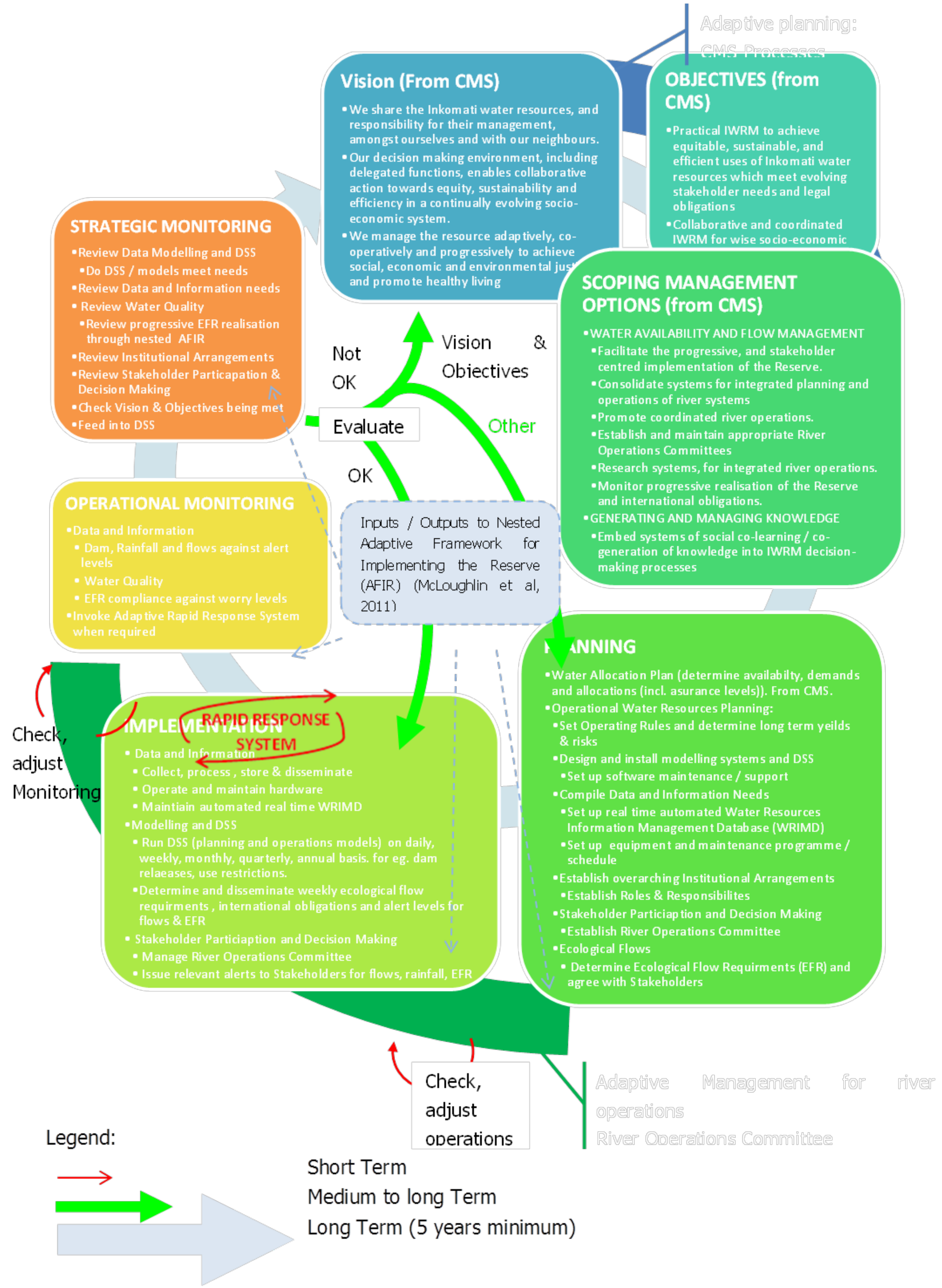


Fig 3.2: A pragmatic Adaptive Operational Water Resources Management Framework for the Crocodile River

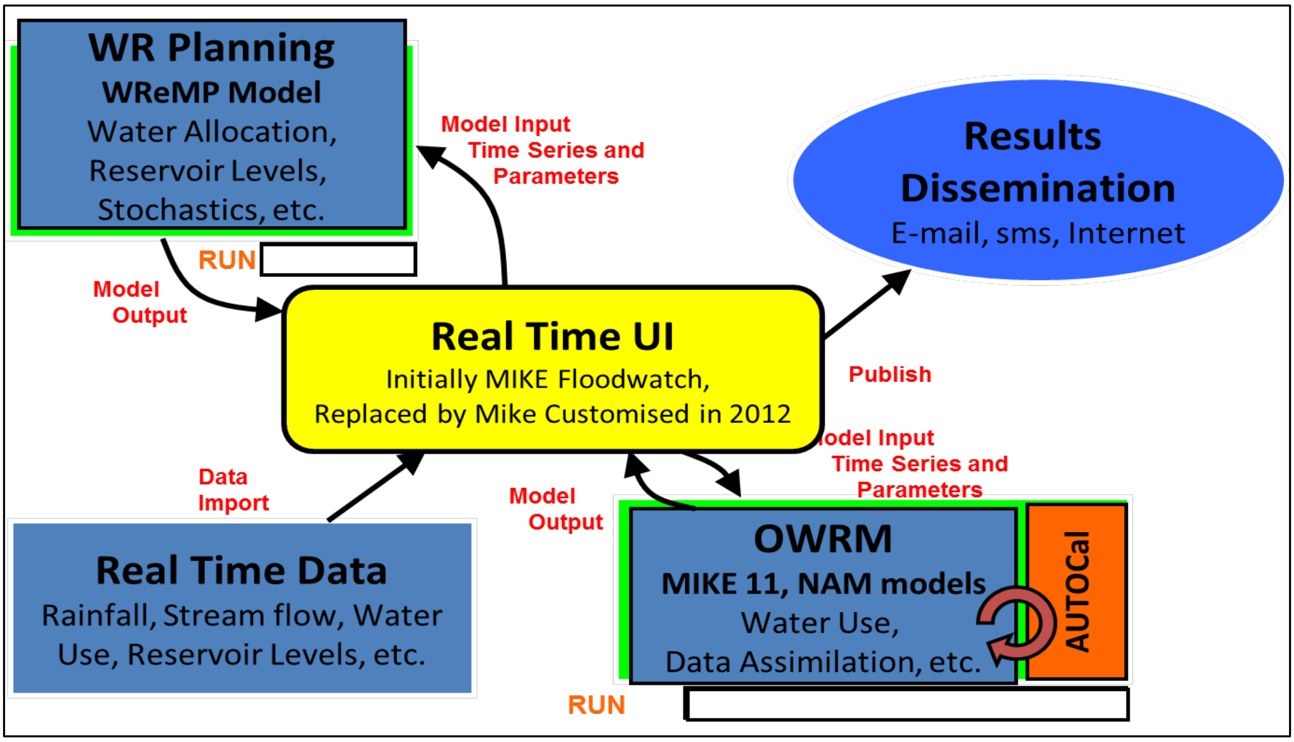


Figure 3.3: Conceptual Representation of the Operational Water Resources Management Decision Support System implemented in the Crocodile Catchment (Hallowes et al., 2007), where the WReMP is the long term water resources planning model and the MIKE suite of tools integrates this and other information for real-time operations for the Crocodile River (for further detail see Report 3 on accompanying CD and Appendix II).

3.1.6. Results of the AOWRMF Implementation

3.1.6.1. Social Evaluation: Stakeholder Participation in Decision Making

The CROCOC enabled the researcher to form bridges across the domains of science, management, and societal values and investigate the lived complexity between scientific, social and management disciplines.

The extensive discussions over the technical implementation of the ecological flows at the CROCOC are evidence of the difficulties faced in obtaining understanding of the technical and scientific aspects amongst the stakeholders and in translating scientific information into understandable information for decision making and practical implementation. However, it has also shown that frequent, focused discussions amongst relevant stakeholders can facilitate sufficient understanding and enable effective implementation of AOWRM.

The social learning outcomes from the questionnaire are summarised in Table 3.1 (Details of which may be found in Appendix 0). Users were asked to provide a score for each question with a score of 5 indicating that they strongly agree, 1 that they strongly disagree and 3 neutral. An average score of higher than three (3) indicates that users are in general agreement, while a minimum score below three (3) indicates that some users do not agree with the general consensus. The results indicate that social learning is fairly well established in the AOWRM of the Crocodile River. The average scores of the questionnaire respondents indicate a high level of agreement. This highlights the importance of the CROCOC for enabling effective AOWRM and its value in fostering social learning and consensus-based decision making. In fact, it is contended here that its existence and effective functioning is critical to effective AOWRM.

The results have reinforced the general trust that the stakeholders now have in the ICMA as a competent technical body to manage the technical aspects of AOWRM and this has enabled much progress on the implementation of AOWRM, which it is suggested would not have been achievable without the existence of the CROCOC. Although at present the drawbacks identified were: the absence of certain sectors, chiefly the municipalities, representatives from Mozambique and emerging farmers, were highlighted as issues of concern that must be addressed. The absence of water use information from the irrigation board was another cause of concern.

Table 3.1: Social Learning Evaluation of Stakeholder Engagement and Participatory Decision Making associated with implementing AOWRM through the CROCOC (for detail see Appendix 0).

Key Capacities for Social Learning

Criteria	Statistics	
	Min	Avg
FAIRNESS:	3	4.2
WISDOM: Competent Decisions	3	4.1
WISDOM: Consensus	4	4.6
STABILITY: decisions not opposed	2	3.4
SENSE OF OWNERSHIP:	4	4.4
CAPACITY BUILDING/LEARNING: Sufficient?	2	3.9
CAPACITY BUILDING/LEARNING: Other perspectives allowed?	4	4.2
AWARENESS: Good awareness	3	4.0
AWARENESS OF SYSTEM COMPLEXITY:	3	4.0
SHARED PROBLEM IDENTIFICATION:	2.5	3.8
INTERDEPENDANCE BETWEEN STAKEHOLDERS: D	2	3.6
LEARNING TO WORK TOGETHER:	3	4.2
RELATIONSHIPS: Formal relationships established?	3	3.8
RELATIONSHIPS: Informal relationships established?	3	3.7
TRUST:	3	4.2

Key Fostering Factors for Social Learning

Criteria	Statistics	
	Min	Avg
ONGOING HIGH MOTIVATION: Amongst the stakeholders?	3	4.0
INDEPENDENT TECHNICAL MEDIATOR: ICMA a good independent technical Mediator?	4	4.8
HIGH COMMITMENT OF LEADERS: Responsible authorities highly committed?	3	4.1
LEGITIMACY: ICMA?	5	5.0
EXCHANGE OF INFORMATION: Good access to and exchange?	3	4.0
INCLUSIVITY (ABILITY TO CONTRIBUTE?): All stakeholders are able to effectively contribute?	2	4.0
DELEGATED LEADERSHIP: Sufficient delegation?	3	4.0
NUMBER OF PARTICIPANTS: Limited participants enables improved deliberations?	3	3.9
FREQUENT, FOCUSED DISCUSSION: Sufficiently frequent, and focused discussion?	3	3.7
EFFICIENCY: Do you feel that the AOWRM in the Crocodile is efficient in achieving its goals?	3	4.1

Key Hindering Factors for Social Learning

Criteria	Statistics	
	Min	Avg
INADEQUATE TIME AND RESOURCES:	3	3.9
LACK OF FEEDBACK OF OUTCOMES:	4	4.2
RELATIONSHIP BETWEEN STAKEHOLDERS AND TECHNICAL TEAMS:	3	4.2
OVERLY TECHNICAL LANGUAGE:	2	3.0
LACK OF CLARITY ON PROJECT AIMS:	3	4.0
CONFLICT IN SCALE OF PROJECT AND STAKEHOLDER INTEREST:	3	4.1
LACK OF OPENNESS:	4	4.1

Consensus-Based Decision Making

Criteria	Statistics	
	Min	Avg
PURPOSE DRIVEN:	4	4.7
INCLUSIVE:	3	4.1
VOLUNTARY PARTICIPATION:	3	4.2
SELF DESIGN:	2	3.6
FLEXIBILITY:	3	3.8
EQUAL OPPORTUNITY:	3	4.0
RESPECT FOR DIVERSE INTERESTS:	2	3.8
ACCOUNTABILITY:	3	3.8
REALISTIC DEADLINES:	4	4.2
IMPLEMENTATION	3.5	4.4

3.1.6.2. Real Time Implementation of the Ecological Water Requirements (Reserve)

Much research has also been done into the state-of-art of the development of ecological flows but general research has shown that ensuring that ecological flows are implemented in practice has received relatively little attention (Mallory, 2012). It has been shown that ecological flows cannot be implemented without implementing real time or near real time operations (McLoughlin et al., 2011), especially in semi-arid run-of-river dominated closing basins.

The first few meetings of the CROCOC clearly showed that the effective determination and implementation of the ecological flow requirements were the main concern and source of conflict amongst the stakeholders. Prior to the commencement of the CROCOC and AOWRMF, no ecological flows were being implemented even though international and ecological flow requirements have the highest priority of supply in terms of the NWA.

It took 2 years of rigorous and frequent discussions at the CROCOC meetings from October 2009 until October 2011 before an effective and trusted real time ecological water requirement determination method and related decision making process was finally implemented at the ICMA. This demonstrates the importance of facilitated discussion amongst all stakeholders (via CROCOC in this case) on matters of conflict and the time it can take to achieve consensus, but the result is much improved trust and ability to implement decisions.

Technical Aspects

Some of the technical issues related to the ecological water requirements present at the initiation of this AOWRMF in 2009 included:

- Ecological water requirement determination methods are undertaken without consideration of the realities of operationalising these. The outputs of the determination studies need to be 'translated' into operational reserve requirements.
- The lack of consideration of the operational realities in the comprehensive reserve determination results available from DWA are demonstrated through the presentation of results in the form of percentage exceedance curves of flows per month. Firstly, these exceedance curves are difficult for most stakeholders to understand; secondly, the monthly time step is not sufficiently short for near real time operational water management and thirdly, it is only possible to determine what the actual ecological flow requirement at any point in time is without first determining the natural flow at that point in time. A process is thus required to calculate the percentile of the natural flow against historical statistics at present day and to then use that percentile to determine the relevant position on the exceedance curve for the ecological flow and finally, the actual ecological reserve flow for the present day. This is especially troublesome if the ecological flows are required to be determined in support of operational near real time water resources management when forecasted natural flow is required, as is the case here. None of the above processing was in place in October 2009, when the AOWRMF was first introduced.
- In South Africa, the ecological reserve is defined as a function of the natural flow which, because the natural flow in a system is not known at any point in time, causes difficulty with real-time implementation (Pollard et al., 2011). Methods developed and applied to date in Southern Africa entail setting up real-time hydrological models to estimate natural flows given real-time rainfall data. However, accurate real time rainfall data is lacking in many catchments (Pollard et al., 2011).
- At the final steering committee meeting of the DWA reserve study, it was decided to maintain the present day flow regime in the Crocodile River and not to implement the recommended reserve class. What "present day flow" actually meant on a daily basis was not determined.

As a result of these issues, and due to insistence stemming from the CROCOC meetings, it was necessary to develop an effective methodology to calculate the ecological reserve in near real time. A method to compute real time naturalisation and ecological flow requirements without the need for accurate real time rainfall data was developed by Mallory (2010), on request of the ICMA. This method uses real time observed river flows, dam levels and estimates of water use (all available) to calculate the natural flow in real time as shown below:

$$NF_t = OF_t + \Sigma WU_t + \Delta S$$

Where: NF is natural flows; OF is observed flows; WU is water use; S is storage; and t refers to a time interval. The method is described in detail by Mallory (2010).

The "present day flows" described in the DWA comprehensive reserve determination project also required determination and operationalisation (Mallory, 2010). These "present day flows" were compared to the original C-Class reserve requirements stemming from the DWA project and presented to the CROCOC stakeholders for discussion and adoption. Discussions over the final ecological flows to be used took place over many months at the CROCOC. The calculated "present day flows" included high flow requirements while the C-class reserve from the DWA project was only determined for low flow ecological requirements. Consensus was eventually reached on the use of a new recommended ecological flow requirement that is the lower of the "present day flow" and the DWA C-class reserve as shown in Figure 3.4.

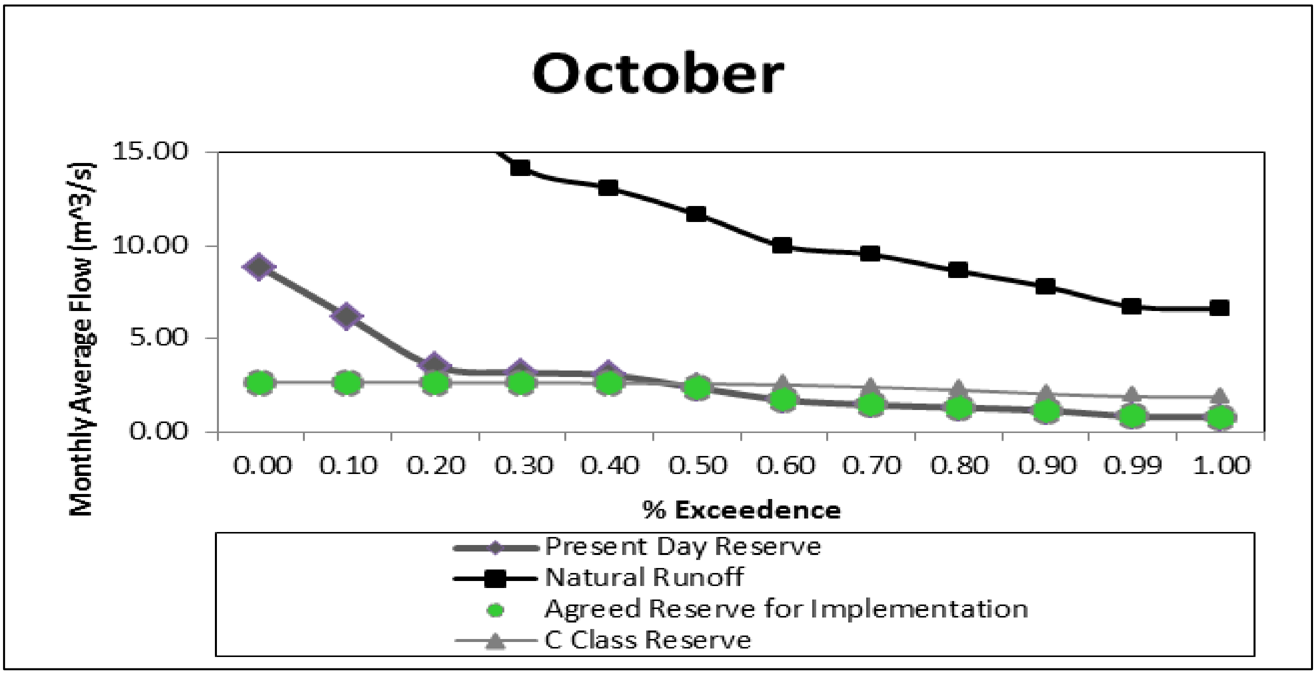
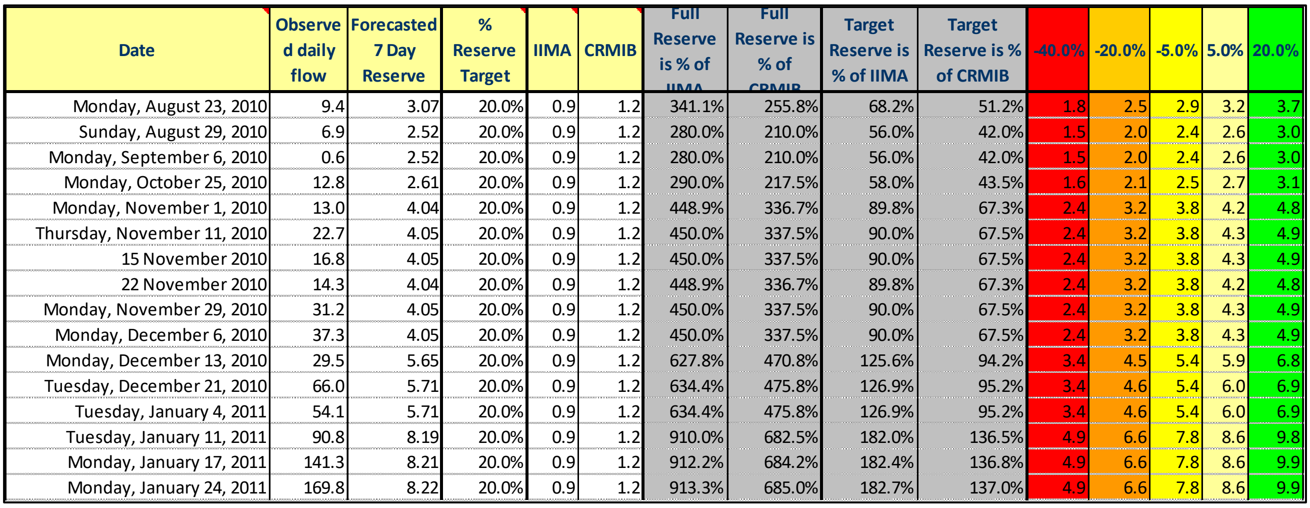


Fig 3.4: Present Day Flows vs. C Class Reserve and Natural Flow for October

Consensus was also reached on the implementation of the ecological reserve at the downstream end of the catchment near the DWA X2H016 (Tenbosch) flow gauge only. This decision was based on the assumption that if the downstream ecological flows were met then the upstream sites would also be met.

The model is run on a weekly basis. The model determines the real time natural flow and then calculates the agreed "present day flow" ecological flow requirement by reading the current natural flow off the relevant monthly exceedance curve, followed by the corresponding ecological flow for the same percentage exceedance. The outputs from the WReMP model are used to calculate weekly ecological reserve flows at the Tenbosch gauge and sent to all relevant CROCOC stakeholders as a spreadsheet shown in Figure 3.5. This spreadsheet forms a critical aspect of the rapid response system and feedback loops of the AOWRMF and is used by the KNP to monitor river flow compliance against the ecological flow requirements and notify stakeholders when the various worry levels are reached. The implementation and efficacy of the rapid response system and feedback loops associated with the ecological reserve is thus reliant on the short term operations aspects of the AOWRMF and the Mike Customised DSS.



Date	Observed daily flow	Forecasted 7 Day Reserve	% Reserve Target	IIMA	CRMIB	Full Reserve is % of IIMA	Full Reserve is % of CRMIB	Target Reserve is % of IIMA	Target Reserve is % of CRMIB	-40.0%	-20.0%	-5.0%	5.0%	20.0%
Monday, August 23, 2010	9.4	3.07	20.0%	0.9	1.2	341.1%	255.8%	68.2%	51.2%	1.8	2.5	2.9	3.2	3.7
Sunday, August 29, 2010	6.9	2.52	20.0%	0.9	1.2	280.0%	210.0%	56.0%	42.0%	1.5	2.0	2.4	2.6	3.0
Monday, September 6, 2010	0.6	2.52	20.0%	0.9	1.2	280.0%	210.0%	56.0%	42.0%	1.5	2.0	2.4	2.6	3.0
Monday, October 25, 2010	12.8	2.61	20.0%	0.9	1.2	290.0%	217.5%	58.0%	43.5%	1.6	2.1	2.5	2.7	3.1
Monday, November 1, 2010	13.0	4.04	20.0%	0.9	1.2	448.9%	336.7%	89.8%	67.3%	2.4	3.2	3.8	4.2	4.8
Thursday, November 11, 2010	22.7	4.05	20.0%	0.9	1.2	450.0%	337.5%	90.0%	67.5%	2.4	3.2	3.8	4.3	4.9
15 November 2010	16.8	4.05	20.0%	0.9	1.2	450.0%	337.5%	90.0%	67.5%	2.4	3.2	3.8	4.3	4.9
22 November 2010	14.3	4.04	20.0%	0.9	1.2	448.9%	336.7%	89.8%	67.3%	2.4	3.2	3.8	4.2	4.8
Monday, November 29, 2010	31.2	4.05	20.0%	0.9	1.2	450.0%	337.5%	90.0%	67.5%	2.4	3.2	3.8	4.3	4.9
Monday, December 6, 2010	37.3	4.05	20.0%	0.9	1.2	450.0%	337.5%	90.0%	67.5%	2.4	3.2	3.8	4.3	4.9
Monday, December 13, 2010	29.5	5.65	20.0%	0.9	1.2	627.8%	470.8%	125.6%	94.2%	3.4	4.5	5.4	5.9	6.8
Tuesday, December 21, 2010	66.0	5.71	20.0%	0.9	1.2	634.4%	475.8%	126.9%	95.2%	3.4	4.6	5.4	6.0	6.9
Tuesday, January 4, 2011	54.1	5.71	20.0%	0.9	1.2	634.4%	475.8%	126.9%	95.2%	3.4	4.6	5.4	6.0	6.9
Tuesday, January 11, 2011	90.8	8.19	20.0%	0.9	1.2	910.0%	682.5%	182.0%	136.5%	4.9	6.6	7.8	8.6	9.8
Monday, January 17, 2011	141.3	8.21	20.0%	0.9	1.2	912.2%	684.2%	182.4%	136.8%	4.9	6.6	7.8	8.6	9.9
Monday, January 24, 2011	169.8	8.22	20.0%	0.9	1.2	913.3%	685.0%	182.7%	137.0%	4.9	6.6	7.8	8.6	9.9

Fig 3.5: Extract of the Weekly Ecological Reserve Spreadsheet emailed to all Relevant CROCOC Stakeholders

Evaluation

The compliance to the ecological reserve has been used as the main means of evaluating the efficacy of the AOWRMF, along with the social learning outcomes. This is apt as the ecological flows were not being implemented at all before the commencement of the AOWRMF and yet were the main source of concern and conflict amongst the stakeholders related to operational water resources management.

The methodology of Riddell et al. (2014), to evaluate the compliance with the ecological flow requirements has been used in this project to ensure consistency with the research and monitoring of compliance previously conducted in the Crocodile River. The methodology determines the extent of non-compliance in terms of four categories: % time non-compliant, the number non-compliant months per year, seasonality of compliance, and magnitude and contiguity of compliance.

The DWA C-Class reserve has been used in accordance with Riddell et al. (2014), although a more lenient "present day flow" requirement has been implemented since October 2009. The non-compliance before and after the implementation of the AOWRMF in 2010 is shown in Figure 3.6.

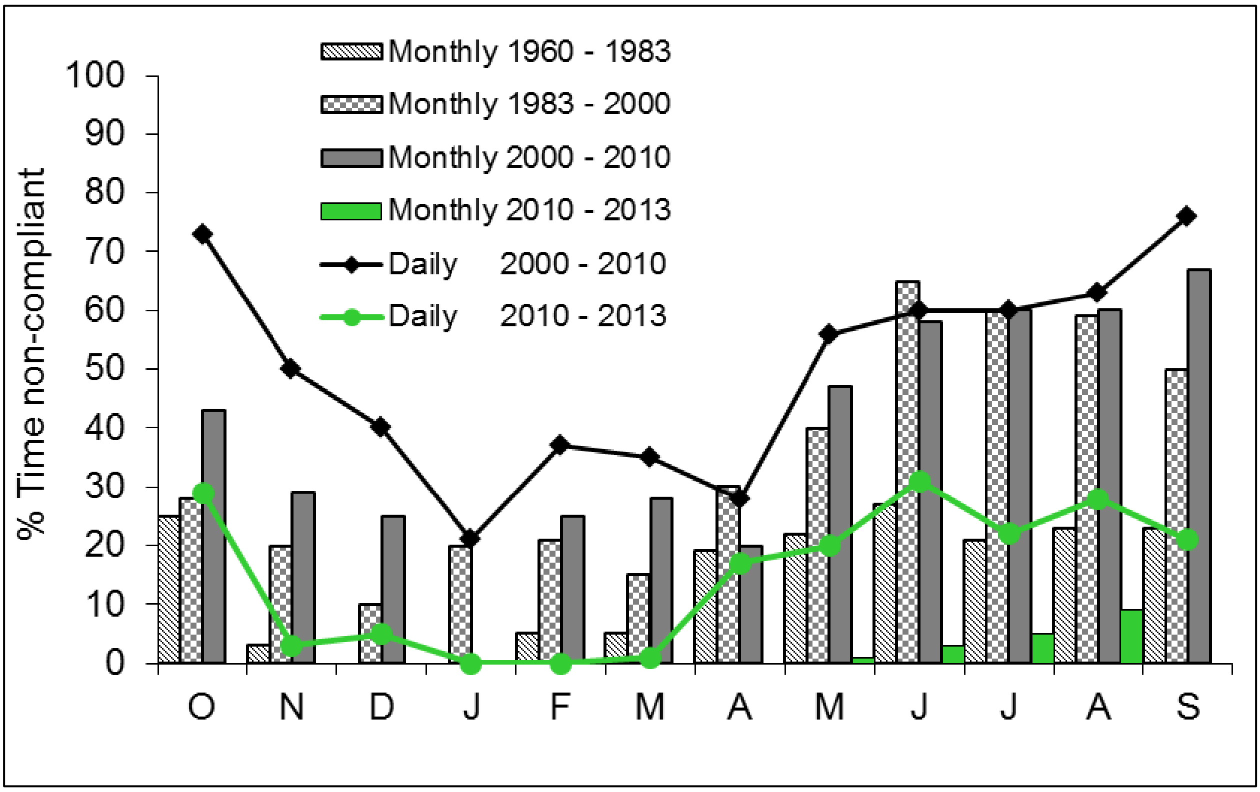


Fig 3.6: Percentage of Time for Monthly Ecological Flow Compliance before and after the implementation of the AOWRMF (green)

The average incidence of failure across all months since 2010 is only 2% with the maximum being 9% during August. Although not all categories are shown here, the percentage time, magnitude and contiguity of non-compliance to the ecological flow requirements have all drastically reduced since October 2009, when the AOWRMF was introduced. Before then, these factors all showed a steady increase in non-compliance since 1960. This is a clear indication of the impact the AOWRMF has had and its efficacy in implementing OWRM. This has been achieved through the sharing and learning from information through consensus, that allows real-time adaptive decisions to effect change.

3.1.7. Conclusions

The results presented under the four categories of the adaptive operational water resources management framework (AOWRMF) clearly demonstrate that an AOWRMF can be effective in implementing operational water resources management in semi-arid, closing and run-of-river dominated catchments. The social learning questionnaire outcomes and the huge improvements in the compliance with the ecological flow requirements are the chief indicators supporting this statement.

Important overarching aspects of an effective AOWRMF for semi-arid, closing and run-of-river dominated catchments stemming from this research include:

- It is developed through a grounded action research methodology with strong stakeholder involvement, cognisant of both scientific and management learning.
- A broad scope of research is necessary to explore the many relevant aspects and levels of the concept and practice of operational water resources management. This includes both social and technical science.
- The AOWRMF is cognisant of requisite simplicity.
- The setting up and use of an operations committee with a defined TOR – developed in collaboration with the stakeholders – to provide the mutually acceptable ethical framework for the action research is crucial.
- It is based on Strategic Adaptive Management principles.
- It includes both water resources planning and operations aspects, links them together in one framework and does not concentrate on the implementation of the operations aspects in isolation.
- A rapid response system incorporating aspects from all four categories the AOWRMF is effective in implementing and facilitating the short term or real time aspects of AOWRM and is a core enabler of openness and inclusivity, as evidenced through the effective implementation and monitoring of the ecological flow requirements though the rapid response system.
- The AOWRM process is continually being refined through continued input from stakeholders and managers. This should help the ICMA towards achieving two of their objectives viz. (i) ensure Effective, Efficient and Sustainable Management of Water Resources, and (ii) ensure collaborative and co-ordinated IWRM for wise socio-economic Development.
- It must be noted that a drought has not occurred since October 2009, when the implementation of AOWRMF commenced and the success of the AOWRMF can thus only be truly known by re-evaluating its performance through the next drought, continued evaluation is thus recommended.

Importantly of course the results of operational practice, be they in the form presented in this AOWRMF, or otherwise, need to speak to the governance goals of the ICMA also. It is believed that the following section 3.2 will make this clear, but it is necessary to provide an example of this at this juncture. Using this metric of progressively realising the implementation of an ecological water requirement (reserve) over the short period of four years in a complex river system is a key performance indicator of achieving some level of water resources sustainability (e.g. the "E" in STEEP). Since reserve implementation is a key criteria as described in the CMS (ICMA, 2010) for achieving the stakeholder derived *vision* for the Inkomati water management area, the steady approaching of those 'goals' in a part of that of WMA should be viewed as a positive, or a step in the right direction (e.g. a green traffic light). Whilst the detail of how this positive direction is being achieved may be cumbersome (and in this section that has already been summarised significantly!) it is necessary to make such outcomes less cryptic, more so where there are a large variety of complex performance indicators. This is a prime example of important information that must not evade those that guide the ICMA at a governance level.

3.2. A Catchment Information Utility in the form of an *Adaptive Operational Governance Dashboard*

(Riddell, ES. Lamba, A, Jackson, B. Thornton-Dibb S & HydroLogic).

3.2.1. Introduction & Rationale

It is not often the case that the natural landscape mirrors the inequalities prevalent in society – the Inkomati basin stands as an exemplar of this. The National Water Act (1998) is an outstanding initiative to help bridge the perceivable disconnect with regard to the multiple disparities that exist in enabling access to water for all in South Africa. The establishment of the Inkomati Catchment Management Agency (ICMA) is South Africa's first attempt at creating a decentralized water management institution at the river basin level in pursuance of the mandate of the National Water Act (NWA, 1998).

The South African National Water Act (Act 36 of 1998) embodies the concept of Integrated Water Resources Management (IWRM) and took a bold step towards ensuring that equity and sustainability remain the two core principles of the water resource management in the country. The principles are meant to ensure transformation in South Africa's water sector towards integration, redistribution, equity in allocation, sustainable use, water resource protection, and participation (Pollard & du Toit, 2008).

The Department of Water Affairs & Forestry (DWAF, 2003a) defines IWRM as 'a philosophy, a process and a management strategy to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits'.

The Inkomati basin epitomizes the complexity of IWRM in a historically deeply contested zone that faces vulnerabilities, risks and uncertainties. The Inkomati simultaneously captures the aspirations of those that draw sustenance from the services that the waters of the basin provide. A key catalyst to help integrate these complexities is through effective decision-making, which weaves together the seemingly incompatible claims of diverse stakeholder representation. For this, dynamic information flows amongst the decision-makers and stakeholders about competing socio-environmental demands on the Inkomati basin is critical for the participatory decision making as compelled in the NWA.

3.2.2. Science-Management-Governance interface in an adaptive setting

Lessons from applied IWRM in South Africa have shown that it should be developed, implemented and continually reflected upon in an *adaptive manner* that stimulates the interaction between practitioners (managers), stakeholders (governors) and scientists (technicians and researchers) through the philosophical approach of *learn-by-doing* or in other words being informed by practice. This is of tantamount importance since traditional systems of governance and management generally do not effectively accommodate the diversity of legitimate stakeholder needs and value-sets as well as the rapidly changing circumstances that confound societal decision making. Nor in many circumstances is credible scientific knowledge integrated in these decision-making frameworks. Of course this has considerable relevance in the South African setting where transformation principles hold considerable leverage, and moreover where these three spheres of influence are embraced in the national decision-making framework.

To this end, it is critical to embrace the triple learning pathways of science, management and governance, whilst acknowledging that these are all disciplinarily confined. For instance in the science field broadly speaking we can compartmentalize into social, technical and biophysical issues, all of which are seen as equally important components in the complex field of water resources management. Nevertheless is could be stated that overall water resource management is fundamentally a social process (Rhoads et al., 1999). This requires social learning which may be defined as achieving concerted action in complex and uncertain contexts and situations (Ison and Watson, 2007). The facilitation of such social learning and the creation of institutions under the adaptive management umbrella are key criteria for the management of complex problem situations (Daniel and Walker, 1996; Jiggins and Roling, 2000). Cleary therefore frameworks and tools that facilitate this collective learning should provide significant benefit to the process of water resource management (e.g. Pahl-Wostl & Hare, 2004). These should allow for the collective conceptualisation of shared resources, where documenting individual or stakeholder groups *mental models* have shown such promise, as documented in the Crocodile sub-basin of the Inkomati Water Management Area by Biggs et al. (2008):

> '...put simply [mental models], are what people use to understand and interpret phenomena of everyday life. These models are frameworks of concepts and relationships that underpin how people understand, filter and process information and contribute to understanding, reasoning, prediction and action.`

The study by Biggs et al. (2008) determined the level of consensus among different stakeholder groups with respect to key questions related in particular to the *ecological reserve*, and developed schematic representations of an individuals or groups mental model of a socio-ecological system. Whilst their methods identified that the concept of the *reserve* is not understood, the benefits of the work revealed that high levels of representation and inclusivity and were achieved through participatory approaches. The tools developed through this process were recommended for further development and refinement in order for the IWRM practitioner to understand how, why and where differences in conceptual understanding, language use, meaning and practices might arise. This social learning approach has already borne fruit as revealed by McLoughlin et al. (2011), Pollard and du Toit (2011) and Riddell et al. (2013) for implementing adaptive resource management for ecological reserve flows in Lowveld catchments of South Africa. The apparent successes being achieved in the Inkomati through management systems which allow for adaptation, and the co-operation of actors (managers and stakeholder) in decision-making, makes this basin an example of successful *adaptive co-management* of water resources. This gives credence to the recommendations for such endeavour made by Folke et al. (2003, 2005), Rogers (2006).

As suggested by Stirzaker et al. (2011), successful adaptive management in a multi-stakeholder context rests on three pillars, namely the ability to form a robust, shared conceptualisation, the ability to monitor key variables that will shed light upon this conceptualisation, and the ability to learn from the experience. If any of these are compromised, the structure will collapse. Hence tools that provide a concrete, but yet dynamic form to the ideas posed within the adaptive management philosophy should allow for the theoretical presuppositions and conceptual constructs to be mirrored in local concrete strategy setting and decision making.

3.2.3. Inkomati Setting

The gradual delegation and assignment of functions from the Regional Office of the Department of Water Affairs (DWA) to the ICMA in pursuance of the NWA's mandate to manage water at the basin level, is slowly paving the way for the ICMA to assume substantive powers with regard water resources management in the Inkomati catchment. The Governing Board which represents the interests of the main existing water users (stakeholders) appointed by the National Minister for Water and Environmental Affairs and the technical experts in the Management Committee (MANCO) form the key decision-makers in the ICMA. Interactions with members of the ICMA Governing Board and the MANCO revealed that provision for dynamic, transparent and comprehendible information flows amongst the key players (actors) in the Inkomati catchment may be a necessary prerequisite for informed and adaptive decision-making within this complex setting. Moreover, the fluid movement of information amongst these actors could help bridge the trust deficit amongst them, which has oftentimes contributed to stymieing the complex participatory decision-making process.

One of the mechanisms to kick-start the flow of versatile information amongst participatory actors is the provision of a tool that offers comprehensive and easily understood information about the quality and quantity of waters and other aspects of the water resource management discourse. By offering a shared and interactive platform for the actors, this tool might be an effective step to weave together the disparate interests of the various stakeholders, thereby integrating a complex system in a systemically simple manner.

3.2.4. Conceptual-Analytical framework to merge Adaptive Operations and Governance into a tool for Decision-Making and reflection

Whilst the potential for a tool sits at the intricate enmesh of societal and ecosystem demands, with the aim of marrying the two to enable resilient decision-making, it will ostensibly, be utilized for decision-making by the ICMA from two different perspectives: at the governance level, wherein the Governing Board will use information to better address stakeholders' concerns; and at the science-management level, wherein the technical experts (MANCO) will use the information from the operational perspective. This tool therefore appears as a bricolage that mirrors the complex decision-making at the science-management-governance interface. In order to explicate the dynamics on which this tool is undergirded, and to help think through such complexity challenges requires the situating this tool theoretically.

Using the conceptual-analytical framework of the ideas developed on *Boundary Work* (Mollinga, 2010) and *Requisite Simplicity* (Stirzaker et al., 2010), the theoretical underpinnings for this tool are developed. Natural resources management systems are complex systems because they are composed of heterogeneous components with a diversity of relations connecting these components (Mollinga, 2010). The water resources management system in the Inkomati catchment is characterized by non-linearity and unpredictability (*ontological complexity*), is populated, managed and governed by different stakeholders (*societal complexity*), and sometimes is also difficult to understand (*analytical complexity*). To effectively straddle boundaries to manage water resources complexities in the Inkomati basin, a transdisciplinary approach to problem solving is useful. Boundary Work provides such a framework to systematically think through complexity challenges (Mollinga, 2010). Thus the theoretical underpinnings for the information dissemination tool can be located within it, since it is nested across the disciplinary boundaries of science-management-governance by the ICMA to effect adaptive decision-making.

Mollinga (2010) identifies three types of boundary work involved in operationalizing transdisciplinary research within the ambit of natural resources management. Boundary concepts provide a way of thinking about the multidimensionality of natural resources management by examining words/concepts through a transdisciplinary lens. *Boundary objects* are the devices and methods that allow acting in situations of incomplete knowledge, non-linearity and divergent interests. *Boundary settings* are the arrangements required to use the concepts and objects in a transdisciplinary manner. A schematic of the following discussion is shown in Figure 3.7.

In this study, ‘adaptive-’ and perhaps even ’resilient-’decision-making may be a useful boundary concept because it allows for multiple understanding and learning pathways, and every interest group can appropriate it in its own way. It thus creates a discursive space for deliberation thereby making such a concept essential for policy. However, it is hoped that this concept can help one understand the interrelatedness of these multiple dimensions adequately. Therefore, analytically, boundary concepts are about adequately capturing concrete instances of complexity (Mollinga, 2013).

As a result, the information dissemination tool may then be regarded as the boundary object for communicating scientific/expert knowledge to other actors and is part of a broader effort to create a particular, more useful decision-making interface. It is the boundary object that helps to facilitate the crossing of boundaries in participatory decision making. It is then useful to bring in the notions of requisite simplicity at this juncture since it shares common grounding with Boundary Work, and in effect acts as a catalyst to operationalize the latter.

Sometimes, highly technical parameters and terms used to provide information on the state of the catchment are not easily understood by non-technical experts, which may include members of the Governing Board and broader stakeholders. And this leads to a ‘participation inertia’ wherein actors do not see any concrete benefits from the participation process, thus rendering consensus driven decision-making null and void. Compounding this complexity is the power dynamics within powerful water sectors in the Inkomati catchment that may be oblivious of the needs of the marginalized. This leads to a scenario wherein the absence of trust and transparency can potentially stall collective action.

To build a shared vision for the catchment as mandated for in the NWA, it is imperative to establish creative methods of communication based on credible and transparent sources of information. The notion of requisite simplicity offers a refreshing approach to contend with the multidimensionality of the water resources discourse in the Inkomati catchment. In this view, there is a requisite level of simplicity behind the complexity that, if identified, can lead to an understanding that is rigorously developed but can be communicated lucidly (Holling, 2001). This is an important concept to be embodied into a decision-making apparatus since it removes the need for decision-making based on reductionist approaches. Rather, it embraces the variability and uncertainty accounted for in the complexity paradigm of real-world problems, as exemplified by Rogers et al. (2013). In this case then the boundary object, the information dissemination tool, can be seen as an embodiment of the concept of requisite simplicity, in that the tool systematically provides comprehensive and comprehendible information at various levels catering to the simple and complex needs of the stakeholders in the catchment.

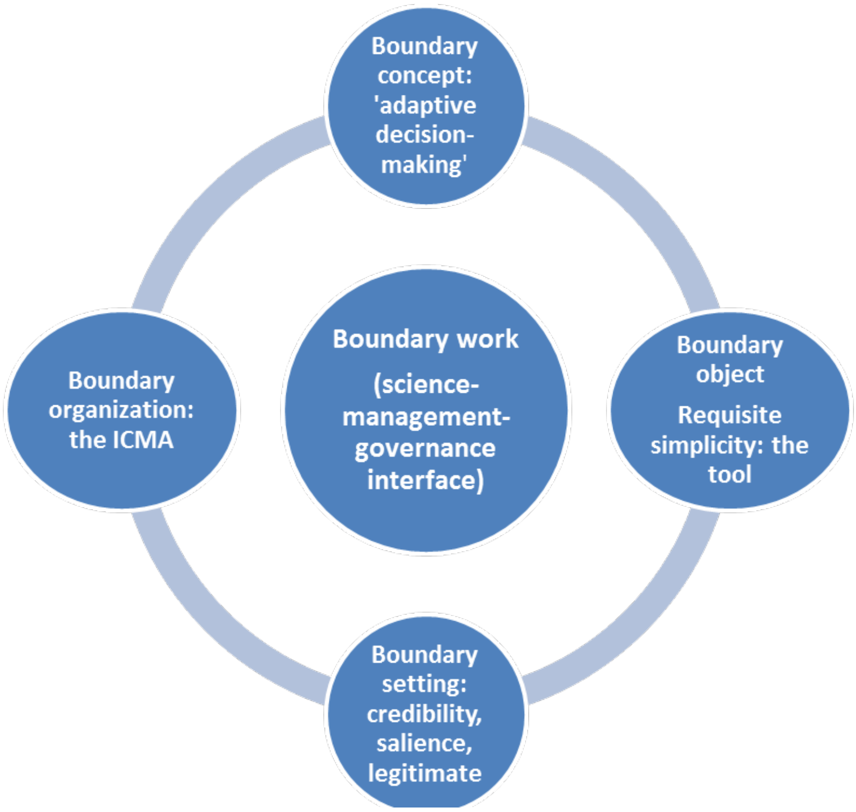


Figure 3.7: Operationalising Boundary Work in the context of the ICMA.

The idea of requisite simplicity is compelling because it holds together what are often competing interests. On the one hand, participating groups have to simplify sufficiently to get the cooperation from groups with different expertise and agendas – from those who are providing the financial resources to those who will be affected by the management intervention. Simultaneously, an attempt is made to steer clear of simplicity that might be an erroneous path to tread (Stirzaker et al., 2010).

The arrangements to make the tool work constitutes the boundary settings, and in this reckoning the tool will only work when it is considered legitimate and useful by those who have to use it. Scientific information is likely to be effective in influencing the evolution of social responses to public issues to the extent that the information is perceived by relevant stakeholders to be not only credible, but also salient and legitimate (Cash et al., 2003). Active, iterative and inclusive communication between experts and decision makers, translation of information (which has impeded information flows due to differences in languages, usages and histories of experts and decision makers) and mediation through increasing transparency, bringing all perspectives to the table and so forth (Cash et al., 2003) are the boundary settings for this tool.

And, Boundary organization is a boundary object writ large – from a simple entity it becomes a full organization within which one or several smaller boundary objects are deployed. A boundary organization could also be defined as a consolidated organizational form for the performance of boundary work – an interface that has been given an enduring organizational form (Mollinga, 2013; Guston, 2001 and Agrawala et al., 2001). Since for the deployment of this tool the ICMA is the deploying organization, the ICMA could broadly be regarded as the boundary organization.

3.2.5. Identifyng the needs of the End-User

A set of recommendations for adaptive learning and reflection had been proposed for the ICMA as it develops and implements its' CMS (Roux et al. 2010). The aims are to facilitate the working knowledge and learning environment of the Inkomati WMA that the members of the ICMA work in and the principles of this are based on those of SAM and to allow the IWRM practitioner to define the context in which they find themselves, or how and when to make a decision. This enables the practitioner to be able to respond, or make decisions on an informed bases, but also to be able to reflect on those decisions as the work moves forward. The framework is summarised in Figure 3.8 and is based on the cornerstone of SAM in terms of developing a 'vision' or desired future state for the catchment.

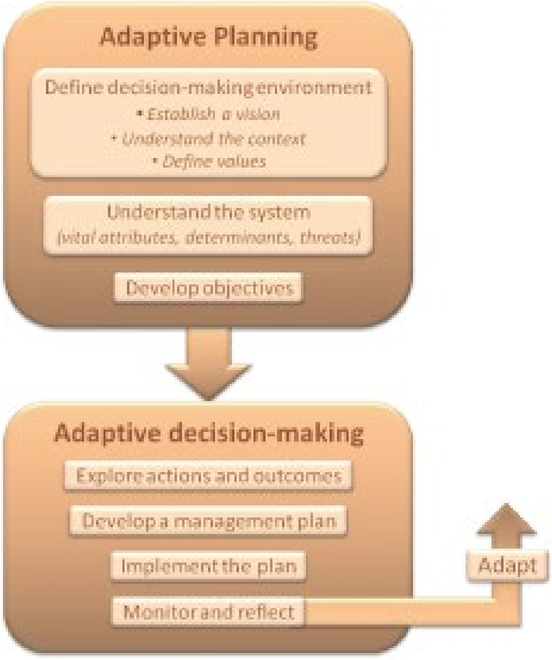


Figure 3.8: Adaptive learning and decision-making (after Roux et al., 2010)

Interaction with members of the ICMA's Governing Board and the MANCO helped understand not only why such an information dissemination tool to facilitate the process essential for adaptive decision-making, but also brought to the fore how such a tool will be of benefit to the ICMA. This is because decision-making and accountability patterns are quite distinctive in the ICMA and takes two different forms. On the one hand, the Governing Board engages in policy decision-making, determines the rules and makes available resources to be used for achieving the mandate of the ICMA. On the other, the MANCO engages in operational decision-making, implements its mandate by utilizing the available resources and functions within the rules established by the Governing Board. The MANCO is in effect accountable to the Governing Board, and the Governing Board to the National Minister for Water and Environmental Affairs.

Given the accountability pattern, it was held that the MANCO could use a tool for self-auditing purposes and as a reporting mechanism to the Governing Board. The Governing Board could in turn consider using a tool to evaluate and assess the functioning of the MANCO. Since novel software informatic approaches will now allow a tool to be designed that will provide holistic information on various facets of the catchment using a common platform that is visually appealing. Therefore such a tool could help to overcome the cumbersome process involved in the conventional reporting style that requires one to wade through seamless reports. Additionally, in a glimpse the tool will highlight the areas that need attention, which remains somewhat hidden in a normal reporting mechanism.

It also became evident that meaningful accountability to the broader stakeholders occurs through 'informal channels' in the form of catchment management forums. However, due to weak communication and reporting channels within the ICMA, the members of the Governing Board and the ICMA have scarce information about what proceeds in these forums, much to their chagrin. It was therefore held that the tool could help bridge this lag by providing local level information, such as summary outcomes of these forums. This information sharing will enable building trust amongst the staff members of the ICMA and between the ICMA and the stakeholders. Dynamic information flows mapped in this tool will help usher in transparency in the functioning of the ICMA and will provide an easier guide for the stakeholders to measure the performance of the ICMA with regard to its mandate derived from the NWA.

3.2.6. Value added: Building resilience in the boundary organization

Through the aforementioned interaction several added values were identifed that could be seen to augment organizational resilience, through continued iteration and reflection on decisions. First, such a tool could be used to instantly follow-up to examine whether the concern areas have been adequately addressed. Second, whilst enabling dynamic information flows and follow-up on actions undertaken, the tool will act as an iterative mechanism and thereby embody fully well the concept of single-, double- and triple-loop thinking and learning for adaptive decision-making. According to this school of thought, maintaining and improving high standards (single-loop thinking), reflecting on core assumptions (double-loop thinking) and the underlying values/paradigms (triple-loop thinking) enables prioritizing incoming knowledge and doing things differently (Roux et al., 2010). Third, the background knowledge for this tool is locally borne out of the South African experience and encapsulates diverse local insights, which is a key source for innovation. For the CMA process to be sustainable, it may be critical to deploy such a tool that reflects South African mores and values, and which could be easily adapted to suit changing demands. Finally, it is hoped that the generic principles for this tool – that is, the necessary but not sufficient conditions, could be utilized by existing and potential catchment management agencies in South Africa, depending on their specific contingencies. Some of the generic principles identified that could be transferred include the application of the norms underlying boundary work, requisite simplicity and single-, double- and triple-loop learning to engender greater resilience in the complex catchment management systems in South Africa.

3.2.7. From policy to the embodiment of tool to operationalize boundary work

A crucial inclusion in this new water resource management paradigm of the NWA (1998) is the focus on water resources management on a catchment basis in which the National Water Resources Strategy (NWRS) provides the framework for doing so in the complexity of a Water Management Area (WMA) (Pollard & du Toit, 2008). Importantly, the 5 yearly NWRS then sets the scene for a more detailed Catchment Management Strategy (CMS) designed for catchment level water resources management, also within a 5 year window. Moreover the CMS is then used to develop strategic plans that in South Africa are designed to achieve the transformation goals of equity, efficiency and sustainability within a WMA. The CMS is developed using the following phases (Pollard & du Toit, 2008):

A. Foundational information: assessment of the water resource management status-quo (water availability, requirements [reconciliation], the *vision* for the WMA)
B. Water Resource Management Sub-strategies
C. Facilitating sub-strategies
D. Integration Strategy

The *Vision* is a key component of any CMS as these set out, through a participatory process with stakeholders, the current situation and desired direction of water resource management in a WMA. Whilst the water resource management sub-strategies are the mechanisms through which the CMA intends to approach its vision within a 5 year CMS, these mechanisms include Resource Directed Measures (RDM) and Source Directed Controls (SDC). The former being designed to protect the state of water resources, whilst the latter intends to control water use. The facilitating sub-strategies provide the enabling environment for RDM and SDC, through management of information and finances for example. The integration strategies promote collaboration through the principles of co-operative governance. This being for instance where multiple institutions have to align their plans.

Utilising the principles of Strategic Adaptive Management (SAM) the Inkomati Catchment Management Agency (ICMA) derived its first CMS in 2010. Emanating from this were its strategic overviews (vision, mission, values, legislative and other mandates, and situational analysis). Henceforth the ICMA developed an Adaptive Planning Process as follows (ICMA, 2012):

- Ensure effective, efficient and sustainable management of water resources
- Ensure collaborative and co-ordinated IWRM for wise socio-economic development
- Promote and pursue an international developmental agenda
- Promote knowledge generation and distribution
- Ensure effective and efficient management of ICMA resources

Thereto the ICMA defined a set of shared values, through stakeholder visioning using vSTEEP criteria (values: Social, Technical; Environmental; Economic; Political [DWAF, 2007] Rogers & Luton, 2011, Kingsford & Biggs, 2012)], to define Strategic Action Programmes (SAPS). These are described in the CMS (ICMA, 2010) and are linked to the Strategic Objectives (SO) and are used to adaptively manage and evaluate the ICMA's performance. These SAPs are classified as follows (ICMA, 2012) and Table 3.2:

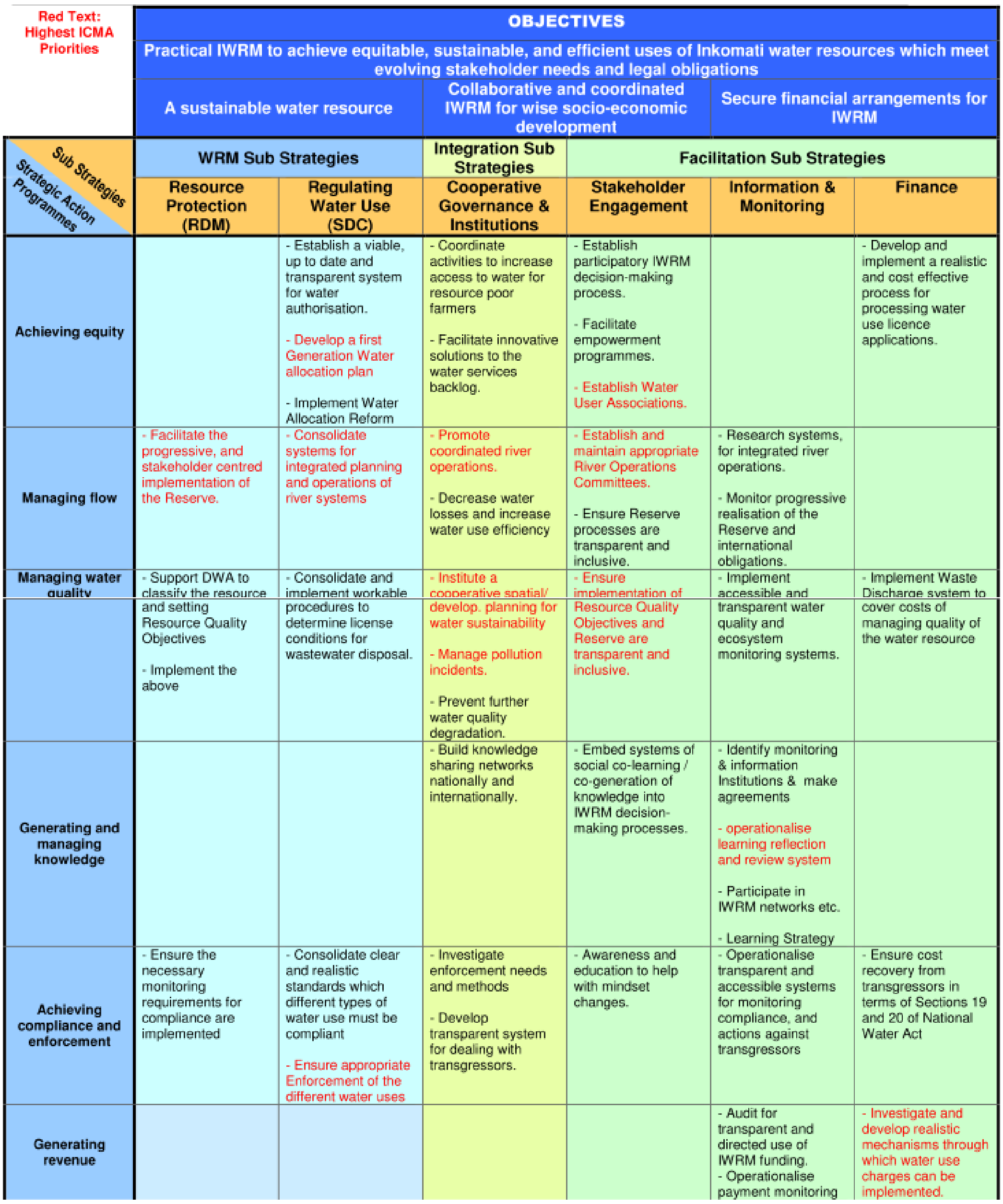
- Achieving Equity	(SAP1)
- Water Availability and Flow Management	(SAP2)
- Managing Water Quality	(SAP3)
- Generating and Managing Knowledge	(SAP4)
- Achieving Compliance and Enforcement	(SAP5)
- Generating Revenue	(SAP6)

3.2.8. An Apparatus for Adaptive Operational Governance

Following the *boundary work* framework described we herewith describe the conceptual architecture of the *boundary object* that can be used to straddle the boundaries beset in the complexities of the water resource management setting of the ICMA. As will now have become clear from our conceptual-analytical framework, any object that attempts to straddle boundaries should embrace simplicity-in-complexity. This is achieved by encapsulating requisite simplicity in order to foster the learning environment that a boundary organisation needs. We therefore describe the product that emanates from this boundary object as a *resilience apparatus.* It facilitates both adaptive decision making and action in the real world of IWRM at operational and governance levels by integrating the SAPs of the ICMA with the vSTEEP indicators of the CMS.

This apparatus may be realised in the conceptual framework of Figure 3.9 where the CMS, SOs and SAPs form the boundary concept for the apparatus. Meanwhile the conceptual approach is to track the visioning outputs that emerge from these. In which case the visioning outputs are categorised into a performance indicator, which carries a metric or weighting. There are several individual output-indicator-metric-STEEP loops for each *requisite simplicity indicator* (i.e. the object*).*

The crux of the approach is to embody this apparatus into a visually simple tool, the precept of a tangible requisite simplicity. It is clear that a traffic-light system is a simple yet straight-forward decision support system, and to this end the status of the STEEP object would be disseminated in colour form as either: red, orange (amber) or green in terms poor, average or good performance, respectively. There would then be an individual traffic light for each of the STEEP criteria, i.e. 5 in total. Importantly these traffic lights would be populated by the aggregate scores of all performance indicators contributing to that STEEP criterion. Furthermore this would then provide the decision-maker (end-user) with an overview of how the ICMA is performing in achieving its vision for the water management area. In order to give the object some context, these traffic lights should be scalable, i.e. populated at basin and sub-basin level, so that visioning could be explicated within a variable geographic reference. Furthermore, the object would also be temporally scalable in order to provision context over various time frames. A schematic structure of the object is given in Figure 3.10. The way this was achieved was to pair the outputs of the Strategic Plan (Table 3.1) by way of primary correspondence to a particular vSTEEP criteria. This was conducted by way of a mind-map exercise as demonstrated in Figure 3.11, whereby various outputs of the ICMA Strategic Plan in any given reporting period (monthly, annually, quarterly) would be used to populate a vSTEEP indicator (Traffic Light). The relative scores of achieving a particular output would be used to calculate the colour of this 'traffic light'.



Red Text: Highest ICMA Priorities	OBJECTIVES					
	Practical IWRM to achieve equitable, sustainable, and efficient uses of Inkomati water resources which meet evolving stakeholder needs and legal obligations					
	A sustainable water resource		Collaborative and coordinated IWRM for wise socio-economic development		Secure financial arrangements for IWRM	
Sub Strategies / Strategic Action Programmes	WRM Sub Strategies		Integration Sub Strategies	Facilitation Sub Strategies		
	Resource Protection (RDM)	Regulating Water Use (SDC)	Cooperative Governance & Institutions	Stakeholder Engagement	Information & Monitoring	Finance
Achieving equity		- Establish a viable, up to date and transparent system for water authorisation. - Develop a first Generation Water allocation plan - Implement Water Allocation Reform	- Coordinate activities to increase access to water for resource poor farmers - Facilitate innovative solutions to the water services backlog.	- Establish participatory IWRM decision-making process. - Facilitate empowerment programmes. - Establish Water User Associations.		- Develop and implement a realistic and cost effective process for processing water use licence applications.
Managing flow	- Facilitate the progressive, and stakeholder centred implementation of the Reserve.	- Consolidate systems for integrated planning and operations of river systems	- Promote coordinated river operations. - Decrease water losses and increase water use efficiency	- Establish and maintain appropriate River Operations Committees. - Ensure Reserve processes are transparent and inclusive.	- Research systems, for integrated river operations. - Monitor progressive realisation of the Reserve and international obligations.	
Managing water quality	- Support DWA to classify the resource and setting Resource Quality Objectives - Implement the above	- Consolidate and implement workable procedures to determine license conditions for wastewater disposal.	- Institute a cooperative spatial/ develop. planning for water sustainability - Manage pollution incidents. - Prevent further water quality degradation.	- Ensure implementation of Resource Quality Objectives and Reserve are transparent and inclusive.	- Implement accessible and transparent water quality and ecosystem monitoring systems.	- Implement Waste Discharge system to cover costs of managing quality of the water resource
Generating and managing knowledge			- Build knowledge sharing networks nationally and internationally.	- Embed systems of social co-learning / co-generation of knowledge into IWRM decision-making processes.	- Identify monitoring & information Institutions & make agreements - operationalise learning reflection and review system - Participate in IWRM networks etc. - Learning Strategy	
Achieving compliance and enforcement	- Ensure the necessary monitoring requirements for compliance are implemented	- Consolidate clear and realistic standards which different types of water use must be compliant - Ensure appropriate Enforcement of the different water uses	- Investigate enforcement needs and methods - Develop transparent system for dealing with transgressors.	- Awareness and education to help with mindset changes.	- Operationalise transparent and accessible systems for monitoring compliance, and actions against transgressors	- Ensure cost recovery from transgressors in terms of Sections 19 and 20 of National Water Act
Generating revenue					- Audit for transparent and directed use of IWRM funding. - Operationalise payment monitoring	- Investigate and develop realistic mechanisms through which water use charges can be implemented.

Table. 3.2: Strategic Objectives and SAPs as linked to the ICMA’s CMS (ICMA, 2010).

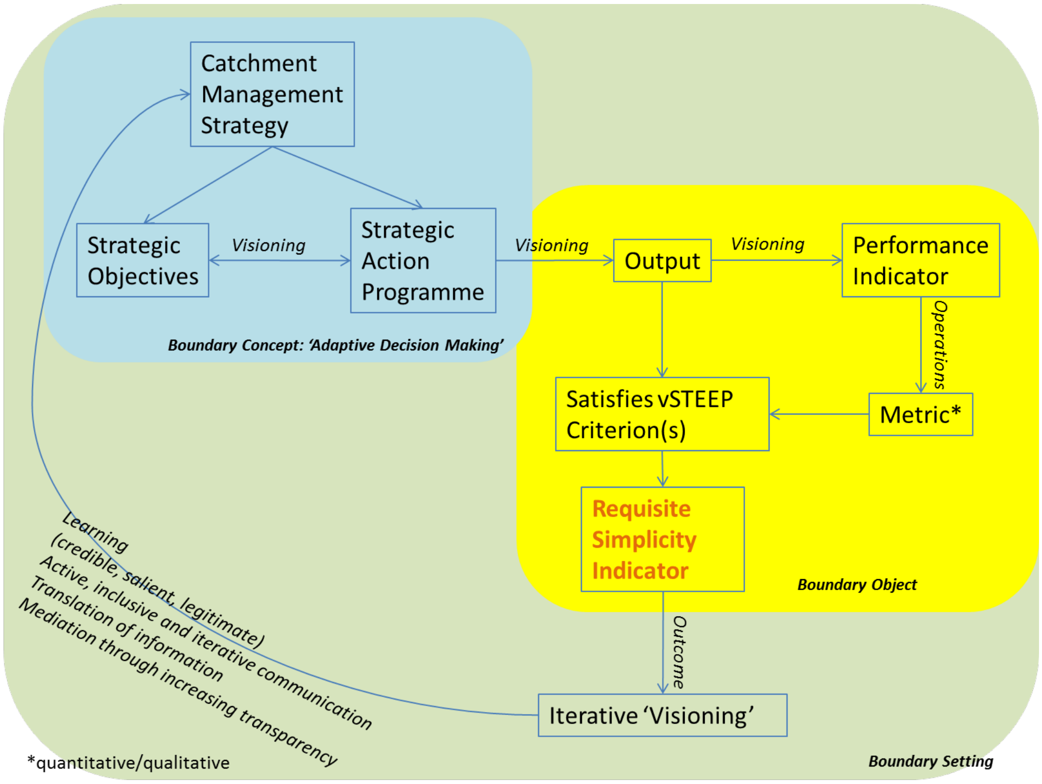


Figure 3.9: Conceptual Framework in which vSTEEP (Requisite Simplicity) indicators may through an information platform augment adaptive governance and operational decision-making within the setting of the ICMA.

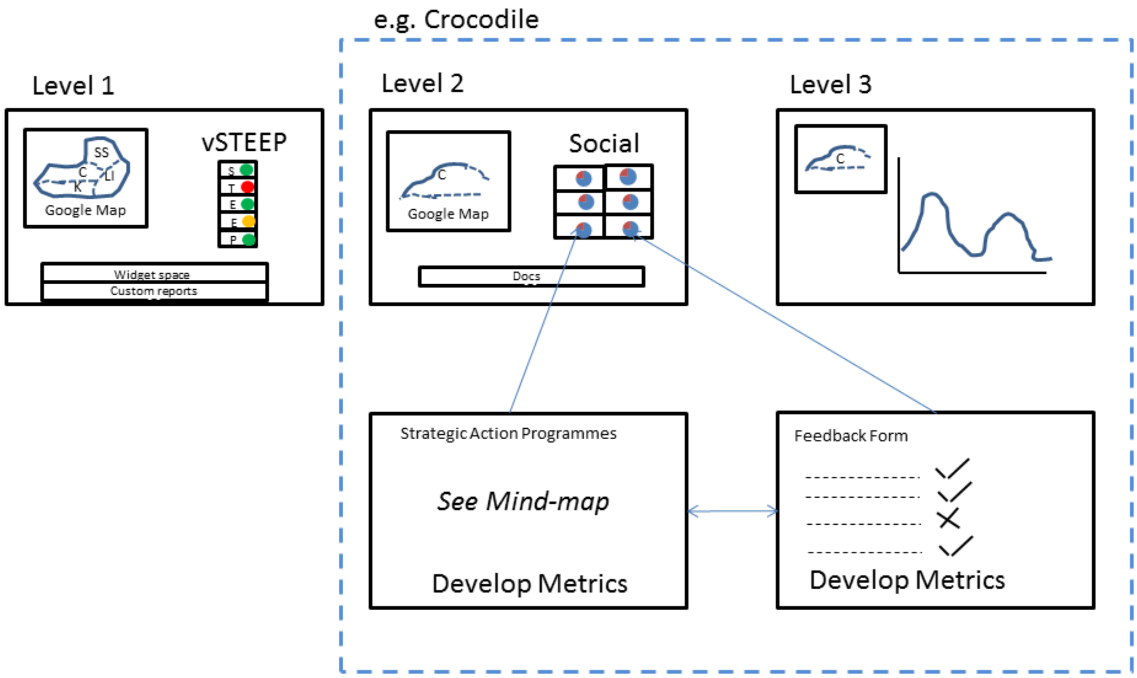


Figure 3.10: Schematic of hierarchical traffic light system for vSTEEP criteria (i.e. level 1 is requisite simplicity further levels to right provide a hierarchy of increasing detail).

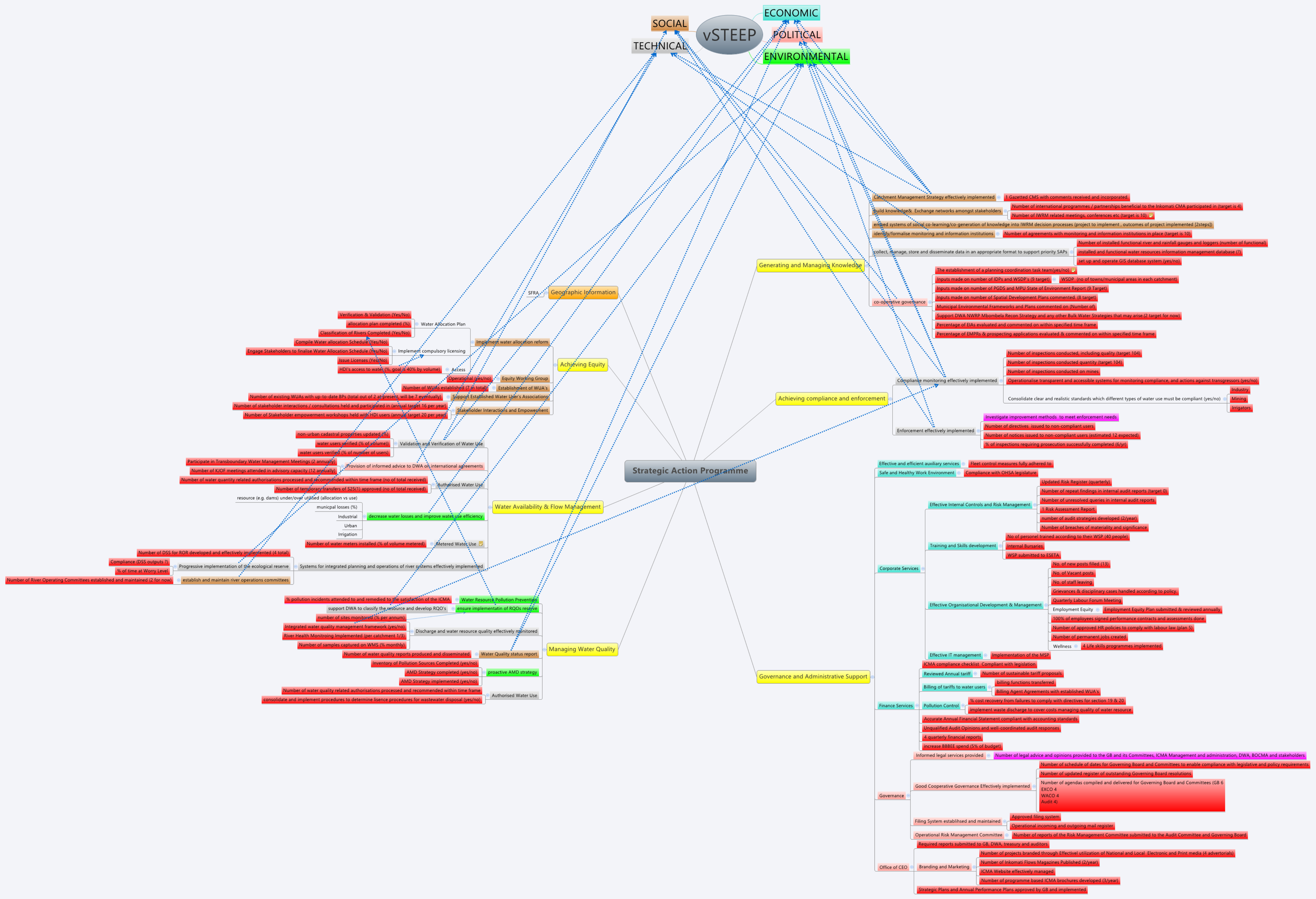


Figure 3.11: Overview of vSTEEP criteria and the ICMA's 5-year Strategic Action Programmes (SAP outcomes are linked to primary vSTEEP groups by colour [secondary relations to other vSTEEP groups appear by dashed arrows]; performance indicators are: quantitative metrics easily applied [red], vague/qualitative metrics [pink], indicators to be determined [blank]).

3.2.9. Technical Description of a Prototype: Adaptive Operational Governance Dashboard (AOGD)

Following the development of the concept in the previous sections, a tangible product would be formed termed the Adaptive Operational Governance Dashboard (AOGD). A working prototype of which was developed with HydroNET (http://www.hydronet.com/) with support from Waterschap Groot Salland (http://www.wgs.nl/) and in collaboration with the ICMA. This prototype uses HydroNet's SaaS (*Software as a Service*) platform.

The aim of the prototype was to provide a generic framework upon which other sections of the STEEP framework can be implemented by the ICMA in the future. The focus of this prototype was the Environment, 'E' traffic light.

Given the conceptual overview described, within the STEEP methodology each component is divided in subcomponents, and each sub-component can be divided in new subcomponents, as per the mind map of Figure 3.11. In this case the AOGD can accommodate a maximum of 4 levels.

The STEEP application is presently accessible via the HydroNET Portal and eventually via a publically available website, and it would have the following user interface components:

- Viewer settings: user controls to change the displayed information: spatial and time scale, end date and show or hide the point layer (top part of both figures);

- Treeview: The STEEP mind map as a treeview (left part of both figures);

- Map: An interactive map showing the status of the selected STEEP mind map element (right part of both figures). The interactive map contains GIS functionality for zooming, panning, and displaying more detailed information like graphs.

The status of the selected mind map element can be displayed for different spatial scales. For ICMA the following spatial scales are defined:

- Whole of the international Incomati catchment (default)

- Primary Inkomati catchments (South Africa)

- Secondary catchments, including international portions of catchments

- Tertiary catchments (South Africa)

The period for which the status is calculated is defined by the combination of end date and time scale. For ICMA the following time scales are defined:

- Month: from 1st day of the month until selected end date

- Quarter: from 1st day of the quarter (January, April, July, October)

- Year (default): from 1st of January of the year until selected end date

- 5 years: April 1st of the selected end date year, and the period start date is 5 years before that end date.

The prototype uses a Microsoft Excel template file as part of the generic STEEP framework, as well as real-time data sources. These are both housed within a DHI-SA server, as per data management contract between the ICMA and DHI-SA. In order to set up the AOGD the end users (i.e. Managers at the ICMA) populate this template file with their reporting data. This file contains among others for each STEEP component a display name, tooltip text, icon, measurement locations and weights.

The user can select a STEEP component by clicking on it in a treeview to the left if the user interface (Figure 3.12). A map of the Incomati basin is the main focus of the interface and is loaded according to user derived spatial and time scales. The user can also click on the status squares in the tree view. More information about the selected element, such as the algorithm and data sources used to define the status colours would then be shown.

At the bottom of the application an indicator appears displaying the current status of the DHI web service: green when the web service is available, red when the web service is offline.

Traffic lights

In the AOGD four traffic light colours are used to define the status of a STEEP mind map element, map area or point:

Red:	alert
Orange:	warning
Green:	normal
Grey:	too little information available

For each STEEP component measurement locations need to be available to calculate the status at these locations. The algorithm to calculate the traffic light colour needs to be specified specifically per STEEP component. Also the data source(s) required to calculate the status need to be selected. The algorithm results in a numerical value (V), where (Equation 3.1):

Red: $0 < V \leq 1$

Orange $1 < V \leq 2$

Green: $2 < V \leq 3$

Grey: $> 25\%\ of\ all\ data\ is\ unavailable$

Once the status of the measurement locations are known, the status of the areas and the STEEP components can be calculated. Each measurement location per area has a weight in order to calculate the weighted average status of this area. By default each location has equal weights, but the end users can change these weights in order to give locations more influence than others. The STEEP component status is derived directly from the primary catchment status. Status of STEEP components higher up in the mind map hierarchy can be calculated based on the under-lying elements. Each sub item has a weight in order to calculate the weighted average status of his parent. Again, by default each sub-item has equal weights, but the end user can change these weights.

When the option 'Show point layer' is yes (default), the available measurement locations of the selected STEEP component are shown in the map. The user can click on these points in order to get more information. Depending on the selected STEEP component, charts, table, image or texts appear. See next paragraph for an example.

Implementation 'E' Traffic light:

In the working prototype the E component uses 3 sub-components to populate it, as follows:

Using the Ecological Water Requirements (EWR), the 'reserve'

Sustainable water quantity status is calculated using EWR at two flow monitoring locations Kruger Gate and Tenbosch, Department of Water Affairs gauges X3H021 and X2H016, respectively. The algorithm to calculate the traffic light colour is defined by the percentage of days that the flow is below the EWR for the selected period (BR), according to Equation 3.2:

$$BR = \frac{\sum_{i=N}^{i=1}(FR(i))}{N}$$

where N is the total number of days, and
$FR(i) = 1$, if $Flow \leq Reserve$ for day i, and
FR(i) = 0, if Flow > Reserve for day i

BR is transformed to a numerical value (V) in order to calculate the current traffic light colour (Equation 3.3):

Red: $V = 0 + \frac{BR-10}{90}$ when BR>10%

Orange: $V = 1 + \frac{BR-5}{5}$ when 10% ≤ BR ≤ 5%

Green $V = 2 + \frac{BR}{5}$ when BR ≤ 5%

When V is known the traffic light colour can be easily derived using Equation 1. The traffic light colours per area are calculated by equal weights for both locations used in this prototype.

After the user selects a measurement location via the interactive map, a popup appears containing a flow chart. The reserve is also displayed in the chart (Figure 3.13).

Using Resource Quality Objectives

The water quality sub-component uses the generalised Resource Quality Objectives for the Inkomati Water Management area, as defined presently by the ICMA, in Table 3.3. In the prototype AOGD, the water quality monitoring stations used to populate it are close to the EWR flow gauges.

Table 3.3: RQO thresholds used to monitor water quality in the Inkomati by the ICMA

Variable	**Green**		**Orange**	**Red**
	Ideal	Acceptable	Tolerable	
pH	6.5-8.4			0-6.49 and 8.41-14
Conductivity (mS/m)	30	50	60	>60
NH3-N (mg/l)	0.015	0.058	0.1	>0.1
PO4 (mg/l)	0.03	0.05	0.1	>0.1
E.Coli (No/100 ml)	10	80	120	>120

Using River Health Programme Indicators

Selected biological indicators have also been used to develop the prototype AOGD so that biological response can be related to adaptive operational governance. This is very early work, so in this prototype simple indicators are used that are expected to only respond to serious shifts in water quality and quantity provision, as shown in Table 3.4.

Table 3.4: Selected Biological Indicators used in the revised KNP River Health Programme (*dummy values used interim)

Biological Indicators	**Green**	**Orange**	**Red**
Tolerant Fish Species			
Mozambique Tilapia (*Oreochomis mossambicus*)	>80	>30 but < 80	<30
Invertebrates			
South African Scoring System (SASS)*	>200	100-200	<100
Average Score per Taxon (ASPT)*			
River Reach Vegetation			
VEGRAI	A	B-C	D

Manipulating the AOGD for end-user needs

The AOGD presently uses a spreadsheet interface to capture data and manage indicator thresholds. It is intended that this eventually is migrated to a server side database with a front-end feedback form at the user end. Importantly however, manipulation of indicator thresholds should remain in the control of the end-user rather than be statically restricted into the hard-coded product of the AOGD, i.e. the HydroNet SaaS. This is imperative to maintain the 'adaptiveness' of the system in the face of changing circumstances in the Inkomati with respect to re-evaluation of catchment management strategies and terms of office of governing board members.

Moreover, this 'loose' coding will give the AOGD the flexibility to be applied in other catchment management agencies throughout the country when they eventually operationalise. This may also have the added value that the AOGD can be used as a starting framework for CMS development in those agencies, building upon the experiences of the ICMA, but applying local contingency to the final design in a particular CMA setting.

Furthermore, it is believed that the AOGD in its' present form, i.e. a simple map interface, will facilitate communication not only between the managers and the governors within the ICMA but also provide an enabling platform for stakeholder outreach. Since the 'traffic lights' will signal the degree of achieving the various vSTEEP criteria in a reporting period (quarterly, annually, etc.), and within a geographical frame of reference (presently tertiary catchments), this information can be applied locally. This will be for instance be by printing the AOGD map web-pages and compiling them into an information pamphlet that can be distributed at local catchment forums, where many stakeholders do not have access to IT platforms. It would then be the responsibility of the ICMA community officers to facilitate reflective discussion on the information these pamphlets provide and in turn relate grass-root stakeholders results back to managers to further populate the AOGD. This then allows for a continual transfer of stakeholder 'visioning' from local level to the Governing Board, for the latter's consideration.

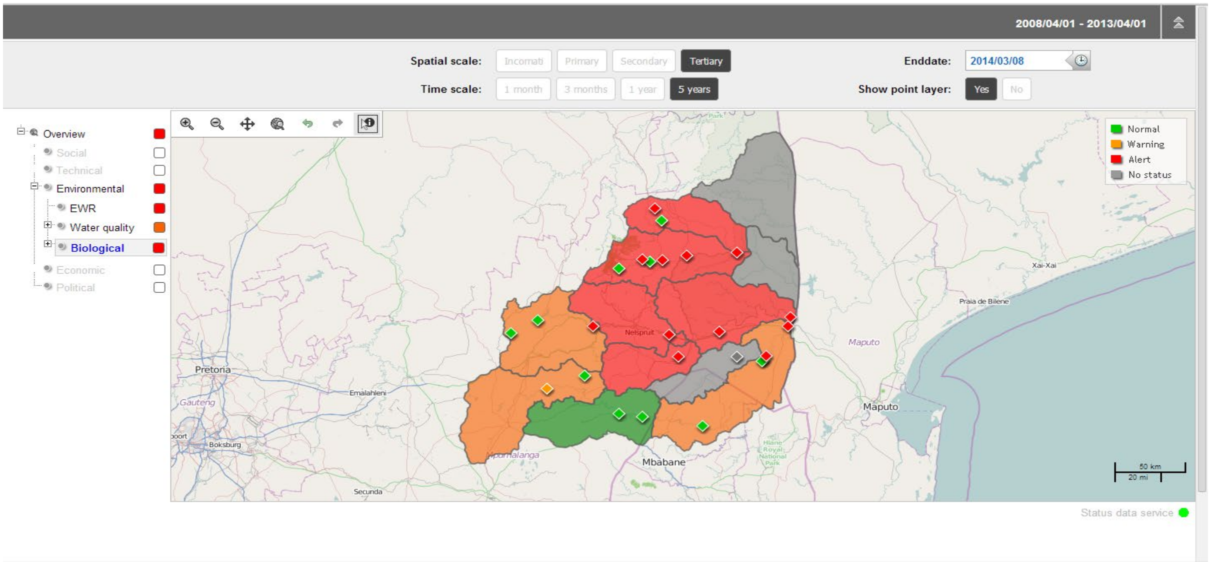


Figure 3.12: Working prototype of an AOGD @ http://portal.hydronet.com/steep.aspx (HydroLogic Systems, 2014)

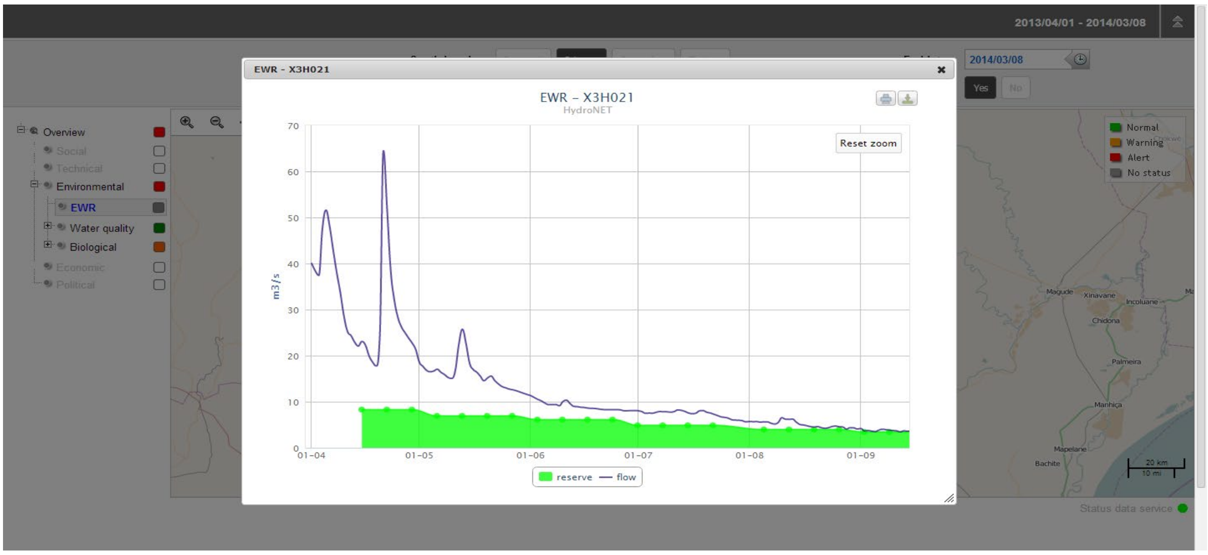


Figure 3.13: Detail providing hydrological information related to EWR (reserve) implementation

4. SYNTHESIS: IMPLICATIONS OF RESEARCH OUTCOMES FOR OPERATIONAL WATER RESOURCES MANAGEMENT IN AN ADAPTIVE SETTING

This project was intended to complement an ongoing research project being implemented by UNESCO-IHE, i.e. "*Risk-based operational water management for the Incomati River Basin (RISKOMAN)*". The two main aims of the WRC project were:

i. The development of an interactive multi-level information system in which information will be provided to different levels of basin water resource stakeholders, with an emphasis on providing the integrated information from RISKOMAN to the level of CMA Board members.
ii. Improved understanding of the hydrological functioning of the Inkomati Basin through focused research on the spatial and temporal variability of hydrological drivers in the catchment with the use of remote sensing methodologies.

However, as the project evolved, the project team were exposed to several other aspects of the operation and management of the Inkomati catchment, particularly through their interaction with the IUCMA. Whilst the two aims of the project remained the focus of the project team, additional aspects which augment the institutionalisation of Strategic Adaptive Management within the ICMA *modus operandi*, as reported in detail by Rogers & Luton (2011) were addressed.

This lead to a:

i. Identification of hydrological information requirements of the water resource managers in the basin, such as the ICMA and other parties.
ii. Contributions to an improved hydrological understanding of the Incomati Basin, through a focus on the identification of variability in the systems hydrological and managerial drivers.
iii. Establishment of tools in support of water resources decision making which are geographically explicit, effective, robust and user-friendly and transferable to other catchments, i.e. a catchment information utility.

Thus, this project was able firstly to improve the hydrological scene-setting for operational water managers in the Inkomati and thereto provide a robust information platform(s) for decision-making in the complex socio-biophysical setting of the Inkomati. The research herein emanated firstly from a combination of desktop study and literature review. Thereafter a combination of field-based studies (hydro-chemistry), hydrological remote sensing analysis and modelling (see Report 2 on accompanying CD for more details), along with the continuous interaction within various water management forums in the Inkomati, most notably the ICMA and its Board guided the project to fruition.

4.1. Improved understanding of the hydrological functioning of the lnkomati Basin

4.1.1. Hydro-chemical and Isotope Derived Information

The hydrological process understanding commenced with an assessment of flow alteration over the period 1950-1996 and analysis of the drivers thereof. This, and the integrated hydrochemical analysis that followed were used to define the broad set of sources and pathways of water at the scale of the entire Incomati basin. This was useful in order to provide a sound template upon which dynamic water resource management can take place and adds a level of detail that was perhaps missing from earlier basin wide assessments such as the Joint Incomati Basin Study (JIBS, 2001) and Inkomati Water Availability Assessment Study (DWAF, 2009). These techniques allow for a characterisation of the variability in the system and how these variabilities are linked to both temporal climatic and land-use variability.

The initial results of the hydrochemistry are detailed in Section 2.1. The research demonstrated that stable isotopes can be very valuable to provide scoping/baseline information for further basin wide process understanding. Furthermore, the profiles of water quality generated can also be useful to understand the overall pattern of water quality in the region. This has future benefits in terms of precision calibration of hydrological models for operational water resources management. These eventually should be designed to implement both the water quantity and water quality components of the ecological Reserve.

At the scale of the Incomati, the research has shed some light on the importance of the Sabie sub-catchment as a buffer of water quality for the Incomati in Mozambique. Results showed that the water in the Sabie system had a significantly lower EC than that of the Crocodile and Komati catchments. This is also an indication that with good management of water resources, and with appropriate indicators, water quality could be improved in the more stressed systems.

Regarding the packaging of this hydrochemical information, the traffic light system that has been adapted in the AOGD can be adopted to convey composite water quality status information, such as pH and EC. However, future development should integrate more monitoring parameters, such as biological indicators (*E. coli*, Dissolved Oxygen, etc.) and adhere to a more frequent and consistent sampling regime. Ideally an automatic water quality sensor should be installed in key locations in the catchment, so that in case of occurrence of extreme loads or rapid changes in pH for example, immediate action can be taken to resolve or manage the problem (e.g. by flashing a red light at the desktop of the water resources manager).

Furthermore it is important to have a consistent data series of isotopic and water quality parameters, to allow the understanding of flow systems at different temporal and spatial scales. Whilst water quality parameters are used in particular to manage for the resource quality objectives in the river systems of the Inkomati, this study has demonstrated their effectiveness in also translating a hydrological processes understanding to the water resources manager.

Thereto, it is recommended that hydro-chemical information should be more effectively implemented in operational river management in the Inkomati in the following ways:

- Install real-time water quality sensors, in key locations, such as close to existing real time flow gauges, in order to improve the monitoring of water quality and pollution incidents;
- Continue with measurement of isotopes, in order to build a solid data-base for further studies of hydrological processes and runoff generation processes;
- Integrate more water quality models with current real time water management models. Water quality can be used to further refine the definition of runoff coefficients used in rainfall-runoff models;
- Monitoring of groundwater quality should be pursued in a consistent manner.

4.1.2. Use of remote sensing data for operational water resources management

Through the project, the application of certain remote sensing products of rainfall, evapotranspiration (ET) and soil moisture as potential sources of information and data for hydrological modelling in the Inkomati were assessed. Whilst remote sensing as applied in the Inkomati basin has shown promise to both contribute to an improved hydrological understanding of a water management area and thence also be integrated with operational water resources management systems and tools, the many difficulties in obtaining and integrating these products in a readily useable way mean that there is much development needed before the goal of a catchment modelling system that fully integrates remote sensing (See Section 2.2) is realised.

The investigations and subsequent conclusions drawn from these studies suggested that rainfall estimates from satellite imagery in particular could be beneficial for the modelling of catchments that severely lack an adequate network of rain gauges, this is important for real-time river systems operations. This was demonstrated mainly with the TRMM rainfall estimates, and to a lesser extent, FEWS rainfall estimates. In South Africa these open-source datasets are of course attractive to minimise the costs associated with effective real-time operational water resources management.

In terms of ET, the open source SEBS model performed poorly in winter by overestimating water use when compared to the observed data. However it does capture the seasonal trends. Other studies (Mengistu et al., 2013 (pers comm) undertaken as part of another WRC Project (K5/2066 Validation of the forcing variables (evaporation and soil moisture) in Hydrometeorogical models) have shown much better simulations with SEBS. Further, implementation will require more work, with on the ground calibration in order to successfully implement it into an operational water resources management model. Nevertheless, since SEBS overestimated water use in this study, especially in winter where there is greatest demand on the Inkomati, from an operational perspective it has utility as a conservative determination of water use. Given the high cost of arguably more accurate propriety products (e.g. SEBAL), and the improvements recently implemented to SEBS (Timmermans et al., 2013) the model warrants further consideration.

In terms of soil moisture estimates from remote sensing products, this study suggests that it is perhaps too early to consider using these in operational water management. Whilst there is promise to use these at larger scales more research and validation is still required at these scales before they should be implemented in effective operational hydrological modelling.

There is clearly potential for the use of remote sensing in operational water resource management models, issues of compatibility, data acquisition and processing need to be overcome whilst at the same time effort is needed to reduce the uncertainty in their outputs in order to adequately represent the hydrology of a catchment. Given the emphasis on trust and relationship building in adaptive operational water resources management, this will be key obstacle to overcome, so that stakeholders who are collectively managing an increasingly finite resource, can be sure that the water manager is fully acquainted and comfortable with the veracity of the hydrological information available.

4.2. Using new hydrological understanding to improve operational water resources management and governance

As demonstrated in section 3.1, operational water resources management, particularly that which has the potential to be adaptive, as encouraged through South African legislation and practice in the Inkomati setting, could use the institutional hierarchy (Section 3.1.5):

• Institutional Arrangements • Stakeholder Participation and Decision Making	Social Scientific Learning	Management Learning
• Data and Information • Modelling and Decision Support Systems	Technical Scientific Learning	

This, so far appears to be succeeding at least in the Crocodile sub catchment by integration of the four aspects into one framework. If one simply utilises the implementation of the ecological reserve as a metric as done in this study, then one realises the crucial role that new and improved hydrological information will have to achieve an element of environmental sustainability (e.g. the E traffic light in the AOGD). This is because such information (flow data, hydrodynamics as explained through hydrochemistry and remote sensing, climate forecasts, etc.) as presented to the stakeholders that constitute the operational committee whose role is to make key decisions around a crucial shared resource such as run-of-river water.

Of course not all the STEEP criteria depend directly on hydrological information, but since water management is the foundation upon which the ICMA was established, then hydrological information can be said to at least indirectly relate to all facets of the STEEP criteria, upon which the AOGD is developed. To this end the better the hydrological information available at the fingertips of the operational water manager the better placed they are informed to relay critical (requisite simplicity) information to decision-makers of influence. For this, dynamic information flows amongst the decision-makers and stakeholders about the competing human and environmental demands, including some understanding of the hydrological processes in the Inkomati basin is critical.

The development of the conceptual framework that underpins the AOGD was the focus of a substantial part of the project activities. This followed a significant effort in engaging with the CMA and its board to better understand their operations and needs. The resultant framework is based on the STEEP factors that guide the implementation of IWRM at the CMA. This in turn provided a sound conceptual basis for the development of a software utility, i.e. the AOGD and guided its design in terms of user interface, underlying databases and functionality required.

However, the development of the AOGD raised many challenges. Whilst the project team was comfortable with, and often lauded for, the development of the conceptual framework underpinning the AOGD, the software development aspects were particularly challenging. The contributions of the commercial company HYDROLOGIC were critical in developing the AOGD interface and its application for E – environmental aspects. This company (www. Hydrologic.com) is dedicated to the development of products where "*advanced ICT technologies can play a major role in solving the world's most urgent water problems".* Its' staff consists of almost 20 ICT professionals and experts. Interactions with this company, the rapidly changing nature of software development and the need to constantly update and amend the AOGD in response to changing user preferences, software developments, etc. highlighted that the level of software development required for this project needs a dedicated Information and Communication Technology (ICT) team. Further development of the AOGD will thus require levels of funding and support beyond that available in this project. The strong conceptual framework detailed in this report, coupled with the ICT input from HYDROLOGIC does provide the opportunity to develop a utility which would be widely applied by water management institutions both locally and internationally. Thus, a well-funded technology transfer project with future commercial implementation should be considered.

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APPENDIX I – SUMMARY OF UNESCO-IHE (UPARF) RESEARCH OUTPUTS

Further information can be found at http://www.unesco-ihe.org/RISKOMAN

ANALYSIS OF WATER ALLOCATION IN THE KOMATI CATCHMENT DOWNSTREAM OF MAGUGA AND DRIEKOPPIES DAMS (Fadzai Mukororira)

Water allocation is a very contentious issue in closing and closed basins. Decision makers normally aim to allocate water in an equitable and efficient manner. Such a case is exemplified in the Komati catchment, shared by South Africa and Swaziland with Mozambique not in the catchment but located downstream. This research aimed at describing the current water allocation, water use and how the cross border flow to Mozambique is impacted. In addition, future development scenarios were tested and how they would affect the water allocation regime in wet and dry years.

Analysis of data was carried out for four river reaches of the Komati catchment downstream of Maguga and Driekoppies dams for years 2004 to 2011. Data was gathered through review of literature, documents and interviews with key informants. AWAFLEX simulation model was also set up using the period 2006 to 2011 for the analysis of future development scenarios in wet, normal and dry periods. These were all normal and wet years and represent the period when ultimate system operating rules started operating. For the dry period, a hypothetical scenario was simulated for the Komati river branch only, due to data constraints. The hypothetical scenario includes four consecutive dry years, at the moment when the reservoirs are full.

Findings from this study show that the current water allocation practices in the Komati are based on the bilateral Treaty on the Development and Utilization of Water consent provided that 2 m^3/s averaged over 3 days (according to the Piggs Peak Treaty) is met at the Mozambique border. However, a recent agreement, the IIMA if implemented is supposed to supersede the current Treaty and this will definitely see a change in the water allocation practices of the Komati. This is because the IIMA allows for consumptive water use increase by the three countries including an increase in the minimum flow at the Mozambique border.

The main water users are irrigation schemes and water abstractions are measured in 3 river reaches and therefore water can be accounted for and any inefficiency can be attended to. Comparison of water requirement and water abstractions by the users along the river reaches was done. Results show that the users along the Komati River in Swaziland abstract what they demand in 90% of the time. Irrigation users along the Lomati River have higher demands 50% of the time as compared to the abstractions.

There is a shortfall on the daily minimum flow requirement for Mozambique from the Komati catchment at Lebombo weir. The shortfall is more extreme during dry periods for example in 2004/2005 the requirement was met only 21% of the time. Even in wet years such as 2010/2011 the requirement does not even reach 100% but comes up to 92% of the time. However, results showed that the Crocodile catchment provides more than its target minimum requirement and therefore covering the deficit for the Komati catchment in all the times at Komatipoort gauging station on the Mozambique border. From the analysis at Komatipoort, the 2 m^3/s minimum flow requirement the highest percentage of time the requirement is met is 98% in the year 2010/2011 which is a wet year. The conjunctive operation of the Komati and Crocodile catchment at Lebombo where the Lebombo is throttled in events when the Crocodile discharges more than its requirement does not result in 100% fulfilment of the 2 m^3/s.

Simulated results using Waflex model show that it is possible to meet the minimum flow requirement if it is given the priority of environmental allocation as according to the National Water Acts of both South Africa and Swaziland. In such a case the irrigators will experience a maximum 3% reduction in satisfaction if the minimum requirement is prioritised. The success of such a scenario will require Mozambique representation in the management of the Komati system. An increase in both the current water demands and the minimum flow will lead to a much tighter system of operation where even in average years the demands will not be fully satisfied. The effects are more extreme on the Lomati system where the level of satisfaction drops from 100% in the base case to 83% in wet and average years.

In dry periods extreme rationing will be experienced especially if the water demands at the current level of development are increased. A hypothetical situation for the Komati river reach with four consecutive dry years indicates that, under the worst case scenario where current water demands are increased by 10% and the minimum flow to 1.43 m^3/s shortages on irrigation demand will occur 80% of the time. From the 27 year data series for Hooggenoeg gauging station that was used as an indicator site for the dry period analysis two extreme periods were identified, which are three consecutive years from 1991 to 1994 and 2001 to 2004. Though there is no defined pattern on the likelihood of the occurrence of such a drought period it can be concluded that in the Komati catchment such a scenario is likely to occur once in every 10-13 years. The benefit-sharing principle which focuses on allocating the outputs from water use, rather than the water itself can be a possible solution in such extreme events. It may be better for irrigators of annual crops to forego a crop during continuous extreme dry years and get compensated by the irrigators with perennial crops than to get low amounts of water and low crop yields. This principle requires a transparent cost and benefit analysis and interaction of water users within the catchment.

GROUNDWATER AS AN EMERGENCY SOURCE FOR DROUGHT MITIGATION IN THE INCOMATI RIVER BASIN – CASE STUDY OF THE CROCODILE RIVER CATCHMENT (Fátima Eunice da Fonseca Mussá)

Global climate change has received much attention worldwide in scientific as well as in political community, indicating that changes in precipitation, extreme droughts and floods may threaten many regions. Droughts are natural hazards that cause social, economical and environmental damages. Governments and affected population are engaged in strategic measures by means of local limited capacity and knowledge as well as by receiving external support, for example to enhance the predictions and early warnings. The lack of knowledge regarding the quantification of variability and changes in the hydro-climatic extremes, changes in hydrology and possible adaptation strategies remain as major obstacles in minimizing the damages to the society caused by the natural disaster. This research aims to study the trends in dry extremes and the use of groundwater as a supplementary source of water to mitigate the drought impacts in the Crocodile River catchment, a sub-catchment of the Incomati River basin.

The research methodology consists mainly of four parts. Firstly, trend detection on the annual precipitation, annual discharge and dry extreme parameters of precipitation and discharge was carried out by means of the CUSUM (Cumulative Sum Charts) and Regime Shift Detection methods to detect trends. Secondly, the spatial and temporal variation of the meteorological and hydrological drought severity and intensity over the catchment was evaluated. The Standardized Precipitation Index (SPI) was used for the meteorological drought and the Standardized Runoff Index (SRI) was used for the hydrological drought. Afterwards, the water deficit in the catchment in the droughts period was computed by using a simple surface water balance method. And finally, a groundwater model using MODLFOW software was built in order to assess the possibility of using groundwater as an emergency source of water to mitigate the drought impacts in the catchment.

The study shows that there are no significant trends on the annual precipitation and on the precipitation dry extremes. However, decreasing step trends were found in the annual discharge and in the discharge dry extreme parameters of some discharge stations mainly caused by increase in the forestry area and water abstractions on the river for irrigation and domestic use. The meteorological drought severity varies accordingly with the precipitation, the low rainfall areas are more vulnerable to severe meteorological droughts while the high rainfall area are less vulnerable to severe meteorological droughts. Though one of the aspects which most influences the discharge is the precipitation, the hydrological drought severity does not follow the same pattern as the meteorological drought severity, it is highly influenced by human interventions. Thus, in general the most water stressed sub-basins are the ones which are more vulnerable to severe hydrological droughts.

The analyses of the groundwater supply during droughts showed that a deficit of 97 Mm^3/yr could be supplied from groundwater without considerable adverse impacts on the river baseflow and groundwater storage. However, spatial variability of groundwater potential needs to be taken into account with restricted supplies from groundwater in Nelspruit and White River sub-catchments due to very high drawdowns and reduction in the base flow contribution to rivers.

ASSESSING IMPACTS OF WATER USE ON STREAMFLOW IN THE KOMATI CATCHMENT (Nompumelelo Matsebula)

The objective of this study was to assess the impacts of water use in the Komati catchment. Time series data of rainfall and runoff were analysed to check inconsistency and non-homogeneity. The data were further analysed using non-parametric tests to check for serial correlation, persistence, absence of linear trend and test of change point. The computer program DScreen was used for statistical analyses of the time series data, the Mann Kendall test was done to test for trend in data and the Pettit method was used for change point analysis. Geographic Information Systems of topography, soils and land use was used for modelling.

The data analysis indicated that the rainfall decreased significantly with approximately 119.6 mm in 10 years at Hooggenoeg gauging station and about 87 mm in 10 years at Tonga gauging station. The annual streamflow did not change significantly in both gauging stations. This shows the influence of water regulation from the two reservoirs upstream of this Hooggenoeg gauging station, the Nooitgedacht and Vyeboom dams. The Tonga gauging station showed significant change in streamflows during months of high and low flows. This indicates the high water use downstream for irrigation, water transfers and the regulation of the Maguga dam.

The Indicators of Hydrologic Alteration method was used for Tonga gauging station since there was a significant change in streamflow. The results shows that, after Maguga dam construction the medians for the post-impact period are mostly lower than those for the pre-impact period, indicating the lower monthly flow fluctuations in the post-impact period due to the regulation of reservoir operation. This is also shown by the decrease in magnitude and duration of annual extremes condition, especially for maximum values.

The SWAT model was set up to obtain the water balance of the catchment. The overall performance gave a Nash-Sutcliffe (NS) of 0.59 and the coefficient of determination of 0.82, this shows the model presented the flow very well although it could not reproduce peak flows quite well but better for low flows and can be further used for water use scenario simulations. The water balance of the Komati catchment shows that the average annual basin precipitation is about 781 mm/a. A significant amount of water is lost through evapotranspiration which is about 85% of total precipitation.

RAINFALL AND STREAMFLOW FORECASTING FOR OPERATIONAL WATER MANAGEMENT IN THE INCOMATI BASIN, SOUTHERN AFRICA (Robert K.M. Sunday)

When future water situation is unclear to water managers and dam operators, problems on water allocation among competing users may arise due to unforeseen water shortages. Thus, rainfall and streamflow forecasting may help to manage the uncertainty. Forecasting estimates how much water is likely to fall as rainfall and flow passing a specific river location during a particular time based on recent meteorological and catchment characteristics. Incomati River Basin in Southern African is almost in a closing status; thus rainfall and streamflow forecasting are significant and relevant.

The main objective of this research was to study the scope of rainfall and streamflow forecasting in the Incomati Basin by reviewing forecasting methods, by examining the needs and usefulness of forecasting, and by testing promising methods for rainfall and streamflow forecasting. The study used statistical methods of correlation and regression analyses. Also to explore the needs and uses, interviews and discussions with water managers, dam operators, water users and other stakeholders were carried out. Data used include Sea Surface Temperature (SST), El Niño Southern Oscillation (ENSO), air temperature, precipitation and streamflow. The study was in three stages; field survey and interviews, correlation and regression analyses, and rainfall and streamflow forecasting. The correlation analysis covered selected climatic and streamflow stations across whole Incomati Basin. However, models for rainfall and streamflow forecasting were tested for the Kaap sub-catchment located in the Crocodile catchment. Forecasting equations per method per time were generated. The forecasts are presented in terciles of above average, average and below average. The forecasts were verified using standard forecast verification scores such as probability of detection (POD), probability of false detection (POFD), false alarm rate (FAR) and accuracy.

The survey results showed that about 97% of water stakeholders need and use rainfall forecasts. The major uses were personal plans like travelling (29%) and dressing (23%). The usefulness in water sector was reported for water allocation (23%), farming (11%) and flood monitoring (9%). On the other hand only 5% showed the need for streamflow forecasting. The rainfall forecasts were presented to have medium to high benefits. Generally, users affirmed the accuracy and benefits of weather forecasts and had no major concerns on the impacts of wrong forecasts. However, respondents indicated the need to improve the accuracy and accessibility of the forecast. Likewise, water managers expressed the need for both rainfall and flow forecasts but indicated that they face hindrances due to financial and human resource constraints. This shows that there is a need to strengthen water related forecasts and the consequent uses in the basin. For effective water management, forecasts should be user specific and the collaboration between meteorology and hydrology is encouraged.

The results of the correlation analysis indicated that, there is a significant correlation between SST, ENSO and rainfall and streamflow in magnitude and in direction. This correlation can be found at the monthly, seasonal and annual scale in one-one level and in lag times. The correlation of ENSO to rainfall over the basin (0.207), as well as ENSO to streamflow in the basin (0.256) was found to be positive (significant at 95% level), which means the increase of ENSO can influence the increase of rainfall and streamflow and vice versa. The SST to rainfall (-0.294), and SST to streamflow (-0.239) correlation was negative (also significant at 95% level) denoting the increase of SST may influence the decrease of rainfall and streamflow and vice versa. There was a significant positive correlation between rainfall and streamflow (0.487 significant at 99% level).

Rainfall forecasting was done by using six methods at monthly and three methods at seasonal time resolutions. The ENSO and SST are found to be significant predictors. The monthly rainfall was best forecasted by methods using the previous season's SST and rainfall; and previous month's SST, ENSO and P; Pt = f (SSTts-1, Pts-1) and Pt = f (SSTt-1, ENSOt-1, Pt-1). In seasonal, both ENSO and SST worked equally well; Pts = f (ENSOts-1, Pts-1) and Pts = f (SSTts-1, Pts-1). Monthly streamflow was forecasted by eight methods. The best forecast was found using the previous month's SST, ENSO, P and Q; Qt = f (SSTt-1, ENSOt-1, Pt-1, Qt-1). Five methods forecasted seasonal streamflow, the best were found to be similar to that of monthly model; Qts = f (SSTts-1, ENSOts-1, Pts-1, Qts-1) and Qt = f (SSTts-1, Pts-1, Qts-1). In general, the tested methods, including the best ones, indicated higher skills (better forecasts) in predicting rainfall and flow in the upper and lower terciles than in the average tercile. The best forecasts for rainfall were found in the wet season while streamflow forecasts were best in low flow periods. The forecasts showed good quality and have value for the users in the studied sub-catchment. The forecast methods developed could be recommended for operational application across the Incomati Basin, after careful verification for other sub-catchments.

Other UNESCO-IHE Outputs

Estimating the economic value of different water uses for optimal water allocation in the Komati Catchment (Krishna Prasad Upadhay)

Sustainable groundwater development and conjunctive management of surface water and groundwater for improving System operations – The case of the Komati Catchment (Mohammed Bakhit)

Assessing the variability and trends in floods and corresponding adaptation options in the Crocodile Catchment (Wenzile Mthethwa)

APPENDIX II – OUTPUTS FROM THE AOWRMF

Key Capacities for Social Learning

Criteria	Users Scores									Statistics	
	AV	CM	ED	ER	JV	NV	RP	SM	TS	Min	Avg
FAIRNESS:	4	4	4	4	5	5	5	4	3	3	4.2
WISDOM: Competent Decisions	4	3	4	4	5	5	4	4	4	3	4.1
WISDOM: Consensus	5	4	5	5	4	4	5	4	5	4	4.6
STABILITY: decisions not opposed	4	3	4	3	2	4	3	4	4	2	3.4
SENSE OF OWNERSHIP:	4	4	5	5	5	4	4	4	5	4	4.4
CAPACITY BUILDING/LEARNING: Sufficient?	2	3	5	4	4	5	4	3	5	2	3.9
CAPACITY BUILDING/LEARNING: Other perspectives allowed?	4	4	4	5	4	5	4	4	4	4	4.2
AWARENESS: Good awareness	3	3	4	4	5	5	4	3	5	3	4.0
AWARENESS OF SYSTEM COMPLEXITY:	4	4	3	4	3	5	3	5	5	3	4.0
SHARED PROBLEM IDENTIFICATION:	4	3	5	4	3	4	3	4	5	2.5	3.8
INTERDEPENDANCE BETWEEN STAKEHOLDERS: D	2	4	5	3	4	4	4	3	3	2	3.6
LEARNING TO WORK TOGETHER:	3	4	5	5	5	5	4	4	4	3	4.2
RELATIONSHIPS: Formal relationships established?	3	4	4	4	4	4	4	4	3	3	3.8
RELATIONSHIPS: Informal relationships established?	4	3	4	4	3	4	4	3	4	3	3.7
TRUST:	4	4	5	4	5	5	4	4	3	3	4.2

Key Fostering Factors for Social Learning

Criteria	Users Scores									Statistics	
	AV	CM	ED	ER	JV	NV	RP	SM	TS	Min	Avg
ONGOING HIGH MOTIVATION: Amongst the stakeholders?	3	3	4	5	5	4	3	4	5	3	4.0
INDEPENDENT TECHNICAL MEDIATOR: ICMA a good independent technical Mediator?	5	5	5	5	5	5	5	4	4	4	4.8
HIGH COMMITMENT OF LEADERS: Responsible authorities highly committed?	4	4	5	4	5	5	3	3	4	3	4.1
LEGITIMACY: ICMA?	5	5	5	5	5	5	5	5	5	5	5.0
EXCHANGE OF INFORMATION: Good access to and exchange?	3	4	4	4	5	4	4	3	5	3	4.0

INCLUSIVITY (ABILITY TO CONTRIBUTE?): All stakeholders are able to effectively contribute?	5	4	5	2	5	5	4	3	3	2	4.0
DELEGATED LEADERSHIP: Sufficient delegation?	4	3	4	3	5	4	4	4	5	3	4.0
NUMBER OF PARTICIPANTS: Limited participants enables improved deliberations?	5	4	4	4	3	4	3	4	4	3	3.9
FREQUENT, FOCUSED DISCUSSION: Sufficiently frequent, and focused discussion?	3	3	4	3	3	5	4	3	5	3	3.7
EFFICIENCY: Do you feel that the AOWRM in the Crocodile is efficient in achieving its goals?	4	4	4	4	3	5	4	4	5	3	4.1

Key Hindering Factors for Social Learning

Criteria	Users Scores									Statistics	
	AV	CM	ED	ER	JV	NV	RP	SM	TS	Min	Avg
INADEQUATE TIME AND RESOURCES:	3	3	5	5	4	3	3	4	5	3	3.9
LACK OF FEEDBACK OF OUTCOMES:	4	4	4	5	5	4	4	4	4	4	4.2
RELATIONSHIP BETWEEN STAKEHOLDERS AND TECHNICAL TEAMS:	3	5	5	5	5	4	3	4	4	3	4.2
OVERLY TECHNICAL LANGUAGE:	2	3	4	4	2	3	2	2	5	2	3.0
LACK OF CLARITY ON PROJECT AIMS:	5	4	4	4	3	4	3	4	5	3	4.0
CONFLICT IN SCALE OF PROJECT AND STAKEHOLDER INTEREST:	3	5	5	5	4	4	4	3	4	3	4.1
LACK OF OPENNESS:	4	4	4	4	5	4	4	4	4	4	4.1

Consensus-Based Decision Making

Criteria	Users Scores									Statistics	
	AV	CM	ED	ER	JV	NV	RP	SM	TS	Min	Avg
PURPOSE DRIVEN:	5	4	5	5	5	5	4	4	5	4	4.7
INCLUSIVE:	4	4	5	3	5	4	4	4	4	3	4.1
VOLUNTARY PARTICIPATION:	4	4	5	5	3	5	3	4	5	3	4.2
SELF DESIGN:	5	2	5	3	3	4	4	3	3	2	3.6
FLEXIBILITY:	4	3	4	4	3	5	4	3	4	3	3.8
EQUAL OPPORTUNITY:	4	4	5	3	4	4	4	4	4	3	4.0
RESPECT FOR DIVERSE INTERESTS:	2	4	5	5	3	4	4	4	3	2	3.8
ACCOUNTABILITY:	4	4	4	3	5	4	3	3	5	3	3.8
REALISTIC DEADLINES:	4	4	4	5	4	4	4	4	5	4	4.2
IMPLEMENTATION	4	4	5	5	5	4	4	4	5	3.5	4.4

Data needs for effective AOWRM

Name	Description/Comments
Data and Information for Water Resources Planning	
Dams	All DWA and major dams are available with detailed hydrological data. The ICMA has recently appointed consultants to determine area/volume relationships for all dams identified from the high resolution landcover and DEM data sources at the ICMA
Rivers	DWA rivers captured from Surveyor General 1:50 000 topographical maps. ICMA rivers coverage derived from the 5 m DEM developed by the ICMA.
Natural Vegetation	Recently completed natural vegetation cover is available from SANBI. It is recommended that hydrological models such as ACRU be updated to incorporate it.
Landcover	A 30 m resolution landcover was produced by DWA in support of the verification of existing water use in 2006 covering the years 1996, 1998 and 2004 for the Inkomati in South Africa. The ICMA has also produced a 2,5 m resolution comprehensive landcover in 2011. This landcover can be used for inter alia: • Farm Dam area identification to improve the planning and operations model outputs • Irrigated land identification to improve water use estimations
WRC WR90 Data	Primary Catchment through to quaternary catchments with basic historical rainfall and hydrological data.

WRC WR2005 Data	Updated data from WR90. Same as IWAAS data for Inkomati
IWAAS hydrology	The latest hydrology available for the Inkomati is from the IWAAS study. The data available from this projects includes: • Water Use estimations. • Alien Vegetation estimation • Ecological requirements. • Water Quality • Historical patched Rainfall data, also summarized per quinary catchment • Hydrology for each quinary catchment
Quinary Catchments	A 5th level of catchment boundaries (or quinary catchment boundaries) was developed by the IWAAS project in 2008. These catchments were created for water resources planning needs on the main stem of the primary and secondary rivers and need to be updated before the current operational water resources management on the crocodile river can be expanded to the tributaries.
Remote Sensing Satellite Imagery	SPOT and Landsat Imagery is freely available. Various Landsat Images are available for the years 1996, 1998 and 2004 from DWA and the ICMA. Remote Sensing is a rapidly growing field. New sources of satellite imagery and techniques to derive water resources information from them are available and continue to be refined.
Water Quality Data	The DWA water quality monitoring network and data is available for several chemical and biological indicators at several locations within the Inkomati WMA. All monitoring is done against standards and presented at the CROCOC
Canals	These are important to capture as they can divert significant water and the planning and operations models must incorporate these diversions.
Wetlands	Wetlands can have significant local impacts on runoff and must thus be properly incorporated in to operational models. A National Wetlands coverage, version 3, is available from SANBI. The new landcover developed by the ICMA has improved on this wetland coverage.
Farm Boundaries	The ICMA has an up to update database from the surveyor general dated 2013. This data is important as water allocations are issued per farm and it can assist with understanding the actual water use vs. allocated water use.
Irrigation Boards	The boundaries and lists of rateable areas for all irrigation Boards, water users associations and government water control areas are available. This is important to understand the water use under the management of the local water management institutions.
Human settlements	Urban and Rural landuse settlements with population data is available from various sources. The various sources of this data differ significantly in their population data and need to be updated.

20 m and 5 m contours	This information has been used by the ICMA to develop a Hydrologically correct high resolution digital elevation model (DEM).
DEM	90 m DEM derived from freely available SRTM data is available. A high resolution DEM was developed by the ICMA in 2013 to enable improved rainfall-runoff and operational modelling. It is yet to be incorporated into the models.
WARMS data	The Water Authorisations and Registration Management System (WARMS) of DWA contains all the water use allocation data. However, it is not up to date and is not being used in the models.
Environmental Flow Requirements	A Preliminary Comprehensive level Ecological Reserve in the Inkomati Water management Area, Mpumalanga, is available. The classification of the Rivers must still be done.
Data for both Long Term Planning and Short Term Operations	
Stream Flow Gauging	DWA have a number of river flow gauging stations in the Crocodile River Catchment. Some of these are real time enabled. The ICMA equipped 28 of these with real time data gathering and dissemination hardware to improve the redundancy of the real time stream flow gauging.
Rainfall Gauging	Real time and historic rainfall gauging data is obtained from DWA, SAWS, SASRI and the ARC. The ICMA has also installed 15 new real time rainfall gauging stations to improve the rainfall data available for modelling. This data is yet to be incorporated into the models.
River Health Programme, MTPA and SANPARKS Biomonitoring data	An agreement between the MTPA and ICMA has been reached whereby Biomonitoring, riparian habitat and other related river health data will be captured for the Sabie, Crocodile and Komati rivers on a rotational basis every three years, starting with the Sabie in 2011. The ICMA is also involved in a project with SANPARKS regarding information feedback loops between the two parties for river health data and the ecological requirements.
Water Use data	Metered water use data on the Crocodile River is automatically sent to the OWRM DSS at the ICMA on a weekly basis by the Crocodile Irrigation Board. Not all irrigators are currently providing their data to the irrigation board, affecting the accuracy of model outputs and this data is consequently not being used in the model yet. Estimated water use data from the IWAAS study is used. The landcover database and verification of existing lawful water use project of the ICMA have both improved the current data but must still feed into the OWRM DSS to improved hydrology and water resources modeling.

Data and information for Short Term Operations	
7 Day flow forecasts	The DSS, NAM model and Mike 11 model with autocal and data assimilation enable the production of forecast flows 7 days into the future. The accuracy of these forecasts is affected by the poor rainfall runoff modeling and poor water use orders from the Irrigation Board.
River and Rainfall Alert levels	High and Low alerts (5 levels) have been defined for the river flows and rainfall to assist in the management responses for operational water resources management and incorporated into the Rapid Response System of the AOWRMF.
Weekly Water Use Orders	These orders are not very accurate as the weekly demand patterns must still be confirmed by the irrigation board. Improvement to automated daily delivery of water use is recommended.
River Cross Sections	River cross sections used in the mike 11 model for the main stem of the Crocodile were developed from 5 m contours, with a small channel in the middle. New sources of improved cross section information such as Lidar should be investigated to improve low flow hydrodynamic modelling
Weekly ecological reserve Requirements	Estimated ecological flow requirements (EFRs) 1 week into the future are calculated in the WReMP model. Refer to the full report for detail on the modelling required to provide this information. Alert levels have also been developed for the EFRs and incorporated into the Rapid Response System of the AOWRMF to assist in their operational management.
Other Supporting Information	
CROCOC TOR	Provides the mutual ethical framework for AOWRMF with the stakeholders.
Memoranda of agreement	MOAs have been entered into with all persons hosting ICMA data gathering hardware. MOAs relating to the river health and bio-monitoring of the rivers have been entered into with SanParks and the MTPA.
Technical Support Contract	Technical support contracts for all software have been entered into between the ICMA and software providers to ensure their stable operation.
Hardware Maintenance Contracts	A hardware maintenance programme incorporating contracts with the hardware suppliers has been implemented to ensure the ongoing reliable and accurate provision of real time data. The programme includes ongoing calibrations of all loggers and probes.
Awareness	A pamphlet highlighting the CROCOC responsibilities has been drafted.

Modelling and Decision Support Systems used in the AOWRMF for the Crocodile River

A suitable real-time DSS for the Crocodile River Catchment (Figure 3.3) that meets these requirements was developed by DWA and refined by the Inkomati CMA through this project. It is based on MIKE CUSTOMISED by DHI and MIKE by DHI software. The DSS is a real time management framework that integrates spatial data, real-time data, forecast models and dissemination tools in a GIS environment. The system is capable of running model engines provided by DHI, *viz.* MIKE 11, MIKE NAM, AUTOCal, and other third party model engines. The system is able to perform a set of tasks (e.g. download information from the web) which are either scheduled to take place at regular intervals or are triggered by certain events (e.g. a low flow threshold is compromised).

This DHI Mike Customised DSS solution has also been used worldwide and has thus been deemed suitable to be used as the DSS for the AOWRMF proposed and the CROCOC members have accepted and adopted the initial real time management framework developed by DWA for use.

Experience in its use has demonstrated that the modelling framework is sufficient to cater for the needs of AOWRM and that the current limitations are mainly data input-based.

Long Term Planning Model

The long term planning aspects are calculated using the WReMP model (Mallory, 2007 and Mallory et al., 2010) which is used to determine the annual operating rules and monthly restriction rules. The method used to develop the stochastic hydrology for the model incorporates monthly serial flow correlation as there is a strong serial correlation of monthly flows in the Crocodile River.

For operational use the model assesses the assurance of supply to different water user groups on a monthly basis by generating 101 stochastic possible hydrological sequences based on the starting month, the flow in the preceding month and the correlation of flow from one month to the next. A simulation is then carried out to determine a range of possible trajectories for the Kwena Dam. Superimposed on these trajectories are the recommended levels at which restrictions must be imposed on the various user sectors.

Short Term Operations Model

The short term operations modelling of the system is performed using the DHI MIKE 11 model. The model is used to determine the short term modifications to the release from Kwena Dam and potential lifting or imposing of short term restrictions on the water users. MIKE 11 uses data assimilation, which updates predicted data with actual measured information from the installed real time river flow data loggers ensuring that forecasts are always using updated boundary conditions. Added to this, suggested releases and restrictions are made using an optimization model named AUTOCal, built into MIKE 11. A detailed description of the set up and use of these various models within the Crocodile River real time DSS has been documented by Greaves et al., 2009.

The NAM hydrological model, which is one of the hydrological models in the MIKE 11 set-up, is used to provide an estimate of forecasted river flows in the short term future at quinary catchment scale for all of the 83 quinary catchments in the Crocodile basin. The NAM Model uses rainfall as input to predict what the likely runoff from the significant ungauged tributaries may be as input into the Mike 11 model. A key output of the model is forecasted flow up to 7 days into the future.