PARTICIPATORY HYDROLOGICAL MODELLING FOR COLLECTIVE EXPLORATION OF CATCHMENT MANAGEMENT IN THE WESTERN ALGOA WATER SUPPLY AREA

Report to the
Water Research Commission

by

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The publication of this report emanates from a project entitled *Participatory Hydrological Modelling for collective exploration of water resource protection, restoration and water use management options in the western Algoa water management area.* (WRC Project No. K5/2527)

EXECUTIVE SUMMARY

1. Background and Rationale

The Baviaanskloof, Kouga and Kromme (BKK) catchments provide over 70% of the current water supply to the Algoa Water Supply System, which includes the city of Port Elizabeth in the Nelson Mandela Bay Municipality (NMBM). Growing water demands and increasing water scarcity have led to a policy focus on water use and allocation in these upstream catchment areas as well as collective catchment management issues such as invasive alien plant (IAP) clearing of high water-use species. There is a critical need to find ways to promote effective water stewardship across a multi-stakeholder platform, securing our water resources and ensuring socially and environmentally acceptable ways of sharing these resources. This requires a common understanding of the social-ecological system, trust, and relationship building for there to be willingness and capacity among diverse stakeholders to work together and find acceptable ways of addressing the challenges. The need for such levels of engagement is recognized in existing water management policy-frameworks, such as those calling for Catchment Management Forums (CMFs); however, practical approaches for achieving this require action research to develop and improve.

This project aimed to foster social learning and group decision-making about catchment management in the BKK by using a participatory process to develop models of local hydrology. The focus was not only on the accuracy and applicability of the models, but also the process of model building as a dialogue facilitation and learning tool for the participants. Through this project, the partnering stakeholders identified potential land and water management scenarios and used understanding of hydrological processes to explore and evaluate likely hydrological and socio-economic outcomes.

2. Research and Practice in Context

The physical characteristics of the landscapes of the BKK catchments influence livelihood strategies, social structures and how people work together to manage shared resources. Understanding the local setting was critical in adapting both the social engagement and hydrological research approaches. Similar projects in different landscapes will require similar exploration and adaptation to the characteristics of the local socio-ecological system.

3. Approach and Methods

The stakeholder engagement approach of this project fits within a broader and longer-term engagement process facilitated by Living Lands. Living Lands has been active in these catchments for several years prior to this project (Baviaanskloof since 2009, Kouga and Kromme since 2015) and will remain engaged for years to come. The long-term goal is to develop a shared understanding of the social-ecological systems and build trust relationships, working towards a common vision of catchment management. Engagements will continue through linked learning platforms developing in the area, namely the Algoa Water Fund, the Honeybush Cultivation Working Group and the Baviaanskloof Conservancy meetings.

The Living Lands approach to participatory research and stakeholder engagement is rooted in Theory U[1], a method of facilitating collective social learning developed at the MIT U Lab. This is a process comprised of five key stages: co-initiating, co-sensing, co-strategising, co-creating and co-evolving. This project targeted the first half of this process, contributing to the broader and ongoing initiative. The 'model-building' process served as a tool for structured interactive learning around water issues (co-initiating, co-sensing). The resulting hydrological model can be used to inform priority areas for pilot interventions (co-strategising). Social learning engagements and empirical data gathering for the conceptual and numerical hydrological models were conducted simultaneously, with feedback to and from the process facilitators, hydrologic modellers and stakeholders.

3.1 Engagement and social learning assessment

Several engagement tools were used to collectively explore water-related issues on the landscape at different levels. These included dialogue interviews, workshops, learning journeys and informal

[1] Scharmer, C. 2009. Theory U: Learning from the future as it emerges. Berrett-Koehler Publishers

gatherings. The outcomes of each engagement informed the focus and approach of subsequent activities. Introductory dialogue interviews informed an initiation workshop. This led to a focus on alien clearing and rehabilitation opportunities in the learning journeys. Larger group activities were interspersed with interactions around the field data collection, further dialogue interviews, and informal social gatherings. Near the end of the project, a sense-making and scenarios workshop was used to synthesize and discuss outcomes of previous engagements and field observations and to develop and explore scenarios of future catchment management.

Social learning is a long-term process which will continue beyond the duration of this project. Initial monitoring of social learning was done through focused reflection sessions during and after learning journeys and dialogue interviews. Reflection was used to investigate: 1) a change in understanding within an individual participating in facilitated activities; 2) a change in understanding among the broader social networks beyond the individuals directly involved in the facilitated activities.

3.2 Hydrological modelling

The foundation of the modelling exercise was to be explicit about the conceptual understanding of hydrological processes, i.e. the flow of water through the landscape and where and how human activities and land cover changes modify flow pathways. This then informed quantitative numerical models. Conceptual model development included review and analysis of existing spatial and hydrometric data, stakeholder observations about hydrological events and processes, targeted field data collection of hydrometric, hydrochemical, and channel and floodplain topographic and geomorphology data. The field data collection gathered in this study targeted improving the understanding of surface-groundwater interactions and land cover impacts in the more heavily used floodplain areas.

The conceptual models were used to develop the structure of the numerical models of the catchments. Following a basic review of potential numerical modelling tools, these were built using MIKE-SHE software (DHI) using a hydrologic response unit (HRU) routing structure and estimates of recent/current land cover distribution. Catchments were split into HRUs for modelling based on topography and land cover, with the decisions of land cover classes to include being informed by the stakeholder engagements. Due to time constraints the model of the Kromme catchment was prioritized for calibration and scenario exploration based on the engagement process. This model was assessed against estimated streamflow from observational data for the past decade. The calibrated model was re-parameterized to assess the potential streamflow and groundwater impacts of selected alternative scenarios of future land management, focused on IAP management.

3.3 Scenario development

The dialogue interviews and workshops were used to develop a set of potential future land and water use management scenarios. Potential changes described by stakeholders were converted into alternative land cover maps using assumptions about potential spatial distributions of different cover types (e.g. areas available for agricultural expansion or vulnerable to black wattle invasion), which were reviewed by stakeholders.

4. Outcomes summary

4.1 Social learning and effective knowledge exchange by employing diverse stakeholder engagement tools

The stakeholder engagement tools were found to be effective in creating spaces for social learning. During the use of these tools, three levels of social learning were evident: cognitive (knowledge-based), affective (emotion-based) and behavioural (action-based). For example, at one of the assessed learning journeys, stakeholders expressed that they gained more knowledge on invasive plants (cognitive learning), stakeholders inspired each other (affective learning) and exchanged contact information to meet again (behavioural learning).

Different engagements and tools provided different insights feeding into the model and scenario development:

- **Dialogue interviews:** Dialogue interviews proved integral for accessing tacit knowledge about the socio-ecological system, local hydrology, and water use. They were also a key method for evaluating change in perspectives, assumptions and relationships. Most took place on the properties of catchment residents, who often showed the team hydrological features, such as springs, wetlands, boreholes, tributary streams, dams, and irrigation systems. This fostered discussion and improved understanding of local hydrology on the part of the project team.
- **Workshops:** The introductory workshop provided critical understanding of the scales in which hydrological flows are perceived and considered. It assisted direction and focus for further development of the model and scenarios, e.g. strong interest was shown in alien clearing. The second workshop aided collective determination of scenarios of future catchment management and lead to discussions of factors influencing water security.
- **Learning Journeys:** During the alien clearing and the rehabilitation learning journeys farmers, landowners, government officials, water specialists and business owners visited sites illustrating natural vegetation, alien infestation, alien clearing, and subsequent rehabilitation. Outcomes were a shared understanding, a sense of community in the midst of the challenges, the connection and inspiration of key role-players, which are pre-requisites for social learning.
- **Informal gatherings:** Informal group events (such as "braai's") provided a comfortable space for sharing and building understanding and trust. Discussions contributed to knowledge exchange between farmers and researchers and further development of the catchment management scenarios.

Working in a highly diverse and large social landscape, some challenges were experienced in the consistency of stakeholder participation at group events. Targeted dialogue interviews were utilised to overcome problems with incompatible time schedules and scales of interest and to reach many and diverse parties in a large landscape.

4.2 Learning platforms for strategic catchment planning and knowledge exchange

Engagement before and during this project resulted in the establishment of three learning platforms which were formed by Living Lands and the stakeholders. This complements the knowledge exchange process of this project. The learning platforms, the Algoa Water Fund, the Honeybush Cultivation Working Group and the Baviaanskloof Conservancy, will continue to facilitate conversations around catchment management beyond the duration of this project. The continuous engagement with diverse stakeholder groups has ensured that these learning platforms are representative of the diversity of the socio-ecological landscapes of the BKK.

4.3 Hydrological model development

The process of developing conceptual models of these three catchments highlighted a diversity of seasonal surface and sub-surface flow pathways active in each catchment. The 2016-2018 drought covered much of the field sampling period. This gave useful insights on groundwater contributions, but meant that high flows were not sampled. Broader inferences about high flows and long-term averages could be made from longer-term monitoring at the major dams. Stakeholder observations of springs and groundwater showed the high spatial diversity of groundwater flows due to the layering, folding, and irregular fracturing of the Table Mountain Group geology. Reported borehole strikes and yields could be highly variable at small spatial scales. Springs that were reported were typically found at quartzite-shale contacts and ranged from being perennial to ephemeral. There was evidence in all catchments that slow-draining mountain bedrock aquifers feed perennial tributary streams and also feed the floodplain alluvial aquifer storage, either directly at aquifer contacts or via stream transmission losses in the alluvium. After large rainfall events, interflow, likely from more highly fractured rock surface layers, appeared to be a dominant process on a time-scale of weeks. In low-flow periods, the floodplain alluvial aquifer storage also feeds the main stream channels to varying degrees across the catchments and seasons. The importance of seasonality of rainfall and of vegetation water use was highlighted by the lower summer streamflow response to rainfall. Field observations and stakeholder accounts showed the influence of black wattle stands in drawing down alluvial aquifer storage and reducing local streamflow in low-flow periods.

These observations were incorporated into the numerical modelling through the parameterization and the connections between surface hydrologic response units (HRUs) representing different topographic settings and vegetation types, interflow reservoirs, and baseflow reservoirs for both the mountain bedrock areas and the floodplains. The baseline numerical model of the Kromme catchment achieved suitable goodness-of-fit to observed data for further application: NSE of 0.8 and mean bias error of 1% for daily average flow 2008-2018. Over-prediction of streamflow peaks from small rain events shows room for future model improvement.

Stakeholder interactions also revealed the diversity of water management practices in the catchments. This is challenging to incorporate into larger-scale numerical models. Irrigating farmers use water from different sources – mountain tributary diversions, main river pumping, deep and shallow aquifer pumping, storage dams – at different times depending on the nature of their specific properties, economic means, arrangements with irrigation groups, and other factors. This had to be simplified in modelling and the influence of this would be a fruitful topic for further work.

4.4 Scenarios development and assessment

Participants in the engagement process thought there was reasonable possibility for change in opposing directions in areas of key interest: Invasive Alien Plant (IAP) cover expansion or sustained clearing, agricultural expansion or reduction, and water use increase or decrease. There was consensus that water use would become more efficient in future. Despite this it was expressed that total use could increase, be maintained, or decrease with agricultural and population expansion, although increases would be limited by licensing. Discussions led to the development of nineteen different land cover maps and water-use practice description scenarios, including baselines of pre-development cover and current cover, single change scenarios, and story-line scenarios.

Unanticipated delays in obtaining and processing the wide variety of data required and the time needed for the desired level of stakeholder engagement left insufficient time to run catchment hydrological models for all the catchments and scenarios developed. A set of alien vegetation expansion and clearing scenario models was run for the Kromme catchment, highlighting the potential for unhindered IAP invasion to reduce average annual water yield by as much a 24%. Further stakeholder vetting and improving these models, as well as applying them to the additional scenarios, will continue through collaboration with the Algoa Water Fund and through an upcoming WRC project (K5/2927): "Critical catchment hydrological model inter-comparison and model use guidance development."

5. Recommendations for similar projects

Many lessons were learned by the team during this project, as well as in the preceding years of Living Lands' work in the catchments, which informed the recommendations below. Using the development of a hydrological model as a boundary object to support integrated catchment management is feasible. However, there are many context-specific elements to be considered. Collaborating and complementing other initiatives is key to the success of such a participatory approach and its outcomes. A considerable amount of time is needed to fully integrate with the landscape, therefore long-term, systems thinking must be employed.

The following recommendations should be taken in to consideration for future work and project development;

- **Ensure diverse language and communication skills:** A two-fold challenge presented itself in this project: 1) translating scientific hydrological terminology to a wide range of practitioners, and 2) translating between English and Afrikaans during fieldwork and feedback sessions. It is important to appoint a diverse team which are competent in the languages of the stakeholders. Enough time should be allocated to translate information to suit the audience. Using visual communication tools and a variety of engagement settings (group size, location, formality) facilitates the process of effective and true knowledge exchange.
- **Take time to build relationships of trust:** It is crucial to acknowledge power dynamics and to attribute enough time to building trust, or partner with a stable local organisation, especially with regards to the data gathering process.
- **Build capacity for monitoring social learning:** Social learning occurs continuously throughout the project and is difficult to monitor, especially when many other types of data

needs exist. It is important to assign a team member, preferably a social scientist, to monitor and capture social learning. Baseline and follow up data will also strengthen results.

- **Beware of the "tyranny" of participation:** Participatory modelling involves asking stakeholders to commit time to a participative process and to share their perspectives in a group. Since one's perspective could relate closely to one's personal worldview, this may lead to participants feeling anxious or disrespected. This experience during group events, along with the time demands placed on stakeholders during participative processes, is described by literature as the "tyranny" of participation. It is important to be sensitive to this and crucial to create a space where people are respectful of each other's worldviews during an event.

- **Matching the different scales:** Each stakeholder and group involved in the project operates on a different scale. Matching discussion topics or presented results with the scale in which the stakeholders think and implement can help ensure that new data informs future actions and it also allows the person to engage with you and the data effectively. Additional scales can then be gradually introduced to discussion over time.

- **Matching the different time schedules:** Each stakeholder group has a different time schedule with important dates according to their profession. For example, farmers function at different timeframes during harvest seasons, as do academics during examination periods. At the start of the project, it is helpful to map these time schedules so that events and deadlines can be planned accordingly.

- **Allocate enough time for conceptual modelling:** The process of developing conceptual models of these three large and complex catchments was ambitious and there were challenges with obtaining and processing data across parties, institutions, and space. This meant that more time was needed for various components than originally planned. The process of engaging all of these parties to obtain and discuss information was fruitful as part of the engagement process and network building.

- **Start with smaller areas to ensure faster feedback to stakeholders:** Focusing on smaller areas for modelling and data/information collection would have sped up the data and assessment turn-around time which would make feedback to stakeholders more frequent. The area of focus could then be increased over time.

- **Field data collection create opportunity for stakeholder engagement:** The additional field data collection done within the catchment areas on private properties added a layer of stakeholder engagement and opportunities for discussions and co-learning during fieldwork visits. Visibility on the landscape increased trust and interest from stakeholders.

6. Policy Implications

This project significantly contributes to the development of local catchment institutions and practices that promote water stewardship across a multi-stakeholder platform. This forms part of what is intended for Catchment Management Forums (CMFs), mandated by Department of Water and Sanitation (DWS) to guide future Catchment Management Agencies (CMAs). Learnings from this project could assist in CMF development in general. The project activities in the BKK have already been linked with CMF establishment locally. The framework developed in this project, based on the Theory U, provides several tools useful for engagement with diverse stakeholder groups, addressing social dynamics to create a comfortable, shared-space for learning. This project highlights the critical need for building capacity and resources for effective stakeholder engagement in water management.

Both government and institutional policies influence land- and water use in various ways. Laws, programmes, incentives, and institutional arrangements could support and lead the way to some of the positive scenarios explored in this project. They influence stakeholder responses on the landscape to factors such as climate variability or market forces. For example, if a payment for ecosystem services model is promoted through the National Water Pricing Strategy and the Biodiversity Act (tax benefits for biodiversity stewardship) rehabilitation of palmiet wetlands may be better prioritised by private landowners. In terms of IAP management; land user incentives such as value added-business opportunities; free herbicide for IAPs and tax benefits for clearing are all factors which could support the clearing of IAPs.

7. Capacity building

Through stakeholder engagement in this project, many different institutions and stakeholder groups were involved from in and around the BKK catchments:

- **Individual catchment residents**: large-scale commercial farmers, small-scale farmers, emerging farmers, non-farming residents, teachers, etc.
- **Agricultural community groups**: Baviaanskloof Hartland Conservancy; De Hoop Farmer's Association; Eastern Cape Agriculture; Gamtoos Farmers Association; Koukamma Emergent Farmers Task Team; Langkloof Honeybush Working Group; Sewefontein Trust; Tchnuganoo Community Farm.
- **Civil society organisations**: Conservation Outcomes – Greater Kromme Stewardship Group; Garden Route Biosphere Reserve; Living Lands; The Nature Conservancy
- **Experts and consultants**: water management engineer, agricultural advisor, honeybush cultivation consultant, nursery specialist
- **Government institutions:** Department of Economic Development Environmental Affairs and Tourism (DEDEAT); Department of Environmental Affairs: National Resource Management (NRM); Department of Water and Sanitation: Catchment Management Agency (CMA); Department of Water and Sanitation: Strategic Catchment Management; Eastern Cape Parks and Tourism Agency (ECPTA)
- **Government Programmes**: Working for Water
- **Irrigation boards and fire protection associations**: Gamtoos Irrigation Board (GIB); Sarah Baartman West Fire Protection Association
- **Municipalities**: Koukamma Municipality; Nelson Mandela Bay Municipality: Water Management and Bulk Supply
- **Research institutions**: University of the Western Cape; South African Environmental Observation Network (SAEON); Nelson Mandela University; Radboud University Nijmegen; The Hague University of Applied Sciences; University of Amsterdam; Van Hall Larenstein University; Wageningen University
- **Business sector**: Coca Cola Company; Grounded; Port Elizabeth Business Sector; Tsala (Pty) Ltd; Woodlands Dairy: Sustainability Department; Santam Ltd

Capacity building around hydrology, land and water management, stakeholder engagement methods, occurred on different levels for different participants, achieved by creating learning platforms for diverse stakeholder groups to participate in knowledge exchange activities. In addition the project included training and mentorship of five postgraduate and seven undergraduate students which are listed below.

List of students trained or mentored during this project

No	Name and Surname	Institution	Qualification	Conferences/workshops/articles	Contribution
1	Faith Jumbi	University of the Western Cape	PhD	Africa Groundwater Network Uganda	Workshop
				Agulhas research open day 2017	Poster
				Waternet symposium Namibia 2017	Presentation
				SAEON graduate student network – Hoedspruit	Presentation
				SAEON newsletter June 2017	Article
				All Living Lands workshops and learning journeys 2017-2019	Participation
2	Pamela Sekese	University of the Western Cape	MSc	Southern African Association of Geomorphology July 2017	Poster
				SAEON newsletter February 2018	Article
				WaterNet/WARFSA/GWP-SA Symposium October 2018	Presentation
				National Wetland Indaba October 2018	Presentation
				Short Course on Instream Flow Assessments May 2019	Participation
				All Living Lands workshops and learning journeys 2017-2019	Participation
3	Current Masunungure	Nelson Mandela University	MSc	Alien Clearing Learning Journey	Participation
4	Daniek Bosch	Radboud University Nijmegen	MSc	Alien Clearing Learning Journey	Participation
5	Noud van Dam	Wageningen	BSc	Alien Clearing Learning Journey	Participation
6	Job Kwakernaak	Wageningen	BSc	Introduction Workshop	Participation
7	Marijn Geerts	Van Hall Larenstein University	BSc	None	
8	Martijn Nettenbreijers	Van Hall Larenstein University	BSc	None	
9	Tobias Otten	The Hague University of Applied Sciences	BSc	Sensemaking Workshop	Participation
10	Quirine van der Meer	Nelson Mandela University	BSc	None	
11	Jara Birkholtz	Avans University of Applied Sciences	BSc	Sensemaking Workshop	Participation
12	Roos van der Deijl	University of Amsterdam	MSc	Algoa Water Supply meeting	Participation

8. Ongoing process

Several locally-based learning platforms developed over the course of this project, the most directly linked of which is the Algoa Water Fund and potentially emerging CMFs. These platforms will be utilised to effectively distribute the outcomes ongoing modelling work to help inform strategic planning for these catchments going forward. With key stakeholders from both public and private entities now aware and engaged in the work, we hope to continue building a rich knowledge network for further social learning. By involving business, these learning platforms can also assist in developing more sustainable finance of rehabilitation activities in the future.

Further review of the conceptual and numerical models developed here against continued data collection, and further stakeholder engagement with the assumptions made in modelling, will serve to improve its realism and usefulness to stakeholders over time. It is anticipated that this is a process that can continue through the Algoa Water Fund using the start that this project has made. A key area for future development highlighted in this process was the need for improved land cover mapping, particularly with regards to invasive alien vegetation, and further assessment of the influence of different model representations of water diversions and irrigation practices on overall water supply prediction outcomes.

Efforts to assess what numerical catchment modelling software tools would have the capability to represent the desired conceptual model of catchment processes, and represent the catchment changes of interest, inspired the proposal for a further WRC project (K5/2927): "Critical catchment hydrological model inter-comparison and model use guidance development." This project will include modelling multiple catchment case-study areas, including the BKK, with multiple modelling tools and comparing them in order to provide guidance for future modellers.

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Ms Isa Thompson	Department of Water and Sanitation (DWS)
Dr Jane Tanner	Rhodes University (RU)
Dr Jessica Cockburn	Rhodes University (RU)
Dr Mark Dent	Alliance for Water Stewardship, South Africa
Ms Nana Mthethwa	Department of Water and Sanitation (DWS)
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LIST OF ABBREVIATIONS AND ACRONYMS

ARC	Agricultural Research Council
AWSS	Algoa Water Supply System
BKK	Baviaanskloof, Kouga, Kromme catchment areas
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data – precipitation dataset
CGS	Council of Geoscience (formerly Geologic Survey of South Africa)
DEA-NRM	Department of Environmental Affairs – Natural Resource Management branch
DEM	Digital elevation map
dGPS	Differential Global Positioning System
DWS	Department of Water and Sanitation
ECPTA	Eastern Cape Parks and Tourism Association
ET	Evapotranspiration; PET – Potential Evapotranspiration; AET – Actual Evapotranspiration
GIB	Gamtoos Irrigation Board
GIS	Geographic Information System
GRA II	Groundwater Resources Assessment Studies, Phase II
GRACE	Gravity Recovery and Climate Experiment satellite
HRU	Hydrologic response unit
IAP	Invasive alien plants
LAI	Leaf area index
LL	Living Lands
MAE	Mean annual evapotranspiration OR mean annual error statistic
MAP	Mean annual precipitation
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NGDB	National Groundwater Database
NGI	National Geo-Spatial Information (Department of Rural Development)
NRF	National Research Foundation
NSE	Nash-Sutcliffe Efficiency statistic
QC	Quaternary catchment
RMSE	Root mean squared error
SAEON	South Africa Environmental Observation Network
SAWS	South African Weather Services

SEBAL	Surface Energy Balance Algorithm for Land
SRTM	Shuttle Radar Topography Mission
SU-DEM	Stellenbosch University Digital Elevation Model dataset
TAMSAT	Tropical Applications of Meteorological Satellites
TRMM	Tropical Rainfall Measuring Mission
WfW	Working for Water programme
WfWetlands	Working for Wetlands programme
WR2012	Water Resources of South Africa 2012 Study
WRSM	Water Resources System Model
WWTW	Waste Water Treatment Works
V&V	Validation & verification of water use and storage relative to registration

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1. BACKGROUND AND RATIONALE

1.1 Western Algoa water supply catchments (“the BKK catchments”)

The Western Algoa water supply area catchments comprise the Baviaanskloof, Kouga, and Kromme catchments (further referred to as the BKK). The BKK provide 78% of the water allocated to the Nelson Mandela Bay Municipality (NMBM), and over 70% of the Algoa Water Supply System as a whole, via the Kouga, Churchill, and iMpofu dams. These catchment areas also supply water to towns and commercial and subsistence agriculture located upstream of the major reservoirs. With a growing human population and water demands inside and outside of the catchments, as well as increased climate variability, there is a need to improve understanding of how changes in land and water management could impact the water security of these catchments.

Together the BKK catchments (Figure 1:1) span an area of 4,910 km^2 which has large variability in climate, vegetation, and land use. They share similar Table Mountain Group geologies and somewhat similar geomorphology: long narrow valleys bounded by steep, rocky, mountains, with rugged mountain terrain dominating the area. The Baviaanskloof is the furthest inland and receives roughly half of the long-term mean annual rainfall of the more coastal Kromme (300 mm vs 640 mm). All have fynbos cover on their high plateaus and mountainous areas, which are less utilized for agricultural activity. The catchments differ in hillslope and valley vegetation and land use. Notably, the wetter Kromme has large permanent palmiet wetlands, whereas the Baviaanskloof has savanna woodland on its valley floor and succulent thicket on its hillslopes. Valleys of the Kouga are dominated by commercial fruit orchards. The Kromme has some orchards and irrigated pasture. The Baviaanskloof has less cultivated agriculture on the valley floor and historically had small stock grazing in the hills. This contributed to the degradation of much of the thicket. Both the Kouga and Kromme have significant coverage of invasive alien trees, primarily black wattle (*Acacia mearnsii*).

The population is approximately 35,000 in the Kouga and Kromme catchments and 2,500 in the Baviaanskloof. The few small towns in these catchments are economically dependent on agriculture. These include: Haarlem, Misgund, Louterwater, Krakeel, Joubertina and Kareedouw in the Kouga and Kromme catchments. Higher density rural settlements in the Baviaanskloof are Sewefontein and Zaaimanshoek.

Figure 1-1 Baviaanskloof, Kouga, and Kromme catchment areas and major water supply reservoirs: the Kouga Dam fed by the Baviaanskloof and Kouga, the Churchill Dam fed by the upper Kromme and the iMpofu Dam fed by the lower Kromme

Living Lands has been present in the area for almost 10 years and are engaging with a variety of stakeholder groups including farmers' associations, fire protection associations, emerging farmers, commercial farmers, municipalities, irrigation boards, catchment management agencies and nature conservancies.

1.2 Catchment modelling as a learning tool

Catchment hydrological modelling is widely used to assist in water resources and catchment management, however, the modelling process itself provides a social learning opportunity that is rarely realised. Models allow exploration of potential impacts of future changes in climate, land cover, and water-use. In applied settings, the work of structuring, parameterizing, and running numerical models is undertaken by specialists who supply model outputs to those in decision-making roles. In general, there is little interaction between stakeholders and modellers around how a model represents catchment processes or the scenarios of change. This ignores knowledge inherent in people on the landscape about hydrological processes and the broader socio-ecological system that would improve the realism of the modelling. This could instead be a space for social learning, on all sides, to improve catchment management efforts going forward.

The process of building and testing a catchment model entails gathering information and/or making assumptions about biophysical processes, connectivity in the landscape, and land and water use behaviours. If stakeholders have a shared understanding of processes and connections, for example, about how different vegetation types impact groundwater and river flow or how surface water and groundwater interact, that could promote more collaborative catchment management planning and implementation. In this project we aimed to facilitate participation in the process of developing a model of catchment hydrology for the Western Algoa region through discussions of observations, assumptions, future scenarios and their likely implications.

This project, titled "Participatory hydrological modelling for collective exploration of water resource protection, restoration, and water use management options in the western Algoa water management area" had two main objectives:

1. To develop accurate and applicable hydrological models of the Baviaanskloof, Kouga and Kromme catchment areas; and,
2. To implement a process of model-building which facilitates dialogue and acts as a learning tool for stakeholders, with a focus on local water and catchment management issues and policies, to foster collaborative water resources management.

2. METHODOLOGY

This participatory hydrological modelling project was managed by Living Lands in collaboration with the South African Environmental Observation Network (SAEON), the Council for Scientific and Industrial Research (CSIR) and the University of the Western Cape (UWC) (Table 2:1). The project was designed as a participatory and collective learning process to develop the human, technical and social capital needed to develop effective collaborative management capacity around catchments and water resources in the study area. It was also intended that the lessons and tools developed in this project can documented to inform and guide similar initiatives in other catchments in South Africa.

The role of the project team was to facilitate the learning of all the stakeholders and create tools and an enabling environment for constructive dialogue and collaboration between all the catchment stakeholders. To enact this, the following approach was taken and communicated to participants:

- The stakeholders will decide for themselves whether and how to participate and what they will contribute;
- The participating experts and catchment stakeholders will work together to decide on;
    - How to set up the model
    - What scenarios to run

- What data outputs to report and present.

The project facilitators focused on creating an enabling environment for stakeholders and experts to come together and learn and get to know one another and explore future policy and governance options for the catchments. The outcomes of these discussions and learning processes however, ultimately depend on the stakeholders themselves and what they can and are willing to bring and contribute. Further details on the stakeholders who were invited to participate and contribute and the stakeholder engagement approach are provided in Section 4 of this report.

The core project team information is captured in Table 2:1. The Living Lands' landscape teams in the Langkloof and Baviaanskloof also formed part of the extended project team throughout the project as needed.

Table 2:1 Core Project Team

Name	Organization	Position	Role in project
Liezl le Roux	Living Lands	Landscape Facilitator	Project leader and stakeholder engagement facilitator
Ancia Cornelius	Living Lands	Landscape Mobiliser	Stakeholder engagement implementer and social learning facilitation
David le Maitre	CSIR	Researcher (plant ecology, catchment hydrology, invasive alien plants – IAPs)	Senior advisor: advise on catchment model design and analyses, particularly regarding IAP water use impacts
Julia Glenday	SAEON	Post-doctoral researcher (ecohydrology, catchment modelling)	Modelling team manager: responsible for model development, testing, output analyses, data management, and communication regarding these tasks
Faith Jumbi	UWC	PhD student (hydrology)	Modelling team: assist in model development, testing, and output analysis through PhD research (modelling the impacts of restoration on streamflow)
Pamela Sekese	UWC	Masters student (hydrology)	Modelling team: assist in model development, testing, and output analysis through MSc research (modelling the impacts of restoration on streamflow)

2.1 Research Approach

A participatory research approach was employed in this project. Participatory research methods are aimed towards planning and conducting the research process with those people whose daily reality and actions are being explored. Consequently, the intention of the enquiry and the research questions are developed and informed out of two perspectives; that of science and of practice (Bergold & Thomas, 2012).

Involving a broad base of stakeholders in the process of developing and using the hydrological model to explore land and water management options is important in order to incorporate their perspectives and knowledge of the social-ecological system. The incorporation of diverse knowledge helps to identify the potential unintended negative consequences of any interventions and ensure that these consequences are minimised, and if possible, avoided. Through interacting with each other and the modelling technicians, the unconscious tacit knowledge embodied in the stakeholders is revealed and incorporated into the model. This is the social information that stakeholders often do not realize they themselves or others have. The collective involvement of the stakeholders in the modelling process, the incorporation of this tacit knowledge into the model, and the collective interrogation of the assumptions in the model enables the generation of socially robust knowledge of the system that gets embodied in the model. In so doing, a more holistic understanding of how stakeholders interact with and perceive the hydrologic system is revealed.

Living Lands has been working in the BKK catchments for between 5 and 10 years. During the years, Living Lands has been building trustworthy relationships with many stakeholders and stakeholder groups in and around these catchments. The organisation spends time to deeply engage with individuals and stakeholder groups in order to understand both the social and ecological systems in the area. By understanding the different roles of these stakeholders within the water and land management context, Living Lands aims to facilitate change processes which lead to social-ecological sustainability. This project therefore fits within a long-term strategy of exploring social-ecological systems for the benefit of catchment management.

Living Lands' approach to participatory research and stakeholder engagement is rooted in Theory U, which is a method of facilitating collective social learning (Scharmer, 2009). Social learning is increasingly recognised as a crucial component of participatory processes aimed at nurturing collective action around common environmental concerns and thus forms an integral part of this process (Cundill & Rodela, 2012).

2.2 The Theory U Methodology

Theory U (Figure 2:1) allows for a deeper integration and understanding of systems that are foreign to oneself. This helps us and the stakeholders with whom we work, to immerse in experiences on deeper levels which then trigger greater emotion and action. Theory U was developed by the Presencing Institute at the Massachusetts Institute of Technology (MIT) for leading profound change. The process provides opportunities for all stakeholders to engage on a deeper level of reflection on the socio-ecological system, to identify and create viable community-based responses through theoretical perspective and practical social technology. This address underlying social problems on an individual, community and institutional level and informs behaviour to better reflect the values of inclusion, fairness and opportunity. The process comprises five key stages: co-initiating, co-sensing, co-strategising, co-creating and co-evolving, described in Figure 2-1.

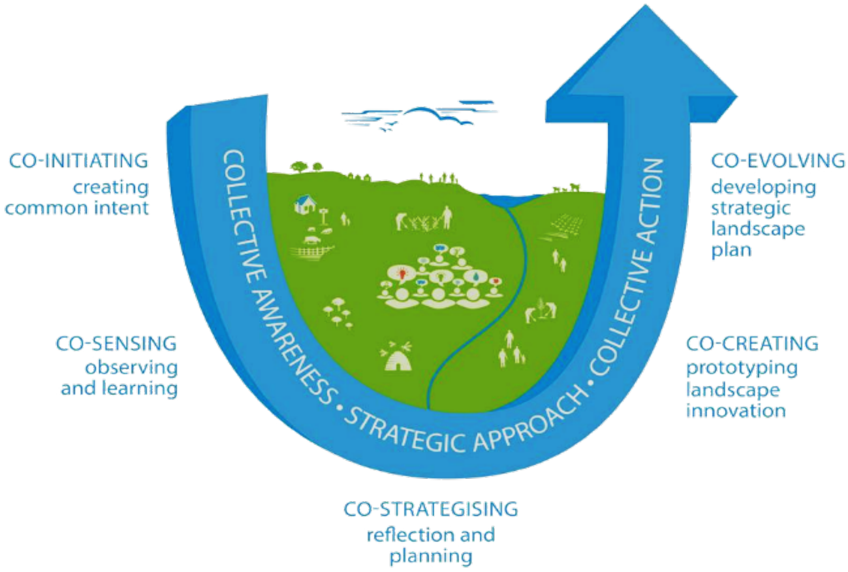


Figure 2-1The Theory U framework, developed by Sharmer (2009) and employed in our current Living Landscape approach to management of social-ecological systems.

This process is by no means linear and can include multiple iterations of the U through time. Drawing from Theory U, several engagement tools were used to collectively explore water related issues in the landscape.

2.2.1 Dialogue interviews

This is a one-on-one interaction where the interviewer employs open ended questions and active listening in order to create a transformative dialogue. The idea is to reflect upon dreams, aspirations, challenges and needs and the manner in which the interviewee engages with the community and landscape. This method was especially useful to capture the process of learning between stakeholders.

2.2.2 Learning Journeys

A Learning Journey involves a group of stakeholders which go on a journey to see the landscape from a new perspective and to collectively generate new ideas. This method is also effective to identify challenges in a complex social-ecological system. Reflection forms a key part of this process and is facilitated at different stages during site visits.

2.2.3 Workshops

Workshops are aimed to bring focus around a challenge and to prototype solutions and promote innovation. This is also an opportunity to exchange knowledge and create collective awareness.

2.2.4 Informal gatherings

Informal gatherings such as a braai at the local office are effective tools to create a comfortable space for stakeholders to gather and exchange information. These were opportunities to update stakeholders on the process of model building and to get more input.

3. RESEARCH AND PRACTICE IN CONTEXT

The Theory U approach requires the project team to be fully embedded within the landscape. Living Lands has offices within the Baviaanskloof and the Langkloof and already works closely with local institutions and landowners on several landscape rehabilitation initiatives. By co-living and co-working with other stakeholders in the same environment, we discover the deeper context of our surroundings, both ecologically and socially. This is an essential part of social learning which broadens our perspective on the current state of the hydrology, ecology and social structures. This information played a crucial role in the modelling process and is a major part of the team learning and reflections which shaped the methodology and approach of this project. These reflections are captured below.

3.1 The Ecological Context

The physical characteristics of the landscape influence how people farm, how people are in contact with one another, and how people work together to manage shared resources (Table 3:1). The ecology and people have adapted, and continue to adapt, to the variable climate and rugged landscape of the region. The BKK catchments are semi-arid, mountainous catchments at the eastern end of the Cape Fold mountain belt. They lie between the winter rainfall and summer rainfall zones and do not have a consistent seasonal pattern of precipitation. There is high inter-annual variability. The Baviaanskloof, being the most inland, receives the least rainfall (roughly 300 mm mean annual precipitation, MAP) and the Kromme, closest to the coast, receives the most (roughly 650 mm MAP). The data collection and stakeholder engagement in this project has been taking place during the most severe multi-year drought in the last century (1984 hydrological year was the driest year on record in the region, but 2016-2017 were third and second and were consecutive). This significantly influenced many interactions and the process of this project.

The geology and geomorphology impact the water resources, land management, and how people can move around the landscape. Folding, faulting, and uplift in the Table Mountain Group (TMG) geologic formation resulted in the Tsitsikama, Kouga, and Baviaanskloof mountain ranges, oriented in series parallel to the coastline and separated by the valleys of the main rivers (Kromme, Kouga, and Baviaanskloof) draining west to east. The area is dominated by erosion-resistant quartzitic sandstones. This geology, combined with the low rainfall, has meant that most of the catchment area (95-98%) is hillslope and mountain with relatively narrow floodplains (2-5% of catchments' areas, valley width range: 20-1760 m) located on the major rivers, which follow major faults and bands of softer shale. The steep mountains make much of these catchment areas inaccessible and result in long travel times between catchments, thereby limiting social connectivity. The TMG quartzitic sandstones are highly fractured and hence water bearing, with groundwater springs emerging from the bedrock aquifer at intersections with the thin shale layer aquicludes, cemented faults, or other transitions. The bedrock aquifers and floodplain alluvial aquifers maintain near-perennial streamflow in mountain tributary streams and most of the main river channels, with the exception of the drier Baviaanskloof. In the Baviaanskloof there are perennial mountain bedrock springs feeding tributary streams, but much of this water seeps into the alluvium in the floodplain and fans such that the surface flow network is not continuous except in very wet periods.

Changes in land cover and use in the catchments impact hydrological processes, and have likely reduced low flows and increased floods compared to a pre-developed state. The dominant indigenous vegetation cover in all three catchments is fynbos. Narrow mountain kloofs support indigenous forest, but closed canopy cover with tall trees would not be expected elsewhere. Other significant indigenous cover types are subtropical thicket on hillslopes and *Vachellia karroo* woodland on wide floodplains in the Baviaanskloof and palmiet *(Prionium serratum*) wetlands in wide valley reaches of the Kromme. Cover conversion has mostly been cultivation on the flatter floodplain and adjacent toe-slopes, and growth of dense stands of invasive black wattle (*Acacia mearnsii*) trees, predominantly in riparian areas in the Kouga and Kromme. In the Kouga, cultivation is mostly commercial apple and stone fruit. The Kromme has a mix of orchards and irrigated pasture for dairy. These cover types have replaced fynbos and wetlands and have different patterns of water use, particularly given irrigation and, in the case of the wattle, deep rooting and fast growth maintaining high ET rates (Le Maitre et al., 2015, Rebelo et al., 2015). Due to public and private clearing efforts, there is less mature wattle cover at present than in the previous decade: Working for Water records suggest that 60% of the 117 km^2 ear-marked for clearing in 2002 had been cleared by 2014. However, mapping of woody cover suggests there may be as much as 170 km^2 remaining (4% and 8% of the Kouga and Kromme areas).

In the Baviaanskloof, in contrast, there has been a loss of dense vegetation cover in some areas. Floodplain cultivation has been for pasture, vegetable seed production, and more recently essential oil production, which are irrigated but may not use significantly more than the *Acacia karroo*. Goat grazing on the hillslopes was the main agricultural activity in previous decades and continues at lower intensities. This resulted in a loss of intact thicket cover over a third of the catchment, increasing storm runoff on hillslopes and potentially decreasing bedrock aquifer recharge (Van Luijk et al., 2014).

Table 3:1 Brief description of the different catchments and municipal areas within the study area.

Agricultural subcommunities / Municipal Areas	Economic Activity	Population & farmlands	Ecology
Baviaanskloof	Protected parks, Livestock, tourism & irrigated cultivation or pastures in valley bottom	+/- 2,000 people +/- 12 farms, 2 rural settlements	Mountainous, +/- 300 mm rainfall pa, Arid, subtropical thicket and fynbos. Degraded vegetation due to stock grazing.
Bo-Kouga, Middel-Langkloof, and Onder-Langkloof	Intensive irrigated Deciduous Fruit Farming in valley bottom	+/- 30,000 people total +/-6,000 ha irrigated orchards	Mountainous and fertile wide valleys in Langkloof. +/- 500 mm pa, Fynbos vegetation and degraded/transformed wetlands.
Onder Kouga & Suurveld	Protected Parks, Livestock, game, tourism & pockets of cultivation	Unknown but limited irrigation	Significant invasive alien plant infestations in riparian areas and mountain slopes.
Bo-Krom and Middel-Krom (above Churchill&	Lifestyle farming, livestock, tourism and dairy (irrigated)	+/- 6,000 people +/- 50 farms +/- 1000 ha irrigated (pasture,	Mountainous, +/- 600 mm pa, Fynbos and degraded/ transformed wetlands and IAP infestations (esp. lower part of catchment)

Agricultural subcommunities / Municipal Areas	Economic Activity	Population & farmlands	Ecology
Impofu dams)		orchards, vegetables)	
Gamtoos	Irrigated intensive citrus, vegetable & dairy farming	7,400 ha of irrigation on 250 farms	Fynbos, thicket and degraded/transformed wetlands.
Nelson Mandela Bay Municipality	Port Elizabeth & Coega Industrial Development Zone	1.15 million people	Outside catchments but downstream water users.
Kou-Kamma Municipality	Kareedouw, Joubertina, Krakeel, Louterwater and Misgund Urban settlements	40 663 people	Kouga, Kromme and Gamtoos Catchments
Kouga Municipality	Humansdorp, St Francis, Cape St Francis, Jeffreys Bay Urban Settlements	98 588 people	Gamtoos and Kromme catchments

Monitoring of rainfall, surface and groundwater levels, soil moisture, and water physicochemical properties, as well as measurements of river channel properties, were performed at selected sites across the catchments to increase conceptual and quantitative understanding of catchment processes. In addition, observations of processes and events have been gathered in stakeholder dialogue interviews, farm visits, and group events. Observations have indicated that there are different geologic layers in the TMG contributing water to river baseflows, shown in the variation of electrical conductivity measured in different boreholes, piezometers, tributary streams, and the main river. Catchment residents have described springs and groundwater seeps which feed wetlands and tributary streams, most of which are perennial, but some of which have seen declines or even cessation of flow in the current drought. This indicates some of their normal flow is from water passing through the aquifer in a matter of a few years. Soil moisture and piezometer data have shown that the black wattle stands transpire more quickly than palmiet and can draw-down floodplain aquifer levels.

3.2 The Social Context

From a social perspective the Baviaanskloof, Kouga and Kromme catchments can be defined as consisting of the Baviaanskloof and the Langkloof (Kouga and Kromme).

3.2.1 The Baviaanskloof

The Western half of the Baviaanskloof, known as the Baviaanskloof Hartland, has been farmed for over 200 years and today there is a community of about 2,500 people living in the area. This is where we have focused engagement in terms of the Baviaanskloof catchment. The majority of economic activities have revolved around agriculture with the past 50 years seeing a steady decline in agricultural production. This economic decline has been largely due to factors related to climate and land use change, resulting in an increase in flooding, drought, overgrazing, erosion and wetland degradation. This has created an atmosphere where rehabilitation innovations could be implemented on a trial basis and the establishment of the Baviaanskloof Hartland Conservancy.

3.2.2 The Langkloof

The Langkloof's social diversity is influenced by the variety of geographical and ecological landscapes within it. Several smaller valleys flowing out of the main river valley cause a variation in agricultural activities and social groups that are associated with specific needs and opportunities. In the past, small family-owned farms were dominant in the valley, but this gradually changed to large commercial fruit companies becoming the major landowners. This greatly affected the social dynamics of the area and the absence of shared cultural heritage resulted in isolation between social groups and a discontinuity in the stewardship of resources. The intricate complexity of this landscape poses challenges which include lack of social cohesion, knowledge exchange, integrated management and institutional fragmentation. However, this increases the capacity for change and diversity of opportunities in the area. Cockburn (2018), identified 7 agricultural subcommunities in the Langkloof through her PhD research (Figure 3:1).

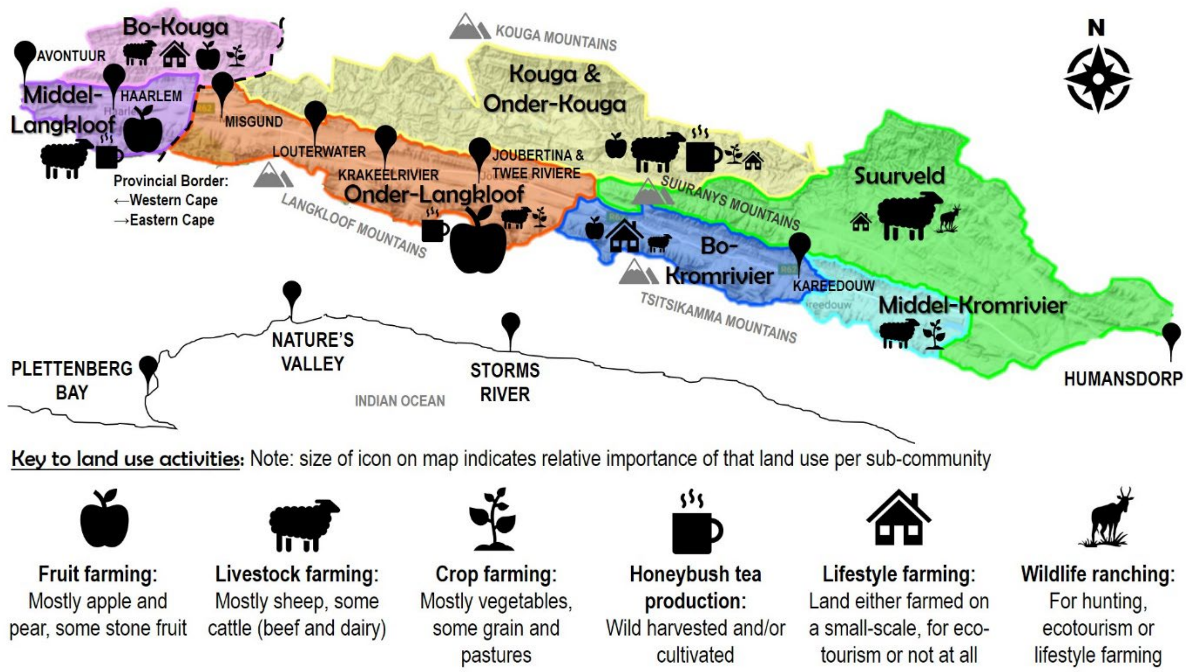


Figure 3-1 Agricultural subcommunities of the Langkloof (Cockburn, 2018).

Each of these subcommunities is characterised by unique social-ecological and agricultural features. Climate, soils, and topography determine what kind of agricultural activities are practiced within each agricultural subcommunity, and inhabitants strongly identify with the characteristic farming activity of their sub-region.

3.3 Previous engagement and research

Living Lands has facilitated various student internships and research projects from local and international universities focused on the Baviaanskloof, Kouga, and Kromme catchment areas. Most of these projects involved some element of stakeholder engagement through interviews, workshops, or smaller discussion groups with local residents, land managers, government agencies, private sector entities, and others. These interactions provide valuable starting points for the more structured engagement in this project through improving a base level understanding of key stakeholder issues and the stakeholder networks in different areas. Studies related to this project was about water and land management such as, farming practices, the clearing of invasive alien plants, riparian rehabilitation and erosion control. Social studies in the area focused on the set-up of water user's associations, social network analyses, perceptions of ecosystem services, inter-organisational trust and spatial planning, social and economic impact studies, social learning pertaining water and land management and enablers and barriers towards collaboration.

Information gathered by these projects provided the basis for planning and initiation for the development of the hydrological model. The themes highlighted through previous work were useful in guiding existing conversations around water management. Certain aspects were explored in further detail such as the management of irrigation, observations of rainfall, hydrological events, changes in weather patterns, river channels, invasive alien vegetation and changes in ground water levels. This information was then employed to develop the conceptual model.

4. STAKEHOLDER PARTICIPATIONS AND SOCIAL LEARNING

To ensure the collective involvement of stakeholders in the modelling process, engagement was centred around three stages, informed by the first three primary stages of the Theory U process, namely;

1. Co-initiating: introducing the project to the stakeholders
2. Co-sensing: feeding in to the catchment hydrology conceptual model
3. Co-strategising: feedback and reflection on future scenarios

Engagements or touch points (Figure 4:1) were planned in order to feed in to the model development at specific intervals which in turn informed the numerical model.

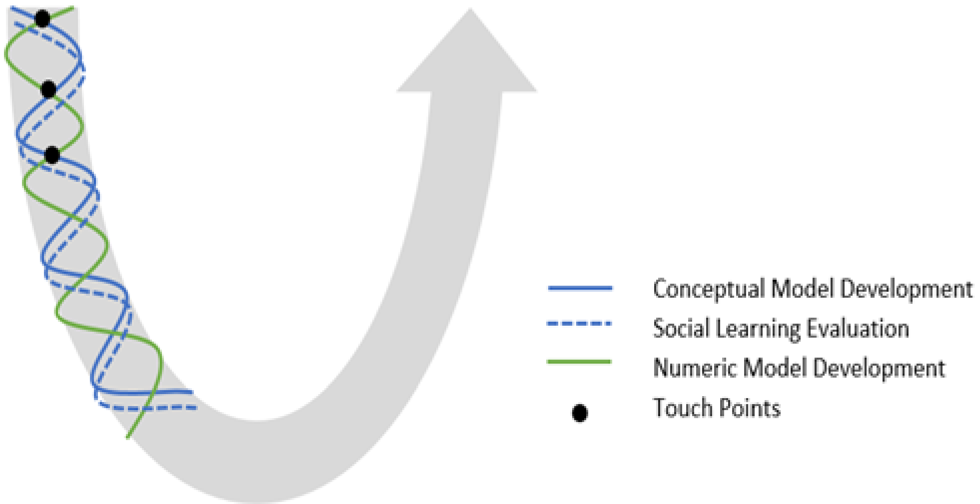


Figure 4-1 The Conceptual (blue)and Numerical (green) model development run in concert and inform each other at strategic intersections (bullet points), while social learning evaluation (blue dashed) follows the progress of the conceptual model.

The stakeholder groups and roles are listed in Table 4:1 below. The stakeholder database was continuously updated throughout the project and levels of participation adapted in accordance with outcomes of stakeholder engagements.

> *To illustrate the interaction between the stakeholder engagement and the hydrological model development in this project, key touch points between these processes are highlighted in text boxes throughout the remainder of the report.*

Table 4:1 Key stakeholder groups, main participants and respective roles

Stakeholders	Role
Living Lands	Project Manager, Stakeholder Engagement Facilitator, public liaison, social learning evaluation
Hydrological modelling team	Co-develop and manage the hydrological model building process
Hydrological & Water Engineers (DWS & Private)	Contribute hydrological and physical data components to the modelling and participate in developing and evaluating the model
Regulated lower catchment intensive commercial agricultural Water Users (i.e. GIB):	Participate and provide data on this agricultural sector perspectives, its water uses and socio-economic relationships
Unregulated upper catchment intensive commercial agricultural Water Users	Participate and provide data on this agricultural sector's perspectives, its water uses and socio-economic relationships
Low commercial agricultural Water Users (livestock, game and tourism land users in all three catchments):	Low commercial agricultural Water Users (livestock, game and tourism land users in all three catchments)
Local Business Sector Water Users (e.g. Woodlands Dairy and Coca Cola)	Downstream water use for industrial activities, play a role in awareness and water stewardship
Municipalities downstream of the Kouga and Churchill Dams	Participate in workshops and meetings. Provide information regarding the management of the supply dams and water treatment systems.
Upstream and downstream public organisations (e.g. Greater Kromme Stewardship Initiative; GIZ; ECPTA)	Promoting water stewardship practices and conservation efforts contributing to water quality and quantity
Other experts and consultants (nursery expert; compost expert, honeybush cultivation expert)	Provide information and assistance with the cultivation of water-wise crops and regenerative agriculture

4.1 Co-Initiating: Introducing the project

Through attentive listening to others we find out what emerges from people that we help bring together.

Dialogue interviews were used in the introduction meetings. The topics which came up in these conversations provided initial information which guided the selection of sampling sites and data collection methods. For example, locating accessible sites with different land cover types and understanding what water level fluctuations are likely at these sites.

Actions:

- Identify relevant stakeholder groups.
- Identify stakeholder contact person for each group.
- Develop invitation letter to the project
- Introduce project and model development process to stakeholder groups with invitation letter and introductory meetings.
- Conduct engagements focused on strengthening relationships and collecting and sharing initial information

Relationships with many of the key catchment management role players in the area already existed via Living Lands. However, there was a need to strengthen these relationships, to further investigate water security issues in the area, to determine and get to know all of the stakeholder groups who should be involved and to create a common intent between researchers, policy makers and practitioners. Introductory and exploratory dialogue interviews as well as an introductory workshop formed part of this stage (Figure 4-2).

During this stage it became evident that different levels of involvement should be considered to fit with the needs and interests of each stakeholder group for example; farmers are interested in the hydrology on farm scale and are less interested in the technical aspects of the model development, while policy makers and practitioners are interested in the technical development of the model and the outputs on catchment scale.

A deliberately short invitation letter was used to introduce the project with the first dialogue interviews. Two broad questions, intended to promote stakeholder brainstorming, were asked in this letter:

- Are there land and water management activities in the Baviaanskloof, Kouga, and Kromme catchments that could increase water supply availability without having negative impacts on the local agricultural economy?
- Could activities have other positive outcomes, such as reducing flood damages, restoring ecosystems, creating additional employment, or others?

The following main stakeholder groups were initially approached:

- The Gamtoos Irrigation Board
- De Hoop Farmers Association
- Emerging farmer of the Koukamma Emergent Farmers Task Team
- Langkloof Farmers Association

These interviews led us to many new connections and other stakeholder groups:

- Water consultants
- Other farmers associations
- Commercial farming company
- Agriculture and irrigation experts
- BEE mentor

The first interviews revealed some of the challenges experienced by stakeholders managing land and water in the BKK catchments. Unpredictable rainfall patterns and cycles of severe floods and droughts make this a harsh environment for farming. It also became clear that there was a lack of communication and planning across management boards and governance structures.

Participants at the introduction workshop were asked to draw their own conceptual models of water flow on their farms or areas around where they live. This provided initial information for the catchment conceptual model. Topics that came up in discussion guided the themes of following events and the development of catchment management scenarios to assess. Introduction of the project team to new stakeholders at the event resulted in the identification of new field sampling sites.

At the introductory workshop several of the topics from the introductory meetings were further explored:

- The path rainwater follows to get to the river channel
- The influence of vegetation in the catchment area and in the river channel
- How the river channel depth and dimensions, and floodplain wetlands, can impact stream flow
- The relation of groundwater to rain water
- Different geological layers and their influence on the flow of groundwater
- Farm-level discussions on the flow and distribution of water
- Alien vegetation impacts on streamflow and groundwater

- Challenges around IAP clearing
- Added-value businesses from alien clearing by-products
- The need for strategic planning towards water management in the entire landscape

Figure 4-2 Introductory Workshops

4.2 Co-sensing: Feeding in to the Catchment Hydrology Conceptual Model

The second stage, co-sensing, refers to activities that helps us connect with and tune in to the contexts that matter.

Actions:

- Continue one-on-one discussions and initiate field data collection
- Bring stakeholder groups together
- Facilitate thematic learning Journeys and workshops
- Create conceptual models
- Sensing workshop
- Report back at existing forums

Initial engagement in the first stage revealed many more layers of information, needs and identified additional interested stakeholders to include. This stage created a space for observation, to listen to the landscape and stakeholders and to delve deeper into relevant topics which emerged through dialogue. Several events were organised in collaboration with other projects and to complement other initiatives in the area (Figure 4-3). Learning Journeys were used as a tool to collectively visit several sites in the landscape and to observe and explore different challenges and opportunities. The events are listed in Table 4:4. Detailed reports of each event are available and can be accessed through Living Lands. Field data was collected in intervals between group events. This added a layer of stakeholder engagement and opportunities for discussions and co-learning during fieldwork visits. Many dialogue interviews were held along with these field trips.

Dialogue interviews were done when scoping and establishing hydrometric monitoring points and at field data collection visits. The information gathered about farming practices, climate observations, river and groundwater responses, river channels, and invasive alien plants informed the conceptual model. Some of this data could also be used to evaluate the numerical model.

General questions that were asked during the dialogue interviews were:

- *General farming practice*
    - What do you farm with?
    - What water sources do you use?
    - What kind of irrigation do you have? How often do you irrigate?
    - How secure or variable is your water supply?
    - Are you part of a larger water supply and monitoring system?
- *Rainfall response*
    - Do you record rainfall?
    - Can you remember specific rainfall events? (floods or droughts) For flood events that stand out to you: How much and for how long did it rain? How long did it take for the water to flow over the ground/dam to overflow/or river to flow?
- *Climate observations*
    - Have you noticed any patterns in the weather? Any changes in rainfall or temperature or frequencies of floods or droughts?
- *River channel observations*
    - Does this river flow all year around?
    - Have you noticed change in the river channel shape or size? Movement of river banks?
- *Groundwater and geology*
    - Do you have a borehole?
    - Has it ever run dry? Does the water level change when it is dry/when it rains? What is the time response to rainfall events?
    - What kind of soils do you have?
- *Invasive alien plants (IAPS)*
    - Do you have IAPS on your farm?
    - Have you tried to clear IAPs?
    - Have you noticed any changes in surface or groundwater levels after clearing?

Dialogue interviews were conducted with a variety of stakeholders. Table 4:2 provides a summary of the main stakeholders interviewed for this project. Conversations with these stakeholders were ongoing through the duration of this project and several follow up visits were made during field trips to gather more information or to refine existing information. This information was used in combination with field data for the development of the conceptual and numerical models. The outcomes of these interviews were broadly categorised in the following themes (Table 4:3).

Table 4:2 Summary of farm visits and dialogue interviews

Farm description	Catchment (Tributary sub-catchment)	Contact type	Key observations
Commercial fruit farm	Kouga (Waboms - south)	office visit	The soil types are highly variable and farming in this area requires sophisticated irrigation management.
Commercial fruit farm	Kouga (Waboms - central)	office visit	Most farmers have backup water supply (such as boreholes) in case of emergency
Commercial fruit farm	Kouga (Krakeel - south)	office visit + farm tour	Groundwater flows along the fault lines from West to East in the Langkloof. The yields of boreholes in the region vary greatly even over small spatial scales.
Subsistence farm	Kouga (Kransfontein)	home visit + farm tour	Soils on the shale band are prone to gullying (more so with the wattles?)
Small scale livestock farm	Kouga (Brandhoek)	home visit + farm tour	Some tributaries of the Kouga never become dry although the mountains greatly reduce rainfall to the north
Small scale livestock farm	Kouga (Kransfontein)	home visit + farm tour	Groundwater flow is controlled by the underground shale layers
Small scale livestock farm	Kromme	home visit + farm tour	There is a great amount of groundwater flowing under the mountains. Tsitsikamma side recharge may feed across to Kouga.
Eco-tourism farm	Kouga (near Braamrivier)	home visit + farm tour	Vegetation plays an important role in mitigating erosion in gullies
Eco-tourism farm & Commercial fruit farm	Kouga (Krakeel)	home visit + farm tour	Mist on the Tsitsikamma mountains is crucial for maintaining water flow in many streams feeding the Krakeel/Waboms River.
N/A (teacher)	Kouga (Waboms River)	home visit	Ravinia is often suffering from a lack of water supply. Lack of sewage treatment facilities can be one of the main water pollution sources
Honeybush farming	Kromme	home visit	Spring which feeds the headwaters of the Kromme River occurs here with a waterfall.
Small scale livestock farm	Kromme	home visit	The tributaries to the Kromme River often flood and exceed banks
Eco-tourism and small scale livestock farm	Kromme (Holgatkloof)	home visit	Clearing of invasive alien species not only affects water levels but can also cause severe erosion downstream
Small scale livestock farm	Kromme	home visit + farm tour	Wattle infestation extends far up into tributary stream valleys and excludes the indigenous palmiet wetlands.
Commercial fruit farm	Kromme	Farm visit	Large scale fruit farms with significant storage dams on tributaries are now also drilling boreholes for water supply due to drought
Dairy Farm	Kromme	Farm visit	Working for Wetlands gabion structure has resulted in significant sedimentation in the riverbed (as it was intended to do). Tributary streams have incised down to bedrock at edge of floodplain.
Small scale livestock farm/ subsistence	Kromme	Farm visit	Small tributary streams feeding the Kromme have perennial flow even during the current drought.
Eco-tourism	Kromme (Wit Els River)	Farm visit	Wit Els River is one of the main tributaries to the Kromme and has a constant flow during droughts. There are some IAPS upstream which are being cleared currently.

Table 4:3 Outcomes of the dialogue interviews by theme

Themes	Summary of main observations of interviewees
Rainfall response	Most interviewees keep track of rainfall per day/month in an informal way (writing in a diary) Catchment responses to rainfall are most often remembered in terms of influences on dam levels and flooding of access bridges and roads. Few interviewees reported observations of river flow, gully flow, and sheet flow responses. Some observations were made of ephemeral streams in valleys after rainfall
Hydrological events	Floods were observed in 2007, 2012 and 2015 The current drought is perceived to be the most severe in the last 80-100 years
Climate observations	The north side of the Langkloof valley (Kouga Mountains) is much drier than the south (Tsitsikamma). In addition to the larger scale rainfall distribution difference, micro-climate variability at smaller scales around the mountains impacts irrigation needs and application. It is perceived that the climate must have changed since 1980s because some areas in the Kouga used to be suitable for pumpkins and wheat, but are now seen as too dry for these crops
River channel observations	Some current channel forms were shaped by large flood events in recent decades (shortcuts in meandering river channel)
Groundwater	Most farms do not use groundwater for irrigation, only as back-up source when it is very dry. Due to the current drought more farms are exploring and drilling boreholes now. More boreholes are being drilled by municipality for domestic supply Some people pump the groundwater into dams to let the minerals settle out before putting into irrigation system Rough average borehole depths: Kouga side – 150 m and Tsitsikamma - 120 m Many properties have groundwater springs in the mountains and there are some artesian wells. Springs described in the Kouga mountains appear to have more variable flow according to accounts than those in the Tsitsikamma mountains.
Soils and erosion	Soils are highly variable across the Langkloof even at small scales - there can be 3-4 soil types in one orchard - which influences irrigation demands. Significant erosion exists on many farms forming gullies along the river channel Soils on the hillslopes and mountains are relatively infertile and support vegetation with low grazing value.
Irrigation and farming practices	Irrigation water in the Langkloof is generally drawn from storage dams. Farm dams are predominantly filled from pipes or furrows coming from tributary streams using weirs, dams, and/or instream-pumping. Most dams are lined and do not receive much water from local seepage. In dry periods some dams are filled from pumped borehole water. Fruit farmers in the Langkloof mostly use microjet and drip irrigation. Movable sprayers are used for pastures. Some farmers favour microjet over drip irrigation for apples because apples do not like “wet feet” and need good drainage. Irrigating months are from November-April
Alien vegetation	Most interviewees were aware of the effect the IAPs have on water levels and some reported observations of changes in streamflow on their properties after clearing. Working for Water teams have been clearing on many farms in the area, but the invasion of alien species are still extensive. Some areas cleared have grown back due to challenges in maintenance. Biological control of IAPs has been tried in the area but effectiveness is not yet clear.
Water associations or shared systems	Local water associations exist in smaller farming communities to manage shared infrastructure along tributary streams of the Kouga River. Most of the major tributaries have larger shared storage dams. There are relatively frequent water supply cut-offs and shortages in residential areas. Prior to the recent drought period these were seen to be due to challenges related to infrastructure and storage rather than the quantity of water available in the catchment area. Boundaries of the Kou-Kamma Municipality extend over significantly different rainfall zones - the Tsitsikamma, Kouga and Suuranys Mountains - which require different strategies and pose different challenges in management.

Stakeholder engagement before and during this project led to the establishment of three learning platforms, formed by stakeholder groups with facilitation from Living Lands. These platforms complemented this stage, since they provided additional enabling environments for knowledge exchange and learning. These platforms are: the Algoa Water Fund (established 2018), the Honeybush Cultivation Working Group (established 2018) and the Baviaanskloof Hartland Conservancy (established 2014). In addition two initial Catchment Management Forum (CMF) meetings, organized by DWS were held during the project period. The project team assisted in inviting stakeholders and in attending CMF meetings. This emerging platform is still taking shape: the appropriate spatial-scale and meeting schedule is being explored, including the potential for CMFs to operate through existing platform meetings.

Participation in meetings of related learning platforms, such as the Algoa Water Fund and the Baviaanskloof Hartland Conservancy, greatly contributed to the development of the model. These meetings created opportunities to exchange and discuss information about hydrology and catchment management, identify additional key stakeholders and additional datasets, share and discuss modelling progress and outputs.

4.2.1 The Algoa Water Fund

The Algoa Water Fund is a platform for private and public entities to collectively manage and coordinate activities which involve investment in ecological infrastructure for long-term water security in the Algoa Water Supply System. It consists of a Steering Committee, which guides strategies, resource allocation, goals and funding streams, and a working group, which is responsible for the implementation and coordination of activities. The purpose of this platform is to create the institution for coordinated rehabilitation projects which ensure long-term water security for upstream and downstream communities. This platform also serves to effectively share information and scientific research between stakeholders and across boundaries.

4.2.2 The Honeybush Cultivation Working Group

The Honeybush Cultivation Working Group is a learning platform that joins experts, researchers and practitioners with the aim to bridge the knowing-doing gap in the Honeybush industry. Honeybush is an indigenous plant species native to the Langkloof which can be used for the production of tea. Honeybush tea can be seen as an alternative, sustainable and water-wise crop with the potential to support the livelihoods of local communities and emerging farmers in the Langkloof.

4.2.3 The Baviaanskloof Hartland Conservancy

The Baviaanskloof Hartland Conservancy was established by the Department of Economic Development and Environmental Affairs (DEDEA) and the private landowners and residents of the Baviaanskloof. This platform provides an opportunity for key stakeholders in the area to be involved in the management of natural resources on catchment scale. This entity greatly contributed to knowledge exchange between landowners and the modellers.

Figure 4-3 Co-sensing engagements

4.3 Co-Strategising: Feedback and Reflection

Co-strategising enables us to explore the future by doing or piloting; e.g. enacting prototypes of the future by linking intelligences, and by iterating through the guidance of fast-cycle feedback from all stakeholders in real time

Actions:

- Report back meetings at existing forums
- Sense-making and scenarios workshop
- Hand-over to continuing local learning platforms (Algoa Water Fund, CMF)

A stakeholder workshop was held to consolidate the information gathered throughout the engagement process into a set of catchment management scenarios which could be discussed and modelled. These were translated into potential future land cover maps for the catchments. A presentation of these scenarios and maps at the Algoa Water Fund meeting allowed for further refinement.

Planning and strategising together defined this phase. The learning platforms which emerged during the previous stage assisted with strategic planning. Feedback events were held with farmers in the Baviaanskloof and Langkloof to share the results of the data collection and their implications for a conceptual model. Feedback hand-outs were produced and shared for those who could not attend. The DWS official tasked with initiating CMFs in the region was invited to the Baviaanskloof Conservancy meeting to introduce the concept and to test interest for establishing a CMF in the Baviaanskloof.

More specific scenarios for future land and water management options were co-developed during this stage. Dialogue interviews and a consolidating workshop were employed to come up with a set of catchment management and land cover scenarios to consider. Based on these stakeholder engagement activities, a preliminary set of land cover and management scenarios were developed around the emergent themes of IAP management, agricultural expansion, and ecological restoration, as further described in Section 7 below.

Table 4:4 List of engagements the project team has convened, facilitated and participated in from 2016-2019 to better understand the complexities of the BKK Catchments and build relationships with the various role players.

Engagement	Intention	Participants	Outputs/Outcomes
Introductory and exploratory dialogue interviews (supported by an invitation letter)	Engage the interviewee in a reflective and generative conversation exploring water security related issues.	The Gamtoos Irrigation Board De Hoop Farmers Association Emergent Farmers Task Team Langkloof Joubertina Farmers Association Individual small and large scale farmers	Build rapport and trust with key stakeholders, understanding the context and challenges in the landscape and identified additional stakeholder groups.
Introductory Workshop	Expand the collective understanding of local hydrology, introduce the concepts of modelling, and discuss the planned process for the project with key stakeholders	Large commercial farmer Small commercial farmer Misgund Kleinboere Trust KouKamma Municipality Consultant for Tulpieskraal University students Aurecon consultant agency SAEON Living Lands	Arising themes and points of discussion: • Different geological layers and its influence on the flow of groundwater • The relation of groundwater to rain water • The path rainwater follows to get to the river channel • The influence of vegetation in the catchment area and in the river channel • How the river channel height impact stream flow • Farm-level discussions on the flow and distribution of water • Added-value businesses from alien clearing by-products • Alien clearing as one of the possible scenarios that can be used to develop the model • The need for strategic planning towards water management in the entire landscape

Engagement	Intention	Participants	Outputs/Outcomes
Alien Clearing Learning Journey	Explore and learn together on the landscape, through visiting sites along the river which are [1]infested by alien vegetation, that [2]have been cleared and are still [3]indigenous. Alien biomass value-added business also formed a key focus.	Business sector Small commercial farmers University students SanParks Grounded Teacher SAEON Living Lands Department of Water and Sanitation Gamtoos Irrigation Board Working for Water Koukamma Municipality Living Lands	Reflections from participants: • I realised I am not alone in this battle against alien vegetation • I learned about the opportunities that exist for alien wood use • I am inspired • I feel hopeful • It is great to hear other people's experiences of the same challenge
Rehabilitation Learning Journey	Explore rehabilitation methods after alien clearing, find a more holistic approach where the biomass of alien clearing can directly be used for the rehabilitation of the soil on the same site.	Small commercial farmers Business Sector Grounded University students SAEON Gamtoos Irrigation Board Town resident Conservation Outcomes Living Lands	Greater understanding of the farm scale and landscape scale effects of alien vegetation, the challenges with clearing and the follow up and rehabilitation techniques needed to prevent regrowth and erosion.
Feedback Braai	Report the initial results of data collected for the model and to test some of the assumptions made with data development	Small Commercial farmers Large Commercial farmers Living Lands Kou-kamma Municipality Grounded University students Garden Route Biosphere Reserve SAEON Tourism/ Conservation	Discussed: • What do we expect from irrigation in future? • Black Wattle: effects on microclimate? • Pine tree invasion in the mountains • Farm adjustments in time of drought (e.g. selling or switching livestock)

Engagement	Intention	Participants	Outputs/Outcomes
Sense-making Workshop	Explore the current knowledge gathered on water flows in the Kouga and Kromme catchments and capture visions and ideas with regards to water security.	Conservation Outcomes Large Commercial farmers Small Commercial farmers Emergent Farmers University students Langkloof Honeybush Association SAEON Living Lands	Several scenarios were discussed. Modellers demonstrated some of the ways data are obtained in the landscape and how it will be fed into the model.
Baviaanskloof Conservancy Research meeting	Report the initial results of data collected for the model and to test some of the assumptions made with data development	Small commercial farmers Tourism Committee University students Sewefontein Trust Tchnuganoo Community Farm SAEON Rehabilitation Implementer Department of Water and Sanitation Living Lands	Outcomes: •Consensus on assumptions •A list of further research questions to explore •Water management related issues, like those to be discussed in CMFs, could potentially be discussed through existing organizational structures in the Baviaanskloof such as the Conservancy.
Water Fund working group meetings	Gather data on a catchment scale and strategically plan priority areas where initiatives should be focused.	Woodlands Dairy Gamtoos Irrigation Board Biodiversity – Department of Environmental Affairs (DEDEAT) Department of Environmental Affairs: National Resource Management (NRM) SAEON Nelson Mandela Bay Municipality: Water Management and Bulk Supply Department of Water and Sanitation:	Reported the initial results of data collected for the model and informed priority areas for clearing and rehabilitation.

Engagement	Intention	Participants	Outputs/Outcomes
		Catchment Management Agency Eastern Cape Agriculture Gamtoos Farmers’ Association Tsala Pty Ltd Conservation Outcomes - Greater Kromme Stewardship Group	
Honeybush Learning Journey	Brought together farmers and harvesters from the Langkloof with the aim of gaining inspiration and ideas from different Honeybush regions and different sectors. The intention was to discuss how to collaborate, to understand the lessons learnt from other industries and start to move forward collectively towards a sustainable honeybush industry in the Langkloof.	Grounded Small Commercial farmers Emergent Farmers Honeybush Harvesters Nursery Specialist Living Lands	Participant Reflections: • There is a need for regular meetings for the group to start working together and discuss matters as they arise • There is a need for a better guideline from the Agricultural Research Council on how to start cultivation. • Regular visits from the on-the-ground team to provide support would be welcomed. • Living Lands and Grounded need to continue making links between farmers, harvesters, processors and market (build the collective), with regular feedback on progress.
Honeybush Association meetings	Promote knowledge exchange, to create inspiration and to share the latest research	Small commercial farmers Honeybush cultivation consultant / expert Living Lands Honeybush harvesters Emergent farmers	Report the initial results of data collected for the model and test assumptions with regard to landuse changes centred around Honeybush harvesting and cultivation.

Engagement	Intention	Participants	Outputs/Outcomes
Water Fund Vision and Mission workshop	For all the Water Fund partners to come together as a group and establish a clear vision and mission for the Algoa Water Fund.	Woodlands Dairy: Sustainability Department Sarah Baartman West Fire Protection Association Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) Department of Water and Sanitation Nelson Mandela University: Business School Department of Economic Development Environmental Affairs and Tourism (DEDEAT) Department of Environmental Affairs: National Resource Management (NRM) Department of Water and Sanitation: Strategic Catchment Management Nelson Mandela Bay Municipality: Water Management and Bulk Supply Gamtoos Irrigation Board (GIB) Conservation Outcomes	Vision: Investment in ecological infrastructure for water security in the Algoa catchments through public-private partnerships and stakeholder collaboration Mission: • Coordinated and aligned governance across stakeholder groups • Knowledge creation and scientific research • Finance for ecological infrastructure and improved livelihoods • Implementation of landscape rehabilitation and conservation agriculture and risk reduction projects • Communication and information sharing across stakeholders and boundaries.

4.4 Social learning evaluation and effective knowledge exchange

Social learning is important for the sustained impact of interventions. Social learning was measured through dialogue interviews with stakeholders before and after events, as well as during learning journeys and meetings, in order to evaluate whether these events had an influence on their perspective or relationships with others. Two layers of learning were used to define social learning in this project:

- Social Layer 1: a change in understanding, which happens within an individual participating in the facilitated activities (learning journeys, etc.);
- Social Layer 2: a change in understanding, which happens among the broader social networks beyond the individuals directly involved in the facilitated activities, i.e. their colleagues, neighbours, friends, etc.

Focused reflection sessions with an individual and/or group served to be useful to investigate these two layers of learning. Sometimes tools such as questionnaires and photos were used in interviews and reflections sessions. This was done with the help of an MSc student, Daniek Bosch, from Radboud University in the Netherlands.

To foster a generative dialogue, the conversations were allowed to flow into different topics. The evaluation of social learning is more about the process than the specific questions asked. It is about allowing oneself to go on a journey with another person to explore his/her worldview which brings both to new insights or ideas. Examples of questions asked are listed below:

Text Box 1: Questions asked in Dialogue Interviews to evaluate social learning

- What are your perceptions of the participatory modelling process?
- How do you perceive the current water related challenges?
- What are your aspirations for future water management in the landscape? To what extent do you feel a hydrological model can be helpful?
- To what extent and under what conditions are you willing to use the model in the future?
- To what extent has this participatory modelling process increased your awareness about hydrology in the Langkloof?
- To what extent has participatory modelling facilitated dialogue between you and other stakeholders?
- To what extent has participatory modelling increased the capacity for collaborations within the stakeholder group?
- To what extent has participatory modelling increased mutual understanding between stakeholders?
- To what extent has participatory modelling increased trust and respect among the stakeholders?

Many observations were made from evaluation of the questions above. These observations were categorised into the following: awareness of hydrology, dialogue between stakeholders, capacity for collaboration, mutual understanding, trust and respect among stakeholders, effective communication and observations from the questionnaires.

4.4.1 Awareness of hydrology:
Many of the interviewed stakeholders had difficulty to understand the term “hydrology”. However, when the term was described, stakeholders’ awareness of hydrology could be attributed to two things: 1) the current drought made people aware of the scarcity of water; 2) participation at some of the events made people more aware of how water flows through a landscape. Interviews that were done

with farmers revealed that many see “hydrology” as the system of irrigation pipes on their land. When asked to draw the flow of water on their farm, farmers would mostly draw the pipe system from the source (fountain/spring) to where his/her storage dam occurs and how this connects with the irrigation of the cultivated fields/orchards. Awareness is also associated with farm scale and not much evidence could be found that the perspective of hydrology shifted to a broader scale of the catchment.

4.4.2 Dialogue between stakeholders:
Although a variety of stakeholders were connected at the group events, participation was inconsistent, and people did not a have a chance to really get to know each other. Some evidence could be found of initial dialogue just after an event, but this contact was eventually lost as some people did not attend the next events. This was one of the challenges in this project and will be described in more detail in the team learnings section. This is where the learning platforms (the Water Fund, Honeybush Working Group and Baviaanskloof Conservancy) would greatly provide support in future with maintaining relationships and connection between the same set of stakeholders with similar interest.

4.4.3 Capacity for collaboration:
During the evaluation, some stakeholders expressed the intention to collaborate. Because the learning process is still in such an early stage, these collaborations did not realise without careful facilitation from Living Lands, and redundancy within these collaborations is yet to be built. For instance, a rehabilitation project was started on one of the farms between two participants and Living Lands after the first learning journey. This project, however, was very short and without long-term commitment and funding, this project fell apart after a year. The Honeybush Working Group and the Water Fund could greatly assist with building redundancy in projects in terms of commitment and funding in the future.

4.4.4 Mutual understanding:
Understanding amongst stakeholders takes time. With little opportunity to get to know each other in a short period of time, evidence of mutual understanding was sparse. It was found that some stakeholders are interested in each other’s views and wants to learn more. One of the stakeholders mentioned that she was surprised by the insight of one of the other participants and would like to explore more of this person’s perspective. This conversation was picked up by Living Lands and resulted in a rehabilitation project where these two participants collaborated.

4.4.5 Trust and respect among stakeholders:
South Africa has a long history of mistrust between government institutions and civilians, racism and friction between different cultural groups. The Baviaanskloof, Kouga and Kromme catchments are no exception. This also became evident in the dialogue interviews with the stakeholders. A lot of frustration was expressed towards government institutions and mistrust between ethnic groups were evident. At group events, however, respect was shown amongst the participants and frustrations were kept in check for the sake of the conversation. This can be an indication of trust in Living Lands, as the facilitator, that provides a space where people feel comfortable and show respect towards others, in spite of their history and differences. This is a conducive space for participants to get to know each other and build trust across cultural and institutional boundaries, as long as a mediator (such as Living Lands) is present. Although people started to listen to each other at these events, no evidence of an increase in trust could yet be identified.

4.4.6 Effective communication:
From the start of the project, many challenges occurred related to the communication between different groups of stakeholders. This was a two-fold problem: scientific terminology vs language in practice and Afrikaans/Xhosa vs English. Effective communication is a crucial element for social learning. Specific efforts were made to overcome these challenges by translating and interpreting presentations and/or conversations. At one of the last group events of this project, an assessment was done to evaluate the effectiveness of the team’s scientific communication during a research feedback event in the Baviaanskloof. The results showed the following:

- People indicated to understand what the research was about
- People felt like they can contribute to future research
- The language which is used by researchers is generally understood

4.4.7 Observations from the questionnaires

At Learning Journeys and workshops, questions were asked in the form of a questionnaire. Statements were made with tick boxes on a Likert scale to rate the statement from one to five, where one indicates strong disagreement and five strong agreement. Examples of these statements at one of the Learning Journeys are:

1. I learned new things in today's workshop.
2. I would attend again next time.
3. I think that a hydrological model is necessary for the catchment area.
4. I am interested in using the model in the future.
5. I trust the project team with the development of the model.

The following results were found in this questionnaire:

Evaluation of the first statement gave some indication of collective learning during the Learning Journey. All the respondents either agreed or strongly agreed and examples of the comments were: *"I got a better understanding of the alien invasion problem"; "The biofuel stuff was mind blowing"; "The story about the gasifier was inspiring"; "Very interesting to hear different perspectives".* This was also the first indication of cognitive learning which means that people gained new knowledge during the event.

Due to conducive learnings mentioned at the first statement, the second statement: "I would attend again next time" also stimulated positive reaction. Many people said they would like to come back in order to learn more: *"I need to learn more about management options that influences the availability of water".*

The third statement, "I think that a hydrological model is necessary for the catchment area." produced mixed reactions. Firstly, it is important to realise that many people that attended the workshops/learning journeys such as farmers, teachers and government officials are not familiar with the concept of hydrological modelling. Although many attempts were made to explain this concept (at the introduction workshop and at the beginning of each event), there was no consistency in the people who attended these events and this idea remained foreign to most. With deeper investigation around the concept of water flow and the management thereof, it became clear that the knowledge about hydrology definitely exists, although not associated with the term "hydrology". Many people commented on the effect of alien trees on the hydrology: *"We had a lot of [black] wattle on the farm, so we sprayed it. You could see: the dam levels immediately went up. Unfortunately, we didn't follow it up, so the dams are empty again. It really makes a difference."* To answer the question about the value of the hydrological model, the responds were mixed: *"Although a model is only a partial representation of the complex real world and is not valuable as a tool with which to facilitate co-learning."; "How applicable is it for land owners?"; "Only in understanding catchment processes."* The scale in which the model is useful, came up often. This model is indeed on catchment level and it is not valuable for water management on farm scale. This is also further discussed in the recommendations.

Evaluation of the next statement: "I am interested in using the model in the future" confirmed the findings at the previous statement. Many people struggled to see how this model is applicable to them and whether it is useful on the scale in which they operate. One of the comments was, for example, "*It's good information to know, but for someone who isn't a hydrologist, how useful is it?*"

Basic levels of trust were present at the events where all respondents agreed with the last statement: "I trust the project team with the development of the model". The accompanying comments indicated that this trust is more in general than specifically related to the model-building itself. The nature of this trust is related to the development of relationships and the approach used by Living Lands. Examples of this can be seen in: *"I'm very impressed by Living Lands' people and approach"; "Impressed with your social facilitation skills & enthusiasm. Well done. Now to maintain momentum"; "Living Lands is quite competent"*.

4.4.8 Summary of conclusions on social learning in this project

In this study, it was found that learning occurred on three levels: cognitive (knowledge-based), affective (emotion-based) and behavioural (action-based). Cognitive learning pertains the exchange of knowledge and the acquisition of new insights. Some people remarked that they gained new knowledge about methods for clearing invasive alien plants, for example. Affective-based learning was evident in the emotional change of the interviewees which portrayed feelings of "being no longer alone" and that others "inspired" them. A short-term collaboration which was initiated by participants after one of the group events indicated the presence of behavioural learning.

The evaluations showed that the pre-requisites for social learning are present, however, momentum should be maintained to increase understanding amongst stakeholders and promote trust in relationships. Social learning processes will be continued through the Algoa Water Fund, the Honeybush Cultivation Working Group and the Baviaanskloof Hartland Conservancy. The establishment of these platforms serve as proof of the development of relationships and trust between Living Lands and the stakeholders. These learning platforms emerged from continuous and diligent facilitation by Living Lands and showed commitment from various groups of stakeholders in the BKK towards improving land and water management. Many challenges were identified during the evaluation process as well as lessons learned, with regards to the matching of scales and the barriers in communication. These were internal team learnings which will be further discussed in Section 10.

5. CATCHMENT HYDROLOGY CONCEPTUAL MODEL

5.1 Conceptual models of catchment processes

A conceptual model of catchment hydrology describes what is known, or assumed, about how water flows through the landscape. Processes, flows, and connections are characterized in the form of diagrams, flow charts, and text. In this project, the intention was to document, develop, and explore the understanding of these catchments' hydrological processes at various spatial scales in order understand likely impacts of various activities and changes. For example, how might additional alien vegetation or groundwater pumping in different locations impact streamflow and groundwater differently. An emphasis was placed on understanding the surface-water groundwater relationships in the more intensively used main-valley floodplain areas of the catchments.

It should be noted that in this usage of the term "conceptual model", we are *not* referring to a type of numerical model in which the algorithms are on the more "conceptual" or empirical side of the spectrum (versus being closer to quantitatively described physics). In our case, prevailing "conceptual models" of catchment processes, also sometimes called "perceptual models", are used to build numerical models by translation into equations and algorithms. The conceptual modelling phase of a modelling exercise lends itself more easily to stakeholder participation than explicitly working with algorithms of numerical models.

To describe flows and processes (infiltration, evapotranspiration, surface flow, etc.) over large areas with diverse topography and land cover, catchment areas can be broken up into sub-units that have distinctive hydrologic behaviours. These are often spatially delineated, i.e. determined by land cover and topography, but can also include vertical units, such as distinctive soil and rock layers. Topographic or geomorphological units, such as plateaus or floodplains, are typically associated with particular vegetation types, soil profiles, micro-climate characteristics, human land uses and other properties that dictate hydrologic processes and responses to rainfall (ARC, 2001; Savenije, 2010). Following this logic, a modelling structure that conceptualizes hydrologic processes at the level of topographically defined units was used to describe the BKK catchments. Topographic units were then subdivided by major land cover types, and types of particular interest for management, to create a set of hydrologic response units (HRUs).

Catchment conceptual models also include descriptions of flow through the river channel network and the connections between the channel network and the rest of the landscape and subsurface.

Geomorphological properties of the channel network in relation to the surrounding riparian area, floodplain, and greater contributing catchment give insights to these processes. Again, to assist in descriptions over large spatial scales, the channel network can be broken up into units likely to have similar processes using topographical analyses.

Conceptual descriptions of hydrological processes are based on observations, ideally in different locations under a variety of conditions, locally or at comparable sites in literature. For example, observations of the presence or absence of surface runoff in different storm intensities in areas of different land cover. Conceptual models of the BKK catchments were built using a combination of literature review, landscape and channel analyses in GIS, discussions with local residents about their observations, analyses of existing hydrometric data and additional hydrometric, chemical, and geomorphological data gathered in this study. Diagnostic analyses were done using existing hydrometric time-series and additional field data gathered in this study to gain insight on processes and connectivity.

Table 5:1 Data used for model development for the Baviaanskloof, Kouga, and Kromme catchments

Category	Type	Data sources	Processing/Preparation
rainfall	time-series (daily)	gauge time-series (SAWS, ARC, DWS, ECPTA, SAEON); gauge and remote sensing derived spatial distribution surfaces (Lynch, 2003, Schulze et al., 2007, CHIRPS)	Rain and temperature gauge time-series obtained & uniformly formatted; Lynch 2003 and CHIRPS spatial rainfall surfaces obtained & compared: Lynch dataset found to be more representative of local spatial distribution PET estimated from temperature using Hargreaves & Samani (1984) Lynch and Schulze et al., 2007 surfaces used to estimate spatially integrated climate parameters for catchment areas and subunits by applying season varying scaling factors to station time-series
potential evapotranspiration (PET) - can be derived from temperature with or without wind & humidity	time-series (daily)		
land cover & management maps	spatial	maps of cover (National Land Cover Dataset, local mapping, Working for Water), biomes (SANBI), and management (DWS) – based on remote sensing and ground-truthing	Overlaid various cover maps for comparison; Selection of cover class / modelling land units set to be used for modelling & class mapping method through combining sources using NLCD and topographic units as a base
vegetation properties of land cover types (canopy interception, ET rate & rooting depth, surface roughness)	parameter/ spatial	estimates in literature (e.g. ACRU cover class property database) & previous modelling (e.g. Pitman/WRSM parameters); derivation from remote sensing	Previous parameter sets used in local and regional modelling obtained Parameter values re-scaled using vegetation specific literature where available
soil type maps	spatial	land type (ARC) maps with descriptions of associated soils by terrain unit; topography (SU-DEM) and geology maps (CGS) to refine	ARC, SU-DEM, and CGS data obtained; Catchment areas discretized into topographical units associated with different soils types using SU-DEM; Field soil observations made at a variety of topographic locations to verify
soil type properties (water retention and conductivity)	parameter/ spatial	existing literature from field sampling and previous modelling study parameter values (ACRU, WRSM-Pitman)	ACRU and ARC soil type property data-bases obtained; Prior WRSM-Pitman modelling calibrated soil storage parameters compiled; Prior study soil sampling data obtained; Soil samples collected at field sites and analysed for texture
geologic maps	spatial	maps available from Council for Geosciences	Map scans obtained and traced in ArcGIS to create shapefiles of bedrock geology
aquifer properties (storage and transmissivity)	parameter/ spatial	existing estimates in literature from field sampling and modelling; streamflow, groundwater, and climate time-series to infer properties	Prior modelling groundwater parameters and National Groundwater Resources Assessment II (GRA II) estimates obtained and compiled; Existing streamflow, groundwater, and climate time-series obtained; Additional surface and groundwater monitoring points added to capture different scales and geomorphological positions

Category	Type	Data sources	Processing/Preparation
catchment topography (digital elevation map – DEM)	spatial	high resolution DEM available (SU-DEM, 5 m)	Data obtained and used to delineate topographic units and sub catchments
river & floodplain topography (surveyed cross sections, very high-resolution DEM)	spatial	National river channel map datasets (mostly low resolution); previously sampled cross sections available for Baviaanskloof and upper Kromme	SU-DEM (5 m resolution) obtained & assessed – found to be adequate for floodplain topography, but not channel planform or channel forms in the floodplain; Topographic surveying of channel forms in representative locations in all 3 catchments completed; Field sampling of channel properties bed material in all 3 catchments
irrigated areas map	spatial	maps available from DWS (Kouga, Kromme) and Living Lands / Four Returns (Baviaanskloof) based on remote sensing & groundtruthing	Obtained existing maps (DWS, LL, NLCD); Visited farms in all 3 catchment areas and discussed practices; Selection of irrigation crop and method classes to be used for modelling
irrigation rates	time-series	estimates available from DWS using SAPWAT, AET from remote sensing (Stellenbosch)	Obtained data from DWS process Discussions of irrigation practices with farmers in all 3 catchment areas
groundwater pumping locations & rates	spatial + time-series	Pumping rates from municipal supply boreholes; private farm pumping records; estimate based on accounts of practices	Obtained estimated municipal pumping rates from design engineers; Preliminary discussions and farm visits revealed an increase in borehole development due to drought; borehole mapping in the National Groundwater Database in incomplete and in places incorrect; Large commercial farms keep pumping records while others often do not
farm dam locations & sizes & uses	spatial	maps available from NLCD and DWS based on remote sensing & ground-truthing	Obtained DWS dam maps and volume estimate data; Obtained various area-volume relationships derived from WARMS registration database and other literature; Discussed farm dam water sources with farmers in various locations
streamflow	time-series (daily)	streamflow gauges (SAEON, DWS) and dam water levels (DWS)	Obtained existing data; Installed additional water level monitoring equipment at 4 locations in the Kromme River catchment
groundwater level	time-series	instrumented boreholes and piezometers in Baviaans (SAEON) and upper Kromme (Rhodes University – WRC project 2548), DWS National Groundwater Database – 2 monitored boreholes in the Kromme	Obtained existing data; Obtained borehole depth, strike, and average water level estimates from farmers during visits where relevant and where possible measured groundwater levels in open boreholes; Installed additional 15 shallow groundwater monitoring piezometers at various locations and vegetation types in the Kromme floodplain
soil moisture	time-series	(remote sensing sources wrong spatial scale for topography)	Installed 3 soil moisture probes in the Kromme catchment in different vegetation types

5.2 Approach to developing conceptual models of the BKK catchments

Development of catchment hydrologic models entailed bringing together a variety of information about climate, topography, soil, vegetation, aquifers and groundwater levels, river channels and streamflow, irrigation, and water management practices. Information and data were obtained by:

- Accessing and reviewing existing datasets from monitoring and research institutions and individuals (farm data collection, etc.)
- Reviewing previous research on these and similar catchments
- Dialogue interviews, workshops, and other stakeholder interactions (described in Section 4) during which catchment residents shared process and event observations (e.g. flood magnitudes, presence of perennial springs, etc.) and information about land and water management.
- Additional field data collection to target specific processes and interactions of interest, which included collection of hydrometric data (rainfall, temperature, streamflow, groundwater levels), water physicochemistry (temperature, pH, electrical conductivity, natural isotope concentrations), river channel and floodplain topography and hydraulic properties.
- Diagnostic analyses of spatial and time-series data and other observations to gain specific insights about catchment processes and properties.

Data collection, both accessing existing institutional data and taking field measurements, supported the stakeholder engagement process. In requesting data, relevant institutions were introduced to the project in advance of being invited to workshops and other engagements. To find and access field data collection sites, catchment residents were consulted and invited to participate. Field monitoring visits provided opportunities for information exchange with residents and regular research team presence on the landscape built trust and interest. Care was taken to coordinate and share data with other previous and ongoing initiatives to prevent repetition and avoid stakeholder fatigue.

A detailed review of available input data was done which included government and research institution databases (SAWS, ARC, DWS, DEA-NRM), available remote sensing data, and data from other previous and ongoing research in these catchments. This study was well timed to collaborate with another WRC supported project K5/2548 which focused on understanding the flow pathways to and through a palmiet wetland area in the upper Kromme catchment (Tanner and Smith, 2018), and data from instrumented sites was shared across projects. A summary of data used in this project given in (Table 5:1)

The data was analysed to:

- Delineate the catchments into units to assist in flow pathway description: sub-catchments, river networks and river type classes, hydrologic response units, and aquifer zones.
- Describe processes within and between these units (i.e. the degree of connectivity between surface water and groundwater in different locations, relative evapotranspiration rates between different land covers in a topographic position).

The approaches to these steps are described in brief below and with more detailed methods and specific results provided in Appendices A-G.

5.2.1 Delineation of conceptual model units

Analyses of Digital Elevation Model (DEM) data, aerial photography, and land cover, use, and vegetation type map datasets done with geographical information systems (GIS) software were used to break up the landscape of the three catchments into HRUs. The HRUs were defined by topographic units (plateaus, cliffs, hillslopes, toe-slopes, alluvial fans, wide valley floodplain, and narrow valley floor) and land cover type combinations. Land cover types were selected to reflect dominant cover types as well as cover types of interest for stakeholders (e.g. cultivated honeybush), mapped as described in Appendix B. Catchment areas were also divided into sub-catchments of major tributaries and groups of minor tributaries with notably different compositions of topography and cover, dominant aspect, and rainfall distribution. These sub catchments define the possible surface and shallow subsurface flow linkages between HRUs and with the channel network. Methods applied to delineate channels sub catchments, and topographic units and to combine topographic with land cover types to produce HRUs are described in Appendix A. To gain insight about likely subsurface storages and flow pathways, geology maps were also overlain on the topography data to infer potential aquifer recharge and outflow areas and connectivity.

The river channel network was classified into reaches likely to have similar channel hydraulic properties (slope, cross sectional area, roughness). This was done using a combination topographic and catchment setting descriptions, such as valley width and stream power indices, and field data collection of channel properties at sites in different settings as described in Appendix C. This was the MSc research of P. Sekese, in affiliation with this project.

5.2.2 Describing processes within and between conceptual units

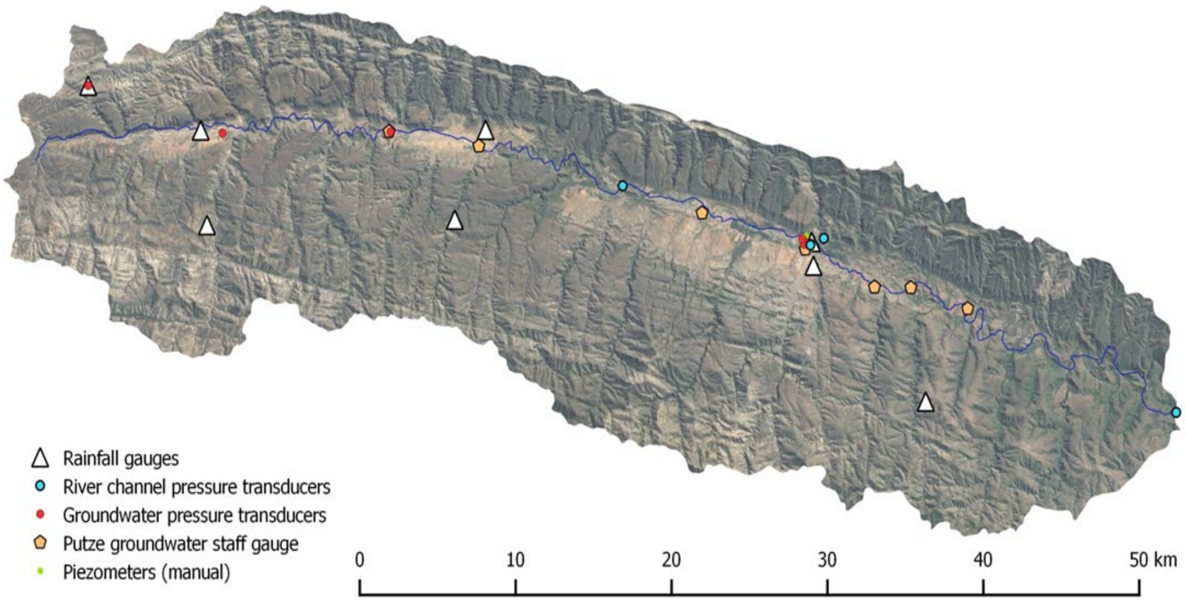
5.2.2.1 Field data collection

In addition to the existing hydrometric data collected by other institutions (Table 5:1), targeted collection of hydrometric and hydrochemistry data was done in the Baviaanskloof and Kromme catchments through the support of the South Africa Environmental Observation Network (SAEON). Sampling sites and analyses were selected to give insights on surface-groundwater connectivity in the floodplain areas and the impacts of invasive alien vegetation (F. Jumbi PhD in progress). Sites were also selected for spatial distribution: along the longitudinal profile of the main valley and on the northern and southern sides. The majority of the field sites were located on private properties, established through visits and discussions with property owners. A summary of the monitoring network is given in Table 5:2 and sites are shown in Figures 5:1 and 5:2.

More detailed methods for the field data collection and sample processing are given in Appendix C.

Table 5:2 Hydrometric and hydrochemistry field data collection network in the Baviaanskloof and Kromme catchments (instrumentation provided by SAEON)

Data	Instrument type	Measurement frequency	Sites by catchment	
			Kromme	Baviaanskloof
Rainfall	tipping bucket gauge	hourly	4	8
Temperature	temperature probe			
Groundwater level	Piezometer with a pressure transducer	hourly	2	3
	Piezometer manually measured	2-3 month	18	15
	Borehole with a pressure transducer	hourly	2	3
	Borehole or open pit manually measured (dip meter or staff gauge)	2-3 month	3	8
River surface water level (to estimate streamflow)	Pressure transducer in channel	hourly	4	4
Soil moisture	soil moisture probe (60 cm long, 6 sensors)	hourly	3	
Water physico-chemical properties (Temperature, EC, pH, natural stable isotope concentrations D&O)	YSI multi-probe and lab analyses of samples	2-3 month	all river and groundwater monitoring sites, plus additional springs and seeps, and 2 rainfall gauges	



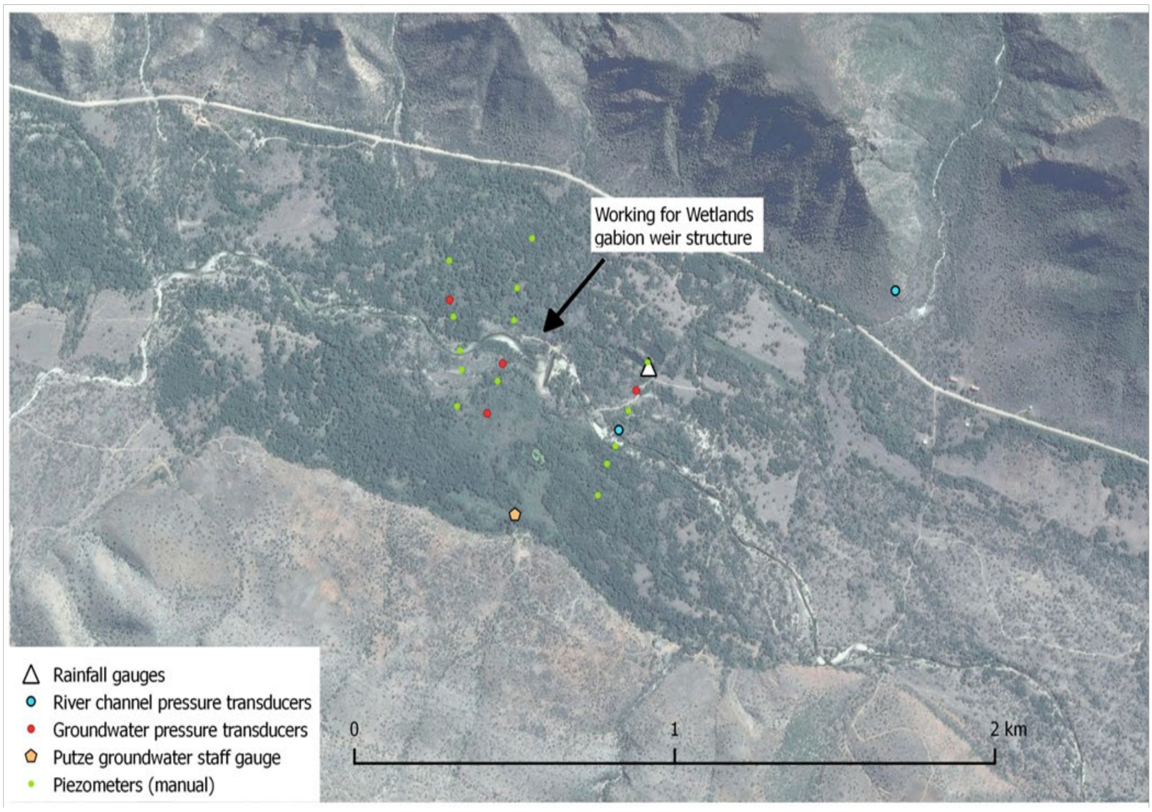


Figure 5-1 Monitoring equipment in the Baviaanskloof catchment collecting data on climate (rainfall gauges include temperature loggers), river water levels, and groundwater levels. Some sites have continuously logging instruments (rainfall gauges & other loggers)

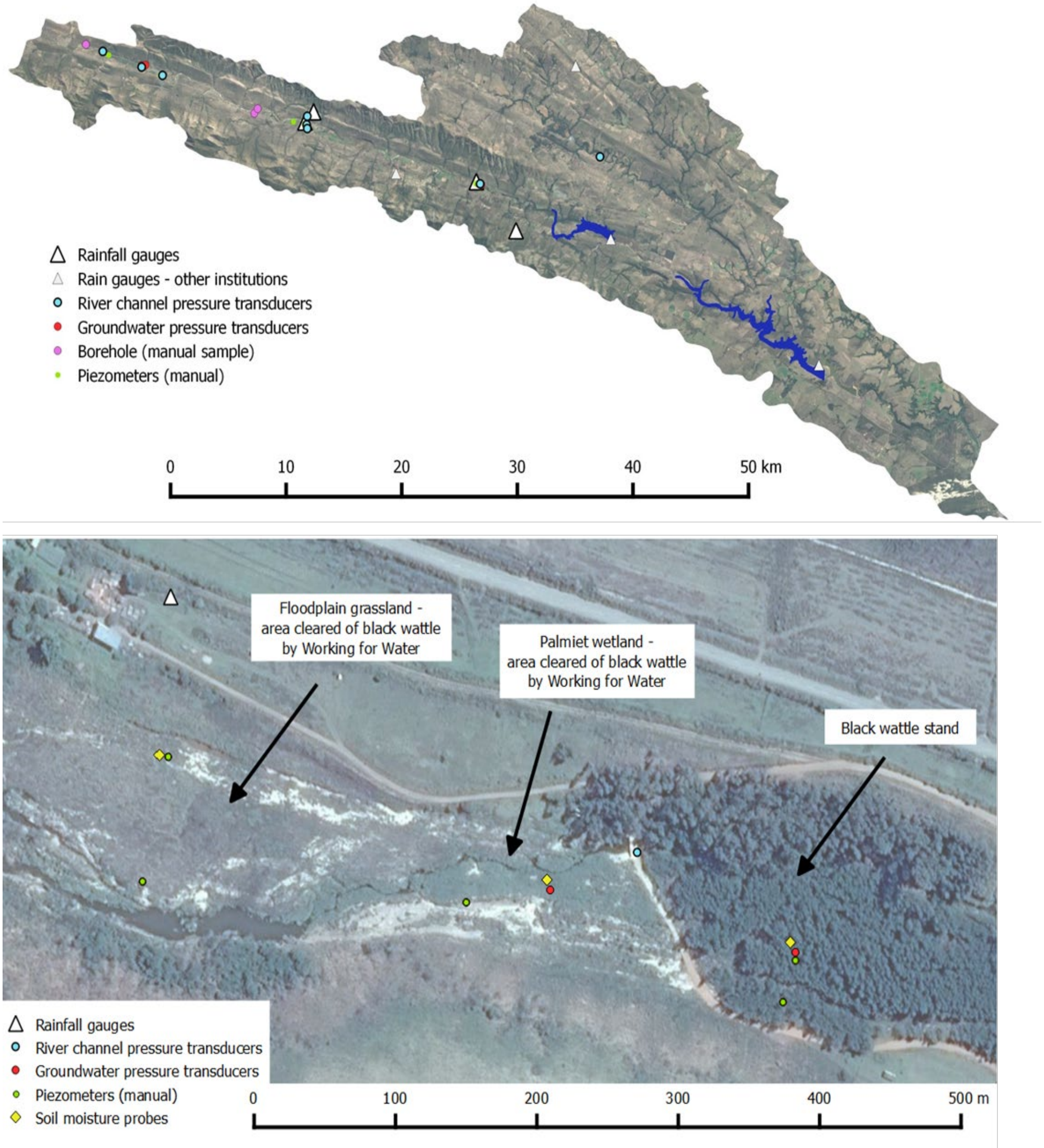


Figure 5-2 Monitoring equipment in the Kromme catchment collecting data on climate, surface and groundwater levels. Stable isotope samples were collected and water physicochemical parameters were measured in situ.

5.2.2.2 Diagnostic analyses to infer processes, thresholds, connections

Multiple diagnostic data analyses, and interpretation of stakeholder observations, were combined to get information regarding different processes in the catchments at different spatial scales, i.e. between topographic units, between aquifers and channels, across the entire catchment, within a mountain tributary sub-catchment. These analyses are described in Table 6:3.

Table 5:3 Summary of data and information analyses used to make inferences about catchment processes

Process / connectivity	Data analyses
Groundwater recharge (floodplain and bedrock)	• Groundwater level change after rainfall; timing and magnitude across locations and aquifer types (floodplain vs. bedrock and formations) • Groundwater isotope composition compared to rainfall (recharge from evaporated source or direct rainfall? In which season?) • Groundwater chemistry change after rainfall events o Magnitude and timing of rainfall events that show a response
Relative surface flow vs. groundwater contribution to streamflow	• Streamflow peak magnitude and timing vs rainfall • Rate of streamflow recession after rain events • Decomposition of hydrograph (i.e. “baseflow filter”) • Streamflow chemistry compared to rain and groundwater
Groundwater flow into mountain tributaries	• Perennial vs. ephemeral mountain streams and seeps observed in drought (locations compared to geology maps) • Groundwater and tributary water chemistry comparisons
Groundwater flow into floodplain channels (& Streamflow loss to floodplain aquifer, “transmission loss”)	• Floodplain groundwater surface elevations above or below adjacent river channels • Gaining or losing streamflow quantity moving downstream (without major tributary inputs) • Groundwater and river water chemistry comparisons; shallow floodplain groundwater likely to be evaporated (isotope enriched)
Groundwater and interflow storage outflow rates (& number of contributing storages)	• Calculation of streamflow recession constants for different periods in a flow recession (i.e. earlier on will represent water following faster flow pathways such as interflow, while later, at lower flows, more water may be coming from a slower draining source
Groundwater storage impacted by evapotranspiration (deep roots and/or shallow groundwater)	• Rates of groundwater level recession during dry periods of similar flow rates at variable temperatures; is recession greater which increased temperature (PET demand)? • Similar analyses on streamflow – reflects change in storages contributing to baseflow and/or transmission losses or direct surface ET
Soil infiltration, water retention and drainage	• Soil moisture peak timing and magnitude after rainfall • Rate of recession of soil moisture after peak • Soil moisture levels maintained after peaks
Vegetation type water use differences	• Relative rates of change in shallow groundwater levels and in soil moisture at sites in the floodplain with different vegetation types • Shallow groundwater levels compared to root zone • Observations of tributary streams that had become ephemeral becoming perennial with removal of IAPs

5.3 Catchment conceptual model structure and units

5.3.1 Surface flow pathways and HRUs

As shown in Table 5:4, all three catchments are dominated by mountainous terrain: hillslopes, cliffs, and high plateaus make up 91% of the Baviaanskloof catchment, 76% of the Kouga catchment, and 61% of the Kromme catchment. The Kouga and Kromme have proportionally more floodplain, alluvial fan, and toe-slope area, 18% and 30% compared to just 4% in the Baviaanskloof. Because of the steep terrain, hard rock geology, and relatively dry climates, these low-lying areas are likely to be the only parts of the landscape with thick sediment and soil deposits, which can act as buffers slowing water flow out of the catchment in intense rain events.

Table 5:4 Distribution of mapped topographic units in the BKK catchments

Topographic land unit	**Baviaanskloof**		**Kouga**		**Kromme**	
	Area (km^2)	**% of catchment**	**Area (km^2)**	**% of catchment**	**Area (km^2)**	**% of catchment**
Wide floodplain	24.2	2%	58.6	2%	10.8	1%
Toe-slope			440.6	17%	246.7	29%
Alluvial fan	26.0	2%			3.3	0.4%
Narrow kloof	57.5	5%	125.3	5%	63.6	8%
Hillslope	325.3	26%	572.4	22%	260.0	31%
Cliff	381.1	31%	644.4	24%	48.8	6%
High plateau	427.5	34%	805.7	30%	200.3	24%
Major Dam			5.3	0.2%	7.5	1%

The upper Kromme and Baviaanskloof catchments have relatively similar, simple drainage patterns with a central valley with developed floodplain that is fed by perpendicularly-oriented mountain tributary sub catchments. The Kouga has floodplain areas along the middle reaches of its major southerly tributaries, developed on a plateau area near the base of the Tsitsikamma Mountains. This area then drains northward in large tributaries that meet the main Kouga River, which is in a deeply incised bedrock valley with no significant floodplain for most of its length. This means the Kouga floodplain areas are likely to behave somewhat differently than those in the central valleys in the upper Kromme and Baviaanskloof: they receive water and sediment from only one mountain range rather than two and have a steeper drainage path downstream. This means they are likely to have smaller accumulated sediment deposits and perhaps less alluvial groundwater storage.

Simplified conceptual flow pathways linking mountainous areas and floodplain areas in the three catchments are shown in Figure 6:3. These diagrams show the mountain tributary sub-catchments as homogeneous units. They were sub-delineated into high plateaus, cliffs, hillslopes, and narrow kloof floors as demonstrated in Figure 6:4. Looking at their locations along a flow path or slope gradient, a generalized catena of topographic units can be assumed from plateau to hillslope to cliff to kloof floor Figure6:4. Surface flow moving along such a catena would then flow to a river channel or potentially spread out across and alluvial fan and infiltrate.

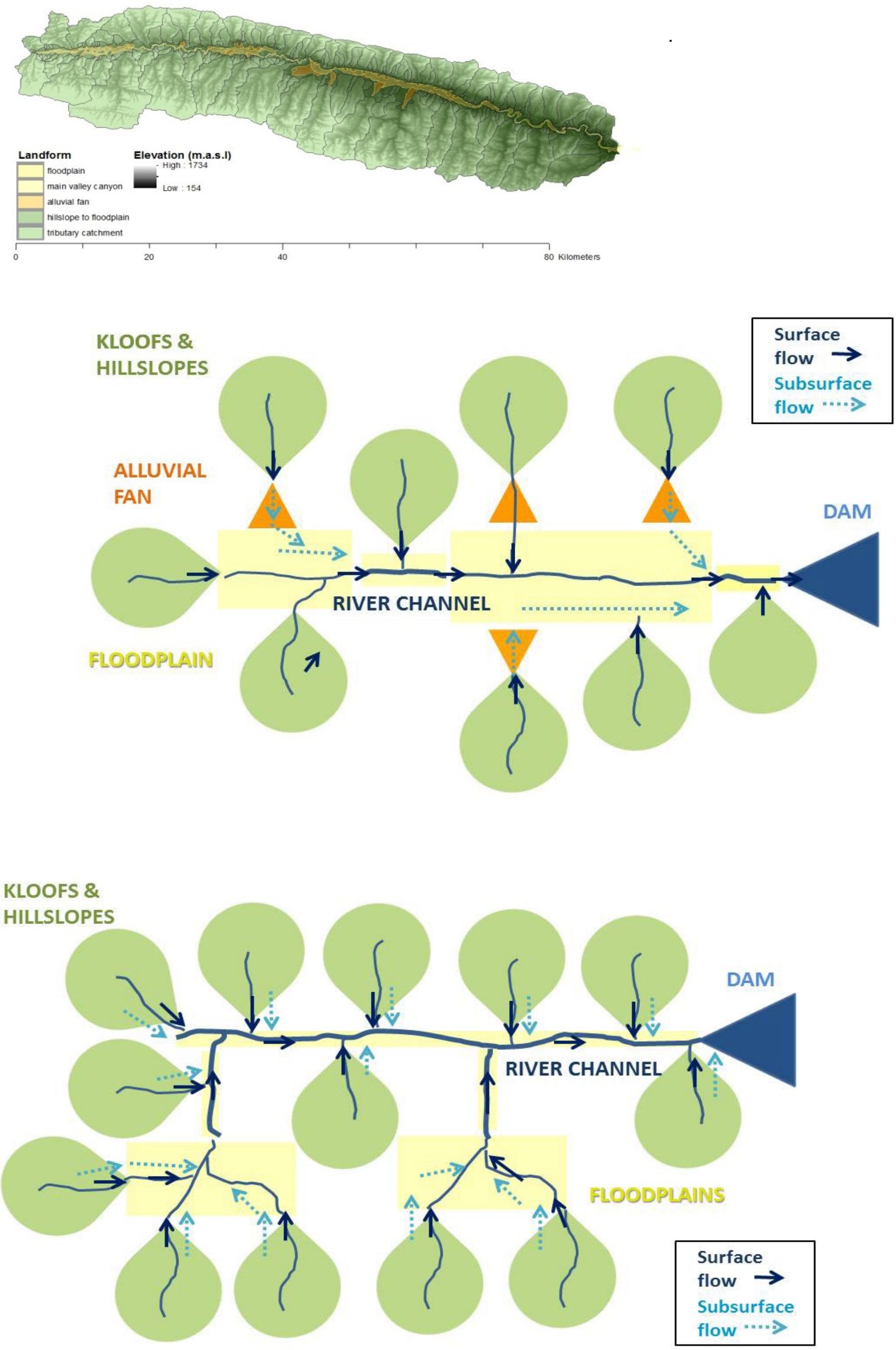


Figure 5-3 Simple conceptual diagrams showing linkages between mountain tributary catchments and floodplain areas in the Baviaanskloof and upper Kromme (upper) and the Kouga (lower) catchments based on delineation of topographic units and subcatcments.

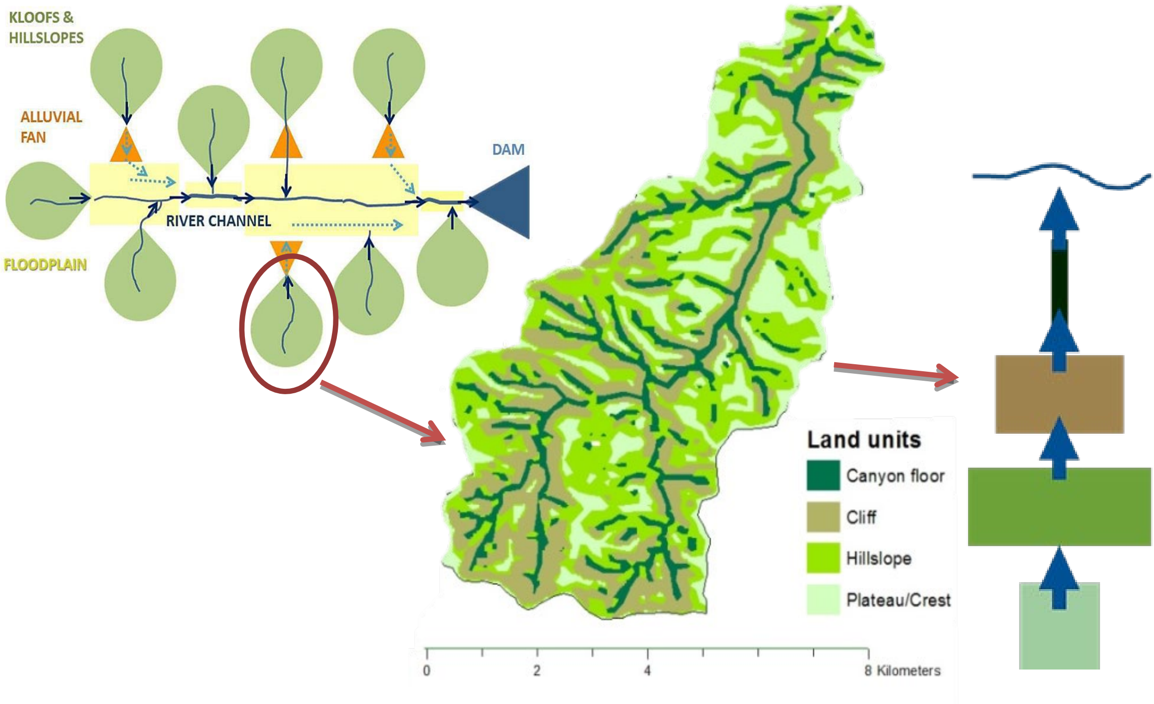


Figure 5-4 Illustration of discretisation of a mountain tributary subcatchment into topographic units and conceptualization of surface and near surface flow along these units as a catena.

The seven topographic units were combined with 27 selected land cover types of interest (Figure 6:5), which resulted in roughly 37 HRU types shown in Table 5:5 (increases when floodplains, toeslopes, and alluvial fans are considered separately). Certain land cover types were assumed to coincide with certain topographic units, such as fynbos on high plateaus, fynbos and thicket on hillslopes, and agricultural covers on lowlands. Other cover types such as black wattle were assumed to be able to occur on all topographic positions.

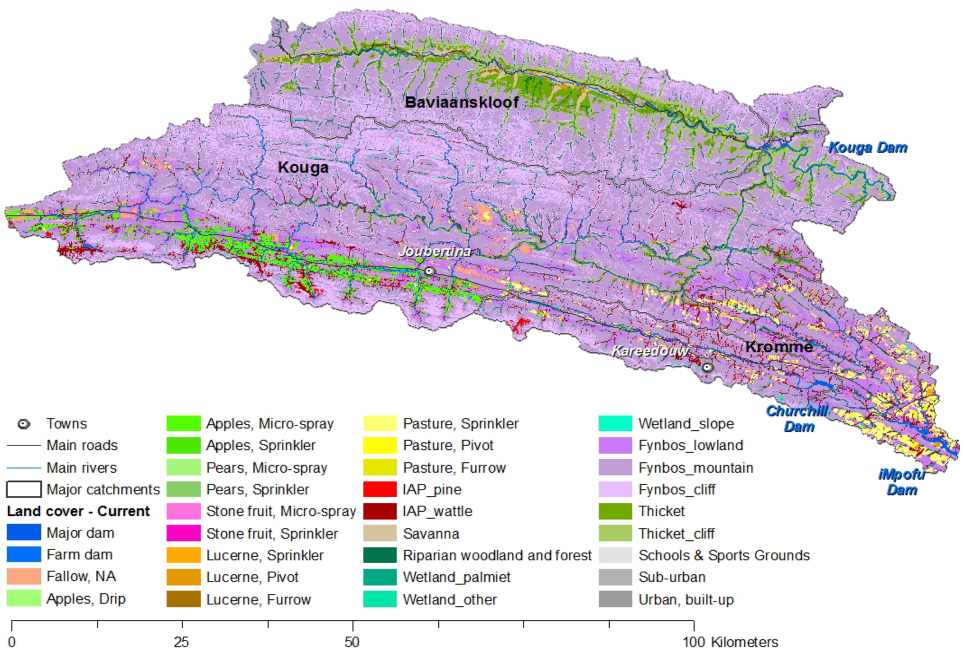


Figure 5-5 Land cover distribution for the Baviaanskloof, Kouga, and Kromme catchments estimated for the recent/current time-period (most data 2013-2014)

Table 5:5 Topographic unit and land cover types used to define hydrologic response units (HRUs) for the Baviaanskloof, Kouga, and Kromme

Topographic land unit	General cover type	Cover Class	Use class	Irrigation
Floodplain, toeslope, alluvial fan	Woodland	Floodplain savanna	grazing	
	Wetland	Reed wetland		
		Palmiet wetland		
	Pasture	Irrigated pasture	grazing	sprayer
		Unirrigated pasture	grazing	
		Fallow field		
	Orchard	Irrigated orchard, apples	crop	microjet
				drip
		Irrigated orchard, pears	crop	microjet
				drip
		Irrigated orchard, stone-fruit	crop	microjet
				drip
	Cropland	Irrigated vegetables	crop	sprayer
				drip
		Unirrigated vegetables	crop	
		Irrigated grains	crop	sprayer
		Irrigated honeybush	crop	drip
		Irrigated essential oil plants	crop	drip
	IAP	Black wattle stand		
		Pine stand	timber	
	Built area	Medium density residential	reside	
		High density residential	reside	
	Open water	Dam		
Canyon floor	Forest	Riparian forest		
	IAP	Black wattle stand		
Cliff	Fynbos & renosterveld	Bare rock fynbos mosaic		
	Thicket	Bare rock thicket mosaic		
Hillslope	Fynbos & renosterveld	Intact fynbos & renosterveld		
		Moderately degraded fynbos/renosterveld	grazing	
	Thicket	Intact thicket		
		Moderately degraded thicket		
		Highly degraded thicket (currently grazed)	grazing	
	IAP	Black wattle stand		
		Pine stand	timber	
Plateau	Fynbos & renosterveld	Intact fynbos & renosterveld		
		Moderately degraded fynbos/renosterveld	grazing	
	IAP	Black wattle stand		

5.3.2 Geology, aquifer properties, and sub-surface flow pathways

These catchments were formed in Table Mountain Group geology which has layering of fractured, water-bearing quartzitic sandstones and shale aquicludes. The two major quartzite formations are the Peninsula and Nardouw, both known to have aquifers. The Peninsula formation has generally been found to be a more significant aquifer (Xu et al., 2009). The Nardouw formation often has more iron-rich minerals, leading to red stained rocks and tinted water when the iron dissolved in the groundwater oxygenates. These layers have been irregularly folded and faulted such that the three catchments have different arrangements in terms of where the main river and floodplains lie compared to major aquifers and aquicludes (Figures 6:6-6:9).

- The Baviaanskloof valley lies along a major half-graben fault line. Faults may become cemented with minerals creating aquicludes, but may also be surrounded by highly fractured zones, the combination of which can result in deep groundwater being forced upward against a vertical aquiclude (Xu et al., 2009). This could the explanation for the hot springs in the catchment. Also some of the floodplain lies on conglomerate and shale aquicludes, but there is contact with the Peninsula at the margin.
- The Kromme valley sits at the centre of a syncline on Bokkeveld shale, with Nardouw quartzite outcropping at the margins. These formations may not feed the floodplain aquifer much themselves, but mountain tributary streams would bring inflows from the Peninsula.
- The Kouga main river lies directly on the Peninsula formation and therefore could interact directly with this aquifer if, where, and when the aquifer water table is high enough. The Langkloof valley/bench in the south lies on a Nardouw and shale syncline that is continuous with the Kromme main valley.

All three catchments have mountain-top outcrops of the highly fractured Peninsula formation quartzite, which would be a recharge zone. There are exposed intersections between this formation and the Cedarburg shale in upper parts of mountain tributaries. It is likely that this interface between aquifer and aquiclude creates some of the springs that are the headwaters many of the mountain tributary streams.

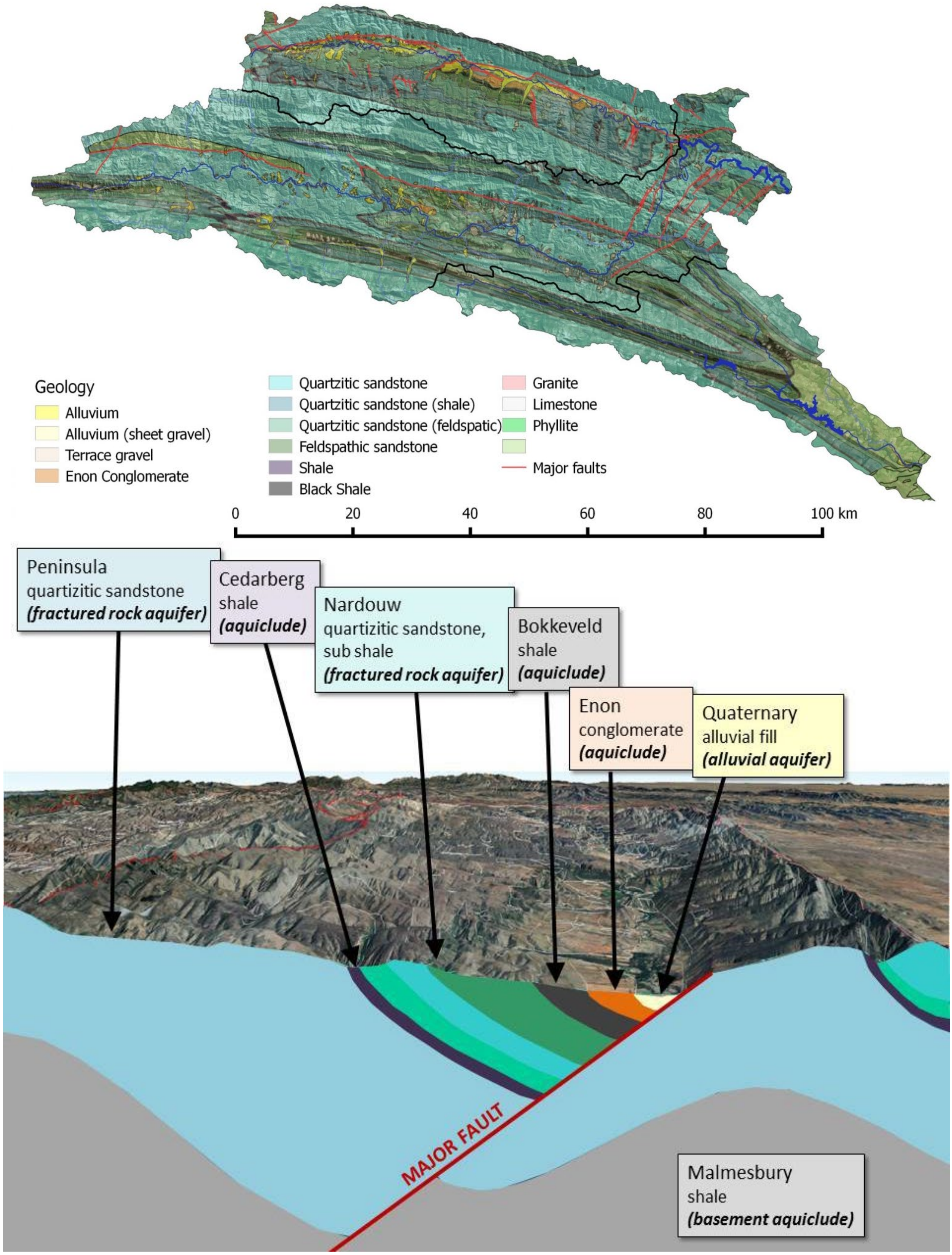


Figure 5-6 Geology map and approximate cross section for the middle of the Baviaanskloof, indicating which layers are significantly water bearing (fractured rock aquifers) and which are aquiclides

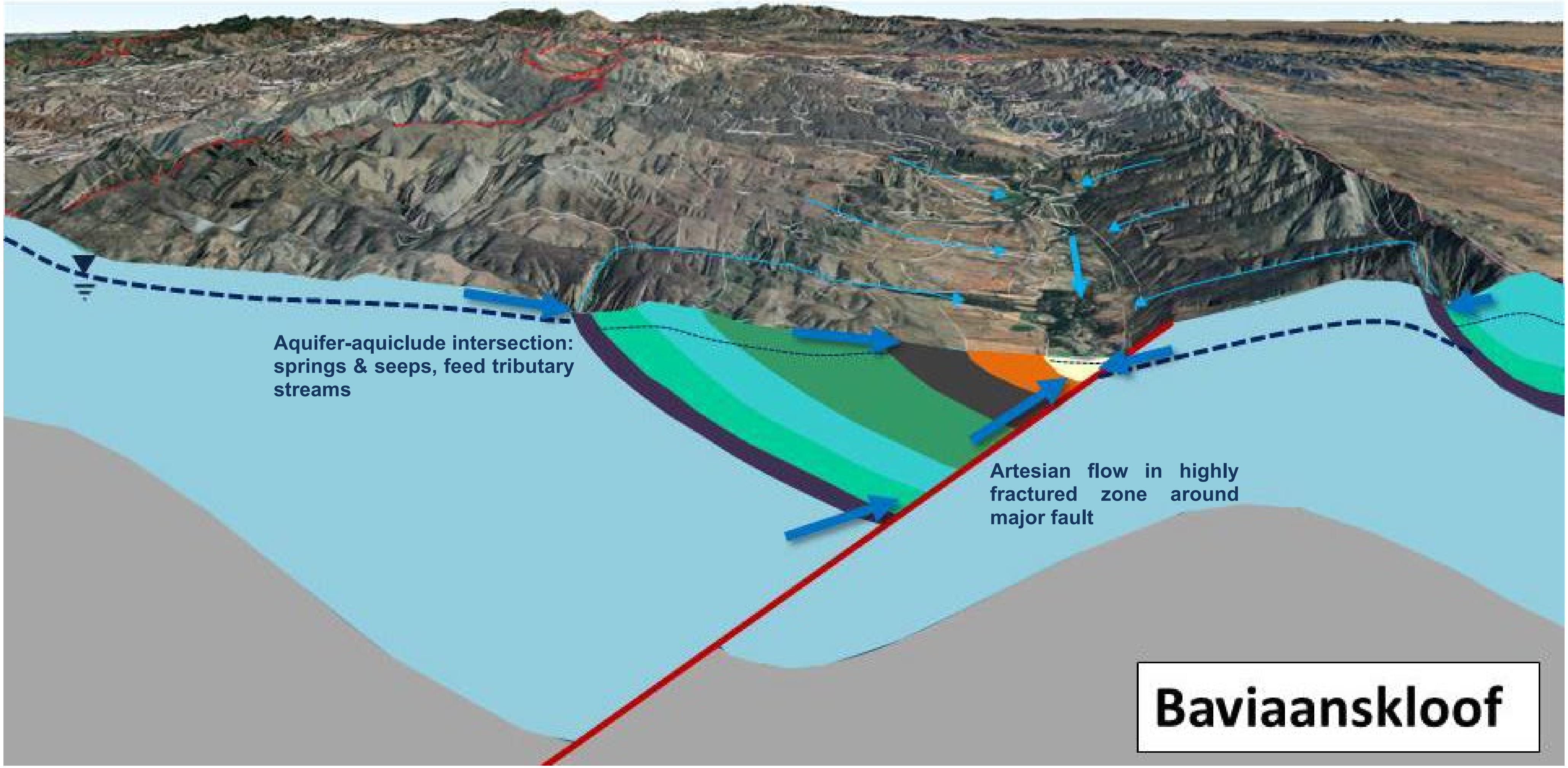


Figure 5-7 Hypothesized geological cross-section and flowpaths in the Baviaanskloof based on the distribution of formations and faults. Large faults may have highly fractured zones surrounding them.

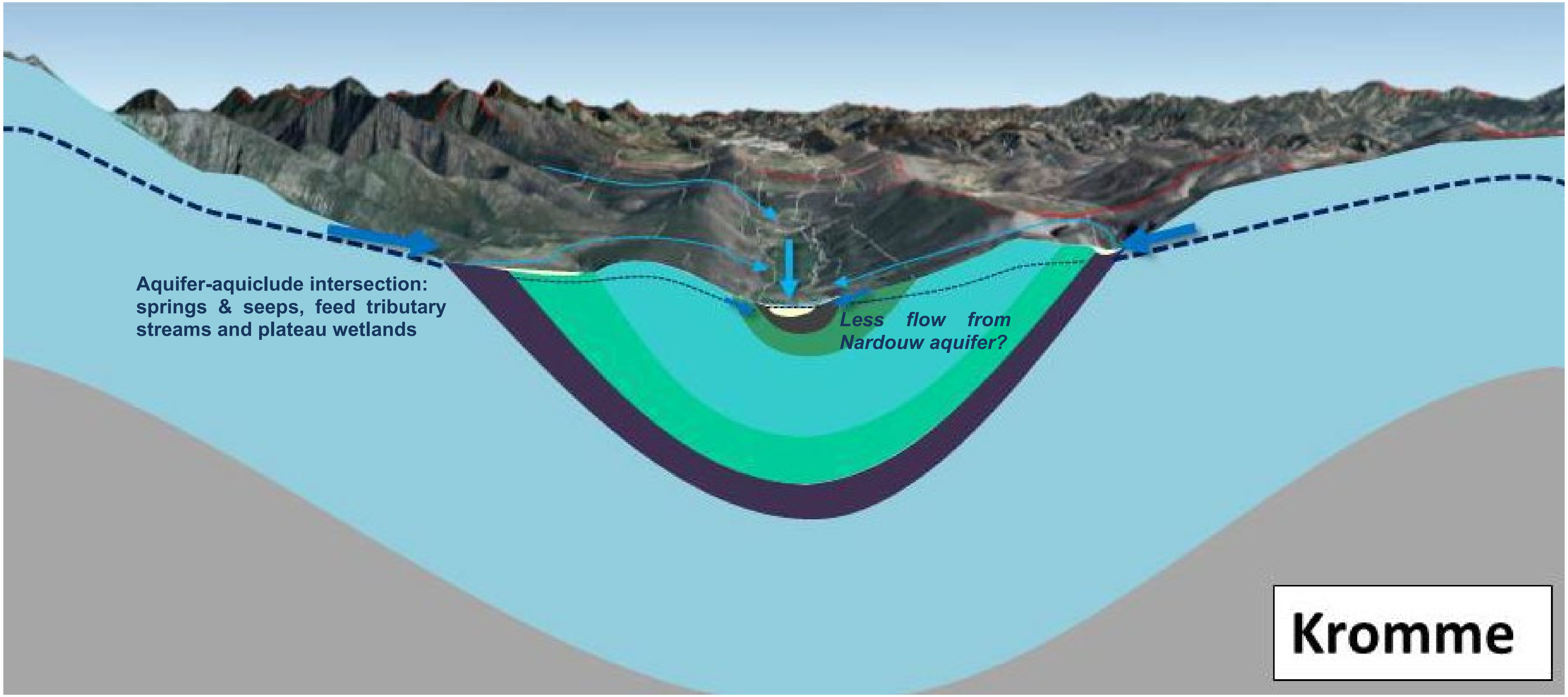


Figure 5-8 Hypothesized geological cross-section and flowpaths in the upper Kromme catchment. Perennial springs are observed in the mountain where the quartzitic sandstone meets the shale. The central floodplain overlies a shale aquiclude for much of the catchment.

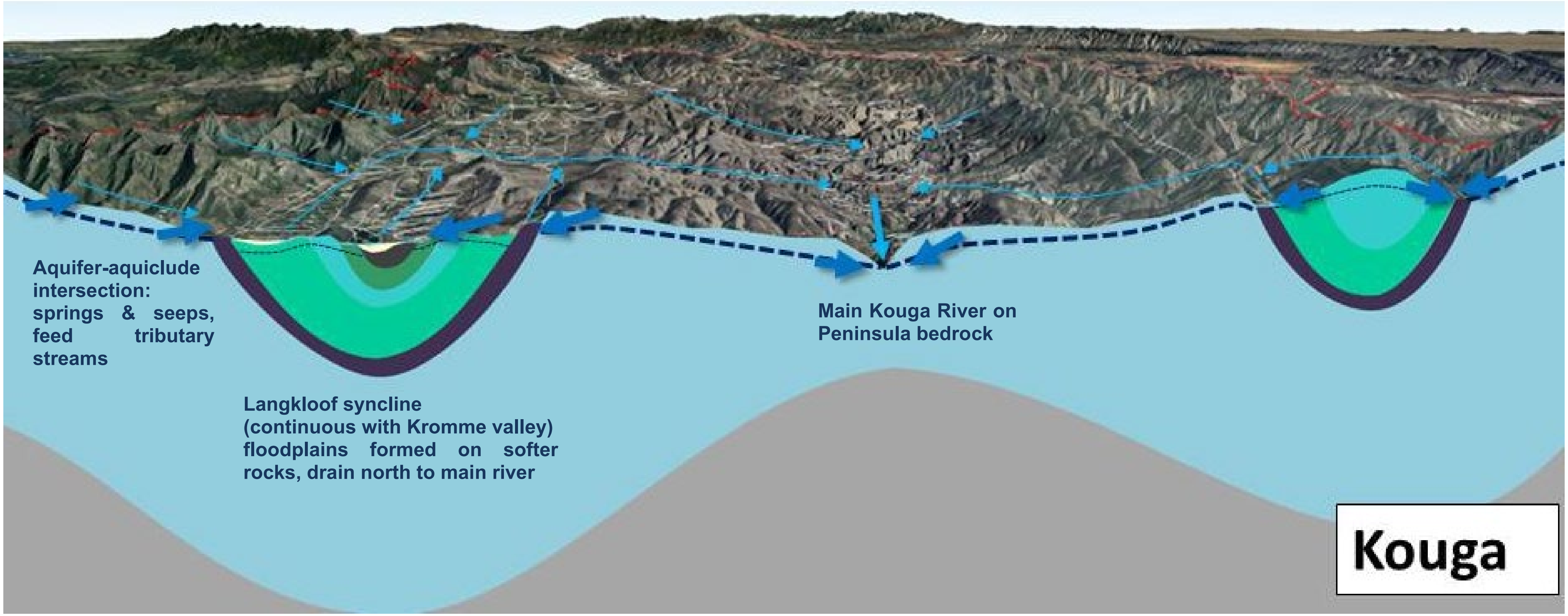


Figure 5-9 Hypothesized geological cross-section and flowpaths in the Kouga catchment. The main Kouga River has eroded a deep incised confined valley in the Peninsula formation quartzites. This could mean direct interaction, gaining or losing, with this bedrock aquifer.

Table 5:6 Summary of local evidence for (or information about) different processes and patterns for the three catchments

Process / connectivity	Evidence		
	Baviaanskloof	**Kromme**	**Kouga**
Groundwater recharge (floodplain and bedrock)	• Floodplain alluvial aquifer is recharged by mountain bedrock aquifer: see near constant groundwater levels at sites in the floodplain aquifer located at mountain fronts. ○ These sites have red tinted, iron-rich water typical of Nardouw formation • Floodplain aquifer recharge, likely by interflow, after large rainfall events: see groundwater level rise weeks after rainfall event. • Borehole isotope concentrations were generally depleted and more similar to colder weather rainfall samples than the summer rainfall – consistent with greater winter storm impacts on groundwater recharge.	• Recharge of mountain bedrock aquifer: borehole levels went up after large winter rainfall events and several borehole EC concentrations went down after large events. • Borehole isotope concentrations were generally depleted and more similar to colder weather rainfall samples than the summer rainfall – consistent with greater winter storm impacts on groundwater recharge.	
Relative surface flow vs. groundwater contribution to streamflow	• Hydrograph shows sharp peaks and fast recession indicating dominance of surface and shallow subsurface water, but there are prolonged elevated baseflows after major winter storms.	• Hydrograph shows sharp peaks and fast recession indicating dominance of surface and shallow subsurface water, but there are prolonged elevated baseflows after major winter storms.	
Groundwater flow into mountain tributaries	• Perennial mountain streams and seeps were observed in drought in tributary valleys close to quartzite-shale interface, but water quickly sinks into the subsurface before reaching tributary outlet.	• Perennial mountain streams and seeps were observed in drought in tributary valleys. • Seeps feeding wetlands were observed in high plateaus in the Tsitsikamma mountains.	
Groundwater flow into floodplain channels (& Streamflow loss to floodplain aquifer, "transmission loss")	• Floodplain groundwater surface elevations above river thalweg elevation for several months to a year after major flood events. • Streamflow stops within days of the floodplain groundwater dropping below the thalweg. • Isotope data showed more similarities between groundwater and surface water during wetter periods. Surface flow isotopes were generally much closer to groundwater concentrations than to rainfall concentrations. • Looking stream flow measurements between	• Water elevations above the channel elevation in most piezometers measured. • Isotope data showed more similarities between groundwater and surface water during wetter periods. • Borehole on a hillslope close to the floodplain, likely in Nardouw formation, has very high EC values and dissimilar chemistry to adjacent stream, so likely little contribution – consistent with idea that more flow comes from the Peninsula formation springs and interflow further up in the tributary catchments.	

Process / connectivity	Evidence		
	Baviaanskloof	Kromme	Kouga
	upstream and downstream sites, losing stream periods were observed in dry period summer months	• Losing stream conditions were not observed, consistent with higher ground water levels observed – water level at or above the stream so no stream transmission loss.	
Groundwater and interflow storage outflow rates (& number of contributing storages)	• Stream flow recession constants: higher than for the other two catchments indicating slower draining sources are more important. Max values around 100 days were seen in the upper catchment, indicating slow drainage out of a bedrock aquifer dominates. Catchment outlet average is 26 days which seems more indicative of interflow and floodplain drainage dominance.	• Recession constants are lower than for the Baviaanskloof, even higher up in the catchment, with means around10 and 20 days as a max, which seems more indicative of interflow and floodplain drainage dominance.	• Recession constants are low for Kouga Dam inflow, average of 8 days, meaning flow dominantly coming from a relatively fast draining source. However a max of 134 days at Stuurmanskraal indicates a slow draining source at times, consistent with the channel contact with the Peninsula aquifer
Groundwater storage impacted by evapotranspiration (deep roots and/or shallow groundwater)	• Floodplain groundwater is within 2 m of the surface for many months in wetter periods • Groundwater levels can also drop below this for years at a time in dry periods. • Acacia karroo floodplain vegetation has very deep roots	• Floodplain groundwater within 2 m of the surface for prolonged periods • Black wattle, common in the floodplain, has roots well over 2 m deep. • Stakeholder accounts of clearing wattle from tributary stream catchments and observing streamflows start where it had previously been dry.	• Stakeholder accounts of clearing wattle from tributary stream catchments and observing streamflows start where it had previously been dry.
Soil infiltration, water retention and drainage		• At Willowvale floodplain sites: water infiltrated into the surface soil layer during almost all rain events, but did not pass 30 cm unless the rainfall event was over 25 mm which may indicate a threshold for percolation. (may also relate to season)	
Vegetation type water use differences		• Wattle vs palmiet vs grass on the floodplain: o soil moisture was lowest in the wattle and showed faster recession after floods than the other vegetation indicating greater transpiration. • Groundwater was deeper at the wattle sites than palmiet sites and showed a faster recession after flood event.	

5.4 Evidence for processes and connectivity

Observational evidence for different flow processes at different spatial scales in the three catchments is summarized in Table 5:6

More detailed accounts of the:

- **surface and ground water level and streamflow analyses** are found in **Appendix E**
- **hydrochemistry and stable isotope analyses** are found in **Appendix F**
- **soil moisture observations** across vegetation types at the Willowvale, Kromme floodplain site are found in **Appendix G**

Similar processes were observed in the different catchments in that mountain bedrock aquifers fed tributary streams' baseflow which in turn contribute to recharging the floodplain aquifer. There was evidence of mountain bedrock aquifer contributions directly into the Baviaanskloof floodplain aquifer at the margins while this did not appear true in the Kromme. Low flows in the main Baviaanskloof and Kromme are linked to groundwater elevations in the floodplain, which is less the case in the main Kouga which has little floodplain storage nearby. The Kromme, being the wetter catchment had floodplain aquifer levels that are more consistently high than in the Baviaanskloof, which is linked to supporting large areas of permanent wetland in the Kromme.

Large winter storms had more proportional impact on streamflow and recharging groundwater, compared to summer ones of similar magnitude. This indicates the importance of summer ET in out drying out soils and lowering water tables such that little recharge or subsurface runoff occurs. Intense summer storms did result in brief periods of surface flow with no change in baseflow or groundwater. Much of the catchment areas are steep and rocky such that very high intensity storms will result in significant flood peaks. If floodplain storage is partially fed by relatively constant outflow from mountain bedrock aquifers, via tributary streams or in the subsurface, water levels in the floodplain could rise in winter compared to summer simply due to lower ET losses of this incoming water regardless of rainfall.

5.5 Implications of key catchment impacts in light of the conceptual model

- IAP cover in Kouga and Kromme: Floodplain aquifer water storage contributes to baseflow well into the driest periods. Draw-down from IAP would reduce flow overall but particularly baseflow. It is known that black wattle has very high evapotranspiration rates, but palmiet ET has been less well studied and may also be high. Results here suggest that palmiet ET rates might be less than wattle even when both are at the same floodplain site.

- Irrigated agriculture: The impacts of irrigation will depend on where the water is withdrawn, stored, and applied along the catchment flow pathways. It has been seen that mountain tributary streams connect mountain bedrock groundwater with the floodplain aquifer storage. Pumping water from the mountain bedrock to irrigate the floodplain would serve to speed up this process and change the spatial distribution. Pumping could draw down mountain streams. Storing water that would have been in aquifers in surface dams will increase ET loses and overall catchment runoff.

- Channelization of rivers: This would increase the drainage rate from the floodplain aquifer into the channel, but only in times when the water table is above the thalweg.

- Climate change: If climate change in this area is manifest as increase in summer rainfall and a decrease in winter rain, then overall runoff ratios and catchment outflows will drop even if the total annual rainfall stays the same.

6. NUMERICAL MODELLING OF CATCHMENT HYDROLOGY

6.1 Selecting and applying a numerical modelling tool

An effort was made to build numerical models that would quantitatively represent the conceptual understanding of flows through each catchment described in Section 6. In an ideal situation numerical models would be programmed specifically for the level and nature of the conceptual understanding of a catchment; however, that was beyond the scope of this project. Instead a basic review of available modelling software commonly used in South Africa was done to select a software tool suited to represent the conceptual understanding and the catchment management scenarios of interest to stakeholders. This review is presented in Appendix I. The MIKE-SHE & MIKE-11 (DHI, 2014; Refsgaard and Storm, 1995) modelling system (hereafter referred to as MIKE-SHE) was chosen for this study, based on its flexibility in methods that can be applied to represent vegetation, soil, subsurface, and channel flow processes. Models were parameterized based on literature on soil, aquifer, and vegetation properties; additional inferences regarding aquifer properties from streamflow analyses; and comparison of trial model outputs to observational estimates of streamflow.

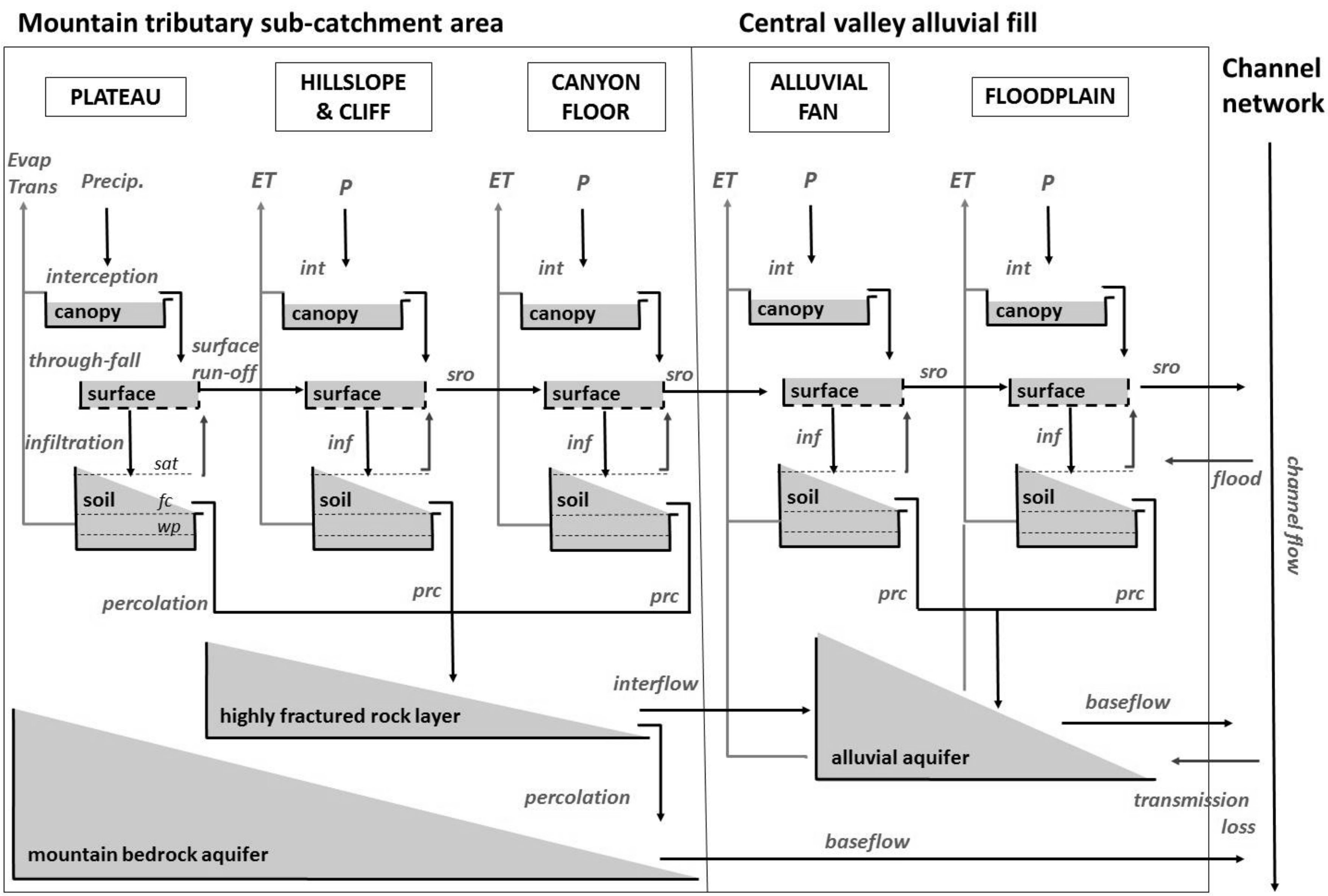
Due to time and process constraints, only the model of the Kromme catchment is presented here. Model development was initiated for all catchments, but adequate calibration for presentation to stakeholders was not completed within the time-frame of this particular project. The upper Kromme catchment was selected as a priority given it has the highest water yield in BKK and a substantial IAP infestation. Modelling work will continue through Living Lands' and SAEON's ongoing engagement with the Algoa Water Fund Technical Steering Committee, the continued PhD research of F. Jumbi, and through a connected modelling tool inter-comparison project started in 2019 (WRC K5/2927). Further outputs will be published and inquiries can be directed to Julia Glenday at Julia@saeon.ac.za.

6.2 Numerical model structure

The models of all three catchments represented surface and unsaturated zone processes at the scale of hydrologic response units (HRUs) within sub-catchments. Interflow and aquifer contributions to baseflow were represented at the sub-catchment scale. The subsurface flows were estimated using linked linear reservoirs for the mountain bedrock and valley-fill alluvium zones. The basic structure and linkages in the model are shown as a schematic diagram in *Figure 6-1*. The delineation of HRUs and sub-catchments based on topography and land cover is described in Appendix B. Surface and subsurface inputs were calculated for river reaches by sub-catchment and routed in the MIKE-11 hydraulic model using channel dimensions described in Appendix D. Process and flow calculations were done at a daily time-step.

MIKE-SHE calculates canopy interception and evaporation, infiltration, surface runoff, evapotranspiration, soil water storage, and percolation from soil into interflow reservoirs for each HRU. Canopy interception is a threshold process such that only rainfall in excess of the threshold reaches the soil surface. Water at the soil surface infiltrates at a specified rate, with excess water in a time-step being available for surface runoff. Surface runoff is routed across the specified catena of downslope land units using Manning's equation to reach the river reach in the sub-catchment. Soil water storage above the specified field capacity percolates to the interflow reservoir. Water in excess of saturation is added to surface flow. Evapotranspiration withdrawals can occur until the soil moisture reaches the specified wilting point. Actual evapotranspiration (AET) from an HRU is calculated based on the potential evapotranspiration (PET) demand and the available water, starting with canopy storage and ponded water evaporation and then vegetation and soil ET up to the remaining PET demand, with rates curtailed by the vegetation type's ET coefficient (or 'crop coefficient') and the available soil water.

Figure 6-1 Schematic diagram of the catchment models built in MIKE-SHE software for the BKK catchments showing the surface and soil processes calculated by HRU and the interflow and aquifer outflow calculated for the bedrock and alluvial fill zones by sub-catchment



The models were set up such that percolation from all HRUs in the mountain areas entered a single interflow reservoir representing the more highly fractured zone of surface rock. Water in this interflow reservoir was parametrized to drain horizontally more quickly than vertical percolation to represent the significant interflow pathway evident in the flow patterns. The vertical percolation from the interflow reservoir recharges the mountain bedrock aquifer. Mountain interflow was assumed to feed the stream network and also recharge the valley alluvial aquifer. This alluvial aquifer is also recharged by direct percolation from overlying floodplain surface units in the model. Both the alluvial aquifer and mountain bedrock aquifer linear reservoirs discharge to the river network.

MIKE-SHE allows for routing between interflow reservoirs, but not between baseflow reservoirs. This means that, in the numerical model, the mountain bedrock aquifer reservoir could not directly contribute to the alluvial aquifer reservoir. However, the model structure options do allow some connections between mountain subsurface flows and the alluvial aquifer: the mountain rock interflow reservoir feeds the alluvial aquifer and channel transmission losses feed the alluvial aquifer, some of which is sourced from the mountain bedrock baseflow. The floodplain alluvium zone was modelled a base-flow linear reservoir which received inflow from the mountain bedrock interflow reservoir and from direct percolation from the floodplain surface.

Surface runoff and baseflow contributions were added to the river channel reaches in a sub-catchment. Hydraulic routing across the channel network done based on Manning's equation and channel properties. Stream channel transmission losses were calculated as a fraction of flow when the alluvial aquifer level is below a specified level. Flow over the channel banks were also subject to infiltration into floodplain HRUs.

6.2.1 Inputs, parameterization, and calibration

The modelling catchment areas were delineated into sub catchments and topographic land units based on SU-DEM data as described above and in Appendix B. The upper Kromme catchment of the Churchill Dam was delineated into 11 sub catchments. Each subcatchment was divided into three climate zones: the southern mountain area (Tsitsikama Mountains), the central floodplain, and the northern mountain area (Kouga and Zuuranys Mountains) (Figure 6-3). Rainfall and PET input climate series were estimated for each climate zone in each subcatchment by scaling and interpolating station time-series data using the spatial rainfall surface of Lynch 2003 and the PET surface of Schulze et al., 2007. The scaling method is described in Appendix A.

Model parameter values for the upper Kromme catchment are given in Tables 6-1 to 6-3. The average surface flow parameters, slope gradient and slope length, of the different topographic units were derived from the DEM. The soil parameters were generalized from ARC land unit data as compiled in the Schulze et al., 2007 South African Atlas of Climatology and Agrohydrology and ACRU input databases. The vegetation evapotranspiration and canopy interception parameters were also derived from these databases as well as vegetation specific local literature (Calder and Dye, 2001; Clulow et al., 2011; Dye and Jarmain, 2004; Dzikiti et al., 2013, 2014; Le Maitre et al., 2015; Meijninger and Jarmain, 2014; Van Niekerk et al., 2018; Rebelo et al., 2015; Schulze, 1995, 2007). Starting values for the linear reservoir parameters were derived from the flow recession analyses (Appendix E), studies in the TMG aquifer region (Xu et al., 2009), and previous MIKE-SHE modelling in this region by Glenday, 2015.

A limited manual calibration was performed in which parameter values were adjusted within the a-priori ranges from literature to improve fit to the observed data. For the upper Kromme catchment, catchment outputs were compared to the estimated inflow to the Churchill Dam estimated by DWS for the last 10 years. Inflow into the dam is estimated as the residual of the estimated volume change, controlled and uncontrolled outflows, evaporation, and rainfall inputs. The time period for comparison was selected as the current land cover distribution was applied and IAP cover was dramatically different in previous decades, affecting streamflow (Rebelo et al., 2015). The mean annual precipitation (MAP) for the comparison period (650 mm) was representative of estimated long-term average (648 mm, 1960-2018 Appendix E) and included both drought periods and flood events.

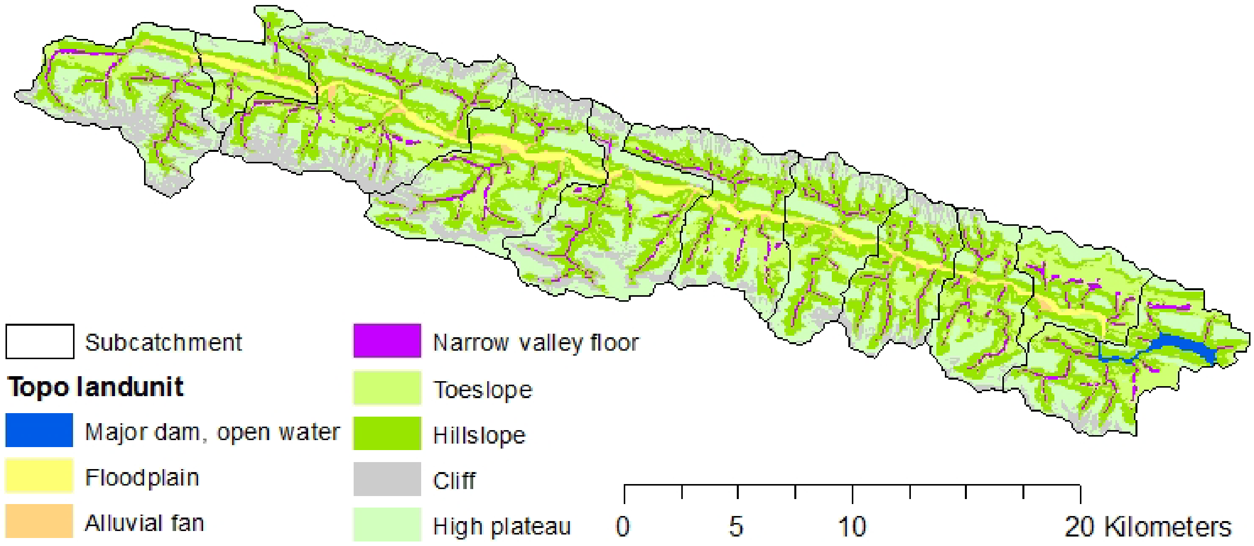


Figure 6-2 Subcatchments and topographic land units used in modelling the upper Kromme catchment

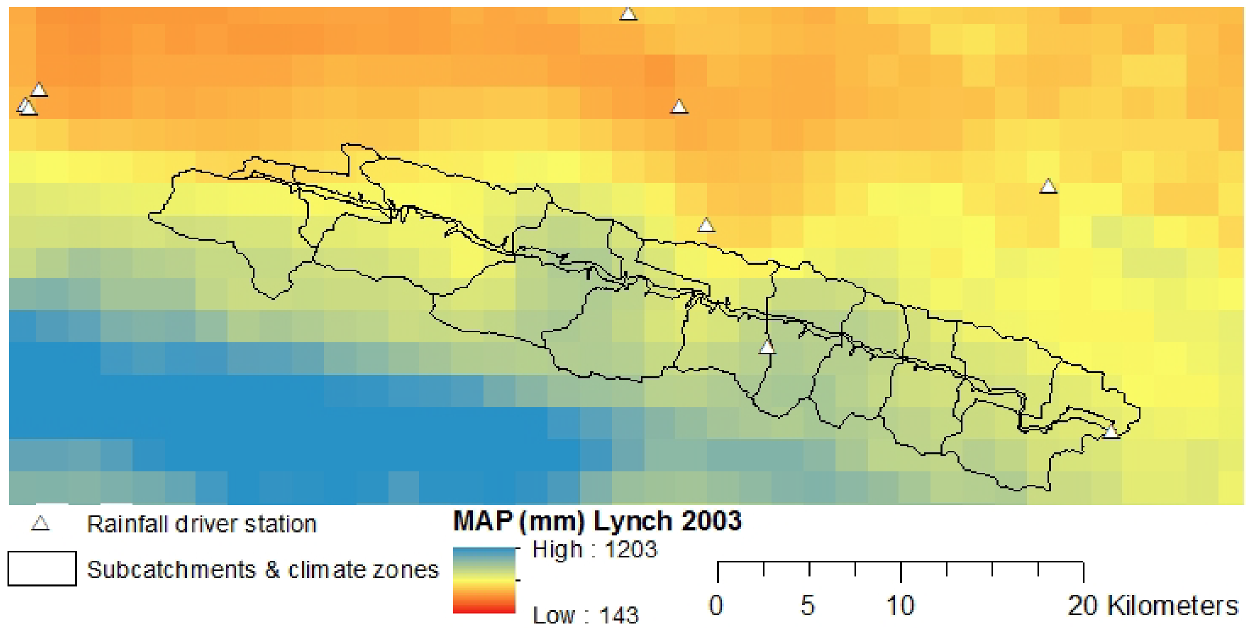


Figure 6-3 Climate zones, rainfall driver stations, and spatial rainfall surface (Lynch 2003) used in modelling the upper Kromme catchment

Table 6:1 HRU land unit surface parameters for the upper Kromme catchment model

Land unit	Soil parameters						Overland flow parameters			
	Depth (m)	Hydraulic conduc-tivity (m/s)	Water content							
			Saturation	Field capacity	Wilting point	Slope	Slope length (m)	Manning's roughness	Detention storage (mm)
Wide floodplain	5	1.00E-04	0.40	0.20	0.05	0.03	150	0.10	10
Palmiet wetland	5	5.00E-04	0.60	0.30	0.10	0.04	150	0.20	20
Alluvial fan	3	5.00E-05	0.43	0.18	0.05	0.06	160	0.10	10
Narrow valley	3	2.00E-04	0.40	0.15	0.05	0.09	50	0.05	5
Toe-slope	2	1.00E-05	0.44	0.18	0.05	0.07	315	0.10	10
Hillslope	1	2.00E-07	0.42	0.20	0.08	0.21	260	0.10	5
Cliff	0.5	1.00E-07	0.05	0.02	0.005	0.62	400	0.05	0
High plateau	1	1.00E-05	0.40	0.18	0.05	0.27	400	0.20	10

Table 6:2 HRU vegetation type parameters for the upper Kromme catchment model

Cover type	Maximum canopy interception (mm)	Maximum root depth (mm)	Evapotranspiration coefficient (ETk)
Palmiet wetland	1	2000	0.8
Riparian woodland/forest	2.5	3000	0.9
Fynbos	1	2000	0.65
Fynbos cliff (sparse)	0.25	1000	0.2
Wattle (dense stand)	2.5	5000	1.2
Pine (dense stand)	2.5	5000	1
Fruit orchard	0.5	1500	0.8
Irrigated pasture	0.5	500	0.75

Table 6:3 HRU Interflow and baseflow reservoir parameters for the upper Kromme catchment model

Subsurface / aquifer unit	Thick-ness (m)	Specific yield	Vertical percolation constant (days)	Lateral outflow constant (days)	Access for ET (capillary rise)
Mountain bedrock					
Interflow	2	0.1	250	10	n/a
Baseflow	300	5.00E-04	n/a	115,000	no
Valley fill aquifer					
Baseflow	10	0.3	n/a	300	yes

6.3 Baseline model performance for the Kromme catchment

The calibrated baseline current cover catchment model for the upper Kromme catchment achieved a very similar long-term mean daily flow value to the observational data-set for the comparison period (2008-2017): the mean modelled flow was 1.22 m^3/s and the observed was 1.23 m^3/s. Nash Sutcliffe Efficiency (NSE) values suggest an acceptable reproduction of observed flow patterns, with a value of 0.81 for modelled daily flows (Figure 6-4) and 0.92 for modelled monthly flows (Figure 6-5). The modelled output had more frequent small to medium flow peaks, 2-20 m^3/s, than in the observation dataset. This meant the mean-absolute-error was 0.90 m^3/s for daily values and 0.41 m^3/s for monthly values. However, there was a good fit for the major flow events in the observed record and the rates of recession after these events. Based on this, the relatively high NSE values, and the close fit of the long-term average, the model was considered fit for further application to scenarios (Section 7).

The model predicted a 16% runoff ratio for the modelled time period: 650 mm MAP with mean annual AET of 550 mm and runoff of 102 mm. Of the predicted runoff, 11% was in the form of overland flow and 89% as subsurface flow. Of the subsurface flow 72% was predicted to come as interflow, 6% from the mountain bedrock aquifer outflow, and 22% from the valley-fill alluvial aquifer.

6.4 Implications for model use and further refinement

The baseline model of the Kromme catchment achieved suitable performance for further application with a relatively minimal calibration effort. This provides support for the basic model structure and parameterization. It appears to produce suitable results for use in evaluating changes long-term average flows and in major peak events. Daily flows in medium flow conditions from the model should be viewed with caution. There are opportunities for further exploration of the realism of the model and the input data should receive attention in further work.

Rainfall is the key input in any hydrological model and the spatial distribution of rainfall within the highly mountainous BKK region needs investigation. The Lynch 2003 rainfall surface does incorporate key variables influencing rainfall distribution in the area including elevation, distance from sea, and aspect, however it was produced at a regional scale with a relatively coarse spatial resolution driven by long-term station records that are mostly located in the floodplain. To investigate its local applicability, additional higher elevation rainfall gauges were installed during the course of this study through the support of SAEON with the intention of gathering a dataset beyond the period of this particular study. With the recent drought conditions a longer time-series of data is needed to use them to evaluate, and potentially improve upon, the Lynch rainfall surface or other sources.

The observational data against which the model was compared can be assumed to have a high level of uncertainty, although this has not been quantified. Inflows into the DWS reservoirs are estimated as the residual of many values that are in term estimated from point measurements and algorithms (i.e. scaling pan evaporation data to the assumed reservoir surface area or estimating changes in dam volume from changes in stage from bathymetry estimates). This means further calibration and comparison of model outputs to this dataset will not necessarily improve model realism. In addition, it was not deemed useful to quantify model output uncertainty against its goodness-of-fit to this dataset. However, through ongoing research, model outputs of subsurface flow proportions at different spatial scales will be compared to the hydrochemistry data collected as well as the groundwater levels and sub-catchment flows monitored during the course of this project (F. Jumbi dissertation, in progress). Other sources of model validation for future work are satellite derived AET estimates which could be compared to modelled AET. These would improve the assessment of the model's realism and may point to additional structural and parameter adjustments that would further improve performance.

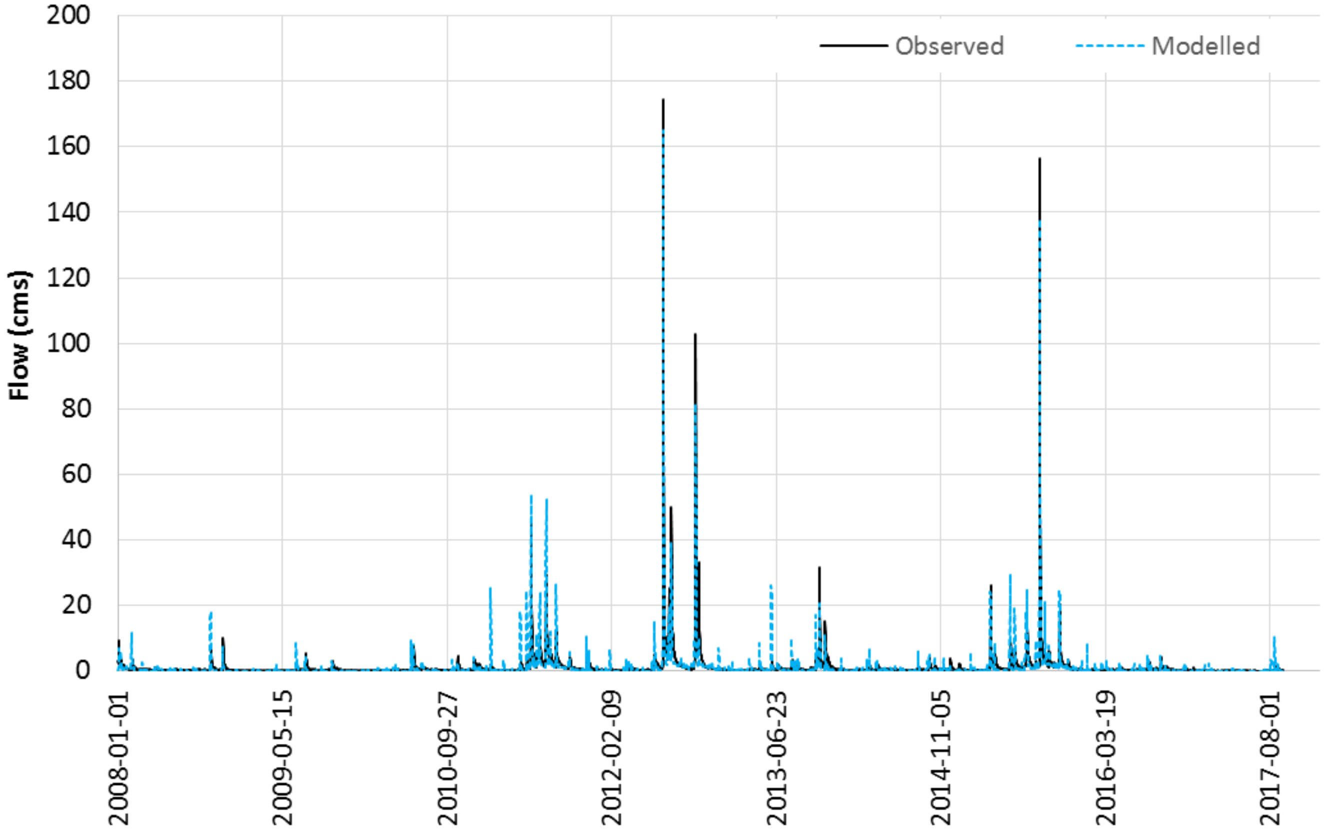


Figure 6-5 Modelled and estimated observed daily flow for the upper Kromme catchment. Observed flow is the estimated inflow into the Churchill Dam (DWS)

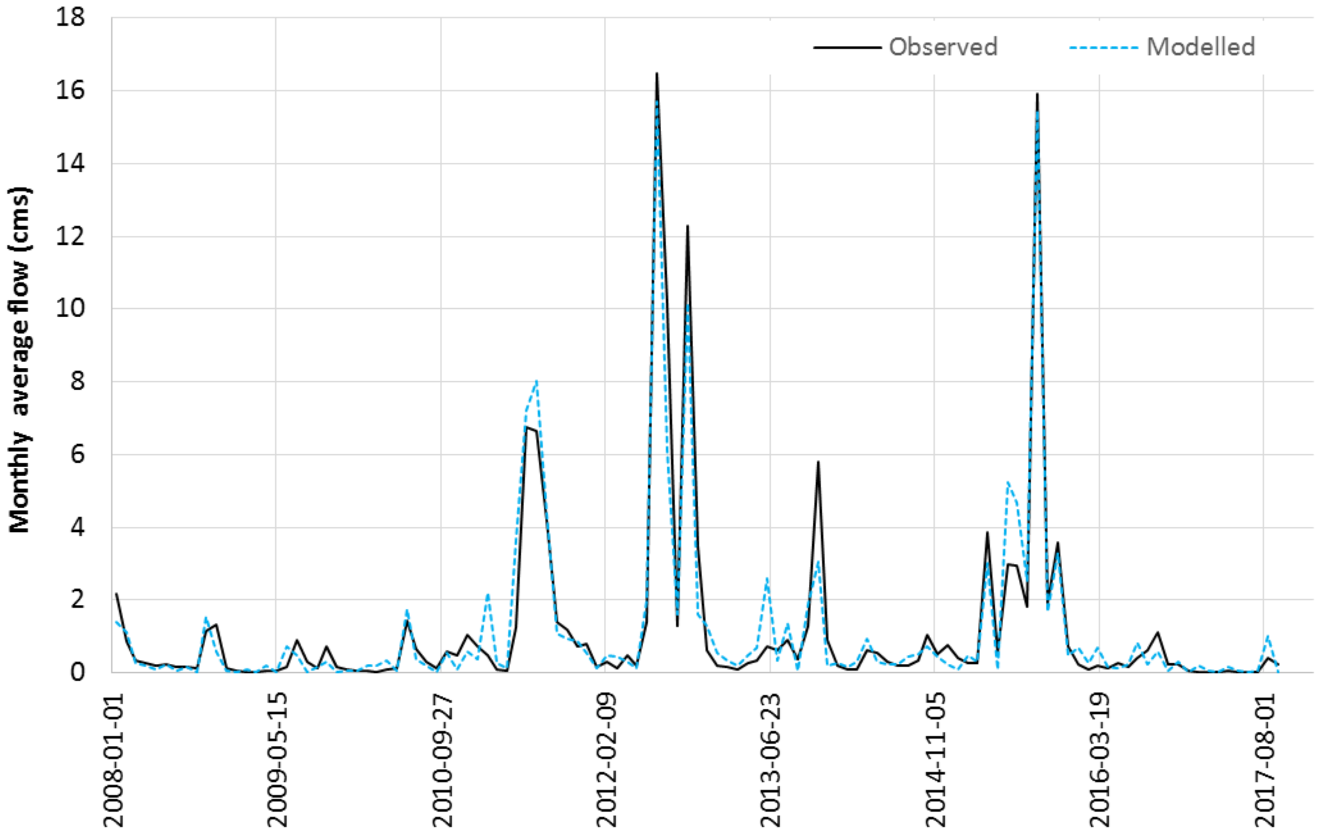


Figure 6-4 Modelled and estimated observed average monthly flow for the upper Kromme catchment. Observed flow is the estimated inflow into the Churchill Dam (DWS)

7. MODELLING FUTURE CATCHMENT MANAGEMENT SCENARIOS

A main aim of building greater, and more collective, understanding of local catchment processes in the BKK catchments in the form of a model was to be able to explore the potential impacts of changing land and water management in the future. It is hoped that improved understanding of the likely impacts of different changes can aid in decision-making at various scales. Potential future scenarios to be assessed for the BKK catchments were developed based on ideas expressed in various levels of stakeholder engagement.

7.1 Developing scenarios

7.1.1 Dialogue interviews and workshop

The sequence of dialogue interviews, farm visits, and learning journeys highlighted key issues of catchment management concern, which were used to structure discussions on scenarios at the "sense-making workshop." During this workshop stakeholders were asked to brainstorm about future changes in their areas over the coming decade. They were further guided to think about changes specifically pertaining to some major themes identified through previous engagements. These were: agricultural growth and farming practices, invasive alien plant cover, water supply methods and use, and extreme events (droughts, floods, hail, fire). Attendees were then asked to discuss how they thought such changes could impact water flows and availability in the area.

These engagements highlighted that local residents saw reasonable possibility for change in multiple directions for both IAP cover and agricultural expansion and water use. Based on these discussions three different types of scenarios were derived:

1. Baseline scenarios, against which other scenarios are compared: current land cover and a pre-development cover scenario.

2. Single change scenarios, in which one aspect of land and water management in the catchment is altered, while the rest of the catchment setting remains unchanged from the baseline (unlikely to occur in reality, but useful to explore the relative impacts of single types of change)

3. Storyline scenarios, which include several changes in land cover and water management that are likely to occur at the same time due to human and ecological responses to major drivers of change, such as water scarcity, agricultural markets, or government policies.

These scenarios are described in Table 8:1

7.1.2 GIS data processing

The scenarios were translated into land cover maps using the methods outlined in Table 7:1. This involved combining data across several sources, a more detailed description of which is given in Appendix C. An effort was made to use national scale land cover products (NLC dataset and SANBI Vegetation Map) as a starting point to potentially make the methods more generalizable. The baseline scenario of pre-development land cover was based on the SANBI Vegetation Map and Euston-Brown, 2006 modified using the topographic unit mapping (e.g. to refine boundaries of types) and wetland mapping from the NLC data, NFEPA wetland mapping, and Rebelo 2012. The recent/current land cover distribution baseline mapping was described above. Expansion rules based on local observations and stakeholder input were applied to map the potential maximum extent of IAP cover and agricultural cover types (Table 7:1). For example, it was assumed that orchards and pastures could potentially be developed on any land in wide valley areas having less than 20% slope.

Table 7:1 Scenario descriptions and mapping methods

Scenario name	Scenario description	Mapping method description
Baselines		
Current cover	current (2014-2018 sources) land cover distribution	National Land Cover dataset (NLC) 2013-2014 is the underlying guide; IAP cover is mapped where NLC maps woody cover and Rebelo 2012, Bolhuis 2013, or Zerroug 2015 mapped IAP cover; agricultural fields and orchards assigned crop types and irrigation methods using DWS data (Bromley, 2015); other vegetation assigned types based on SANBI Veg Map with exceptions for palmiet wetlands, mapped using Rebelo 2012, and riparian woodland and forest mapped to kloof floors from topography
Pre-development: Indigenous vegetation	full extent coverage of indigenous vegetation types; no agriculture, built up areas, or IAP	SANBI Vegetation Map is used as the underlying guide; modifications made for kloof forest - mapped to kloof floors using topography analyses - and palmiet wetlands - mapped using Rebelo 2012 and wide valley floors in the Kromme, excluding alluvial fans, with other wetlands mapped in NLC
Single change - commercial agriculture		
Maximum commercial agriculture extent	all areas that could be practically cultivated are commercial fruit orchards or irrigated pasture	All areas in or bordering main farmed valleys, and wide valley reaches, with slopes under 20%, are converted to orchards, lucerne, or pasture with types determined by the nearest existing agriculture
Single change - irrigation methods and sources		
ALL efficient irrigation	All irrigated orchards, pastures, and crops switch to the most efficient irrigation methods and practices appropriate for the crop type (orchards: adaptive scheduled drip, mulch, cover crops; pasture & lucerne: pivot /sprinkler with scheduling)	Land cover distribution stays the same as baseline current cover scenario, only the irrigation types and properties change
ALL inefficient irrigation	All irrigated orchards, pastures, and crops switch to the most inefficient irrigation methods and practices out of those currently applied to the crop type (poorly scheduled sprayers, no mulch)	Land cover distribution stays the same as baseline current cover scenario, only the irrigation types and properties change
ALL water shortages compensated with boreholes	Current farming areas, crops, and methods, but instead of cutting back irrigation and having losses in dry years, the ideal irrigation need for the crops are met by groundwater pumping when there isn't enough surface water. (Assume a borehole on every property)	Land cover distribution stays the same as baseline current cover scenario, only the irrigation amounts and the groundwater withdrawal changes

Single change - IAP cover (Kouga & Kromme focus)		
Maximum IAP extent	all areas that are not actively farmed are covered with dense IAPs	All areas NOT mapped as cliffs, high plateaus, orchards, irrigated fields, or built-up areas are mapped as IAP cover: pines on hillslopes on the Tsitsikama side, wattles in riparian areas, lowlands, and hillslopes
Clear ALL IAP + restore	all IAPs cleared; cleared areas are restored to their indigenous vegetation type	Areas mapped as IAP are changed to the vegetation type mapped in the pre-development, indigenous vegetation scenario; agriculture doesn't change
Clear ALL IAP + farm	all IAPs cleared; cleared areas farmed if they can be (slope, proximity), others restored to their indigenous vegetation type	Areas mapped as IAP on wide valley floors and under 20% slopes near existing agriculture (areas mapped as agriculture in the maximum commercial agriculture scenario) are changed to the agricultural cover type they are closest to (orchard, lucerne, pasture); IAP outside wide valley floors changed to the vegetation type mapped in pre-development scenario
Clear main valley IAP + restore	IAPs cleared in the main valley floor area; cleared areas are restored to their indigenous vegetation type; IAP cover in hillslopes, mountains, kloofs does NOT increase	Only areas of IAP that are in the main valley floodplain areas (i.e. lowlands adjacent to existing agriculture) are converted to other cover types, convert these IAP areas to indigenous cover types as mapped in the pre-development scenario, IAP cover in hillslopes, mountains, kloofs kept as in baseline
Clear main valley IAP + farm	IAPs cleared in the main valley floor area; cleared areas are converted to orchards or irrigated pastures; IAP cover in hillslopes, mountains, kloofs does NOT increase	Only areas of IAP that are in the main valley floodplain areas (i.e. lowlands adjacent to existing agriculture) are converted to other cover types, convert these IAP areas to orchards and pastures as mapped in the maximum agricultural extent, IAP cover in hillslopes, mountains, kloofs kept as in baseline
Clear main valley IAP + farm + mountain IAP expansion	IAPs are completely cleared in the main valley floor area because people are farming there; cleared areas are converted to orchards or irrigated pastures; IAP cover in hillslopes, mountains, kloofs increases on all un-farmed areas, except on the main valley palmiet	Only areas of IAP that are in the main valley floodplain areas are converted to other cover types, convert these IAP areas to orchards and pastures as mapped in the maximum agricultural extent; palmiet in the valley bottom stays as is in baseline; hillslope, kloof, mountain areas not farmed or developed in the baseline are converted to IAP cover as in max IAP extent scenario
Single change - palmiet wetlands (Kromme focus)		
Restore ALL palmiet	Palmiet wetlands are restored to their historical extent, which entails clearing aliens and pulling back orchards and pastures	Palmiet wetland cover on all places mapped as palmiet in the pre-development scenario, replaces current IAP, orchards, pastures, etc. on the main valley floor, everything else remains unchanged

Convert ALL palmiet to pasture	Palmiet wetlands are converted to pasture irrigated with sprinkler systems; no other changes	Palmiet converted to pasture; everything else remains unchanged from baseline current cover scenario
Single change - honeybush cultivation (Kouga & Kromme focus)		
Cultivated honeybush on fallow land	Honeybush cultivation is done only on areas that are currently fallow land. The honeybush is efficiently irrigated (drip, mulch, scheduling)	Fallow field land is converted to honeybush; everything else unchanged from baseline current scenario
Cultivated honeybush on fallow land & riparian buffer	Honeybush cultivation is done on areas that are currently fallow land as well as a riparian buffer area on apple orchards and other commercial agriculture	Fallow field land plus current agricultural area that is within a 30 m buffer from rivers is converted to honeybush; everything else unchanged from baseline current scenario
Single change - thicket restoration (Baviaanskloof focus)		
Full thicket restoration	All currently degraded thicket hillslopes are restored to full thicket vegetation density	Land cover mapping does not change from current scenario but vegetation and soil properties of degraded thicket is changed to that of intact (as mapped by Euston-Brown).
Storylines		
Water scarcity adaptations	IAPs are completely cleared in the main valley where people are farming and cleared area is converted to agriculture; IAP cover everywhere else stays the same; irrigation is more efficient and deficits in surface water supplies against irrigation demand are met with groundwater pumping	Same cover as in the "Clear main valley IAP + farm" scenario; irrigation types and properties change
Diverse & sustainable farming	IAPs are completely cleared in the main valley and cleared area is restored to palmiet cover or cultivated honeybush; IAP cover everywhere else stays the same; honeybush is also cultivated on fallow lands and riparian buffers; irrigation is more efficient throughout	Only areas of IAP that are in the main valley floodplain areas are converted to other cover types, convert these IAP areas to palmiet where mapped in pre-development scenario and cultivated honeybush everywhere else; fallow land (mapped as described above) is converted to honeybush; a riparian buffer on all agricultural land in the baseline scenario is converted to cultivated honeybush

7.2 Scenario descriptions and land cover composition

The resulting scenario maps are presented in Figures 7-1 to 7-7 and the distribution of land cover in the scenarios are presented in Appendix C. A total of 32 different land cover classes were mapped with agricultural classes including the irrigation method.

7.2.1 Current vs. pre-development cover

In comparing the current cover scenario to the pre-development scenario (Figure 7-2), the most obvious changes are the loss of floodplain and lowland vegetation to agriculture and alien invasive cover in the Kouga and Kromme. While the Baviaanskloof catchment shows far less change in land cover types, and the Kouga and Kromme catchments as a whole remain dominated by fynbos, there have been changes in the condition of these natural vegetation types (Euston-Brown, 2006; Mander et al., 2010; Powell et al., 2011) that can be captured in model parameters. The changes in floodplain vegetation can be disproportionately important to catchment hydrology due to the greater access of this vegetation to water resources. The mapping methods described above resulted in estimates of 110 km^2 and 67 km^2 of black wattle (*Acacia mearnsii*) IAP cover in the Kouga and Kromme catchments respectively, covering 4% and 8% of the areas of these catchments. No significant IAP cover has been mapped for the Baviaanskloof. Agricultural cover types were mapped on 1%, 6%, and 14% of the Baviaanskloof, Kouga, and Kromme catchments respectively, dominated by apple orchards in the Kouga (97 km^2, 4% of the catchment) and irrigated pasture in the Kromme (89 km^2, 11% of the catchment). IAP invasion, conversion to agriculture, and channel modification have reduced the area of palmiet wetlands that would otherwise dominate the upper Kromme floodplain. This mapping effort suggested that there could have been 10 km^2 of palmiet wetland while there is only 1.5 km^2 mapped in the current scenario (Figure 9).

7.2.2 IAP expansion and clearing scenarios

If IAPs are assumed to expand uncontrolled across all lowlands and hillslopes which are not currently farmed or developed in the Langkloof (Figure 7-3), this could result in an additional roughly 1,360 km^2 of black wattle and 130 km^2 of pine infested area. IAP stands would cover 42% of the Kouga and 66% of the Kromme. This is seen as an unlikely extreme end point, certainly in the near future, but is explored for illustration purposes. Allowing uncontrolled expansion while clearing only low lying areas adjacent to agriculture was predicted to make a relatively insignificant change to the total increase (then 1,300 km^2 net increase in wattle cover).

Clearing existing IAPs in low slope areas adjacent to existing agriculture was estimated to provide an additional 34 km^2 of potential agricultural land in the Kouga and 17 km^2 in the Kromme. If all IAPs were cleared and cleared areas were instead restored to indigenous vegetation cover, the greatest increases by area would be in fynbos cover (55 km^2 in the Kouga and 46 km^2 in the Kromme, roughly 10% increases) and riparian woodlands (45 km^2 in the Kouga and 19 km^2 in the Kromme, roughly 60% increases). There would also be an increase in wetland cover: mapping suggested an additional 10 km^2 seep and valley wetland in Kouga and 3 km^2 palmiet in the Kromme. The change from IAP trees to fynbos is anticipated to result in the biggest drop in vegetation water use among these transitions.

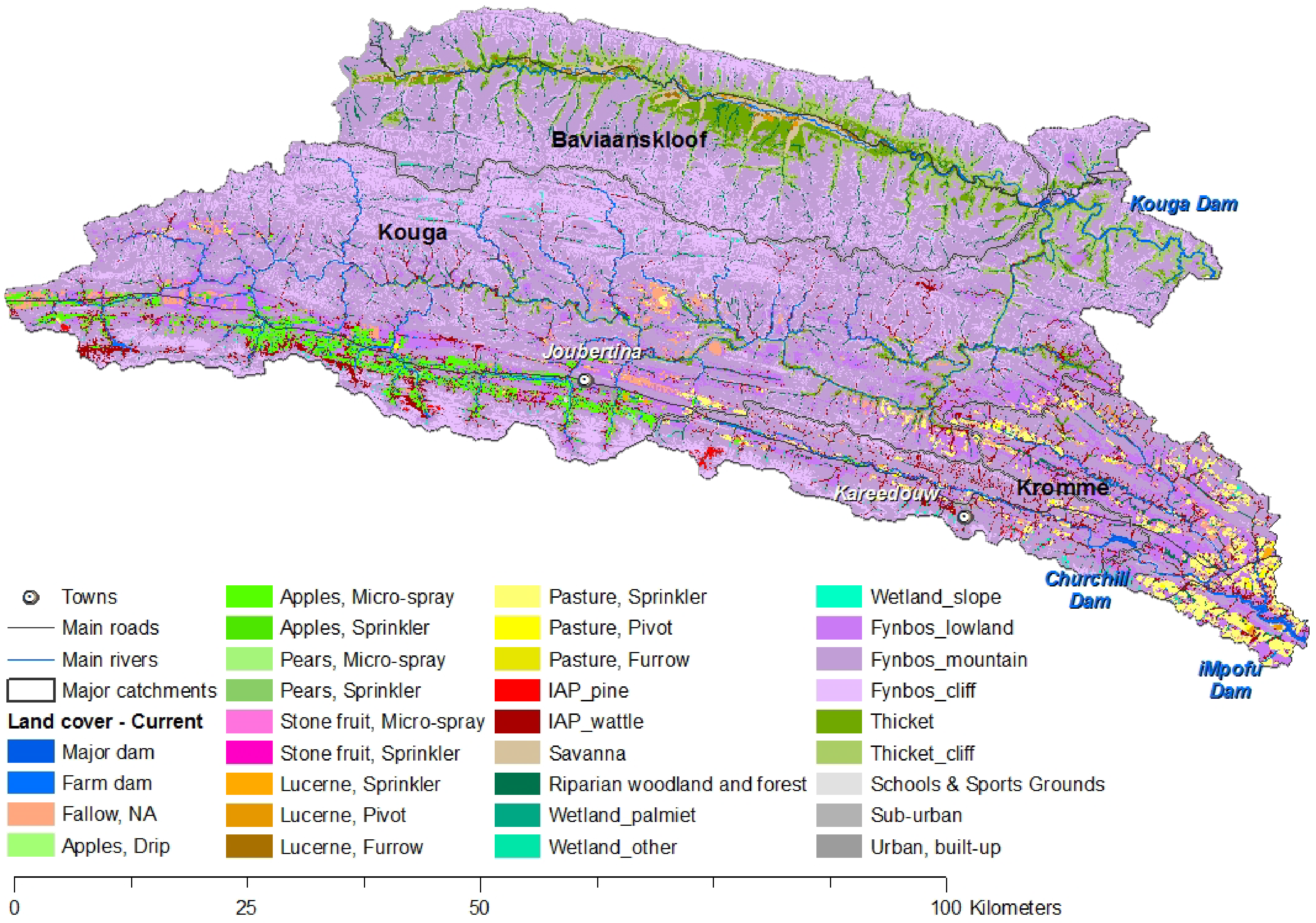


Figure 7-1 Current land cover (2013-2014) baseline map for the Baviaanskloof, Kouga, and Kromme catchments extending to the major water supply dams

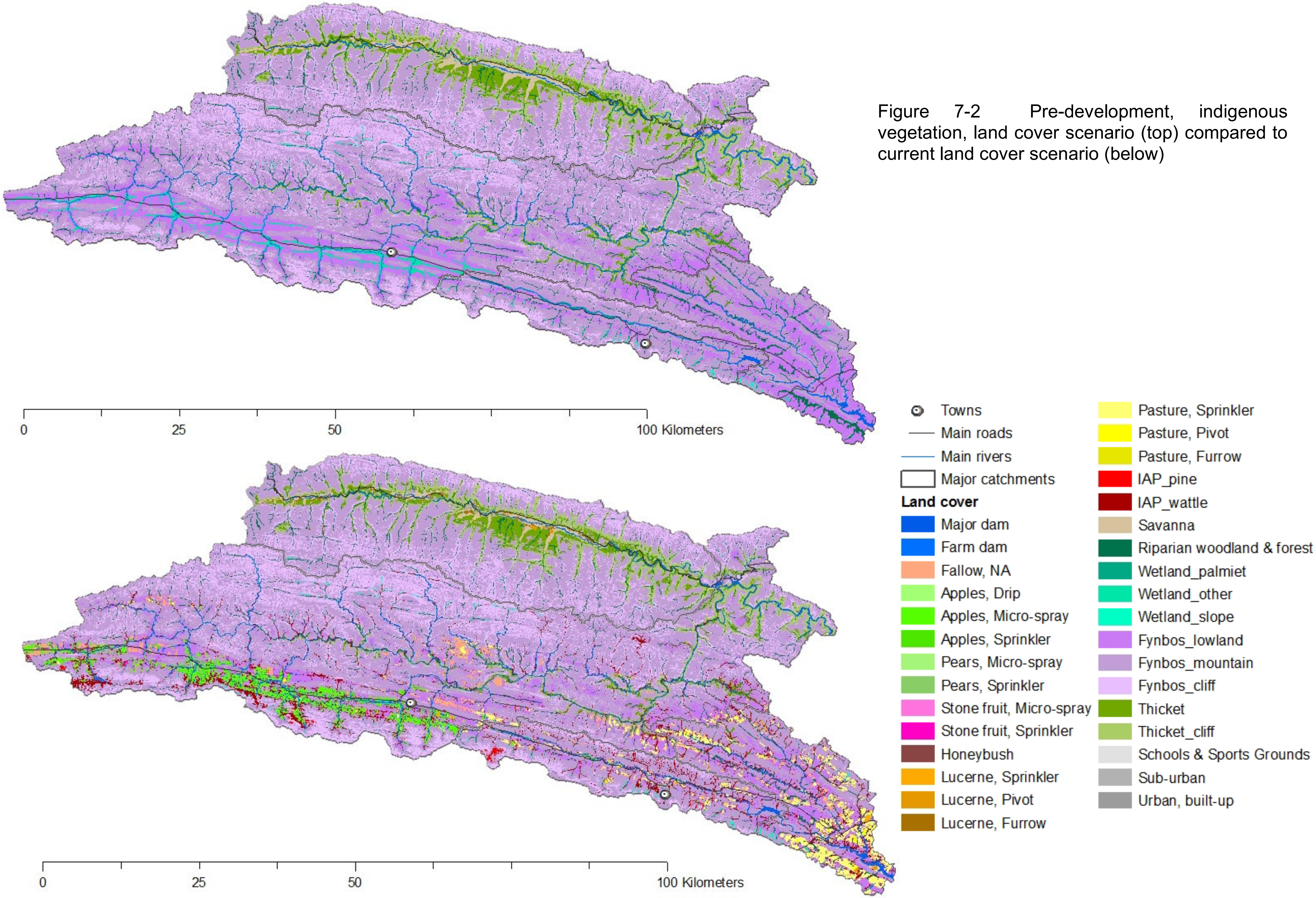


Figure 7-2 Pre-development, indigenous vegetation, land cover scenario (top) compared to current land cover scenario (below)

Figure 7-3 Current land cover scenario (top) compared to assumed maximum IAP extent scenario (below)

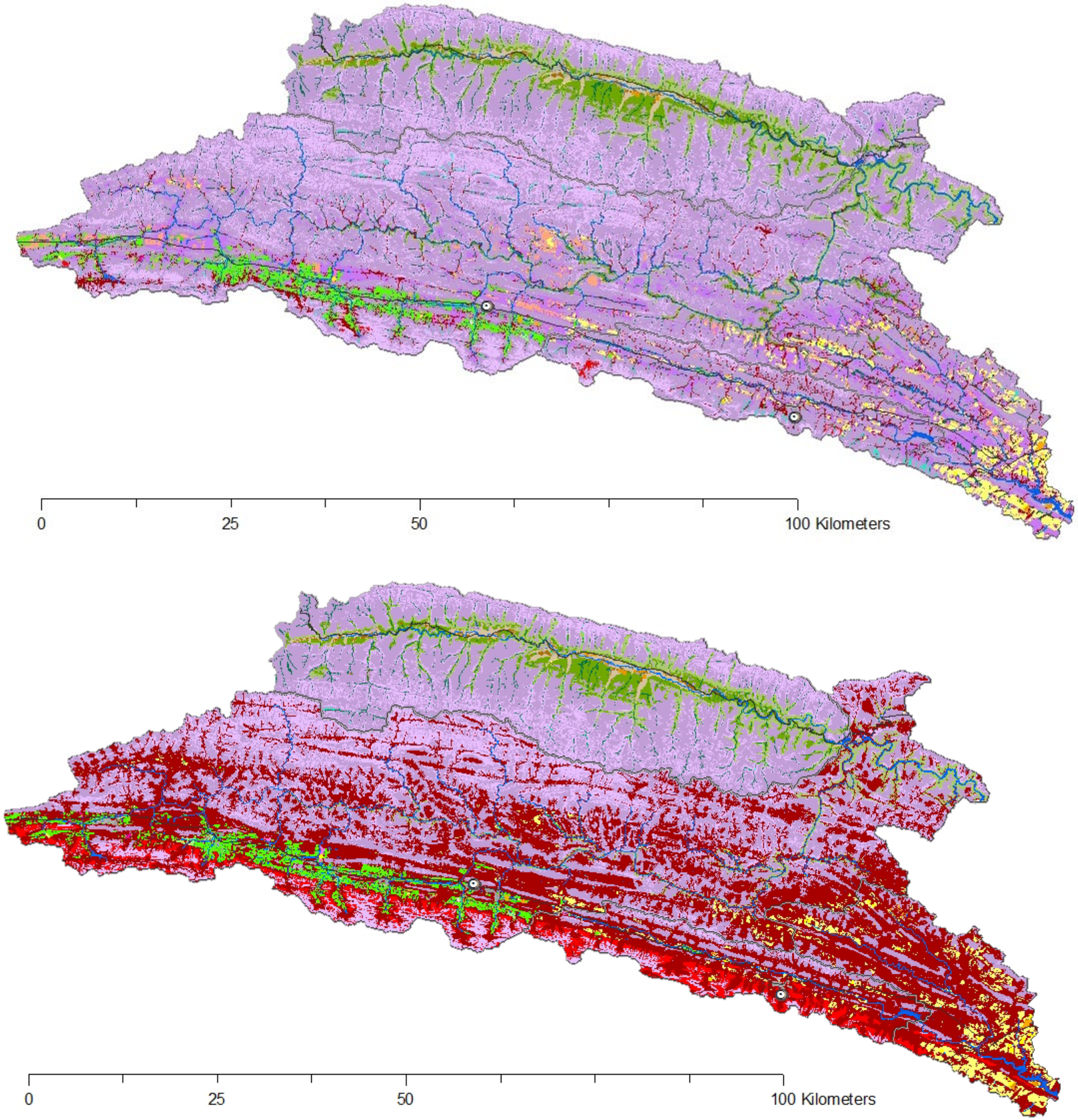
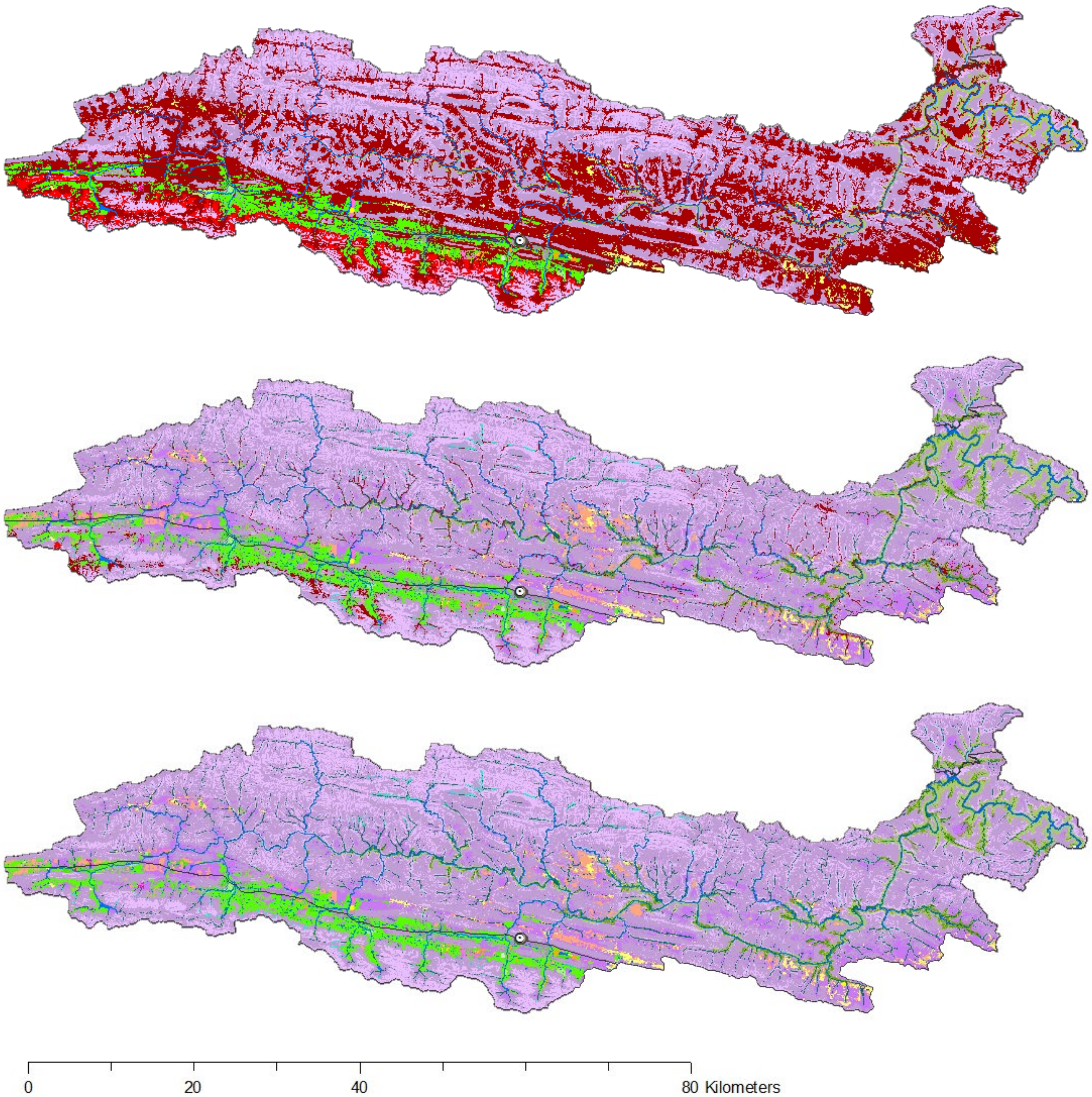


Figure 7-4 Various scenarios of IAP expansion and clearing shown for the Kouga:
clearing only potential agricultural land with expansion of IAP in the mountainous areas (top),
clearing only potential agricultural land with maintenance of current IAP cover in the mountainous areas (middle),
clearing of all IAPs with agriculture replacement on suitable land and indigenous vegetation restored in mountainous areas (bottom)



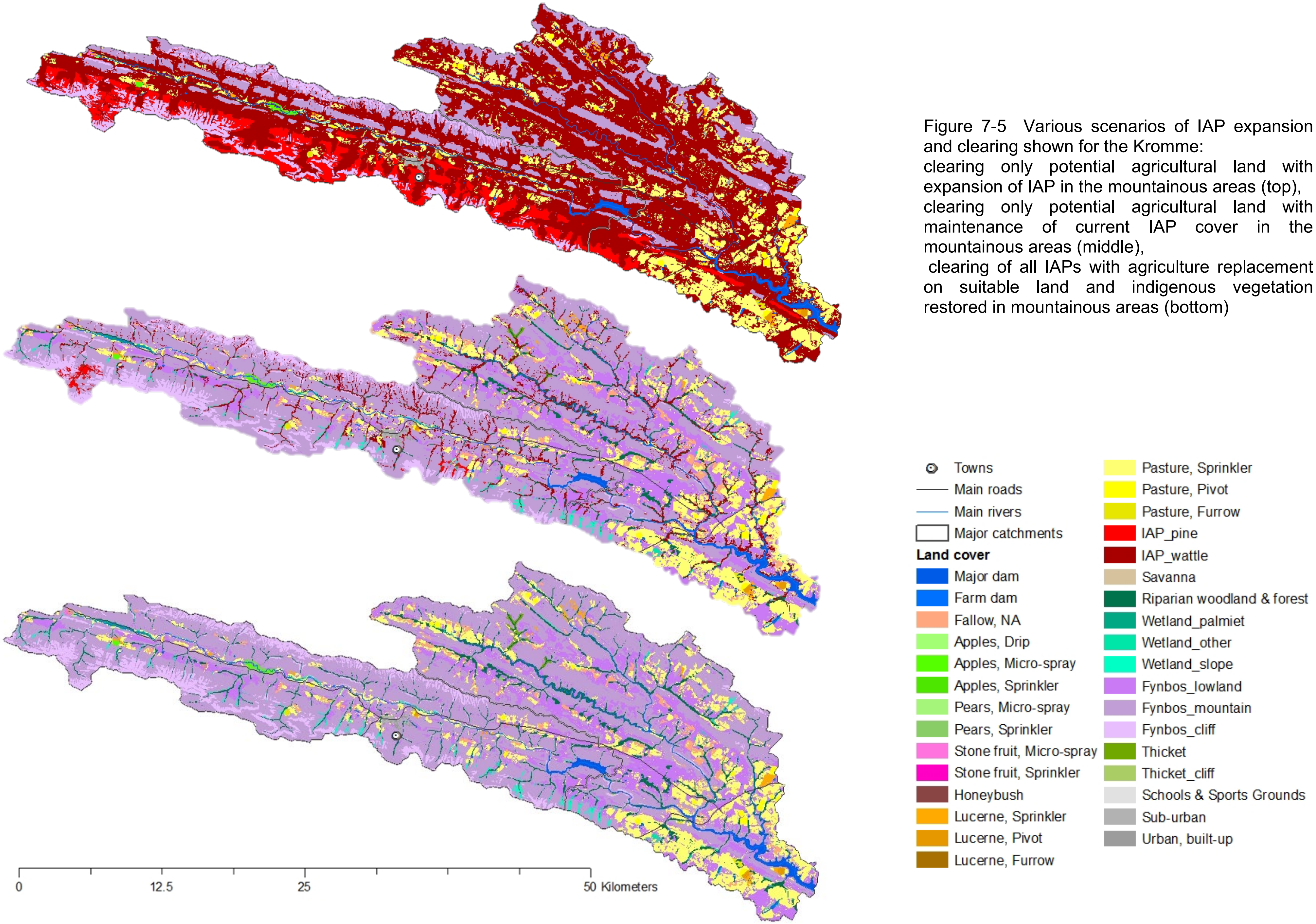


Figure 7-5 Various scenarios of IAP expansion and clearing shown for the Kromme: clearing only potential agricultural land with expansion of IAP in the mountainous areas (top), clearing only potential agricultural land with maintenance of current IAP cover in the mountainous areas (middle), clearing of all IAPs with agriculture replacement on suitable land and indigenous vegetation restored in mountainous areas (bottom)

Figure 7-6 Current land cover scenario (top) compared to assumed maximum agriculture expansion extent scenario (below)

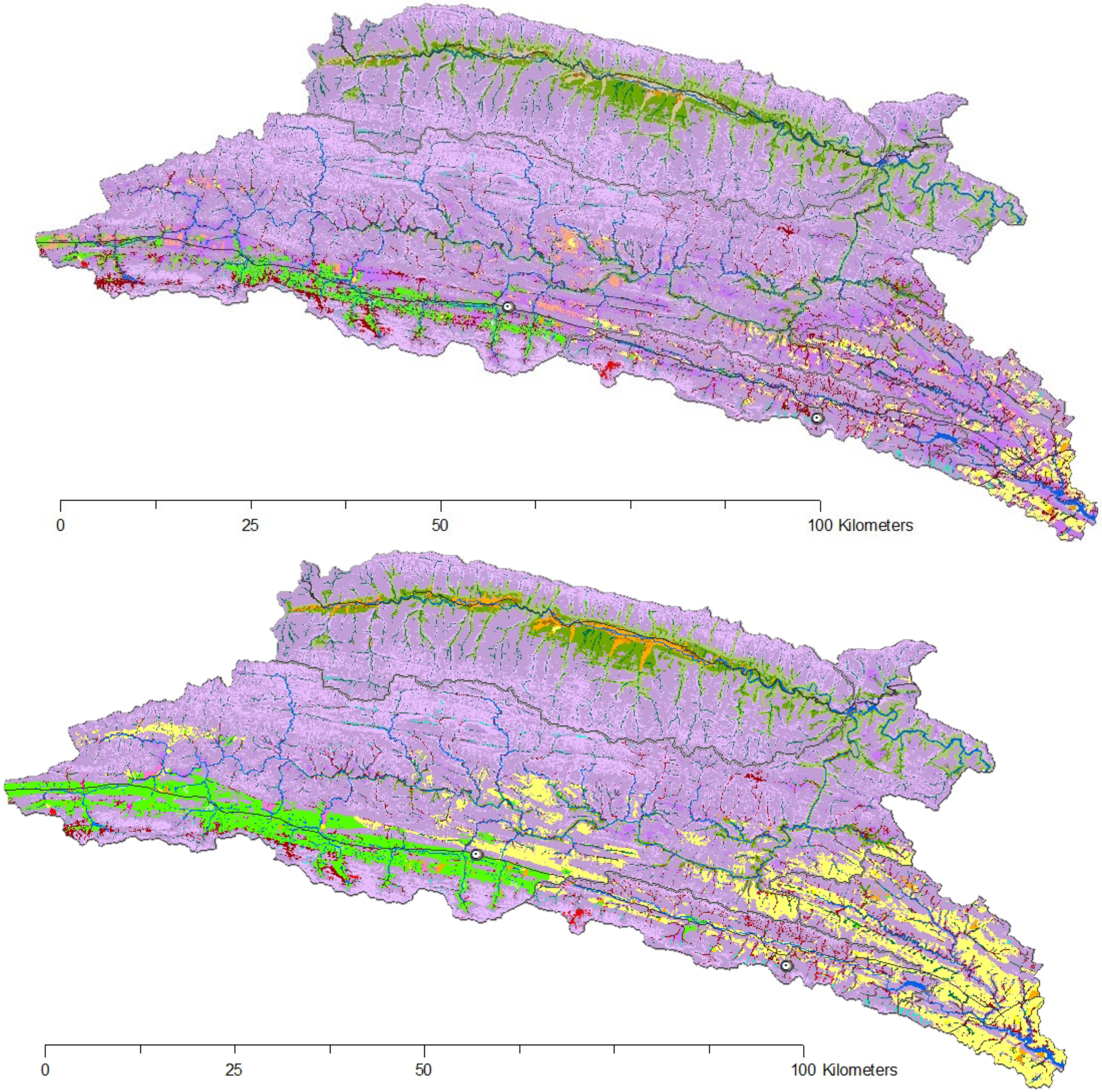
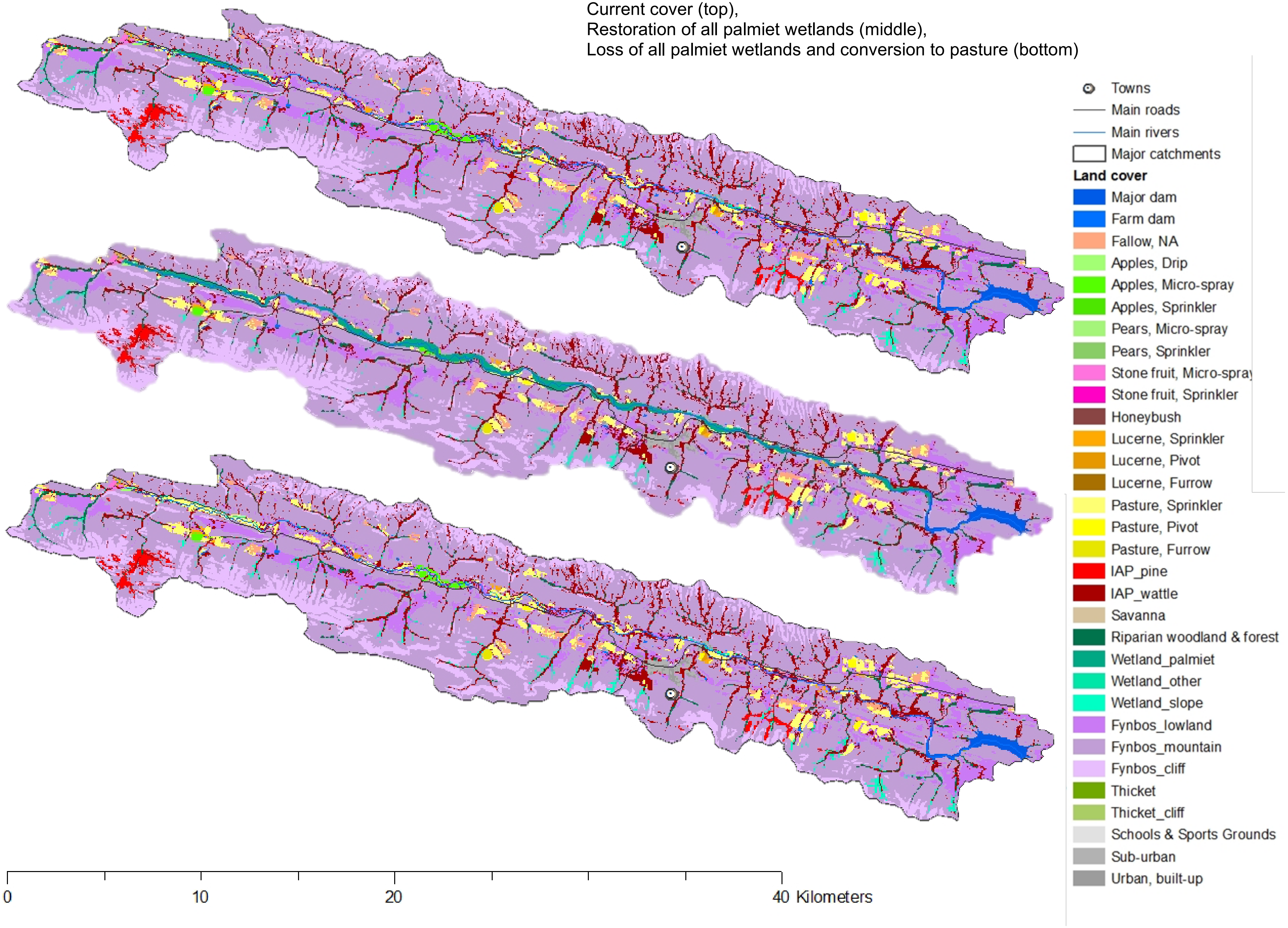


Figure 7-7 Various scenarios of palmiet wetland cover for the upper Kromme:
Current cover (top),
Restoration of all palmiet wetlands (middle),
Loss of all palmiet wetlands and conversion to pasture (bottom)



7.2.3 Agricultural scenarios

Based on topography and access (areas near existing agriculture, and hence roads, etc.), it was estimated that agriculture could expand to cover an additional 294 km^2 in the Kouga and 185 km^2 in the Kromme (Figure 8, Table 10). This includes activation of the 45 km^2 and 19 km^2 areas mapped as fallow in the Kouga and Kromme in the current scenario. Assuming areas were converted to the same agricultural type as the nearest existing field or orchard, there would be significant increase in fruit orchards in the Kouga 145 km^2, but almost equally of irrigated pasture 148 km^2 located in areas further from the R62. The great majority of the increase in the Kromme was assumed to be pasture given the current balance of agricultural cover in the area, however, it may be likely that commercial fruit growing expands there if water supplies are accessible. This expansion would result in the clearing of 31% (35 km^2) and 27% (18 km^2) of the black wattle cover mapped in the Kouga and Kromme catchments in the current scenario. It would also come at a loss of remaining lowland indigenous vegetation types mapped as lowland fynbos and valley wetlands, predicted to lose 72% and 87% in the Kouga and 93% and 100% in the Kromme. This is an extreme expansion scenario, again being explored for illustration purposes.

Stakeholders have taken an interest in the possibility of cultivating honeybush as a relatively high value and low input indigenous crop. This mapping exercise identified about 65 km^2 as potentially fallow agricultural land across the Kouga and Kromme that could be used for honeybush cultivation in the current scenario. A 30 m buffer around river lines passing through currently cultivated areas converted to honeybush would add a minor amount, about 4 km^2, to the honeybush area, but could have important ecological impacts on the river.

7.3 Numerical modelling of the Kromme IAP scenarios

Only numerical modelling of the IAP scenarios of the upper Kromme catchment were completed within the time period of this project. This catchment and these scenarios were prioritized through the Algoa Water Fund Technical Working Group as that likely to have the most significant water yield impacts at the regional scale. Modelling work on the other catchments and scenarios will continue beyond this project as described in Section 7.1. The catchment model structure, parameterization, and performance of the MIKE-SHE model built for the upper Kromme catchment is described in Section 6. To estimate the change in long-term average flows due to either IAP expansion or IAP clearing, the land cover maps created for each scenario were used in the model. The vegetation types and topographic units were assigned the same parameter values as presented in Section 6 (Table 6-2), however the total areas of different the cover-type and land unit HRUs were changed. Models were run using rainfall and PET inputs for 2008-2018 at a daily time-step

Applying the scenario of full expansion of IAP cover to the upper Kromme catchment indicated that this could lead to 24% decrease in average annual catchment yield given the weather conditions estimated for 2008-2018. The model predicted a 5% increase in average annual AET from the catchment, the largest catchment flux, from 550 mm to 570 mm. This resulted in a 9% decrease in the catchment's annual average overland flow and a 27% decrease in average annual subsurface flow output for the modelled period (Table 7-2). This decreased the modelled average annual yield from 40 Mm^3 to 30 Mm^3 for 2008-2018. This 10 Mm^3 decline is equal to 47% of the total volume of the Churchill Dam and 12% of the total water allocation to the Nelson Mandela Municipality (NMM) across all sources in the Algoa Water Supply System (AWSS). The magnitude of the predicted declines in outflow varied across the time period (Figures 7-8 and 7-9). The largest volumetric declines were in wetter periods and largest percentage declines in drier periods in general. However, the decline in flow was tied to rainfall event magnitude and timing which was highly variable over the time period. The total rainfall for a year alone was a poor predictor of the magnitude of change in flow due to IAP expansion.

Modelling the complete clearance of IAP cover, with replacement by agriculture in low slope areas and indigenous vegetation elsewhere, was predicted to increase average annual catchment yield by

1 Mm^3 or 3% given 2008-2018 weather conditions. This is equivalent to 6% of the Churchill Dam volume and 2% of the total supply to the NMM. Predicted annual catchment AET declined by 1% from 550 mm to 546 mm, resulting in a 4% increase in the predicted annual average subsurface flow (Table 7-2). There was little predicted change in the overland flow output compared to the current cover scenario. As with the IAP expansion scenario, changes in predicted flow compared to current cover varied over time with the largest volume increases generally occurring during wetter periods and the largest percentage increases in drier (Figure 7-8). In the most extreme drought periods (2009 and 2017), so little runoff was predicted that the vegetation cover made almost no difference. In dry years following wetter years, such as 2013 and 2016, vegetation cover water use was predicted to impact the receding higher flows causing larger percentage changes in outflow (Figure 7-9).

Table 7:2 Modelled average annual water balance for the upper Kromme catchment for 2008-2018 applying different land cover scenarios

Water balance component	**Modelled annual average catchment water flux (mm)**		
	Current cover	**IAP Clearing – farming & restoration**	**IAP Expansion**
Precipitation	651	651	651
Actual evapotranspiration (AET)	550	546	575
Runoff	102	105	77
Overland flow	*12*	*12*	*11*
Subsurface flow	*90*	*93*	*66*

It should be noted that, given the estimated evapotranspiration coefficients for vegetation types, it is likely water yields from IAP clearing would be higher if fewer areas cleared of IAPs were used for irrigated agriculture. However, the scenario of farming after clearing on lower slope areas was selected for this initial modelling attempt both as a conservative estimate of the potential water benefits to the downstream reservoir users and as a conservative prediction regarding the likelihood of maintaining IAP clearance based on stakeholders' discussions. Many expressed that areas which were then farmed were more likely to remain cleared of IAPs in the long-term.

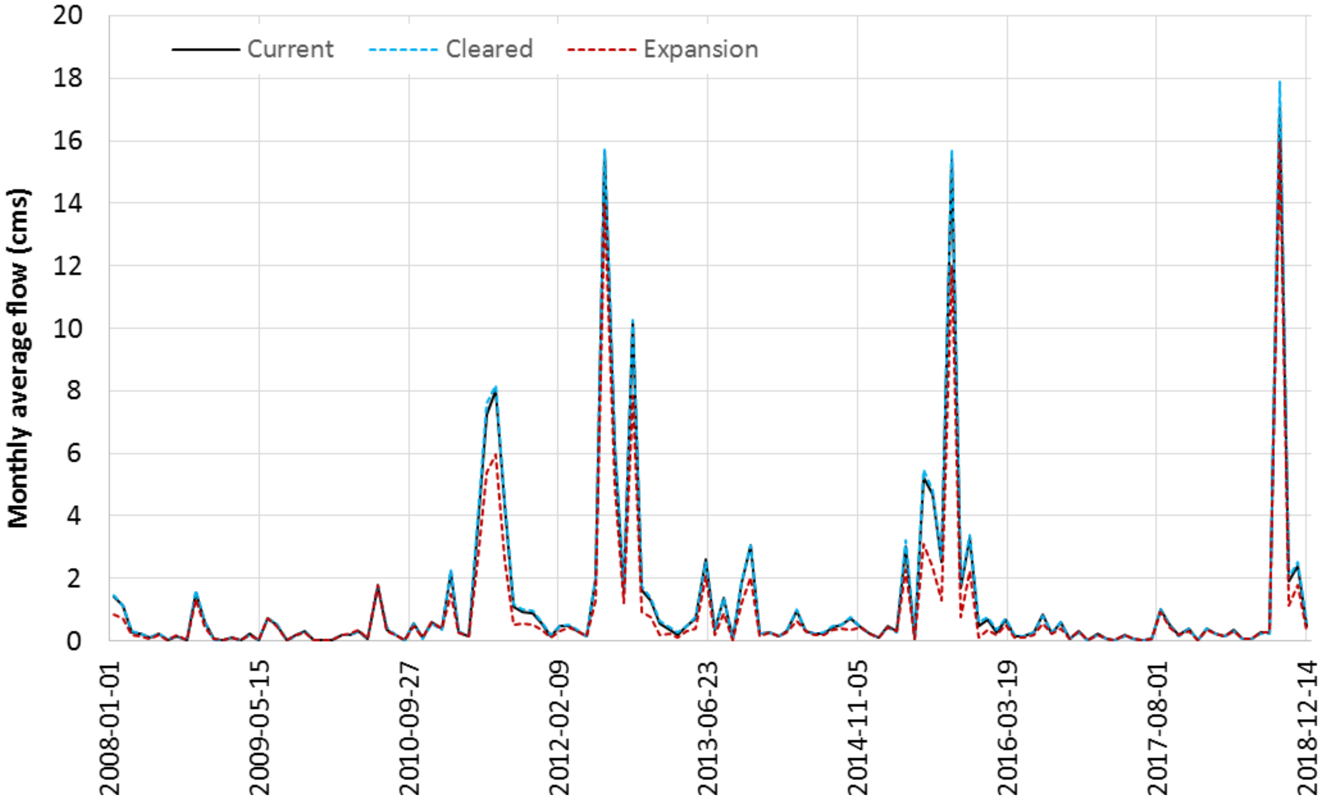


Figure 7-9 Modelled monthly average flow from the upper Kromme catchment for 2008-2018 applying different land cover scenarios: current cover scenario, IAP expansion, and complete IAP clearing with a mix of farming and restoration as replacement covers

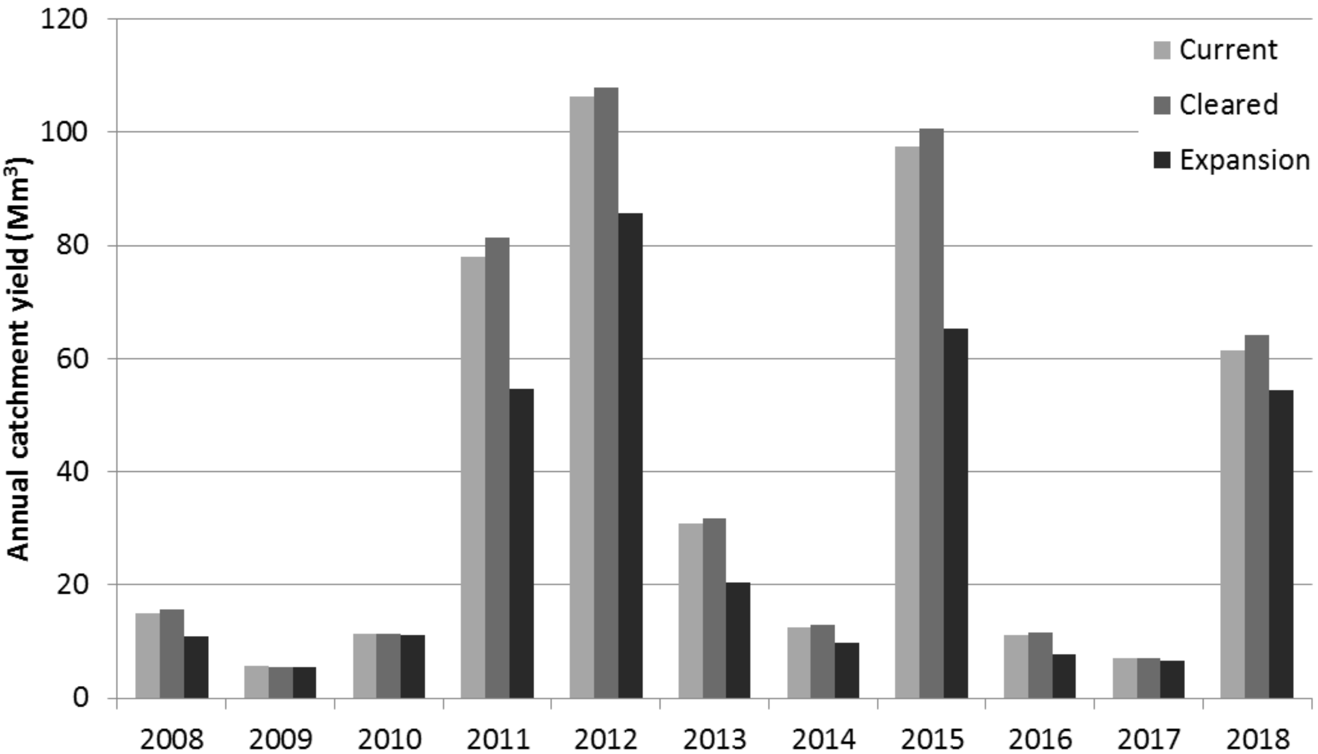


Figure 7-8 Modelled annual catchment yield from the upper Kromme for 2008-2018 applying different land cover scenarios: current cover scenario, IAP expansion, and complete IAP clearing with a mix of farming and restoration as replacement covers

7.4 Implications for catchment management

Interactions with stakeholders suggest that local decision makers see opportunities for a wide variety of future land and water management scenarios in the BKK. There wasn't a deterministic sense of a future trajectory in terms of IAP cover or farming practices. Many drivers of change were brought up in discussions and there was an overall awareness expressed of the need to adapt to climate variability, increasing unpredictability in water availability, and socio-economic drivers to achieve sustainability. There was divergence in ideas on what form this would take and the likelihood of different future land cover options, such as achieving complete IAP clearance for example. This can be seen as a fertile space for ongoing discussions about what a preferred future would look like and how to get there.

The process of mapping different land cover scenarios discussed by stakeholders highlighted the relative magnitudes of change in cover that might occur in different parts of the BKK and the spatial arrangement of this. This provided a discussion point for stakeholders to consider the overall impacts of changes on the catchment scale water balance.

More quantitative estimates of the scenarios developed were produced for the IAP expansion and clearing scenarios for the upper Kromme catchment feeding the Churchill Dam, suggesting the potential for important impacts on water supply. Modelling suggested that uncontrolled expansion of the IAP cover in the catchment could reduce average annual catchment yields by as much as 24%, equivalent to 12% of the total water supply to NMM. Clearing and maintaining the clearance of the remain IAP area in the catchment could increase average outflow by 3%, or more depending on the resulting land cover of the cleared areas. The suite of benefits of different replacement covers after IAP in different locations, terms of maintenance, agricultural production, and other ecosystem services is being explored by stakeholders through ongoing research and facilitation with Living Lands and the Algoa Water Fund.

7.5 Uncertainties and suggestions for future work

The process of mapping the land cover scenarios and building the catchment models highlighted a number of important uncertainties in input data that could be address through future monitoring and research. Addressing these would further improve the accuracy of conceptual and numerical models and understanding of the likely implications of future changes in these catchments. As mentioned in Section 7, further quantification of the spatial distribution of rainfall in these highly heterogeneous catchments is needed. The process of creating scenario land cover maps also highlighted the need for improved land cover mapping at the local scale as there was no pre-existing map of verified IAP cover across the entire region of interest. Mapping this using remote sensing analyses with ground-truthing at regular time intervals would be highly beneficial.

There were recognized uncertainties in the mapping of current, pre-development, and future scenarios of land cover. For the current cover mapping, combining existing data sources, key uncertainties include:

- Differentiation of IAP cover from other woody vegetation types (indigenous forest, woodland, and thicket)
- Identification of specific crop and irrigation types (e.g. Apples vs. Stone-fruit, drip vs. Micro-spray) within the broader classes (e.g. orchard vs field).

Uncertainties in areas of these key cover types influence estimated vegetation and irrigation water use. However, at a higher-order level of impact, correctly mapping the treed cover types compared to lower vegetation is likely more critical to estimating landscape scale water use than the sub-divisions within treed and less woody types. Land cover is dynamic over relatively short time periods: cover changes constantly due to its rapid growth, clearing, and fires. Agricultural cover also changes rapidly, as orchards are rotated or refreshed, fields may be left fallow in one year and used the next, etc. Therefore the goal was to achieve a roughly representative distribution of these cover types for the current decade.

In creating the future scenarios, simplified assumptions were made about:

- Areas and topographic positions where IAP vegetation could colonize and its ability to spread in any direction.
- Areas suitable for different crop types and what is likely to be farmed in the future.

These were made based on stakeholder discussions and field observations, but would benefit from more detail vetting. This will occur through ongoing stakeholder engagement and the Algoa Water Fund Technical Steering committee.

Despite the identified uncertainties, and the need to quantify their likely ranges in future work, the outcomes of the scenario modelling process did yield helpful outcomes in terms of consideration of the magnitudes of likely changes in land cover and water yields. Discussion, visualization, and quantification of these potential pathways using the best currently available data has been a productive step towards participatory and informed catchment management planning.

8. POLICY IMPLICATIONS

8.1 Capacity for facilitation of stakeholder engagement in CMFs

The National Water Resource Strategy (NWRS-2) supports the National Water Act (NWA) for the establishment and transformation of institutions to assist DWS in giving effects to its core mandate – the development, protection, conservation and allocation of water resources, and regulation of water services and water use.

Chapter 8 of NWRS-2 provides for the establishment of Catchment Management Forums (CMFs). These forums aim to promote, improve and strengthen a value-driven and integrated approach to water resources management at local water management areas. CMFs are entities which are not statutory and consist of interested and affected stakeholders. A commitment is made by NWA and NWRS-2 to enhance transparent and effective participation in catchment management which include the empowerment of previously marginalised stakeholders.

This project significantly contributes to the development of a framework which ensures effective participation and representation of stakeholder groups in catchment management. A great need exists for platforms that are accessible and promote equity and a conducive, respectful space for social learning. One of the crucial elements in this framework is facilitation. Capacity should be built to effectively support long-term stakeholder engagement which includes deep listening, evaluation of social learning and sensitive facilitation of collaborations which contributes to land and water management on catchment scale. During stakeholder engagement in this project, three platforms emerged, which shows the need for smaller forums, representative of an area, which can feed into larger ones. One of these learning platforms has the ability to fulfil the needs of a CMF in the area. The other two platforms are not effective substitutes for CMFs, but can assist in knowledge exchange and awareness. Communication skills are required in a variety of languages representative of the area. The engagement tools suggested in this project, based on the Theory U, provides effective ways in which social dynamics can be addressed and comfortable, safe-spaces can be created to increase social cohesion and learning. Local CMF officials have been involved in the stakeholder engagement of this project and basic introductions were made for the set-up of these forums in the BKK catchments. Policies should be developed to include the suggested framework to increase the capacity for facilitation of stakeholder engagement which supports CMFs.

Tools for stakeholder engagement based on the Theory U framework:

- *Dialogue interviews – concerns deep listening in one-on-one interactions*
- *Learning Journeys – Site visits with a variety of stakeholders with embedded reflection to stimulate new ideas and create different perspective*
- *Meetings – formal gatherings for knowledge exchange*
- *Workshops – group events for collective brainstorming and exploration*
- *Informal gatherings – casual group events which stimulate discussion and feedback*
- *Photovoice – using pictures to lure reflective discussion at workshops, meetings and dialogue interviews*

Policies can influence land- and water use in various ways. This section aims to answer the question; 'How might existing and future government policies and institutional arrangements lead to the scenarios explored through this modelling process?'

8.2 Water Reforms

There is much political concern and pressure to ensure that the historical inequalities in access to water are redressed. This is a major requirement of the Water Act and includes also ensuring that enough water is left in the river systems to ensure the healthy functioning of the aquatic ecosystems.

The DWS is currently implementing a verification and validation (V&V) process for existing registered water uses, and determining (through consultation) the required ‘management classification’ of these river systems. In the BKK the V&V process began in 2014 in the top third of the Kouga catchment. DWS plan to role this process out to the rest of the BKK catchments within the next 3-5 years.

One of the difficulties DWS experiences in making decisions around applications for dams and new water licences is a lack of information about how much water is available and how much is already being used (legally and illegally). While the registered rights and use of water by farmers in the governments Gamtoos irrigation scheme are known and regulated, those for the upper catchment farmers are not known or regulated. Their registered water uses are only now beginning to be checked and verified and this is proving to be a difficult task and does not actually give them information on how much water is actually being used. Some farmers indicate that they are also not comfortable with the idea of sharing this information with DWS due to fears about their water allocations being cut.

8.3 Water losses due to IAP and land degradation

Water losses from the spread of IAPs is another factor that is threatening water security. This continues to be a considerable problem in the Kouga and Kromme. The WfW programme has not been able to keep pace with the spread of these plants and new ways to expand the programme (such as land owner incentive programmes) are being sought to address this.

The change in hillslope vegetation cover, loss of wetlands and changes to the river channels from agricultural and other social activities have also changed the hydrological flow dynamics in the rivers to the current state where there is very little if any flow in the BKK rivers during the dry periods, but large intense flood flows during significant rainfall events. This is partly because many wetland areas, and the natural channel dynamics, which would slow down the flow of the water in the system, have been lost. Land degradation and fires also reduce the infiltration of rain water into the ground and increase surface runoff and contribute to these drought/flood dynamics.

8.4 Governance and collaborative capacity

In terms of water governance, the area can be characterised as being in-between an old system of water administration (based on land ownership) and a new one (based on state ownership of water) that has been made law and is slowly being implemented. DWS has recently initiated the process of setting up the new water governance structures required under the Water Act (1997) such as the CMA and CMFs that need to involve all the key water users and stakeholders. In 2016, the CMA for the Umzimbuvu to Tsitsikamma area was approved by the Minister and the Proto CMA set up in April. The process of establishing the CMFs is in its infancy. The CMF for the Kouga is one of the Proto-CMA’s priority areas in the province.

Interaction with policies could lead to or inform response to climate variability and change (i.e. droughts and drought frequency) and local and international markets (i.e. determining the value of agricultural produce, cost of production and transport). It is important to engage with specific policies and stakeholders in this regard. Policies and strategies which affect land- and water use in the BKK include:

- Conservation of Agricultural Resources Act 43 of 1983
- Environmental Conservation Act 73 of 1989
- Disaster Management Act 57 of 2002
- Mountain Catchment Areas Act 63 of 1970
- National Environmental Management Act 107 of 1998
- National Environmental Management: Biodiversity Act 10 of 2004
- National Environmental Management: Protected Areas Act 57 of 2003
- The Biodiversity Act
- National Water Act 36 of 1998
- Algoa Water Supply System Reconciliation Strategy
- National Water Pricing Strategy

- Green Economy Strategy
- Municipal Integrated Development Plans (IDP) for upstream and downstream municipalities in the area: Sarah Baartman District Municipality, Kou-Kamma Local Municipality (Kouga and Kromme), Dr Beyers Naude Local Municipality (Baviaanskloof), Kouga Local Municipality (Gamtoos irrigated area and towns) and Nelson Mandela Municipality
- Internal policies and Global Gap guidelines (e.g. Woodland's Dairy guidelines, Du Toit's policies on irrigation management, etc.)

Stakeholder groups and institutions who form part of the governance structure and inform policies and strategies on land and water management include:

- The Algoa Water Fund group
- Catchment Management Forum
- Gamtoos Irrigation Board
- Water Users Associations
- Algoa Water Supply Reconciliation Steering Committee
- Municipal government departments
- Department of Water Affairs
- Department of Environmental Affairs (particularly Natural Resources Management branch)
- Department of Agriculture
- Department of Rural Development and Land Reform

The following inputs to policies and institutional collaborations could lead to the scenarios explored through this modelling process;

Table 8:1 Inputs to policies and institutional collaborations

Theme	Scenario	Policy change/enforcement	Key Institution
Palmiet wetland extent	Increase	A payment for ecosystem services model is promoted though the National Water Pricing Strategy and the Biodiversity Act (Tax benefits for biodiversity stewardship). Foregrounding this may lead to rehabilitation of palmiet wetlands	DWS DEA:NRM EPWP
	Decrease	If no sustainable funding models are promoted or applied rehabilitation of wetlands is not feasible.	WaterFund DEA:NRM
Invasive Alien Plant (IAPs) extent	Increase	A lack of support/implementation of the DEA: NRM Working for programmes and a lack of enforcement of NEMBA on clearing IAPs on private land will allow the spread of IAPs.	Dept Agri DEA NRM
	Decrease	Land user incentive: value added-business opportunities; free herbicide for IAPs; tax benefits for clearing are all factors which support the clearing of IAPs	DEA: NRM Dept Agri EPWP
Agricultural land extent	Increase	Green Economy growth Climate Smart Agri growth Export produce promoted	Dept Agri DEA Dept Economic Development
	Decrease	The Biodiversity Act (i.e. tax benefits for biodiversity stewardship) and the National Water Pricing Strategy: limit irrigation and water use including water restrictions could lead to the decrease in agricultural land use.	DWS DEA

9. CAPACITY BUILDING

The BKK catchments cover a large area which includes a great variety of stakeholders with a vested interested in the management of these catchments. During this project many different institutions and stakeholder groups were involved, even internationally, to improve data collection, enhance social learning and improve the accuracy of the model. Capacity building was done by training and mentorship of students as well as creating learning platforms for diverse stakeholder groups to participate in knowledge exchange activities.

The following stakeholder groups were involved in this project:

- **Individual catchment residents:** large-scale commercial farmers, small-scale farmers, emerging farmers, non-farming residents, teachers, etc.
- **Agricultural community groups**: Baviaanskloof Hartland Conservancy; Eastern Cape Agriculture; Gamtoos Farmers Association; Langkloof Honeybush Working Group; Sewefontein Trust; Tchnuganoo Community Farm
- **Civil society organisations**: Conservation Outcomes – Greater Kromme Stewardship Group; Garden Route Biosphere Reserve; Living Lands; The Nature Conservancy
- **Experts and consultants**: water management engineer, agricultural advisor, honeybush cultivation consultant, nursery specialist
- **Government institutions:** Department of Economic Development Environmental Affairs and Tourism (DEDEAT); Department of Environmental Affairs: National Resource Management (NRM); Department of Water and Sanitation: Catchment Management Agency (CMA); Department of Water and Sanitation: Strategic Catchment Management; Eastern Cape Parks and Tourism Agency (ECPTA)
- **Government Programmes**: Working for Water
- **Irrigation boards and fire protection associations**: Gamtoos Irrigation Board (GIB); Sarah Baartman West Fire Protection Association
- **Municipalities**: Koukamma Municipality; Nelson Mandela Bay Municipality: Water Management and Bulk Supply
- **Research institutions**: University of the Western Cape; South African Environmental Observation Network (SAEON); Nelson Mandela University; Radboud University Nijmegen; The Hague University of Applied Sciences; University of Amsterdam; Van Hall Larenstein University; Wageningen University
- **Business sector**: Coca Cola Company; Grounded; Port Elizabeth Business Sector; Tsala Pty Ltd; Woodlands Dairy: Sustainability Department; Santam Ltd

With such a large group of stakeholders involved it is hard to find the exact measure in which capacity was built. That said, some tangible outcomes of this capacity building can be named:

- Two students involved in this project obtained a master's degree
- One student obtained a PhD and became part of the Reference Group of this project
- Two students will obtain a masters and PhD respectively in the coming year.
- Participation at group events led to collaborations which resulted in training of several individuals for rehabilitation activities.

The following table depicts the list of students who were involved in this project. Students were provided with training and mentorship.

Table 9:1 List of students trained or mentored during this project

No	Name and Surname	Institution	Qualification	Conferences/workshops/articles	Contribution
1	Faith Jumbi	University of the Western Cape	PhD	Africa Groundwater Network Uganda	Workshop
				Agulhas research open day 2017	Poster
				Waternet symposium Namibia 2017	Presentation
				SAEON graduate student network - Hoedspruit	Presentation
				SAEON newsletter June 2017	Article
				All Living Lands workshops and learning journeys 2017-2019	Participation
2	Pamela Sekese	University of the Western Cape	MSc	Southern African Association of Geomorphology July 2017	Poster
				SAEON newsletter February 2018	Article
				WaterNet/WARFSA/GWP-SA Symposium October 2018	Presentation
				National Wetland Indaba October 2018	Presentation
				Short Course on Instream Flow Assessments May 2019	Participation
				All Living Lands workshops and learning journeys 2017-2019	Participation
3	Current Masunungure	Nelson Mandela University	MSc	Alien Clearing Learning Journey	Participation
4	Daniek Bosch	Radboud University Nijmegen	MSc	Alien Clearing Learning Journey	Participation
5	Noud van Dam	Wageningen	BSc	Alien Clearing Learning Journey	Participation
6	Job Kwakernaak	Wageningen	BSc	Introduction Workshop	Participation
7	Marijn Geerts	Van Hall Larenstein University	BSc	None	
8	Martijn Nettenbreijers	Van Hall Larenstein University	BSc	None	
9	Tobias Otten	The Hague University of Applied Sciences	BSc	Sensemaking Workshop	Participation
10	Quirine van der Meer	Nelson Mandela University	BSc	None	
11	Jara Birkholtz	Avans University of Applied Sciences	BSc	Sensemaking Workshop	Participation
12	Roos van der Deijl	University of Amsterdam	MSc	Algoa Water Supply meeting	Participation

10. TEAM LEARNINGS: CHALLENGES AND RECOMMENDATIONS

Using the development of a hydrological model as a boundary object to support integrated catchment management is feasible, however, many challenges were experienced related to context specific elements that need to be considered. Collaborating and complementing other initiatives is key to the success of such a participatory approach and its outcomes. A considerable amount of time is needed to fully integrate with the landscape, therefore long-term, systems thinking must be employed.

10.1 Challenges

The following challenges were experienced during the project;

- **Power dynamics at group events:** By bringing stakeholders from different ethnic groups together in a room, presented power dynamics. Some stakeholders were dominating the conversation where other stakeholders did not get enough opportunity to present their opinion. Dealing with power dynamics that come from a long history of inequality in South Africa, takes a lot of experience and skill. Although group events did not present too severe situations, a lack of experience with facilitation of power dynamics in the team was a challenge.
- **People operate on different scales:** A great variety of stakeholders participated in this project. Some work on farm scale where others work on provincial scale. Since each of these participants operate in a different frame of mind, challenges often occurred in communicating the applicability of this model to the variety of people present in a room. Although this model operates mostly on catchment scale, inputs are needed from a variety of scales to improve the accuracy of the outputs.
- **Communication barriers:** A crucial element for social learning to occur is effective communication. By involving a great variety of stakeholders with different professions in this project many challenges occurred regarding the communication of information. Not only did participants speak different languages (English, Afrikaans and IsiXhosa), they also use jargon related to their profession (scientific terminology versus words used by practitioners).
- **Inconsistency of participation:** The BKK catchments are large and geographically isolated. To the project team's ability, representative and key stakeholders were identified and involved in several ways, but many barriers caused participation to be inconsistent. These barriers include a mismatch of participants' time-schedules, travel distances to workshops and meetings and the lack of communication devices or means of communication (no email, phone or reception). This greatly inhibited social learning and relationships were lost and collaborations disintegrated. No progress was made in the understanding of hydrological modelling and the applicability thereof.
- **Obtaining existing data from various sources:** It was anticipated at the start of this project that certain existing data, for example data on IAPs, will be easily retrievable from government institutions. This, however, brought upon a variety of challenges. This data is not stored in one place and it cannot by retrieved from one source, but are kept by many different institutions with different data agreements. The data itself also occurred in many different formats, which added to the time for processing of the data.
- **The current drought:** During the time-period of this project a severe drought occurred in the catchments. Many challenges occurred in obtaining enough data to effectively calibrate the model.

10.2 Recommendations

These challenges added to a wealth of learnings which the team obtained during this project. The following lessons were learned during this process and should be taken in to cognisance for future work and project development;

10.2.1 Complementarity and collaboration with other projects

The approach to develop the hydrological model should complement other initiatives in the area. Co-ordination of meetings and the sharing of data should be carefully facilitated. Flexibility in timelines is crucial.

10.2.2 Ensure diverse language and communication skills

A two-fold challenge presented itself in this project: 1) translating scientific hydrological terminology to a wide range of practitioners, 2) translating between English and Afrikaans during fieldwork and feedback sessions. It is important to take the time to translate information to suit the audience and using visual communication tools facilitates this process.

10.2.3 Trustworthy relationships

It is crucial to acknowledge power dynamics and to attribute enough time to building trust especially in regard to the data gathering process.

10.2.4 Build capacity for monitoring of social learning

Social learning occurs continuously through the duration of the project. It is important to assign at least one person in the team to take responsibility to monitor and capture social learning. Baseline and follow up data will also strengthen results.

10.2.5 Beware of the "tyranny" of participation

Participatory modelling involves asking stakeholders to share their perspectives in a group. Since your perspective could relate closely to your personal worldview, this may lead to feeling of anxiety for participants. This extreme experience during group events is described by literature as the "tyranny" of participation. It is important to be sensitive to this and crucial to create a space where people are respectful of each other's worldviews during an event.

10.2.6 Matching the different scales

Each stakeholder group involved in the project operate on a different scale. It is important to identify on which scale each group operates. When communicating results, take note to match it with the scale in which the stakeholders think and implement.

10.2.7 Matching the different time schedules

Each stakeholder group has a different time schedule with important dates according to their profession. For example, farmers function at different timeframes during harvest seasons, as do academics during examination periods. At the start of the project, it is helpful to map these time schedules so that events and deadlines can be planned accordingly.

10.2.8 Allocate enough time for gathering data

To develop a conceptual model for three large catchments requires a lot of data. To obtain and process this data across many institutions was challenging and took more time than originally planned. This did however, presented the opportunity to engage with a variety of parties which contributed to the engagement process and network building.

10.2.9 Start with smaller areas to ensure faster feedback to stakeholders

Regular feedback to stakeholders is crucial for building trust and maintaining interest. Starting with smaller areas speed up processing time which can greatly contribute to feedback to stakeholders.

10.2.10 Field data collection create opportunity for stakeholder engagement

The collection of field data on private properties presented many more opportunities to engage with stakeholders and greatly contributed to knowledge engage and social learning. It was very valuable to combine field collection activities with social learning evaluation.

11. ONGOING WORK IN THESE CATCHMENTS

11.1.1 Learning platforms

By making use of the Algoa Water Fund, the Honeybush Cultivation Working Group, and the Baviaanskloof Hartland Conservancy platforms, and hopefully localized CMFs, Living Lands aims to co-develop and prototype initiatives which contribute to water security in the area. As the platforms were initiated by some of those who were part of the model development process, these platforms will assist to effectively distribute the outcomes of the model. This will inform strategic planning for the BKK catchments in the future. A rich knowledge network with key stakeholders from public and private parties now exist to inform new initiatives and promote social learning going forward. By involving business, these learning platforms could also assist in developing more redundancy in finance of rehabilitation projects in the future.

Further review of the conceptual and numerical models developed here against continued data collection, and further stakeholder engagement with the assumptions made in modelling, will serve to improve its realism and usefulness to stakeholders over time. It is anticipated that this is a process that can continue through the Algoa Water Fund using the start that this project has made. Some key areas for future development that were highlighted in this process was the need for improved land cover mapping, particularly with regards to invasive alien vegetation, and further assessment of the influence of different model representations of water diversions and irrigation practices on overall water supply prediction outcomes.

11.1.2 Model inter-comparison project

Efforts to assess what numerical catchment modelling software tools would have the capability to represent the desired conceptual model of catchment processes, and represent the catchment changes of interest, inspired the proposal for a further WRC project (K5/2927): “Critical catchment hydrological model inter-comparison and model use guidance development.” This project will include modelling multiple catchment case-study areas, including the BKK with multiple modelling tools and comparing them in order to provide guidance for future modellers.

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13. APPENDICES

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A. RAINFALL SURFACE COMPARISON AND INTERPOLATION OF STATION CLIMATE DATA

A.1. Rainfall surface comparison and selection

Of the variety of available satellite data derived rainfall surfaces (TRMM, TAMSAT, MODIS, CHIRPS, etc.), CHIRPS (Funk et al., 2015) was selected for further analyses: comparison to the surfaces derived by Lynch 2003 and to local gauging station data. CHIRPS was chosen because its surfaces are modified and calibrated using station data, the spatial and temporal resolution is comparatively high (1 km grid, 5-day data), and surfaces are available from 1981 to present. Its performance in comparison to South African gauge data, done by UCT's Climate Systems Analysis Group (CSAG), was the best of those assessed, despite noted biases in winter frontal rainfall zones (SANCIAHS, 2016).

A mean annual precipitation (MAP) surface and monthly average precipitation surfaces for 1981-2016 (35 years) were extracted from the CHIRPS dataset using GeoCLIM software and compared to the MAP and monthly surfaces derived by (Lynch 2003). The Lynch 2003 surface was derived for South Africa using station data from 1950-2000 (50 years) and regional multiple regression equations using position variables including elevation and distance from sea. This dataset is typically applied when modelling with ACRU. These surfaces are derived from data from different time-periods, but it was assumed that spatial and seasonal trends would be consistent between given both cover multiple decades.

The CHIRPS dataset shows less spatial variation in MAP both within and between the three catchments compared to the Lynch surface (Figures A1 & A2, Table A1). Due to a band of higher predicted rainfall in the Kouga mountains in the CHIRPS dataset, the Kouga catchment was predicted to have a higher catchment average MAP than Kromme. The opposite is true in Lynch's MAP surface. CHIRPS shows greater seasonal variation in monthly average precipitation than predicted by Lynch 2003 (Figure A3). This could be due to the shorter duration of the data used to derive the CHIRPS averages and high inter-annual variability in rainfall seasonality in the region. Use of the CHIRPS dataset is attractive because it offers a time-series of surfaces, rather than assuming stationary seasonal spatial distributions when applying Lynch's mean monthly rainfall surfaces. However, it is clear that using one or the other surface to interpolate the station data will lead to significantly different estimates of rainfall time-series for model units.

The Lynch surface was selected for this study given the finer and seemingly more accurate spatial distribution and the fact that it has been more commonly applied in South Africa to date.

Table A 1: Comparison of mean annual precipitation (MAP) for the 3 study catchments estimated using different rainfall surfaces

Catchment	Spatially averaged MAP (mm)	
	Lynch 2003	**CHIRPS 2017**
	1950-2000	*1981-2016*
Kromme	643	569
Kouga	459	588
Baviaanskloof	293	511

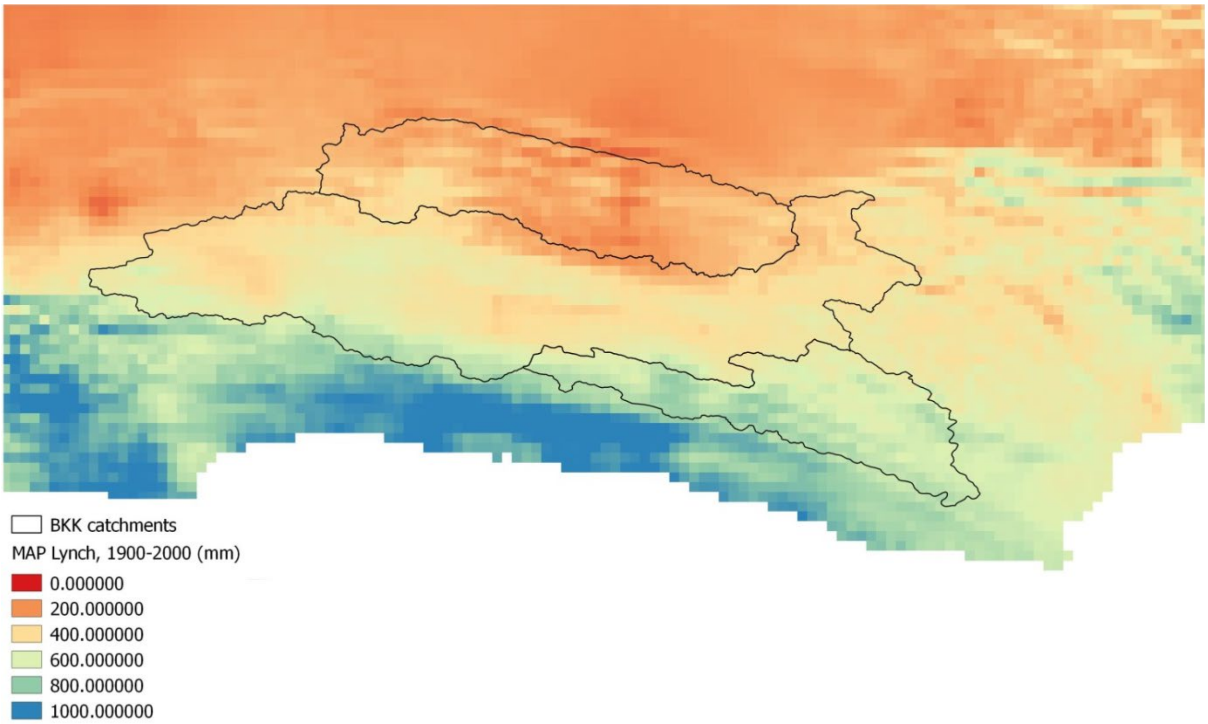

Figure A 1: Mean annual precipitation surface derived by Lynch 2003

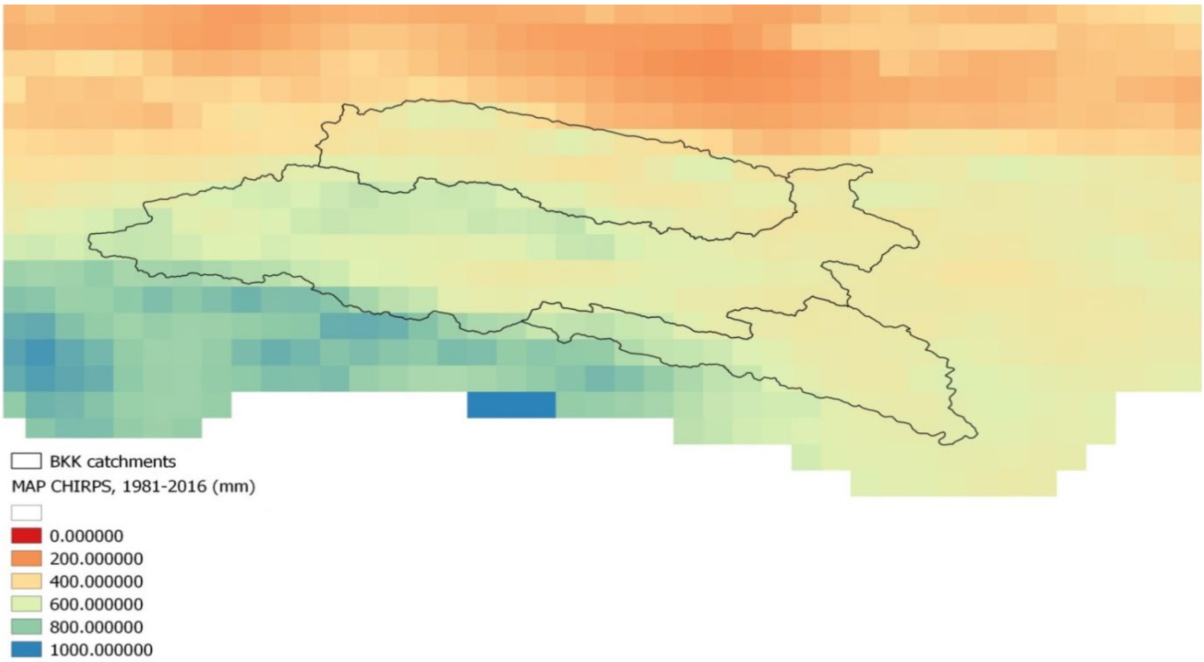

Figure A 2: Mean annual precipitation surface derived from CHIRPS dataset

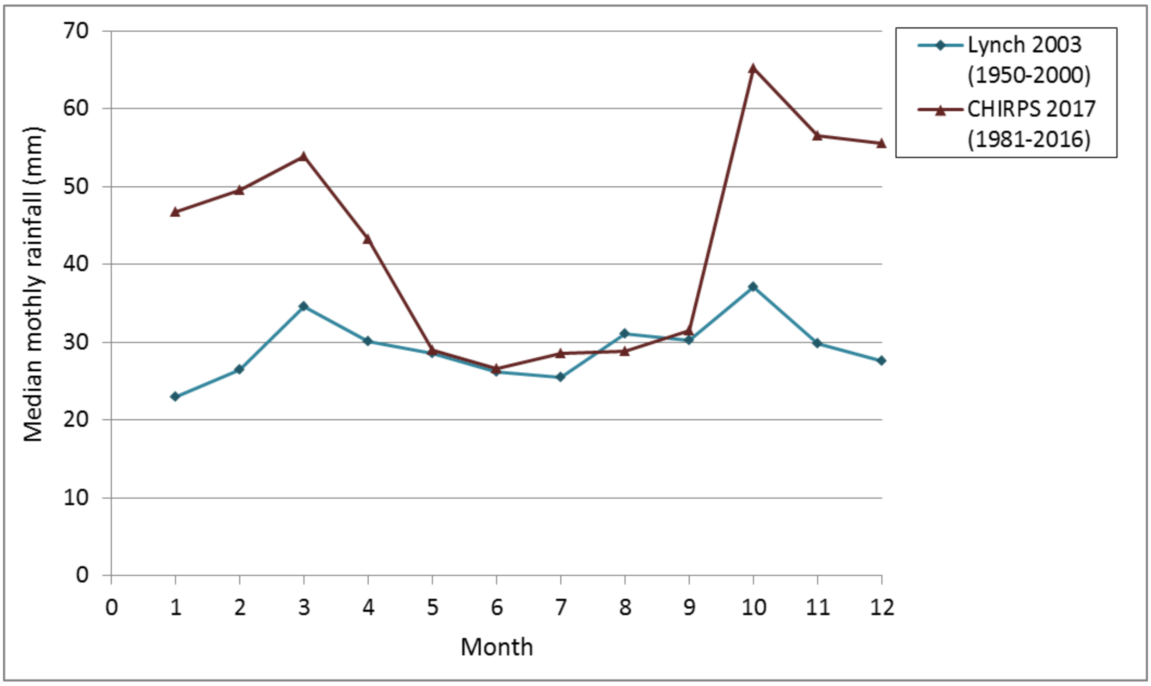

Figure A 3: Comparison of mean monthly rainfalls over the Baviaanskloof catchment estimated using different rainfall surfaces

A.2. Rainfall station data spatial interpolation method

The Lynch 2003 mean monthly rainfall surfaces were used to interpolate from station data and produce spatially averaged estimated rainfall time-series for different catchments, sub-catchments, or land-unit areas of interest. The method was designed to preserve the spatial rainfall distribution estimated by Lynch in terms of long-term averages, but have relative magnitudes and spatial distributions of individual events be driven by the station data. Rainfall gauges with data for over 10 years and having data within the last 15 years were selected to be driver stations. Record gaps were patched using monthly ratios against the mostly closely correlated station with an over 5 year overlap period located within 30 km. Driver station records were patched using both driver and non-driver stations to have time-series of equal length (1960-2019) for use in scenario modelling.

The following steps were used to spatially interpolate the driver station data for different land units by scaling from station to grid cell, grid cell to sub-area, and sub-area to land-unit:

- The Lynch estimated long-term average monthly rainfall values and MAP (mean annual precipitation) were extracted for the grid cell in which each rainfall driver station is located.
- To preserve the Lynch MAP spatial distribution, station time-series data were scaled such that their long-term MAP matched the Lynch surface grid cell they were located in.
- Thiessen polygons were created for the driver rainfall stations.
- Land unit shapefiles were overlain on the driver station theissen polygons to delineate sub-areas within the land units to be “driven” by their closest driver station.
- Zonal statistics were done using the Lynch rainfall monthly surface grid cells in each sub-area to find the spatially-averaged, long-term average, monthly rainfall for the sub-area.
- The grid-cell scaled station time-series were then scaled to match the sub-area. This was done using the monthly ratios of the station’s grid-cell value to the spatially-averaged sub-area value.

The result was a sub-area rainfall time-series. This scaling was done with a smoothed time-series of scaling ratios: the monthly station-grid-cell to sub-area ratios were assigned to the middle day of each month and linearly interpolated between mid-month values. This was done to prevent sharp steps in the scaling ratios.

- To get a rainfall time-series for the whole land-unit, the proportional area-weighted sum of all the sub-areas within the land-unit was taken.

A.3. Potential evapotranspiration (PET) spatial interpolation method

The same method as described above was used to create spatially averaged PET time-series for catchments or land units of interest. There is a greater number of temperature logging stations compared to PET measuring stations across the BKK, and so these were used as drivers with PET time-series estimated from daily temperature data using the algorithm of Hargreaves and Samani, 1984. These station based PET time-series were scaled to the mean annual PET and monthly PET surfaces of Schulze et al., 2007 to create land-unit time-series using the station to grid-cell PET ratio, grid-cell to sub-area PET ratio, and sub-area to whole land-unit area ratio.

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B. DELINEATING SUB-CATCHMENTS AND HYDROLOGIC RESPONSE UNITS (HRUS)

To describe flow patterns across the Baviaanskloof, Kouga, and Kromme catchments, the catchment areas were delineated into hydrological response units (HRUs), land areas assumed to have distinct hydrological behaviour compared to others, and into sub catchments, which would define the surface and shallow subsurface flowpath linkages between HRUs and with the channel network.

B.1. Stream line and sub-catchment delineation

Stream lines (river channels) and sub catchments were delineated using SU-DEM elevation data (Van Niekerk, 2016) and TauDEM tools (Tarboton, 2015) in ArcGIS 10.1. Stream lines were defined using thresholds of contributing flow accumulation area (upslope area on contributing flow paths) assigned to grid cells of the DEM. Thresholds were selected based on visual comparison of the mapped outputs with channels evident in aerial photography.

These catchments have a dominant trellis drainage pattern, with a main river in the central valley, running roughly west to east, which is fed by tributaries oriented perpendicularly coming from the bounding mountain ranges (Figure 1:1). The main river channel in each catchment was defined in the central valley using a flow accumulation area threshold of over 15 km^2 for the Kromme, 20 km^2 for the Kouga, and 50 km^2 for the Baviaanskloof River. Tributary channels were mapped using a 1 km^2 flow accumulation threshold. The Kouga catchment has a more complex geomorphology with a widened floodplain area along a west-east band of softer shale geology that is located to the south of the main Kouga River. This valley was created by the major tributaries coming from the Tsitsikamma Mountain side. An additional class of major tributaries of the Kouga were delineated as those with over 20 km^2 flow accumulation but not in the main central valley.

The central valleys of the Baviaanskloof and Kromme catchment have a fluctuating pattern of valley widths along the longitudinal profile. Major sub catchments were delineated along the main river for distinctive wide and narrow reaches, while minor sub-catchments were delineated for the mountain tributaries. In the Kouga catchment, sub catchments were delineated for each major tributary, while minor sub catchments were defined where tributary streams crossed from steep mountain to flatter topography. Catchment areas contributing to flows, and potentially groundwater levels, at monitoring locations were also delineated.

B.2. Topographic land unit delineation

SU-DEM elevation data (Van Niekerk, 2016) was used to delineate topographic units. Due to the scale of the area and the source of the dataset (SRTM 30 m data and national contour and spot heights), the DEM resolution was coarsened from 5 m to 10 m resolution. The units mapped were: plateaus/ridges, cliffs, canyons (narrow valley floors, kloofs), hillslopes, toe-slopes (in wide valleys), alluvial fans, and (wide valley) floodplains (Figure 6:4). Unit discretization was attempted using various thresholds of several different indices calculated from the DEM: flow accumulation, slope, slope position indices, topographic position indices (TPI), combined TPI's using multiple analysis window sizes (Dilts, 2010), height above nearest drainage (HAND), and valley floor mapping using a valley confinement algorithm (VCA). The VCA used the distance from a mapped channel and an area's cumulative slope toward channel (Nagel et al., 2014). HAND analysis was done using the "vertical drop" tool in TauDEM.

Topographic unit outputs of the methods trialled were visually assessed against obvious transitions in slope and vegetation visible in aerial photography and against mapped distributions of natural vegetation types (Euston-Brown, 2006) and land cover from the National Landcover Dataset (DEA, 2015; GeoTerraImage, 2015). For example, a slope threshold of 50% was found to delineate areas which were steep enough to be dominated by exposed rock with little vegetation, evident in aerial photography, and likely to have little soil. In the more heavily cultivated Kouga catchment, agriculture was evident on almost all land located in valleys with a slope under 20%. However, not all of this area would be considered a floodplain. A wide-valley "toe-slope" class was made to encompass this area separately from other hillslopes.

No single automated procedure (i.e. slope classes, TPI classes, HAND classes) proved satisfactory for all the desired units based on visual assessment and so a mixed method approach was applied as outlined in Table B1.

Table B 1: Mapping procedure for topographic units (HAND is height above nearest drainage, VCA is valley confinement algorithm)

Topographic unit	**Mapping method / classification rules**
Main floodplain	areas with 0-10 m HAND values referring to main rivers (and major tributaries of the Kouga) and areas classified as valley floor using the Valley Confinement Algorithm (VCA), slope < 10%, valley width > 300 m
Toeslope	areas with slope < 20% and with < 100 m HAND referring to main rivers (and major tributaries of the Kouga)
Alluvial fan	areas bordering the main floodplain at the mouths of tributary valleys having over 5% slope and 2.5-10 m HAND referring to the main river.
Canyon/gorge floor	areas with 0-5 m HAND referring to tributary channels
Cliff	all areas with slope > 50%
Hillslope	areas with 5-100 m HAND referring to all mapped channels, 10% < slope < 50% not assigned to any other class
Plateau	areas with > 100 m HAND referring to all mapped channels and slope < 50%

B.3. Hydrological response units (HRUs)

Land cover types were combined with topographic units to create hydrological response units (HRUs). The methods used to map land cover types are described in Appendix C below. The number of land cover type-topographic unit combinations included in the final set was limited to the dominant ones to make the modelling problem tractable. Because most land cover types were associated with topographic positions and topographic unit delineation was guided by land cover observations, this only resulted in minor changes to the resulting composition. For example fruit orchard areas were rarely found on the hillslope, cliff, or plateau land units and thicket was generally confined to hillslopes and cliffs. Reclassifying the small areas mapped as orchard overlapping with hillslope changed less than 1% of the total orchard area.

The average slope, slope length, and distance from a channel of HRU types in each major catchment were determined in GIS using the SU-DEM data and river channels described above. Other properties such as soil type and depth and vegetation canopy cover for HRU types were approximated from relevant literature, national databases, field observations, and stakeholder information.

B.4. References

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C. LAND COVER MAPPING METHODS

C.1. Approach and data sources

A variety of data sources were combined to create the current cover and the pre-development indigenous vegetation baseline scenarios. These data sources and descriptions are given in Tables C 1-3. In addition, topographic units (high plateaus, cliffs, hillslopes, toe-slopes, alluvial fans, narrow valleys/kloofs, and wide floodplains) were delineated through analyses of a digital elevation model (DEM) dataset (see Appendix A). Analyses of aerial imagery compared to topographic indices and topographic unit mapping, showed that vegetation types and human land uses generally coincide with topographic positions, i.e. riparian forest on kloof floors, thicket on hillslopes, fynbos on hillslopes and high plateaus, palmiet wetlands on wide floodplains, agricultural fields and orchards on land with under 20% slope. A summary of the approach to combining these datasets to create the scenario maps was described in Table 8-1 in the main report.

An effort was made to use the 2013-2014 National Land Cover (NLC) dataset (DEA, 2015; GeoTerraImage, 2015) as an underlying guide in an attempt to make the methods somewhat generalizable for other study areas. This resulted in the scenario land cover maps having a 30 m resolution. The “current” land cover scenario is therefore most representative of 2013-2014. The NLC does not map invasive alien plant (IAP) cover nor does it specify particular crop or irrigation types and so the additional datasets listed were used to reclassify relevant cover types in the NLC into the desired set of types for the scenarios. However in combining the various datasets, inconsistencies were encountered between the NLC, the other datasets, and aerial photography. These included inconsistencies in the extent and type of agricultural areas mapped in the NLC compared to Bromley et al., 2015, in the NLC woody cover type extents and the densities listed in the Working for Water NBAL dataset, and in the NLC water and wetland cover and in farm dams mapped by Bromley et al., 2015. To aid in mapping farm dams and wetlands, an additional dataset was consulted: the National Freshwater Ecosystem Priority Areas (NFEPA) wetland maps (Nel et al., 2011). Aerial photography was used to guide development of rules for combining the data layers and reclassifying parts of the NLC as described below.

Table C 1: Maps of land cover and vegetation types covering the BKK catchment areas in "current cover" mapping

Dataset	Source / Owner	Type	Resolution / Scale	Extent	Cover dates	Cover classes	Input spatial data	Method
South African National Land Cover Dataset (NLCD) 2013-2014	(DEA, 2015; GeoTerraImage, 2015)	raster	30 m	South Africa	2013-2014	built and cultivated covers and broad vegetation cover types; 72 classes; 7 non-agricultural vegetation types, feral IAPs not specified; irrigated fields inferred as medium and high productivity classes	Landsat 8 imagery	Mixture of automated and manual classification from multi-seasonal multispectral imagery (April 2013-March 2014). Used SANBI biome data, DAFF SPOT cultivated field mapping, other national and provincial resource mapping as guides.
SANBI VegMap 2012	(Mucina et al., 2014; SANBI, 2015)	shapefile		South Africa	-	indigenous vegetation types only	Aerial photography, terrain maps	Aerial photography, ground-truthing, expert knowledge of biogeographical factors, plot data used to map of present indigenous vegetation cover types, and hypothesized indigenous cover where development is present, based on national classifications by Mucina and Rutherford, 2007 and more fine scale mapping by local entities.
BKK indigenous vegetation and degradation class map	(Euston-Brown, 2006)	shapefile	(1:25,000)	BKK (Kromme to Churchill)	-	indigenous vegetation types only, with specified degradation levels; 7 broad biomes, 65 vegetation types, 5 degradation classes	Aerial photography, terrain maps	Aerial photography, ground-truthing, expert knowledge of biogeographical factors, plot data, used to map present indigenous vegetation types, and hypothesized indigenous cover where development is present. Areas were assigned degradation classes.
Rebelo MSc, Kromme land cover maps	(Rebelo, 2012)	shapefile	5 m	Kromme to Churchill	1954, 1969, 1986, 2007	built and cultivated covers and broad vegetation cover types; 15 classes; 9 non-agricultural vegetation types; 3 IAP classes (wattle, pine, other); irrigated vs. dryland farming separated	Aerial photography	Georeferenced aerial photography, manual tracing of cover types, ground-truthing, and comparison to NLCD, SANBI VegMap, Working for Water and other datasets

Table C 2: Maps of agricultural fields and land use and management covering the BKK catchment areas used in "current cover" mapping

Dataset	Source / Owner	Type	Resolution / Scale	Extent	Cover dates	Cover classes	Input spatial data	Method
Kouga & Kromme Water Use Validation & Verification agriculture & dam maps	DWS (Bromley et al., 2015)	shapefile	10-30 m (1998); 0.5-10 m (2011)	Kouga & Kromme	1998, 2011	only agricultural areas; pastures, orchards, vegetable fields divided into irrigated and non-irrigated + dams	SPOT-5 (2011) & Landsat-7 (1998) & aerial photography	Manual mapping from satellite imagery and aerial photography with ground-truthing. ***NB: These outputs have NOT been officially adopted by DWS. A re-mapping effort is underway.***
Stokhof de Jong MA, Baviaanskloof land use maps	(Stokhof de Jong, 2013) & Living Lands	shapefile	10 m	Baviaans	2011	land use classes: cultivated fields, grazing lands, stewardship or unused land on privately owned areas	Aerial photography	Interviewed landowners in the field with printed aerial photos of their properties and had them specify which portions are under which uses, including crop and stock types.
Living Lands Baviaanskloof agricultural field map	Living Lands / 4 Returns	shapefile	5-10 m	Baviaans	2015	only agricultural fields	Aerial photography	Manual mapping from aerial photography

Table C 3: Maps of Invasive Alien Plant (IAP cover) in the BKK catchment areas used in "current cover" mapping

Dataset	Source / Owner	Type	Resolution / Scale	Extent	Cover dates	Cover classes	Input spatial data	Method
WfW IAP NBAL unit maps	WfW – DEA-NRM	shapefile	NBAL units range 0.01-7,105 ha	Kouga & Kromme	2018	Units are assigned dominant IAP species, estimated density, and life stage	Aerial photography	Manual mapping from aerial photography (and satellite imagery?) and ground-truthing
Zerroug BSc, Kouga black wattle stand map	(Zerroug, 2015) & Living Lands	shapefile	5-10 m	Kouga	2013	only dense black wattle stands (over 50% cover by black wattle)	Aerial photography	Manual mapping from aerial photography with ground-truthing
Bolhuis BSc, Kouga black wattle stand & other IAP	(Bolhuis, 2013) & Living Lands	shapefile	5-10 m	L82A & L82D Kouga	1971, 1990, 2010	dense black wattle stands (over 50% cover by black wattle), other IAPs	Aerial photography (1971, 1990), SPOT-5 (2010)	Georeferenced aerial photography, manual tracing of cover types, and ground-truthing

C.2. Specific methods: baseline "current" land cover scenario map

C.2.1 IAP tree cover

The National Land Cover dataset does not include mapping of dense stands of IAP trees, only of more generic vegetation structural types (e.g. forest, open vs. closed woodland, etc.). Visual inspection of the NLC data overlaid with aerial photography revealed that dense woody cover vegetation types (forest, dense woodland, and tree plantation), as well as wetlands, had been mapped in the NLC dataset in locations where dense stands of mature pine and black wattle (*Acacia mearnsii*) were obvious. It was hoped that where NLC mapped woody cover in locations that should be floodplain wetland or fynbos (i.e. on open hillslopes rather than kloofs, which should be riparian forest), these areas could be assumed to have IAP tree cover (wattles or pines). However, the same woody NLC cover types that coincided with IAP stands were also mapped where the woody cover was less dense and areas where the cover appeared to be older and more woody-shrub-dominated fynbos, indigenous woodlands and forests, and wetlands. This meant that when the NLC wooded cover types were mapped on what should be fynbos-covered hillslopes, this did not necessarily equate to IAP invasion.

A comparison of the NLC mapped wooded cover vegetation types in the Working for Water NBAL units compared to the cover densities predicted for those units in 2013-2014 showed no strong correlation. This can be due to the varying age of the vegetation, timing of estimates and clearing compared to the 2013-2014 imagery used for the NLC, the methods for estimating density, and the methods for spectrally defining woody cover in the NLC.

The method that was finally used to estimate the current cover of dense IAP stands in a way consistent with the NLC mapping was as follows:

- It was assumed there are no significant dense IAP tree stands in the Baviaanskloof catchment. The following reclassifications were only applied within the Kouga and Kromme catchments.
- NLC mapped "Plantation/woodlots" were re-classified as IAP stands.
- NLC dense woody cover types (forest, dense bush, and woodland) that were mapped within 100 m of mapped agricultural cover, and were not on high plateaus or cliffs, were re-classified as IAP stands and assumed to be black wattle.
- NLC dense woody cover types and wetlands falling within or touching the boundaries of IAP stand areas previously manually mapped from aerial photography by (Rebelo 2012) for the year 2007 for the Kromme, by (Bolhuis, 2013) for 2010 for the Kouga, and (Zerroug, 2015) for 2013 for the Kouga, were re-classified as IAP stands.
    - These previous IAP stand maps were used in the combination with the NLC's woody cover types rather than on their own because of the different years of the maps and the mapping methods. IAP clearing activities, fire, or IAP growth could have changed the area of dense IAP cover between the mapping periods (2007, 2010, 2013) and the 2013-2014 imagery composites used in the NLC.
- The maps by Rebelo 2012 and Bolhuis 2013 differentiated between wattle and pine stands. Areas re-classified as IAP stands were further classified as pine if within or touching an area mapped as pine by Rebelo 2012 or Bolhuis 2013.

C.2.2 Agricultural fields and orchards

The NLC dataset maps cultivated areas, differentiating orchards from fields and classifying round fields as pivot irrigation. Cultivated areas are further categorized into levels of estimated productivity (high, medium, low) based on greenness indices, which also gives an indication of the likely level of irrigation, particularly in more arid locations. It does not further classify crop types or irrigation method types.

The maps produced by Bromley et al., 2015 for the DWS Validation and Verification process used the WARMS database and visual interpretation to classify agricultural areas by crop and by irrigation type. It should be noted that the outputs of this study were not officially adopted by DWS as the water use estimates produced and other aspects were contested by stakeholders. Part of the discrepancies may have been due to the mapping of cultivated areas and classifications of crop and irrigation types, but may also have been due to the estimates of water usage by type. A re-mapping and re-calculation effort along with the form validation and verification process is currently underway and the data is not yet available for release. As such, the Bromley et al., 2015 study is used as an approximate classification of agricultural types, acknowledging likely errors.

To avoid having too many different agricultural classes to parameterize in modelling, and to deal with some inconsistencies, the following reclassifications were made to Bromley et al.'s crop and irrigation classes before working further with the dataset:

- As a less prevalent crop type, different stone fruit orchards (apricots, peaches, plums) were lumped into a stone-fruit orchard class.
- Small areas were mapped as oranges and as olives, these were re-classified as apples and stone-fruit respectively.
- In areas with specified irrigation that is either inconsistent or highly uncommon for the specified crop type (i.e. drip irrigation specified for lucerne, pivot irrigation for orchards), the irrigation type was switched to the most commonly occurring type for the crop (i.e. sprinkler for pasture and lucerne, micro-spray for fruit orchards).

Overlays of mapped agricultural cover from the NLC dataset and Bromley et al., 2015, showed that while the datasets were mostly consistent with each other, there were fields and orchards mapped in each which were missed by the other and areas with inconsistent classifications across the maps (e.g. areas classified as pasture in one and orchard in another). Bromley et al., 2015 mapped both agriculture presumed to be active in 1997 (qualifying period) and in 2011 (current period) using aerial photography and remote sensing from those years. There were cultivated area polygons mapped in both of the 1997 and 2011 datasets with no attribute information (no classification of crop and irrigation type) in one year or the other or both. Some areas were explicitly classified as fallow fields.

An overlay union of the three datasets (NLC and Bromley et al., 2015 mapping for 1997 and 2011) was created to make a new dataset of polygons covering their combined areas and with attributes from any of the three that exist at the location. The following steps were then applied (using R software) to the resulting attribute dataset of these polygons to assign each one with a crop and irrigation type:

- Apply the Bromley et al., 2015 classifications for 2011 for all areas where this data exists, then reclassify based on inconsistencies with NLC where present, and then classify areas without 2011 attribute data using the NLC data and 1997 data where present.

- If an area is mapped as agriculture in Bromley et al., 2015 for the 1997 period, but no classification is given for 2011 AND the NLC 2013-2014 maps it as indigenous vegetation or a low yield field, classify it as fallow.
- If an area is mapped as fallow by Bromley et al., 2015, but is mapped as a high or medium yielding agricultural field or orchard in the NLC, do NOT classify it as fallow.
    - Use the NLC classification and apply a consistent field (pasture, lucerne) or orchard type (apple, pear, stone fruit, plus irrigation type) based on what was specified for the area in the 1997 dataset if any. If no data exists in the 1997 dataset, classify based on the classification of the neighbouring polygon with the largest shared border if this has data and is of a consistent general type, or based on the otherwise closest classified polygon of the same general type.
- If an area is mapped as a field or orchard in the NLC, but not mapped at all in Bromley et al., 2015, (2011 or 1997), use the field or orchard classification of the bordering polygon, if there is one of a consistent general type.
    - If there is no classified bordering polygon, use the default types for the area where the polygon occurs (e.g. orchard default is micro-spray apple orchard for most of the area and the field default is pasture with sprinkler the lower Kromme).
        - Defaults by general NLC type were determined by quaternary catchment using the maximum area of a classified type within each general NLC type for the area where datasets overlap and have attributes.
- For areas of over 1 ha where the NLC maps high to medium producing orchard while Bromley at al mapped pasture, lucerne, or fallow, do a visual inspection of the aerial photography to resolve the classification.
- Because of differences in field polygon borders in the various maps and differences in the classifications it was possible to have what is, in reality, a single cultivated field, broken up into pieces with different classifications using the rules above. To fix this, all polygons within a field assigned a field record number by Bromley et al, were assigned the crop and irrigation type which had been given to the largest sub-polygon in that particular field.

C.2.3 Farm dams

Where Bromley et al., 2015 mapped farm dams, the NLC dataset often classified areas as wetlands and very rarely as open water. Because the NLC also mapped wetlands where there are natural wetlands, riparian zones, and wetland vegetation surrounding farm dams, it was found that the NLC cannot be used to map farm dams. The NFEPA wetlands dataset (Nel et al., 2011) includes an artificial wetlands category which, on inspection with the aerial photography, was found to be generally mapping the farm dams in the Langkloof. In addition, some NFEPA wetland classified as natural also appeared to be farm dams in the photography. Comparing the NFEPA dataset, the Bromley et al., 2015 farm dams, and aerial photography showed that the NFEPA dataset captured the shape and location of the dams more accurately. Each of the datasets included dams that were missing in the other set, but were visible in the imagery. This is likely because of differences in how full each dam was at the time of the imagery being used to do the mapping and because of the spectral signatures applied to classify. Also farm dams can have very different colours to one another in imagery due to nutrients and solutes in the water, algae, and aquatic plants which can influence their mapping.

For this study, dams mapped in the NFEPA dataset were used with priority given their more accurate shape. The datasets were processed and combined as follows:

- Bromley et al., 2015 mapped farm dams for 1990, 1996, and 2013. Most of the dams present in the datasets for earlier years were present in later ones, albeit with different shapes. However this wasn't always the case. Visual inspection of dams mapped in 1990 or 1996 which were not present in the later datasets showed that most were still evident in the aerial photography. Therefore these were selected out and added to the 2013 dataset to make a consolidated set.
- All the artificial wetland polygons in the NFEPA dataset, and the natural wetland polygons in NFEPA which were overlapping with Bromley et al.'s mapped farm dams, were selected out of the larger NFEPA wetland dataset.
    - Very large polygons (several hectares) were flagged and inspected. Those which included large vegetated wetland areas were deleted from the set so that the Bromley et al. polygon would be used instead.
- Dam polygons mapped by Bromley et al., 2015 which overlapped with the set of identified NFEPA dam polygons were deleted.
- Dams polygons in the Bromley et al., 2015 dataset which were not in the selected NFEPA set were then added to make the final dataset.

C.2.4 Major dams

The NLC mapped open water for the footprints of the major dams, Kouga, Churchill, and iMpofu. Other open water areas in the NLC were covered by the farm dam areas and wetlands. While the surface areas of these large dams change over time with their water level, this was not considered in the cover mapping and a consistent shape was applied across all scenarios. The fluctuations in surface area for evapotranspiration calculations can be accounted for within the hydrological model and do not need to be included in the cover maps.

C.2.5 Urban, suburban, and other transformed cover types

The NLC classifies several urban, suburban, rural residential, and recreational cover types. To reduce the number of cover types to be considered in hydrological modelling at this scale these were reduced to two classes, as shown in Table B 4, based on assumptions about their relative vegetative cover based on a brief scoping against aerial photography. Because these areas make up small proportions of the catchments, more quantitative analyses of their properties for grouping was deemed unnecessary.

Areas classified as bare ground by the NLC dataset in the main floodplain were lumped into the urban/bare cover class, but not in the mountainous parts of the catchments. In these areas, bare ground areas were predominantly mapped on the steep slopes classified as cliffs in the topographic analysis. The cliff topographic units were assigned to their own classes, fynbos-cliff and thicket-cliff, in which the low vegetation cover and dominance of bare rock will be included in the model parameterization.

Table C 4: Reclassification of NLC developed land cover classes

New cover class	NLC cover class name
Sub-urban	Urban built-up (dense trees / bush)
	Urban informal (dense trees / bush)
	Urban informal (open trees / bush)
	Urban residential (dense trees / bush)
	Urban residential (open trees / bush)
	Urban school and sports ground
	Urban smallholding (dense trees / bush)
	Urban smallholding (open trees / bush)
	Urban sports and golf (dense tree / bush)
	Urban sports and golf (low veg / grass)
	Urban sports and golf (open tree / bush)
	Urban township (dense trees / bush)
	Urban village (dense trees / bush)
	Urban village (open trees / bush)
Urban / bare	Bare none vegetated
	Erosion (donga)
	Mine buildings
	Mines 1 bare
	Mines 2 semi-bare
	Urban built-up (bare)
	Urban built-up (low veg / grass)
	Urban built-up (open trees / bush)
	Urban commercial
	Urban industrial
	Urban informal (bare)
	Urban informal (low veg / grass)
	Urban residential (bare)
	Urban residential (low veg / grass)
	Urban smallholding (bare)
	Urban smallholding (low veg / grass)
	Urban sports and golf (bare)
	Urban township (bare)
	Urban township (low veg / grass)
	Urban township (open trees / bush)
	Urban village (bare)
	Urban village (low veg / grass)

C.2.6 Indigenous vegetation

Areas not classified as transformed cover types, i.e. agriculture, dams, urban and suburban cover, and dense IAP tree stands, were assigned to different indigenous vegetation cover classes using the NLC 2013-2014 map, the SANBI Vegetation Map, Euston-Brown, 2006, Rebelo 2012, and the topographic unit mapping. Resulting classes were: riparian forest and woodland, savanna / open woodland, thicket, fynbos, palmiet wetlands, and other herbaceous wetlands. The NLC maps classify different vegetation structures (e.g. forest, shrubland, dense bush/thicket, open woodland, grassland) and also differentiate fynbos as a shrubland type. Using spectral wetness indices the NLC also identified wetlands; however, many of these were farm dams or areas infested with IAP vegetation, as described above. The SANBI Vegetation Map and Euston-Brown, 2006 map different indigenous vegetation types or communities that theoretically should occur in different areas based on field observations and climate, geology, topography, etc. prior to human influence. Neither map classifies wetland areas. Rebelo 2012 mapped areas of palmiet and other wetlands in the upper Kromme catchment for 2007. The various information sources were combined as described below.

C.2.6.1 Wetlands

Areas classified as wetlands by the NLC which were not classified as farm dams or IAP stands as described above, and were not classified as riparian forest or woodland as described below, were classified as wetlands (herbaceous) in the current cover map. These generally matched areas mapped as natural wetlands in the NFEPA maps, but had more restricted, potentially more accurate boundaries. In the Baviaanskloof, groundwater supported wetlands in the main floodplain were additionally mapped from the aerial photography and ground-truthing. Wetlands mapped on hillslope and cliff topographic units were classified as wetland-slope, assuming these would have relatively little organic soil accumulation.

Palmiet wetlands were considered separately. Areas mapped as palmiet wetlands in 2007 by Rebelo 2012 which were not classified as treed cover (assumed to be IAP), agriculture, or other transformed type in the NLC 2013-2014, were classified as palmiet wetlands in the current cover map. In the pre-development scenario, areas classified as floodplain in the topographic analysis of the upper Kromme catchment were assumed to be palmiet wetlands. This excludes alluvial fan and toe-slope areas.

In the pre-development scenario the floodplain area within the wider valleys of the Kouga was assumed to have been wetland, although it is not known if it would have been palmiet.

C.2.6.2 Non-wetland vegetation

Areas mapped as narrow valleys or kloofs in the topographic unit analyses were classified as having riparian forest or woodland vegetation in the pre-development scenario. This class was maintained in the current scenario unless the area was mapped as having IAP tree cover as described above.

Wide valley floors and alluvial fans mapped in the topographic analyses in the Baviaanskloof were classified as having savanna / open woodland vegetation in the pre-development scenario, consistent with the SANBI Vegetation Map and Euston-Brown 2006 maps. Toe-slopes, fans, and wide-valley floors that were not wetlands in the Kouga and Kromme were classified as lowland fynbos (and renosterveld), consistent with the Vegetation Map and Euston-Brown 2006 maps. In the current cover map some of these areas were classified as agriculture or suburban covers as described above.

Visual comparison of the SANBI Vegetation Map and Euston-Brown 2006 with the topographic unit mapping and aerial photography showed that generally areas mapped as thicket were confined to the mapped hillslope and cliff topographic units, with little extension onto areas classified as high plateau. Therefore all hillslope and cliff units dominated by thicket in these vegetation maps were classified as thicket in the current cover map. The remaining hillslope, plateau, and cliff units were classified as mountain fynbos (and renosterveld).

Renosterveld types were not considered as a separate class, but instead grouped with fynbos. This is floristically incorrect, however it was assumed that structurally and hydrologically these two types are more similar to one another than they are to the other types mapped and the difference between them is smaller than the differences between any other pair of classes.

Both fynbos and thicket areas mapped on the cliff topographic units were assigned to separate fynbos-cliff and thicket-cliff classes. The reason for this is that these areas are dominated by bare rock with much lower vegetation cover and very little soil when compared to other parts of the landscape, and so are likely to have a notably different hydrological response.

C.2.7 Final land cover type set for the current cover map

The methods and data sources used in the mapping of the current cover scenario are summarized in Table C 4. Processing of various data sources was done in a mix of polygon and raster data formats depending on the input data, but the various cover type layers created were converted to raster datasets with a 30 m resolution matching the NLC 2013-2014 dataset and merged into a single raster dataset. Cover type rasters were merged such that transformed covers took preference in mapping overlaps: dams over IAP over other transformed types over agriculture over wetlands over the remaining indigenous vegetation types.

A “majority filter” was applied in ArcGIS on the merged layer containing agriculture, other transformed cover, wetlands, and indigenous vegetation to remove isolated 30 m pixels of single cover types surrounded by others. This was done before layering on IAPs and dams because small areas of these were considered likely and important.

Table C 5: Summary of mapping methods for different cover types in the 'current cover' scenario (2013-2014)

Broad type	Cover	Mapping method and source description
Open water	Major dam	NLC 2013-2014 open water
	Farm dam	Combined NFEPA artificial wetlands and Bromley et al., 2015
IAP tree stands	IAP-wattle IAP-pine	NLC 2013-2014 woody (plantation, forest, dense bush) and wetland cover types coinciding with Rebelo 2012, Bolhuis 2013, and Zerroug 2014 mapping of wattles and pines; NLC woody cover types within 100 m of agriculture with manual cleaning
Orchards	Apples, Sprinkler	Combined and reconciled mapping from both NLC 2013-2014 and Bromley et al., 2015
	Apples, Micro-spray	
	Apples, Drip	
	Pears, Sprinkler	
	Pears, Micro-spray	
	Stone fruit, Sprinkler	
	Stone fruit, Micro-spray	
Fields	Lucerne, Sprinkler	
	Lucerne, Pivot	
	Lucerne, Furrow	
	Pasture, Sprinkler	
	Pasture, Pivot	
	Pasture, Furrow	
	Fallow, NA	
Other transformed	Urban / bare	NLC 2013-2014 urban cover types and residential types with low vegetation cover; bare ground in the main inhabitated valleys
	Sub-urban	NLC 2013-2014 urban and residential cover types with specified bush and tree cover and sports fields, parks, and golf courses
Indigenous vegetation	Wetland-palmiet	Rebelo 2012 mapping where not classified as agricultural, IAP, or other transformed covers in NLC 2013-2014
	Wetland-other Wetland-slope	NLC 2013-2014 wetland not otherwise classified as IAP or dam; subclassified as 'slope' if on hillslope or cliff topographic units
	Riparian woodland & forest	Narrow valley / kloof topographic unit, unless classified as IAP
	Savanna, open woodland	Wide valley and alluvial fan topographic unit in the Baviaanskloof (consistent with SANBI Vegetation Map and Euston Brown 2006), unless classified as agriculture or other transformed type
	Fynbos-lowland	Wide valley, toe-slope and alluvial fan topographic unit in the Kouga and Kromme (consistent with SANBI Vegetation Map and Euston-Brown 2006), unless classified as IAP, agriculture, dams, or other transformed type
	Fynbos-mountain Fynbos-cliff	Hillslope, cliff, and plateau topographic units in the Baviaanskloof, Kouga, and Kromme catchments mapped as fynbos or renosterveld in the SANBI Vegetation Map and Euston-Brown 2006; subclass for cliff units assumed to be rock dominated
	Thicket Thicket-cliff	Hillslope and cliff topographic units (not high plateau) in the Baviaanskloof, Kouga, and Kromme catchments mapped as thicket in the SANBI Vegetation Map and Euston Brown 2006; subclass for cliff units assumed to be rock dominated

C.3. Specific methods: maximum agricultural expansion scenario

The maximum agriculture expansion scenario map was made using the following steps and assumptions:

- Delineate the areas practically available for agriculture:
  - It was assumed that floodplain, alluvial fan, and toe-slope (under 20% slope) topographic units could be practically used for fields and orchards given the current locations of agricultural lands. Appropriate units were selected from a polygon file of topographic units.
  - It was assumed that areas distant (over 1km) from existing agriculture, hence from roads and other infrastructure, were unlikely to be developed given difficult the terrain and access in the region. From the selected set of topographic unit polygons, those further than 1 km of existing agriculture in the current cover scenario were excluded.
  - It was assumed that small (under 5 ha), isolated patches of lower sloped ground would not be worth developing into fields or orchards. Polygons with an area of less than 5 ha were excluded from the set.
  - In the lower Kromme catchment area, below the Churchill Dam, the topography is notably less rugged and difficult and so access for agricultural development is simpler. It was noted that the above rules excluded some large patches of low slope area that appeared relatively accessible. Therefore in this area, all polygons of the appropriate topography that were over 10 ha were included in the potential agriculture area regardless of distance to existing mapped agriculture.

- Predict the agricultural cover type that would be developed on currently unfarmed areas:
  - Lacking other information, a simple assumption was made that further agricultural development would follow the spatial arrangement currently observed. To do this, the "nibble" function in ArcGIS was applied using the current cover agricultural areas and the "mask" of the area considered available for agriculture. This tool assigns all the new areas (not currently agriculture) the land cover type code of the nearest classified agricultural area. This resulted in predominantly apple orchard area in the main valley of the Kouga and pasture in the more remote agricultural areas in the Kouga and throughout the Kromme.

- Combine the new agricultural layer with the other cover types to make a consolidated map
  - The new agricultural layer was overlaid on top of the wetland and indigenous vegetation mapping. In this case it was also assumed the IAP clearing would occur to make way for the agricultural expansion, so it was also on top of the IAP layer. The dams and other urban and suburban cover layers were layered on top.

C.4. Outputs: land cover distributions in mapped cover scenarios

Table C 6: Pre-development, indigenous vegetation, vs current cover scenario land cover distribution for the BKK catchments

Cover type	Baviaanskloof				Kouga				Kromme			
	Pre-development		Current cover		Pre-development		Current cover		Pre-development		Current cover	
	Area (km^2)	% of catch-ment	Area (km^2)	% of catch-ment	Area (km^2)	% of catch-ment	Area (km^2)	% of catch-ment	Area (km^2)	% of catch-ment	Area (km^2)	% of catch-ment
Major dam	0.0	0.0%	0.0	0.0%	5.2	0.2%	5.2	0.2%	7.5	0.9%	7.3	0.9%
Farm dam	0.0	0.0%	0.2	0.0%	0.0	0.0%	13.5	0.5%	0.0	0.0%	2.8	0.3%
Wetland_palmiet	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	10.8	1.3%	1.5	0.2%
Wetland_other	0.1	0.0%	0.2	0.0%	60.9	2.3%	5.9	0.2%	3.1	0.4%	3.3	0.4%
Wetland_slope	1.6	0.1%	1.6	0.1%	10.2	0.4%	8.9	0.3%	5.2	0.6%	4.8	0.6%
Riparian woodland & forest	57.6	4.6%	56.7	4.6%	125.7	4.7%	72.1	2.7%	63.7	7.6%	29.9	3.6%
Savanna	49.9	4.0%	37.9	3.1%	1.0	0.0%	0.8	0.0%	0.0	0.0%	0.0	0.0%
Fynbos_lowland	0.2	0.0%	0.2	0.0%	424.8	16.0%	271.5	10.2%	245.5	29.2%	151.8	18.1%
Fynbos_mountain	652.0	52.5%	651.7	52.5%	1,342.2	50.6%	1,302.4	49.1%	454.7	54.1%	405.1	48.2%
Fynbos_cliff	265.8	21.4%	265.8	21.4%	552.7	20.8%	550.3	20.8%	48.1	5.7%	46.5	5.5%
Thicket	101.8	8.2%	101.2	8.1%	47.3	1.8%	45.5	1.7%	1.6	0.2%	1.1	0.1%
Thicket_cliff	112.7	9.1%	112.7	9.1%	82.0	3.1%	81.6	3.1%	0.0	0.0%	0.0	0.0%
IAP_wattle	0.0	0.0%	0.0	0.0%	0.0	0.0%	110.8	4.2%	0.0	0.0%	66.9	8.0%
IAP_pine	0.0	0.0%	0.0	0.0%	0.0	0.0%	1.7	0.1%	0.0	0.0%	3.3	0.4%
Apples, Sprinkler	0.0	0.0%	0.0	0.0%	0.0	0.0%	5.5	0.2%	0.0	0.0%	0.0	0.0%
Apples, Micro-spray	0.0	0.0%	0.0	0.0%	0.0	0.0%	91.3	3.4%	0.0	0.0%	1.1	0.1%
Apples, Drip	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.6	0.0%	0.0	0.0%	0.1	0.0%
Pears, Sprinkler	0.0	0.0%	0.0	0.0%	0.0	0.0%	1.4	0.1%	0.0	0.0%	0.0	0.0%
Pears, Micro-spray	0.0	0.0%	0.0	0.0%	0.0	0.0%	2.0	0.1%	0.0	0.0%	0.0	0.0%
Stone fruit, Sprinkler	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.7	0.0%	0.0	0.0%	0.0	0.0%
Stone fruit, Micro-spray	0.0	0.0%	0.0	0.0%	0.0	0.0%	1.7	0.1%	0.0	0.0%	0.2	0.0%
Honeybush	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Lucerne, Sprinkler	0.0	0.0%	0.6	0.1%	0.0	0.0%	2.6	0.1%	0.0	0.0%	3.4	0.4%
Lucerne, Pivot	0.0	0.0%	2.9	0.2%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.7	0.1%
Lucerne, Furrow	0.0	0.0%	8.8	0.7%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%
Pasture, Sprinkler	0.0	0.0%	0.1	0.0%	0.0	0.0%	18.6	0.7%	0.0	0.0%	84.8	10.1%
Pasture, Pivot	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.5	0.0%	0.0	0.0%	3.9	0.5%
Pasture, Furrow	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.6	0.1%
Fallow, NA	0.0	0.0%	0.6	0.0%	0.0	0.0%	45.1	1.7%	0.0	0.0%	18.7	2.2%
Urban, built-up	0.0	0.0%	0.2	0.0%	0.0	0.0%	7.3	0.3%	0.0	0.0%	1.3	0.2%
Sub-urban	0.0	0.0%	0.2	0.0%	0.0	0.0%	4.3	0.2%	0.0	0.0%	1.4	0.2%
Schools & Sports Grounds	0.0	0.0%	0.0	0.0%	0.0	0.0%	0.3	0.0%	0.0	0.0%	0.0	0.0%

Table C 7: Land cover distribution in the Kouga catchment for IAP clearing and expansion scenarios

Cover type	Kouga - IAP Scenarios											
	Clear all & restore		Clear all, farm valley, & restore mountains		Clear valley & restore		Clear valley & farm		Clear valley & farm, expand in mountains		Full IAP expansion (on non-ag)	
	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change
Major dam	5	0%	5	0%	5	0%	5	0%	5	0%	5	0%
Farm dam	13	0%	13	0%	13	0%	13	0%	13	0%	13	0%
Wetland_palmiet	0		0		0		0		0		0	
Wetland_other	15	156%	6	5%	15	152%	6	0%	0	-100%	0	-100%
Wetland_slope	10	14%	10	14%	9	0%	9	0%	0	-100%	0	-100%
Riparian woodland & forest	117	62%	117	62%	72	0%	72	0%	0	-100%	0	-100%
Savanna	1	19%	1	19%	1	19%	1	0%	0	-100%	0	-100%
Fynbos_lowland	300	10%	274	1%	296	9%	271	0%	0	-100%	0	-100%
Fynbos_mountain	1,327	2%	1,326	2%	1,303	0%	1,302	0%	751	-42%	751	-42%
Fynbos_cliff	553	0%	553	0%	550	0%	550	0%	548	0%	548	0%
Thicket	47	3%	47	3%	46	0%	46	0%	2	-96%	2	-96%
Thicket_cliff	82	0%	82	0%	82	0%	82	0%	81	-1%	81	-1%
IAP_wattle	0	-100%	0	-100%	77	-31%	78	-30%	1,014	815%	1,047	845%
IAP_pine	0	-100%	0	-100%	2	-3%	2	-3%	68	3996%	68	3999%
Apples, Sprinkler	5	0%	6	3%	5	0%	6	3%	6	3%	5	0%
Apples, Micro-spray	91	0%	118	29%	91	0%	117	28%	117	28%	91	0%
Apples, Drip	1	0%	1	14%	1	0%	1	14%	2	259%	2	244%
Pears, Sprinkler	1	0%	1	1%	1	0%	1	1%	0	-99%	0	-100%
Pears, Micro-spray	2	0%	2	25%	2	0%	2	25%	2	25%	2	0%
Stone fruit, Sprinkler	1	0%	1	8%	1	0%	1	7%	1	7%	1	0%
Stone fruit, Micro-spray	2	0%	3	51%	2	0%	3	51%	3	51%	2	0%
Honeybush	0		0		0		0		0		0	
Lucerne, Sprinkler	3	0%	3	34%	3	0%	3	33%	3	33%	3	0%
Lucerne, Pivot	0		0		0		0		0		0	
Lucerne, Furrow	0		0		0		0		0		0	
Pasture, Sprinkler	19	0%	24	31%	19	0%	23	26%	23	26%	19	0%
Pasture, Pivot	1	0%	1	2%	1	0%	1	2%	1	2%	1	0%
Pasture, Furrow	0	0%	0	4%	0	0%	0	0%	0	0%	0	0%
Fallow, NA	45	0%	45	0%	45	0%	45	0%	0	-100%	0	-100%
Urban, built-up	7	0%	7	0%	7	0%	7	0%	7	0%	7	0%
Sub-urban	4	0%	4	0%	4	0%	4	0%	4	0%	4	0%
Schools & Sports Grounds	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%

Table C 8: Land cover distribution in the Kromme catchment for IAP clearing and expansion scenarios

Cover type	Kromme - IAP Scenarios											
	Clear all & restore		**Clear all, farm valley, & restore mountains**		**Clear valley & restore**		**Clear valley & farm**		**Clear valley & farm, expand in mountains**		**Full IAP expansion (on non-ag)**	
	Area (km^2)	**% change**	**Area (km^2)**	**% change**	**Area (km^2)**	**% change**	**Area (km^2)**	**% change**	**Area (km^2)**	**% change**	**Area (km^2)**	**% change**
Major dam	7	3%	7	3%	7	0%	7	0%	7	0%	7	0%
Farm dam	3	0%	3	0%	3	0%	3	0%	3	0%	3	0%
Wetland_palmiet	5	224%	1	0%	5	224%	1	0%	0	-100%	0	-100%
Wetland_other	4	8%	3	1%	3	7%	3	0%	0	-100%	0	-100%
Wetland_slope	5	9%	5	9%	5	0%	5	0%	0	-100%	0	-100%
Riparian woodland & forest	49	64%	49	64%	30	0%	30	0%	0	-100%	0	-100%
Savanna	0		0		0		0		0		0	
Fynbos_lowland	168	10%	153	1%	165	9%	152	0%	0	-100%	0	-100%
Fynbos_mountain	434	7%	434	7%	405	0%	405	0%	133	-67%	133	-67%
Fynbos_cliff	48	4%	48	4%	46	0%	46	0%	46	-1%	46	-1%
Thicket	1	36%	1	36%	1	0%	1	0%	0	-99%	0	-99%
Thicket_cliff	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
IAP_wattle	0	-100%	0	-100%	50	-25%	50	-25%	471	604%	488	629%
IAP_pine	0	-100%	0	-100%	3	-2%	3	-2%	65	1902%	65	1904%
Apples, Sprinkler	0		0		0		0		0		0	
Apples, Micro-spray	1	0%	1	28%	1	0%	1	25%	1	25%	1	0%
Apples, Drip	0	0%	0	20%	0	0%	0	20%	0	20%	0	0%
Pears, Sprinkler	0		0		0		0		0		0	
Pears, Micro-spray	0		0		0		0		0		0	
Stone fruit, Sprinkler	0		0		0		0		0		0	
Stone fruit, Micro-spray	0	0%	0	15%	0	0%	0	15%	0	15%	0	0%
Honeybush	0		0		0		0		0		0	
Lucerne, Sprinkler	3	0%	4	19%	3	0%	4	16%	4	16%	3	0%
Lucerne, Pivot	1	0%	1	0%	1	0%	1	0%	1	0%	1	0%
Lucerne, Furrow	0		0		0		0		0		0	
Pasture, Sprinkler	85	0%	102	20%	85	0%	101	19%	101	19%	85	0%
Pasture, Pivot	4	0%	4	0%	4	0%	4	0%	4	0%	4	0%
Pasture, Furrow	1	0%	1	0%	1	0%	1	0%	1	0%	1	0%
Fallow, NA	19	0%	19	0%	19	0%	19	0%	0	-100%	0	-100%
Urban, built-up	1	0%	1	0%	1	0%	1	0%	1	0%	1	0%
Sub-urban	1	0%	1	0%	1	0%	1	0%	1	0%	1	0%
Schools & Sports Grounds	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%

Table C 9: Land cover distribution in the Kouga and Kromme catchment for different agriculture scenarios

Cover type	Kouga						Kromme					
	Full agricultural expansion		Honeybush on fallow		Honeybush on fallow and riparian		Full agricultural expansion		Honeybush on fallow		Honeybush on fallow and riparian	
	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change	Area (km^2)	% change
Major dam	5	0%	5	0%	5	0%	7	0%	7	0%	7	0%
Farm dam	13	0%	13	0%	13	0%	3	0%	3	0%	3	0%
Wetland_palmiet	0	NA	0	NA	0	NA	0	-100%	1	0%	1	0%
Wetland_other	1	-87%	6	0%	6	0%	1	-84%	3	0%	3	0%
Wetland_slope	9	0%	9	0%	9	0%	5	0%	5	0%	5	0%
Riparian woodland & forest	72	0%	72	0%	72	0%	30	-1%	30	0%	30	0%
Savanna	1	0%	1	0%	1	0%	0		0		0	
Fynbos_lowland	76	-72%	271	0%	271	0%	10	-93%	152	0%	152	0%
Fynbos_mountain	1,301	0%	1,302	0%	1,302	0%	404	0%	405	0%	405	0%
Fynbos_cliff	550	0%	550	0%	550	0%	46	0%	46	0%	46	0%
Thicket	45	0%	46	0%	46	0%	1	0%	1	0%	1	0%
Thicket_cliff	82	0%	82	0%	82	0%	0	0%	0	0%	0	0%
IAP_wattle	76	-31%	111	0%	111	0%	49	-27%	67	0%	67	0%
IAP_pine	2	-3%	2	0%	2	0%	3	-3%	3	0%	3	0%
Apples, Sprinkler	6	3%	5	0%	5	-2%	0		0		0	
Apples, Micro-spray	229	151%	91	0%	89	-2%	4	222%	1	0%	1	-10%
Apples, Drip	1	28%	1	0%	1	-9%	0	36%	0	0%	0	-10%
Pears, Sprinkler	1	1%	1	0%	1	-5%	0		0		0	
Pears, Micro-spray	4	129%	2	0%	2	-2%	0		0		0	
Stone fruit, Sprinkler	1	9%	1	0%	1	-2%	0		0		0	
Stone fruit, Micro-spray	6	269%	2	0%	2	0%	0	34%	0	0%	0	0%
Honeybush	0		45		48		0		19		19	
Lucerne, Sprinkler	6	144%	3	0%	3	-2%	8	125%	3	0%	3	-3%
Lucerne, Pivot	0		0		0		1	0%	1	0%	1	0%
Lucerne, Furrow	0		0		0		0		0		0	
Pasture, Sprinkler	163	778%	19	0%	18	-3%	263	211%	85	0%	84	-1%
Pasture, Pivot	1	2%	1	0%	1	0%	4	0%	4	0%	4	0%
Pasture, Furrow	0	4%	0	0%	0	0%	1	0%	1	0%	1	0%
Fallow, NA	0	-100%	0	-100%	0	-100%	0	-100%	0	-100%	0	-100%
Urban, built-up	0	-95%	7	0%	7	0%	0	-64%	1	0%	1	0%
Sub-urban	0	-94%	4	0%	4	0%	1	-62%	1	0%	1	0%
Schools & Sports Grounds	0	-100%	0	0%	0	0%	0	-56%	0	0%	0	0%

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D. RIVER CHANNEL GEOMORPHOLOGY AND HYDRAULIC PROPERTY ANALYSES

D.1. Background

To conceptualize river channel processes in the BKK catchments and model channel flow and surface-subsurface interactions numerically, both GIS and field-based analyses of channel network geomorphology were done. Because of the size of the catchments the scope of this was limited to the main river channel in the central valley of each catchment. The largest tributaries in the Kouga catchment were also included as they have substantial floodplains which are actively farmed. A method to segment channel network into units likely to have similar channel properties (i.e. slope, dimensions, and roughness) was developed and tested. Segmentation was done in GIS using indices of major catchment-scale drivers of geomorphology: valley confinement and stream power. Valley confinement refers to the width of the valley floor available for the river to move laterally which influences its flow energy distribution and sediment erosion and deposition patterns. Stream power is an index of the energy the river has to potentially move sediment.

Cognizant of the semi-arid conditions and local geomorphology, an alternative index of stream power was proposed and used in this study, termed 'valley-specific stream power' (VSSP). Valley specific stream power is typically estimated for different points along a river as a function of bankfull flow or mean annual flood, slope, and channel width (Sekese, 2019). Channel width is a measure of the space available to disperse the energy of the flow. Where field measurements of channel width are not available it is often estimated as a function of flow, which is, in turn, often estimated as a function of rainfall, contributing catchment area, and other catchment properties influencing runoff rations (Dollar *et al.*, 2007; Jaeger *et al.*, 2017). However, in dry systems with coarse sediment, channels are often multi-threaded and have flood-outs and other features that make estimation of channel width challenging and, in some areas, less relevant (Sekese, 2019). To deal with this, valley floor width was used, instead of estimated channel width, as an indicator of the area available to disperse flow energy at a location. Valley width could be more directly measured from readily available topography data (DEM) with fewer assumptions when compared to estimating likely channel widths based on estimates of likely flow volumes (Nagel et al., 2014; Roux et al., 2015).

To relate the GIS derived indices to channel properties, field measurements were taken at sites with a range of valley confinement and stream power conditions. Thirteen variables for sixteen sites were derived from the GIS analyses and field measurements, including valley parameters (valley confinement, and valley specific stream power) and channel-reach parameters (elevation, channel width, channel cross-sectional area, channel depth, width to depth ratio, channel roughness, channel slope, median grain size, soil texture, and fluvial style).

D.2. Methods

D.2.1 GIS analyses

The study developed an automated method for continuously mapping valley confinement and estimated specific stream power along the river profile. This used the Valley Bottom Extraction Tool (Gilbert et al., 2016) which mapped the extent and shape of unconfined valley bottoms using the DEM and stream network (Figure D1). Unconfined valleys had large sedimentary fills with well-developed floodplain whereas confined valleys were set within exposed bedrock or terrace material, limiting the formation of floodplains. Valley metrics were consequently generated for calculating valley specific stream power (VSSP) by using a 5 m resolution DEM to determine channel slope, flow accumulation grid surfaces and a weighted rainfall surface as a discharge proxy for each catchment (Figure D2). The longitudinal pattern of the valley specific stream power and valley confinement for each catchment was assessed.

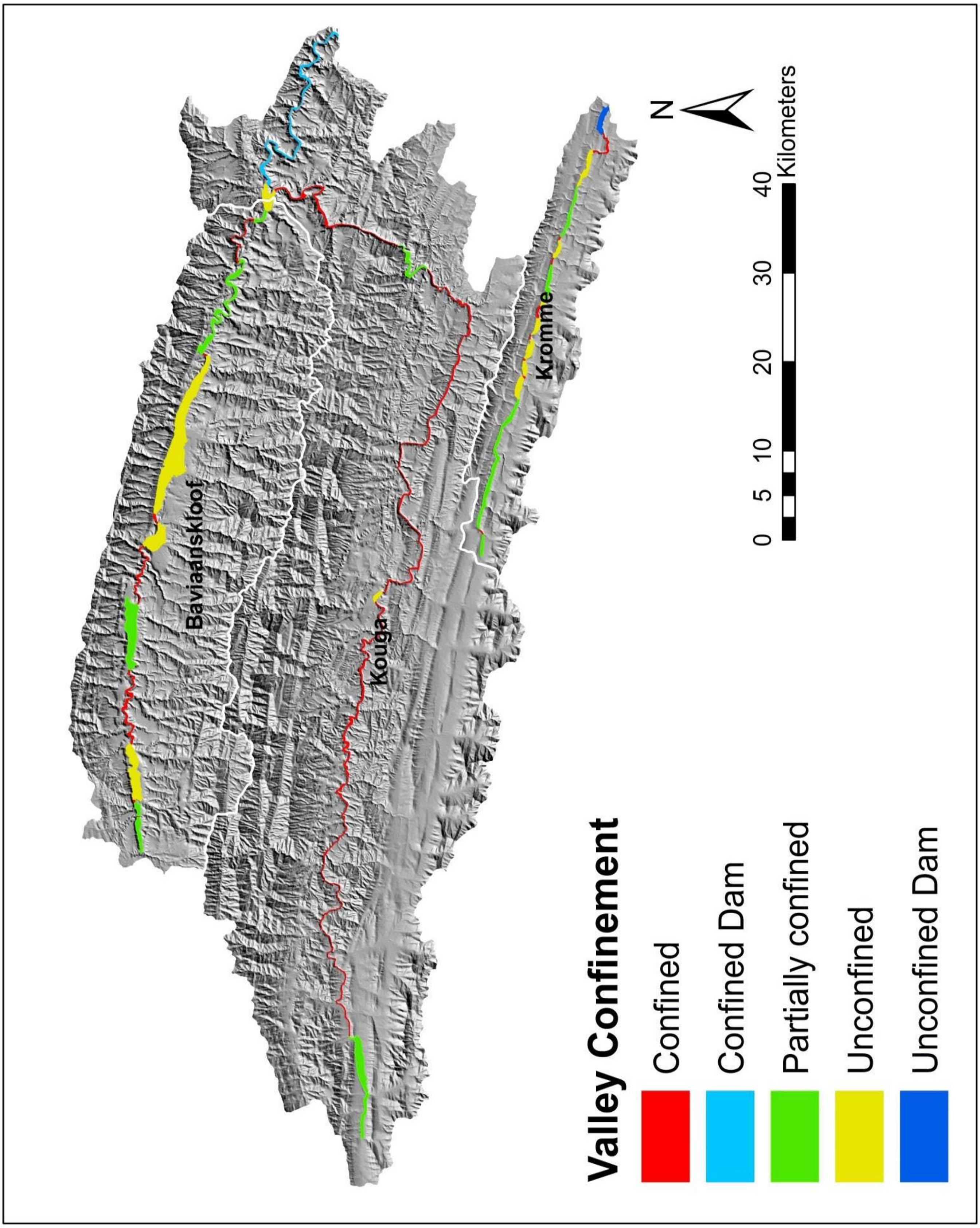

Figure D 1: Map showing the various valley confinement types in the three catchments

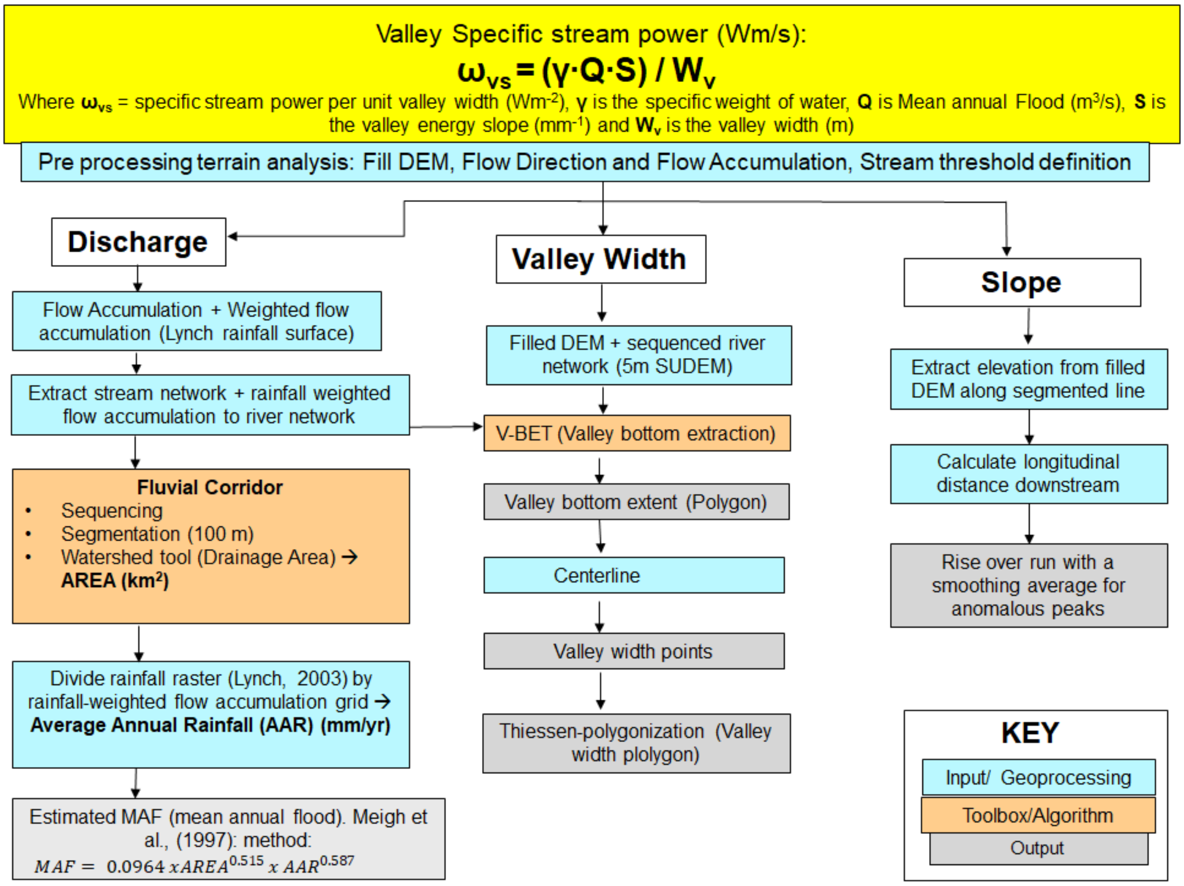

Figure D 2: Methodological workflow to calculate valley specific stream power in a GIS environment

D.2.2 Field data collection

Channel cross-sections were surveyed, channel patterns were described, and sediments were sampled at sixteen field sites to examine channel properties across various valley settings. Topographic surveying of channel cross sections was done during the period of May to August 2017 using a differential Global Positioning System (dGPS, GeoMax Zenith 20 GPS GNSS Base RTK Rover system). At two confined valley locations, satellite signal was too weak for dGPS readings due to steep rock faces, and so a theodolite was used. Three cross sections were surveyed at the majority of the 16 sites. At 5 of the sites only two cross sections were surveyed because of logistical difficulties and depths of pools. Channel attributes of slope, width, depth and cross-section area, width/depth ratio were calculated using the cross section topography data.

Channel bed and bank sediment analysis was done at all sites. The coarse sediment fraction was characterised using gravelometer transects and fine sediment samples were collected for the laboratory analyses. Particle size distribution of the fine grained sediments was determined using the hydrometer and dry-sieve method at the Elsenburg laboratory. The D50 and D85 grain sizes were determined for the coarse and fine fractions.

Channel patterns (straight, meandering or braided) and geomorphic features (terraces, fans, etc.) at each site were identified during the surveying, and subsequent aerial photo analyses, using published descriptions. Fluvial styles were assigned by looking at a) valley margin and fill type, b) channel shape (straight, wandering, meandering or braided and anabranching) and change over time, c) vegetation density and change over time, all analysed for 2003 (pre flood year), 2012 (flood year) and 2017 (post flood year). Planform (fluvial) types were named according to the procedural attributes used to name river types in the River Style Framework (Fryirs and Brierley, 2018) for consistency with contemporary river classifications. Manning's roughness (n) was estimated using the incremental method of Chow (1959).

The channel property data from the field sites was then compared to the patterns in the GIS-derived indices of catchment-scale drivers to investigate groupings of properties and river styles.

D.3. Results summary

Analyses of VSSP along the longitudinal profiles of the main channels revealed multi-peaked specific stream power profiles for the Baviaanskloof, Kouga and Kromme (BKK) catchments. When comparing the three catchments, the Baviaanskloof had a peak in the mid-section and at the end of the valley while the Kouga has multiple peaks. The Kromme valley followed a similar pattern to the Baviaanskloof with an additional peak at the start of the valley (Figure D3). While estimated discharge increases along the profile, slope and valley width fluctuated up and down creating these VSSP peaks. One could expect a decreasing slope and increasing width trend to create a decreasing pattern of valley specific stream power in low flow systems, or increasing discharge to dominate, driving an increase. Instead, these catchments had a highly fluctuating, multi-peak pattern which is more common for non-perennial rivers (Figure D3, Table D1).

From the field data analyses it was observed that catchments are dominated by mixed bed load channels, which reflects the uneven distribution of valley specific stream power and its ability to move the sediments within its fluvial corridor which is the lateral extent of the valley. The analysis of energy (valley specific stream power) versus resistance (median bed grain size and bank content of silt and clay) allowed the river typing of the rivers in these catchments. For the Baviaanskloof most of the segments were assigned a mixed bed, medium to low sinuosity, margin controlled (alluvial fans and bedrock) fluvial style. Where the valley was laterally unconfined, one would expect an anabranching river pattern. In the Kouga, a few fluvial styles were found, such as mixed bed and sand bed, high to low sinuosity and there were also discontinuous floodplain fluvial styles. All the Kouga fluvial styles had bedrock margin control, irrespective of the valley confinement type. The Kromme catchment experienced a similar pattern of fluvial styles as Baviaanskloof with the exception of occasional floodplain pockets, fine sand valley fill present in the Kromme.

Table below is a summary of catchment, valley and channel properties derived from the sixteen sampled sites which represent a variety of valley confinement and stream power conditions. The GIS framework provided a geomorphic-driver based approach to divide the river network into units based on valley confinement and specific stream power classes. To assign channel properties on other segments in the catchments, the data was extrapolated using these classes, using the field measurement data and channel properties measured from aerial photography within the segment type (Table D1).

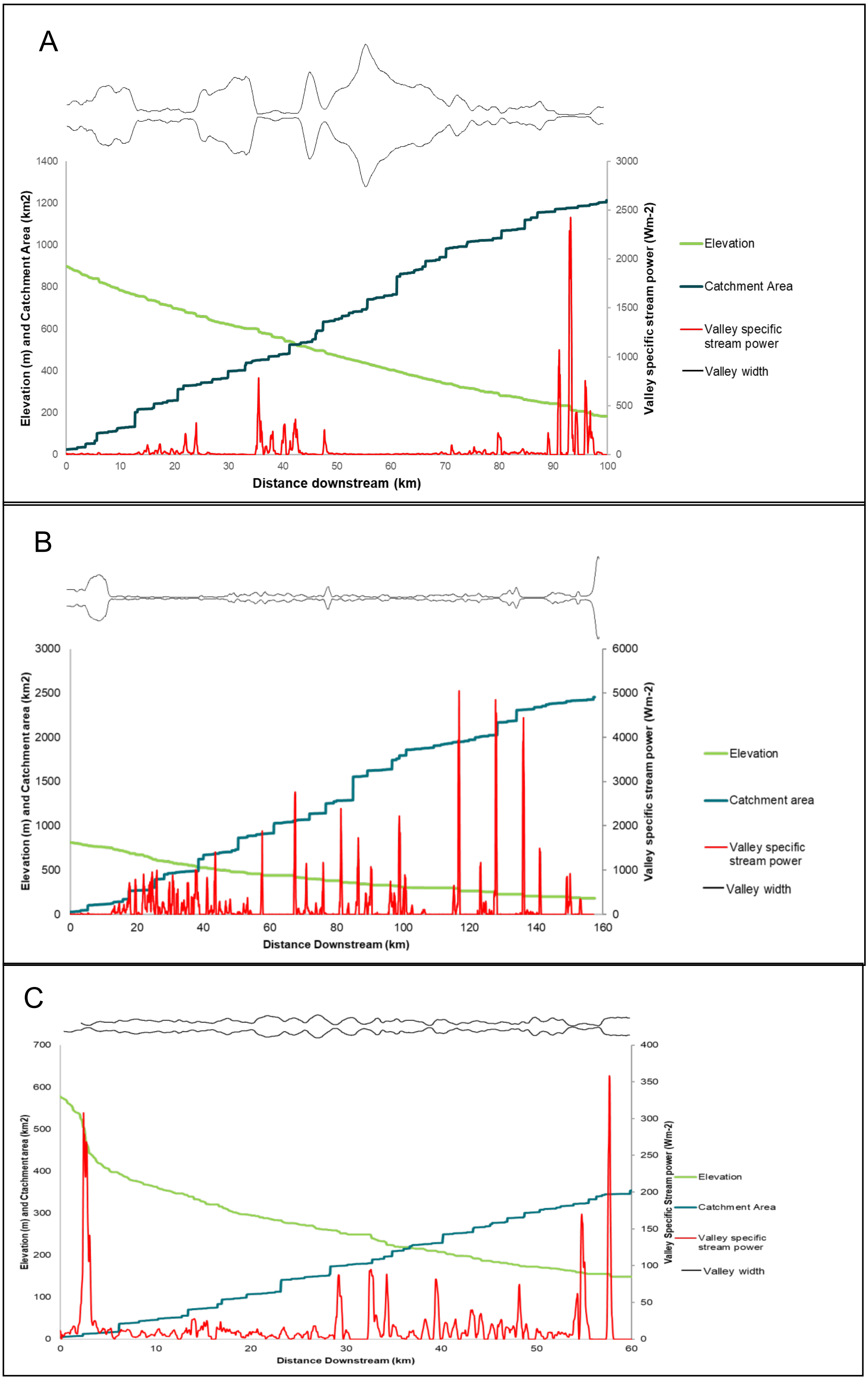

Figure D 3: Longitudinal variation of valley specific stream power, valley bottom shape (based on valley width) and catchment area in the A). Baviaanskloof B). Kouga and C). Kromme

Table D 1: Channel attributes of sample sites

Catchment	SN	E	VSSP	VC	CA	CW	CD	WDR	MR	S	D50_C	D50_F	STCSS	FS
Kromme	Kompanjiesdrift	336	12	Confined	120	47	4,5	10	0,06	0,018	0,030	0,0002	7	C_fmc_Ofp_Ms_Cb
Kouga	Kritplaas-Brandhoek	400	94	Confined	114	56	3,26	17	0,08	0,0104	0,086	0,0003	11	C_bmc_Ls_Ofp_Cb
		Average	**53**		**117**	**52**	**3,88**	**14**	**0,07**	**0,0142**	**0,058**	**0,0003**	**9**	
Kouga	BVK-KGA Confluence	174	0,2	Laterally unconfined	61	112	2,39	47	0,14	0,0126	0,085	0,0005	13	LU_dc_M_Cb
Baviaanskloof	Rus en vrede	443	3	Laterally unconfined	67	59	2,12	28	0,10	0,0105	0,012	0,0025	8,8	LU_cc_Ab_Sb
Kromme	Jagerbos	254	7	Laterally unconfined	55	68	1,56	44	0,07	0,0028	0,047	0,0002	6,3	LU_dc_Vf_Fgs
Baviaanskloof	Joachimskraal	394	9	Laterally unconfined	39	53	1,51	35	0,12	0,0077	0,011	0,0009	9	LU_cc_Ab_Sb
		Average	**6**		**55**	**73**	**1,90**	**39**	**0,11**	**0,0084**	**0,039**	**0,0010**	**9**	
Baviaanskloof	Kamerkloof	517	9	Confined	23	34	1,74	20	0,09	0,0067	0,010	0,0002	29	C_tc_Ls_Gb
Kromme	Krugers Kraal	403	14	Partially confined	30	19	2,81	7	0,12	0,0095	0,030	0,0004	11,8	PC_fmc_Lms_Gb

Kouga	Braamrivier	775	28	Laterally unconfined	40	46	2,26	20	0,09	0,0038	0,012	0,0009	23	LU_cc_Hs_Sb
Kromme	Melkhoute Kraal	209	75	Confined	64	36	3,9	9	0,14	0,0003	0,000	0,0002	9	C_fmc_Ls_Vbf_Sb
		Average	**39**		**39**	**34**	**2,68**	**14**	**0,11**	**0,0051**	**0,013**	**0,0004**	**18**	
Baviaanskloof	NatRes	245	136	Confined	2	9	0.68	13	0,09	0,003	0,006	0,0005	14,8	C_bmc_Ls_Mb
Baviaanskloof	BoKloof	590	457	Confined	2	10	0,76	13	0,06	0,007	0,022	0,0006	9,8	C_bmc_Ls_Mb
		Average	**297**		**2**	**10**	**0,76**	**13**	**0,08**	**0,0050**	**0,014**	**0,0006**	**12**	
Baviaanskloof	Verlorenrivier2	628	4	Laterally unconfined	9	38	1,13	34	0,04	0,0048	0,010	0,0011	16,3	LU_cc_W_Sb
Baviaanskloof	Nuwekloof	874	5	Partially confined	7	11	0,99	11	0,04	0,0108	0,029	0,0002	6	PC_pc_Ms_Tc_Gb
Baviaanskloof	Rietrivier	760	15	Partially confined	18	20	0,4	50	0,08	0,0071	0,021	0,0016	8	PC_pc_Ms_Tc_Gb_
Baviaanskloof	Verlorenrivier1	655	19	Partially confined	28	34	1,04	33	0,03	0,0055	0,011	0,0005	14,6	PC_mc_W_Df_Cb
		Average	**13**		**16**	**26**	**0,89**	**32**	**0,05**	**0,0071**	**0,018**	**0,0009**	**11**	

Key: E = Elevation (m), VVSP = Valley specific stream power (Wm/s), VC = Valley confinement setting, CW = Channel width (m), CA = Channel Cross-sectional area (m2), CD = Channel depth (m), WDR= Width to depth ratio, MR = Manning's roughness, S = bed channel slope (m/m), D50_F = Median grain size for fine sediments (m), D50_C = Median grain size for coarse sediments (m), STCSS = Soil texture for clay and silt, FS = Fluvial style

Table D 2: Summary of segmented catchment, valley and channel attributes in the three catchments

Catchment	VC	Length (km)	Area (km^2)	DA (km^2)	Rainfall (mm/yr)	Width (m)	Eleva-tion (m)	Slope (m/m)	MAF (m^3/s)	VSSP (Wm^{-2})	CA (m^2)	CW (m)	CD (m)	WDR	MR	D50_C (m)	D50_F (m)	STCSS (%)
BVK	Confined	30,85	3,27	589,59	315,91	109	525	0,0093	71,03	123,90	11	25	1,15	22	0,0682	0,014	0,00056	21
	Partially confined	36,10	15,32	734,69	302,43	475	457	0,0066	75,89	16,55	23	20	0,52	38	0,0447	0,023	0,00087	8
	Unconfined	33,05	29,43	614,09	301,06	974	506	0,0082	71,17	6,16	37	53	1,83	29	0,0750	0,010	0,00170	10
KGA	Confined	133,20	9,56	1337,10	470,10	70	397	0,0046	139,05	173,26	110	53	2,25	24	0,09667	0,069	0,0005	12
	Partially confined	19,85	7,36	792,94	498,36	381	593	0,0047	86,43	14,94	122	50	3,01	17	0,08333	0,037	0,0008	19
	Unconfined	4,43	2,96	1931,82	460,53	722	259	0,0007	171,58	3,41	55	85	2,63	32	0,09000	0,038	0,0006	16
KRM	Confined	5,20	0,53	168,17	649,62	137	271	0,0204	58,13	60,34	90	46	3,90	12	0,09990	0,018	0,0003	10
	Partially confined	31,05	7,82	122,98	628,77	274	313	0,0095	46,09	12,27	35,00	30	2,50	12	0,00680	0,060	0,0007	15
	Unconfined	18,70	6,58	204,91	651,54	393	232	0,0040	66,12	7,03	61	76	1,70	45	0,05335	0,077	0,0001	13

Key: VC = Valley confinement setting, DA =Drainage Area (km^2), MAF = Mean annual flood (m^3/s), VSSP = Valley specific stream power (Wm^{-2}), CA = Channel Cross-sectional area (m^2), CW = Channel width (m), CD = Channel depth (m), WDR= Width to depth ratio, MR = Manning's roughness, D50_F = Median grain size for fine sediments (m), D50_C = Median grain size for coarse sediments (m), STCSS = Soil texture for clay and silt (%)

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E. HYDROMETRIC FIELD DATA COLLECTION AND ANALYSES

E.1. Introduction

To make inferences about catchment processes at various spatial scales, climate, surface, and groundwater level data were collected at sites across the Baviaanskloof and Kromme catchments. Sites were selected to get information about areas not monitored by DWS, SAWS, ECPTA, ARC, or Rhodes University and, in some cases, to target certain vegetation types of interest. All equipment was provided by SAEON and data will be made available through SAEON's online observations database. Some monitoring sites in the Baviaanskloof were pre-existing, active since 2012 and initiated during the research of Glenday 2015 also with support from SAEON. Basic water physicochemical properties and natural isotope levels were also measured at most monitoring sites, as described in Appendix F, and soil moisture was measured across vegetation types at a single site in the Kromme, described in Appendix G.

E.2. Methods

E.2.1 Climate data

Rainfall and temperature was monitored at eight stations in the Baviaanskloof and four stations in the Kromme (Figure E1) using Davis tipping bucket rain gages with HOBO data loggers and temperature sensors. Stations were located to monitor rainfall near other sampling sites as well as to better understand the spatial distribution of rainfall between high and low elevations in the catchments.

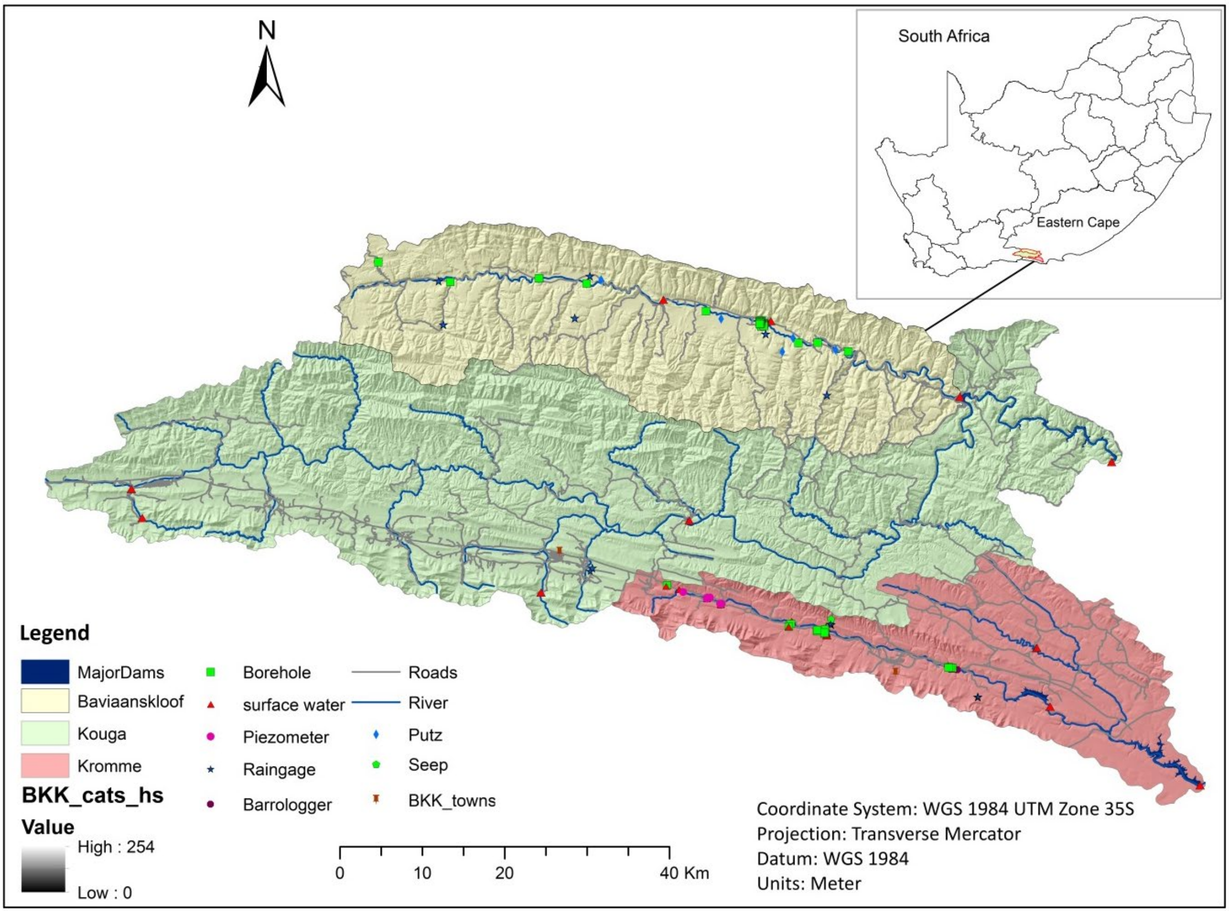

Figure E 1: Monitoring equipment in the Kromme, Kouga and Baviaanskloof catchment collecting data on climate, river and groundwater levels and hydrochemistry.

E.2.2 River water levels and streamflow estimation

Stream water levels were monitored at selected locations along the main river channels and at mountain tributaries (Figure E1) using continuously logging pressure transducers (Solinst LevelLoggers). Pressure transducer data was compensated for atmospheric pressure using data from a barometric logger (Solinst BaroLogger) in each catchment, adjusted to site altitude. This resulted in time-series of water levels above the instruments, which was converted to depth above thalweg where needed for flow estimation, and water surface elevation for comparison to groundwater table elevations.

Logging sites were selected to give insights on flow patterns at different spatial scales and some were also located in areas with riparian vegetation cover of interest (i.e. floodplain wetland, black wattle stands). In the Baviaanskloof water levels were recorded at four sites: the catchment outlet at the confluence with the Kouga River, two upstream sites on the main river, and one tributary stream from the Baviaanskloof Mountain side. In the Kromme catchment, water levels were recorded at six sites: four sites along the main channel, one on a tributary from the Kouga Mountains, and one on a tributary from the Tsitsikama Mountains. In as much as possible specific installation positions within desired sites were selected using the World Meteorological guidelines whereby channels should be free of aquatic weeds, water flow confined to a single channel with a regular profile and stable banks (WMO, 2008). The naturally branching floodplain channels, wetland areas, and rocky tributary streams constrained and complicated site selection. Some monitoring points were sited near gabion structures and bridges that provided artificial control sections.

Streamflow was estimated from the pressure transducer water level data using rating curves that were developed and tested with a combination of methods. Channel cross sections and slopes were surveyed at the monitoring sites with a differential GPS (GeoMax Zenith 20 GPS GNSS Base RTK Rover system). Manual flow measurements and wetted cross-section area data were gathered at all sites using an MF-Pro flow meter during quarterly field visits. The manual flow readings, combined with the cross section and slope measurements, were used to estimate Manning's n roughness coefficients and the variation in n values with river depth. Rating curves were developed in MIKE-11 (DHI) hydraulic software, based on Manning's equation and the channel cross sections. However most of the sampling period was during a time of drought and it was not possible to measure flows during the short peaks that did occur. Parameters of the rating curves (water surface slopes and effective roughness n values) for high flows were therefore estimated based on literature and then manually adjusted by comparing the resulting estimated flows to reference flows based on the nearest DWS gauging site.

To achieve rating curves which produced reasonable high-flow streamflow estimates, the output streamflow values were compared to various reference time-series to assess the need for parameter adjustment. It was assumed that during high flow periods, streamflow at all the monitoring points must be lower than the DWS inflow estimates for the relevant downstream reservoir, the Churchill, iMpofu, or Kouga Dam. In addition the contributing catchment area for each stream monitoring site was delineated and it was assumed that in high flow periods, larger catchment areas within the same major catchment (i.e. Baviaanskloof or Kromme) would have larger streamflow than sites with smaller catchment areas. Lastly, the runoff ratios modelled at quaternary catchment level in Water Resources 2012 (Bailey & Pitman 2015) study and the relative catchment areas were used to scale the dam inflow data and produce approximate reference datasets for the monitoring sites against which to evaluate and adjust each rating curve (example shown in Figure E2).

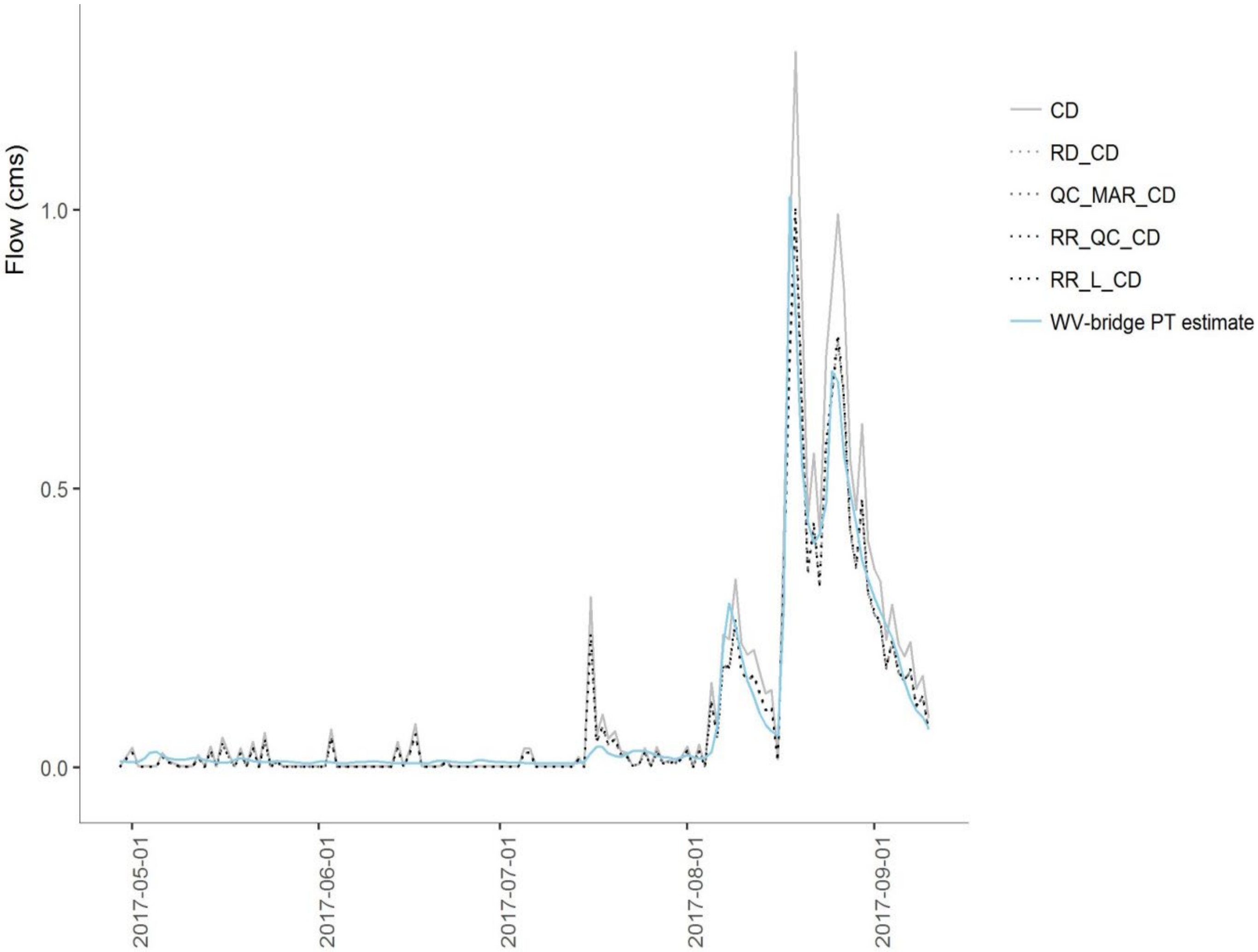

Figure E 2: Daily flow estimate from the pressure transducer data at Willowvale site (WV-bridge)

compared to the estimated daily inflow into the Churchill Dam from DWS data (CD) and various attempts at scaling the Churchill Dam inflow to predict likely flow at Willowvale (i.e. using runoff ratios (RR) and quaternary catchment (QC) mean annual runoff (MAR) estimates from WR, (2012) to evaluate the reasonableness of the rating curve applied.

E.2.3 Groundwater levels

Shallow groundwater levels in the floodplain alluvium were monitored with piezometers (1.5-3 m deep) and deep bedrock aquifer groundwater levels were monitored in pre-existing open boreholes on farms distributed across the catchments. Sites were selected for spatial distribution and to target particular land cover types and topographic positions, however were limited by accessibility. Some sites were equipped with pressure transducers (Solinist LevelLoggers) with data processed as described for streamflow sites above. Other sites were monitored manually at quarterly visits. Topographic surveys with a dGPS allowed river and groundwater surface elevations to be compared across adjacent monitoring locations.

In the Baviaanskloof, eighteen piezometers (four with pressure transducers) were monitored in three transects along a single 1 km floodplain reach at Joachimskraal, located in the catchment's largest wide-valley section, targeting a Working for Wetlands floodplain channel restoration intervention. Water levels in floodplain alluvium were also manually read from staff gages installed in pre-existing groundwater pits (5-15 m deep) used for farm water supply (monitored since 2011 by LivingLands and

SAEON). These pit (putze) sites are distributed along the floodplain with some located in wide-valley areas while others are up against mountain fronts. Three boreholes in the upper catchment were also monitored, two of which have pressure transducers. One borehole is located on a high mountain plateau on the Baviaanskloof mountain side, while the other two are in the main floodplain.

In the Kromme catchment, sets of piezometers were installed at three sites along the main floodplain: Kompanjiesdrif, an upstream site near a palmiet wetland basin; Hudsonvale, an actively farmed site midway down the catchment with some remnant wetland area; and Willowvale a downstream site with a large mature stand of black wattle and an area that has been cleared of wattle, where palmiet wetland is re-establishing. In addition three boreholes were monitored, two with pressure transducers. These two were located adjacent to one another with one located in the mouth of mountain tributary on the Tsitsikama Mountain side while the other is in the main valley floodplain immediately downslope.

E.2.4 Data analyses

The resulting hydrometric data sets were used to analyse the response of surface and groundwater to rainfall events and temperature fluctuations and to compare the responses of the surface water and the groundwater to gain information about their connections. Climate and streamflow datasets from DWS, SAWS, ARC, ECPTA, and Rhodes University, including the estimated inflow series for the Kouga Dam, the Churchill Dam, and the iMpofu Dam, were also considered in these analyses. Visual assessments of surface and groundwater hydrographs compared to rainfall events were done, comparing sites at different locations. Water surface elevations at adjacent river and groundwater sites were plotted together to determine when and where groundwater levels were above or below surface water levels and river thalweg elevations. In addition rainfall-runoff ratios, “slow-flow” or baseflow proportion estimates, and streamflow recession constants were calculated.

To estimate the rainfall runoff ratios, streamflow volumes were converted into depths and spatially averaged rainfall was estimated for the contributing catchment each monitoring site. The contributing catchment areas were delineated using methods described in Appendix B. Spatially averaged rainfall estimates were calculated for these areas from station data using the interpolation methods described in Appendix A. Monthly, yearly, and long-term average monthly and annual ratios were calculated to address the lag time in event flow reaching a monitoring point at larger catchment sites and the timing of events (i.e. occurring at month or year ends).

Baseflow was estimated using a simple recursive digital filtering technique applied to monthly flows as described by Smakhtin 2001 and previously applied to TMG catchment areas by Xu et al., 2009. Because this is a purely numeric signal processing algorithm, it cannot be claimed that this proportion of the flow is necessarily derived from any particular flow-path (i.e. interflow or groundwater flow through a particular aquifer). The technique does separate a portion of the hydrograph that changes quickly from that which changes gradually, an estimate of baseflow. No attempt was made to adjust or calibrate the algorithm filtering parameters at this stage, but a future step is to use the hydrochemistry to do so.

Streamflow recession constants were calculated for streamflow time-series. This was done to characterise the outflow from different catchment storages which feed delayed flows to the stream: interflow and groundwater contributions from different aquifers. If these storages are conceptualized as linear reservoirs from which drainage, hence streamflow, is proportional to storage, a recession constant can be calculated from recession periods during which there is no recharge of storage, only outflow.

A recession constant (k), with units of days was calculated by re-arranging the linear reservoir equation as shown:

$Q_{t2} = Q_{t1}\, e^{-(1/k)*(t_2-t_1)}$

$k = 1 / (\ln Q_{t1} - \ln Q_{t2})$

in which Q is the stream flow at time t_x and k is a recession constant with the same units as the timestep analysed (t_2-t_1).

Recession periods analysed were time periods with declining flow occurring 5 days or more since the last effective rainfall event, considered to be an event of 2 mm or more. Variable length time-steps were used to assess declining flow and the rate following the accumulated volume method described by (Rupp and Selker, 2006). This method smooths data in low flow periods to account for flow variability approaching measurement accuracy when values are small: relatively small apparent increases in estimated flow due to measurement accuracy will cause a period to not be considered a recession. A critical accumulated flow volume per time-step of greater than or equal to the 25th percentile of observed flow observed at a site was applied. Outputs were normalized back to daily recession rates.

E.3. Results

E.3.1 Relative surface water-groundwater elevations

Comparing paired surface water and groundwater levels at different adjacent sites showed the coupling of the alluvial floodplain aquifer and the streamflow in both the Baviaanskloof and Kromme. Surface flow patterns are well correlated with floodplain groundwater levels. Reaches of the Baviaanskloof River in wide-valley areas have non-perennial flow, with no flow for months at a time in dry periods when the floodplain groundwater levels are below the channel thalweg. The catchment outlet has near perennial flow with the exception of the extreme drought conditions in 2017. The main Kromme River has perennial flow and floodplain groundwater levels were generally above adjacent river thalweg elevations (in some cases the groundwater level fell below the piezometer depths and the piezometer depths were above the adjacent thalweg, at which point there is no information).

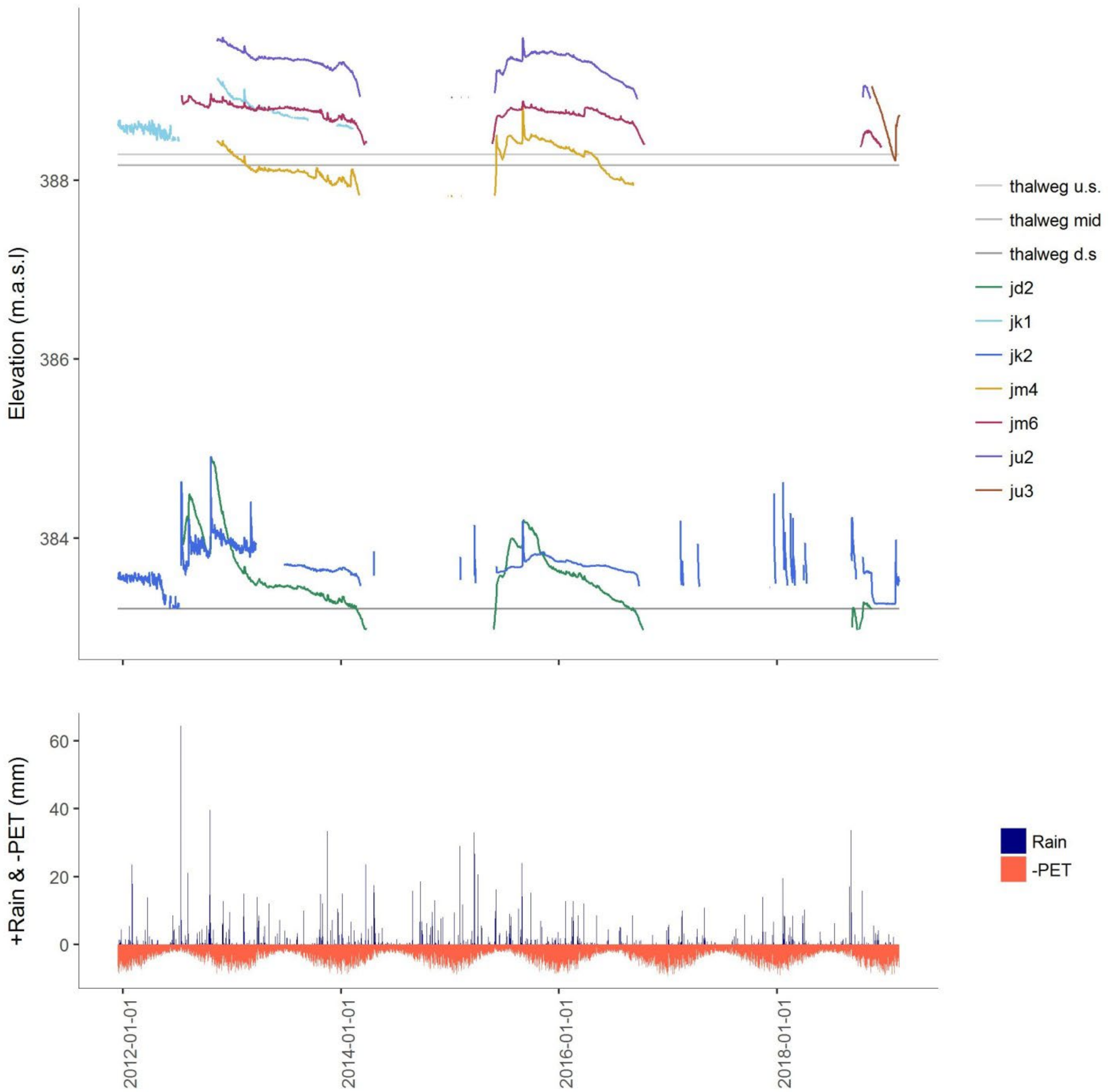

Figure E 3: Surface and groundwater elevations for piezometers and river monitoring points in the Baviaanskloof, Joachimskraal site. The river thalweg elevation is shown as a grey line for each transect. The flow sites (jk1 and jk2) are shown in blue. A gap in readings at groundwater sites indicates the water level is below the piezometer depth.

As seen in (Figure E3) at the Joachimskraal site, a central site in the Baviaanskloof, the floodplain groundwater was at higher elevations than the adjacent river thalweg for periods of almost a year following large winter rainfall events, associated with prolonged river baseflow at what is a non-perennial river site. The surface flow drying up coincides with the floodplain water level dropping below the channel thalweg. There were some short pulse streamflow responses to short, intense storms in 2018, but these were insufficient to replenish the groundwater and there was no baseflow. Only after the major event in 2018-09 did groundwater levels rise to within 2 meters of the surface following the 2017-2018 drought.

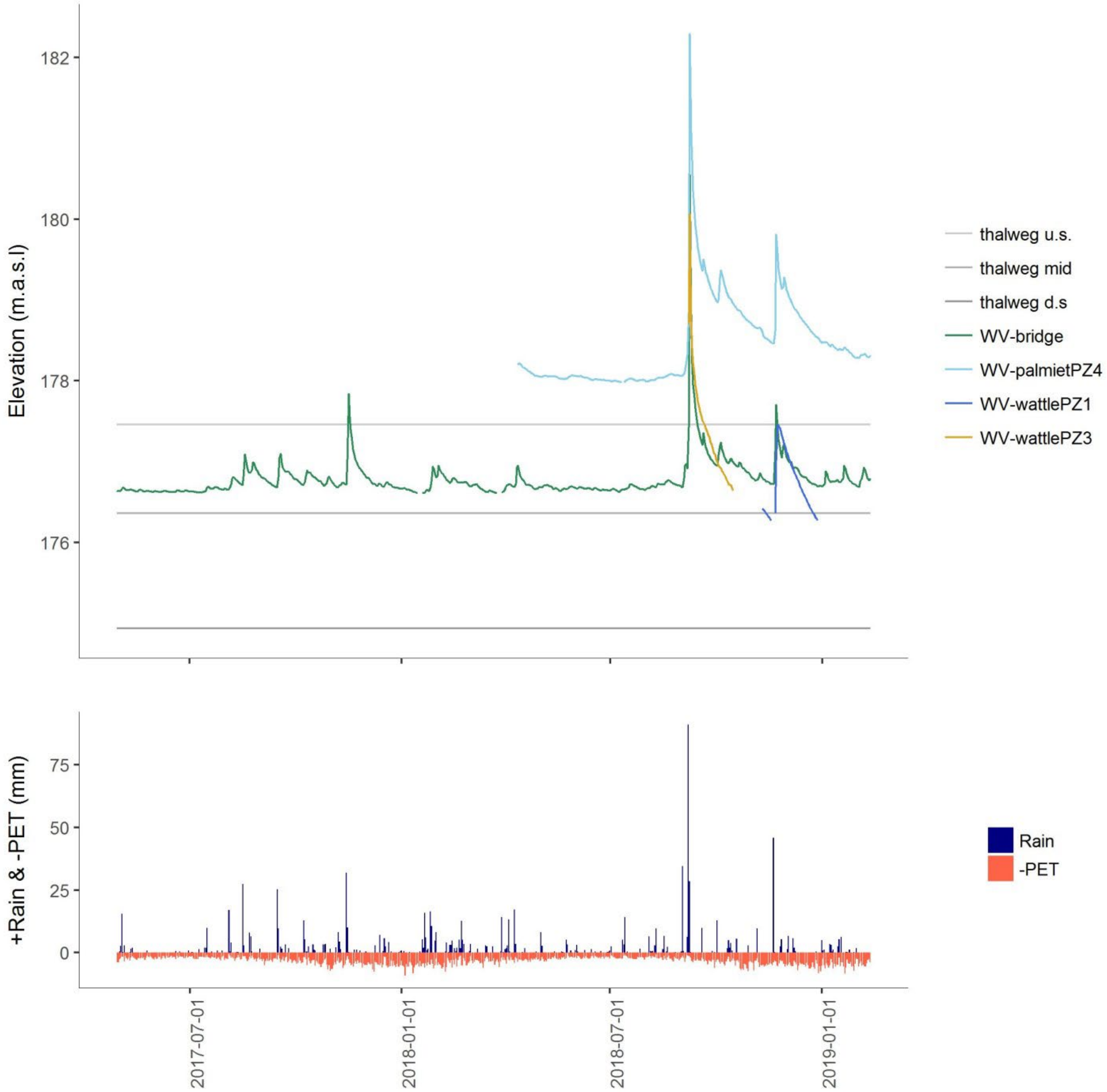

Figure E 4: Surface and groundwater elevations for piezometers and river monitoring points in the Kromme, Willowvale site. The river thalweg elevation is shown as a grey line for each transect The WV-bridge site is the streamflow while the others are piezometers. A gap in readings at groundwater sites indicates the water level is below the piezometer depth with the exception of WV-palmiet PZ which only began data collection in 05-2018

At the Kromme sample sites the groundwater levels at the floodplain piezometers monitored were more consistently above the river thalweg, therefore feeding the river flow. At the Willowvale site the groundwater depths rose sharply following the large 09-2018 rain event coincident with the streamflow peak, but the palmiet site showed a delayed recession compared to the stream (Figure E4). The groundwater levels in the wattle stand were below the depth of the piezometer for much of the sampling period, below 2.5 m from the surface, unlike at the palmiet site. The water level recession at the wattle site was steeper than that of the groundwater.

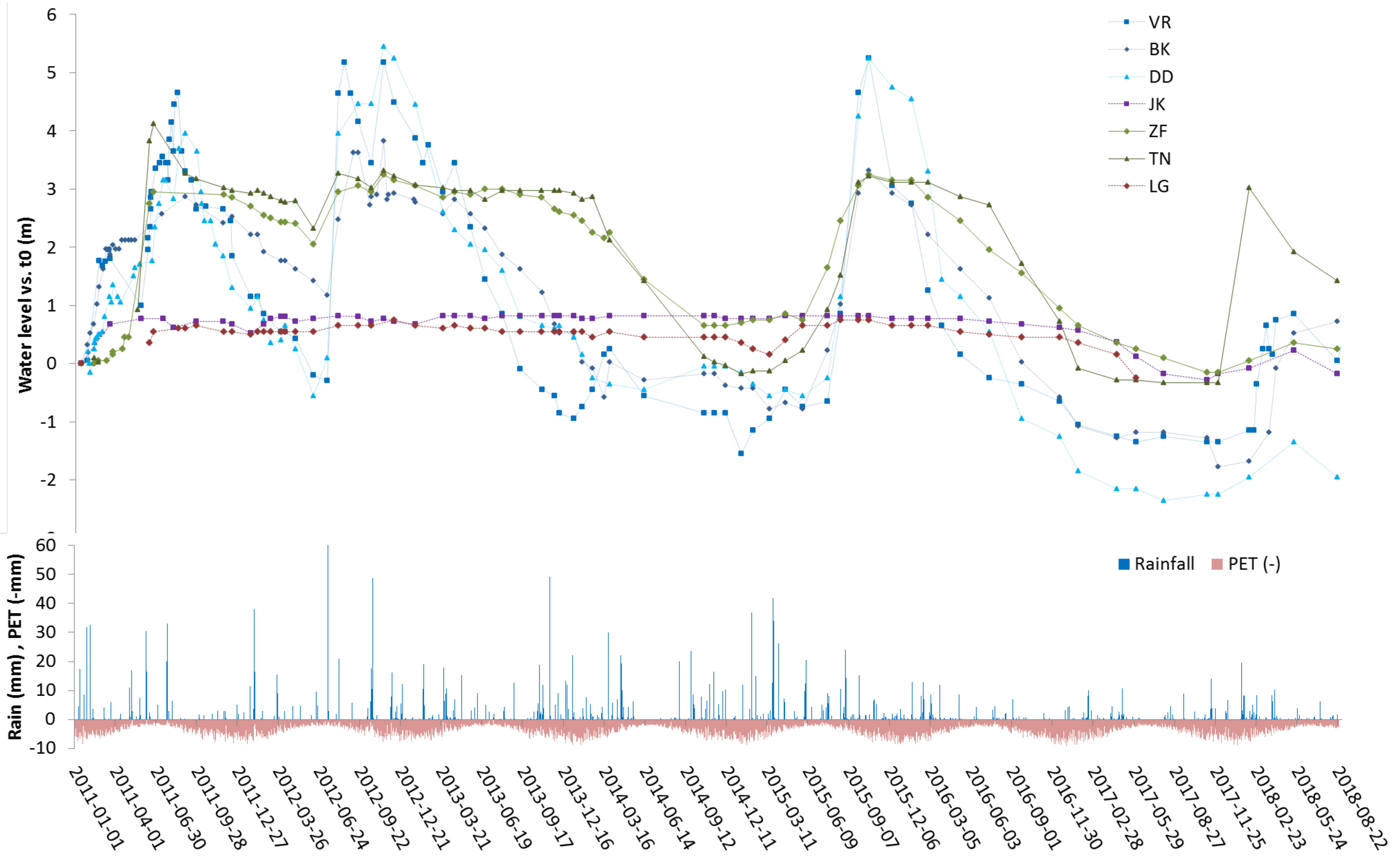

Figure E 5: Putze relative water surface elevation at sites across the Baviaanskloof floodplain. The sites in blue are located in the central valley, which the others are more downstream and closer to mountain fronts. Both JK and LG, which don't respond to rainfall events or dry periods are located against mountain fronts and have red tinted water.

Groundwater level fluctuations at different manually monitored groundwater pit sites in the Baviaanskloof are shown in (Figure E5). Several patterns are notable here:

- Sites JK and LG are almost not responsive to rainfall or dry periods, indicating a near constant water source. These sites are both located against the Kouga-side mountain front and had red tinted water, indicating they are fed by iron rich groundwater of the Nardouw formation.
- ZF and TN show a more moderate and delayed response to climate than VR, BK, DD, but more responsive than JK and LG. These also close to mountain fronts but also quite far downstream and so may represent delayed flow from the upslope catchment. They did not have obviously red water.
- VR, BK, DD are located further upstream and also in the middle of the valley floor in the valley alluvium. They were the most responsive to climate, peaking with rain and descending in the following dry periods.
- The delay in peak after rainfall at VR, BK, DD was generally on the order of weeks (not able to determine this in later data due to less frequent data collection) and the meters of rise were greater than could be produced with rain directly on the floodplain indicating broader catchment contributions.

E.3.2 Streamflow responses to rainfall

Observed streamflow in the both the Baviaanskloof and the Kromme showed fast and extreme responses to significant winter storms, with relatively less response to rainfall events in warmer periods (season indicated graphically by the magnitude of estimate PET in the figures below, (Figures E6, E7).

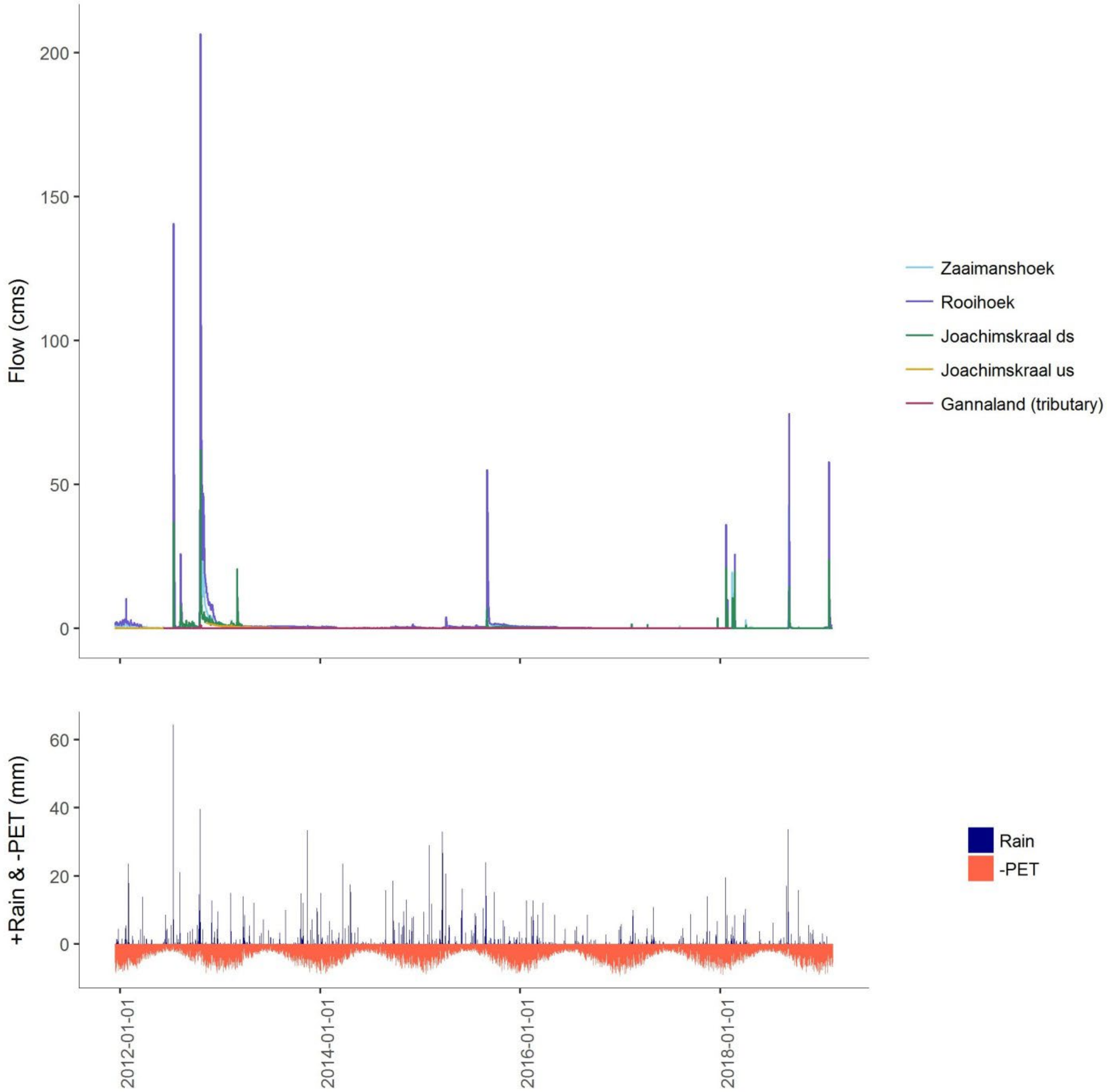

Figure E 6: Streamflow estimated at multiple sites in the Baviaanskloof (2012-2018) shown with rainfall and estimated potential evapotranspiration (PET)

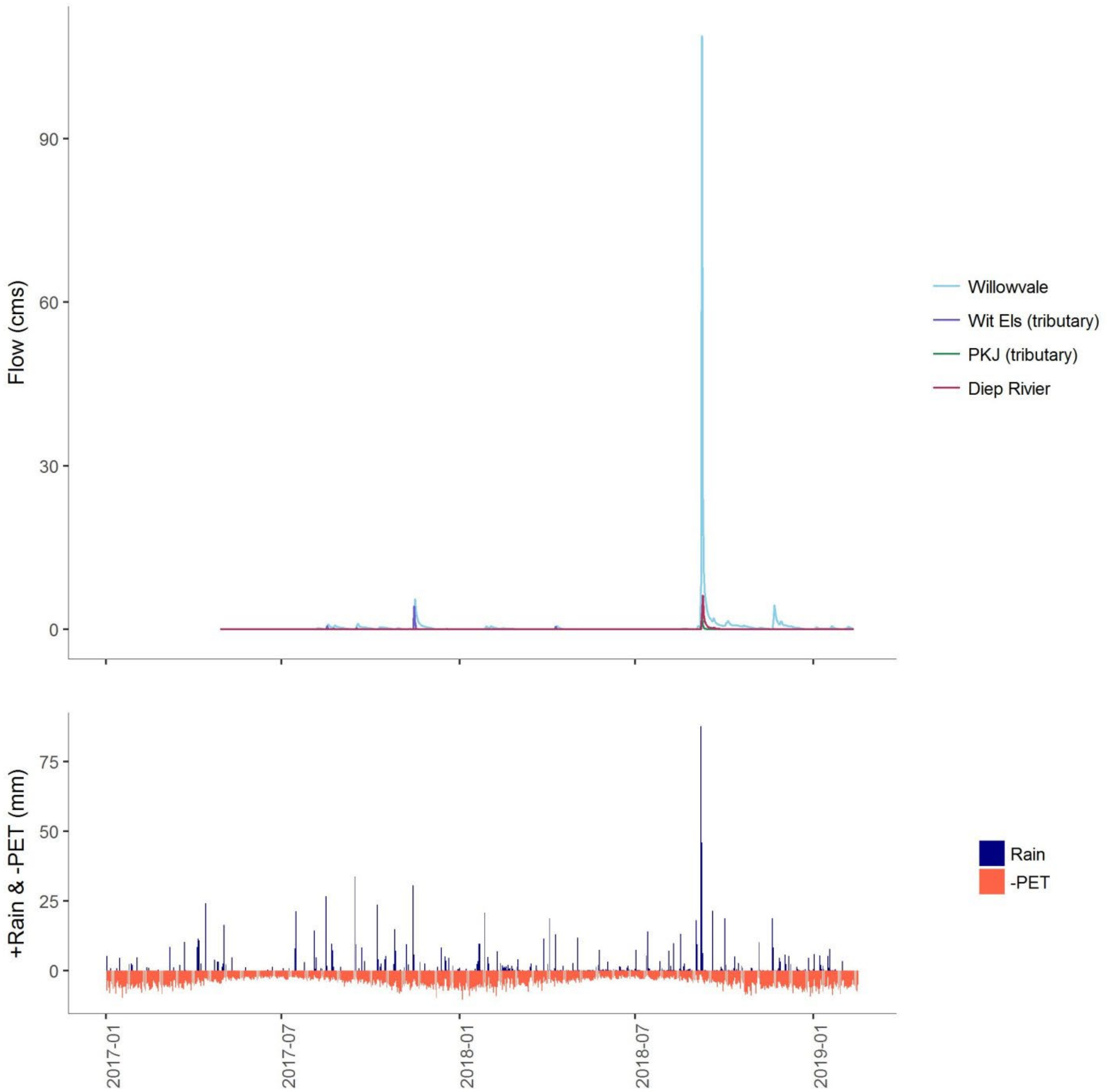

Figure E 7: Streamflow estimated at multiple sites in the Kromme (2017-2018) shown with rainfall and estimated potential evapotranspiration (PET)

E.3.3 Runoff ratios

Long-term runoff ratio estimates for the major catchments showed that the upper Kromme, Churchill Dam catchment, which receives the most rainfall (approximately 650 mm mean annual precipitation, MAP), has the highest percentage of the rainfall leaving the catchment as runoff, roughly 20% (Table E1). Wetter catchments typically have higher runoff ratios as the thresholds of runoff production are more frequently met by the larger rainfall events and wetter antecedent conditions. The lower Kromme, Impofu Dam catchment, receives less rainfall (611 mm) and has a lower average runoff ratio. This catchment also has less steep topography, cliffs, and bare rock, and may have deeper soils, and has a higher proportion IAP cover. The estimated runoff ratio for the Kouga Dam catchment, which includes both the Kouga and Baviaanskloof catchments was far lower: 9% of the estimated 477 mm MAP. The Stuurmanskraal weir in the central Kouga catchment had a higher runoff ratio, 13%, than the entire Kouga Dam catchment despite the slightly lower MAP (390 mm). It should be noted there is high interannual variability and these catchments were sampled across different time periods. It was assumed multidecadal averages could be compared, but this will be explored further.

Average seasonal runoff ratios (Figure E8) from the major catchments with multi-decadal records show the higher conversion of rainfall to runoff in the winter to spring compared to summer and fall. This is related to the seasonality of rain events large enough to exceed storage thresholds in the catchment and the impacts of lower evapotranspiration allowing for wetter antecedent conditions.

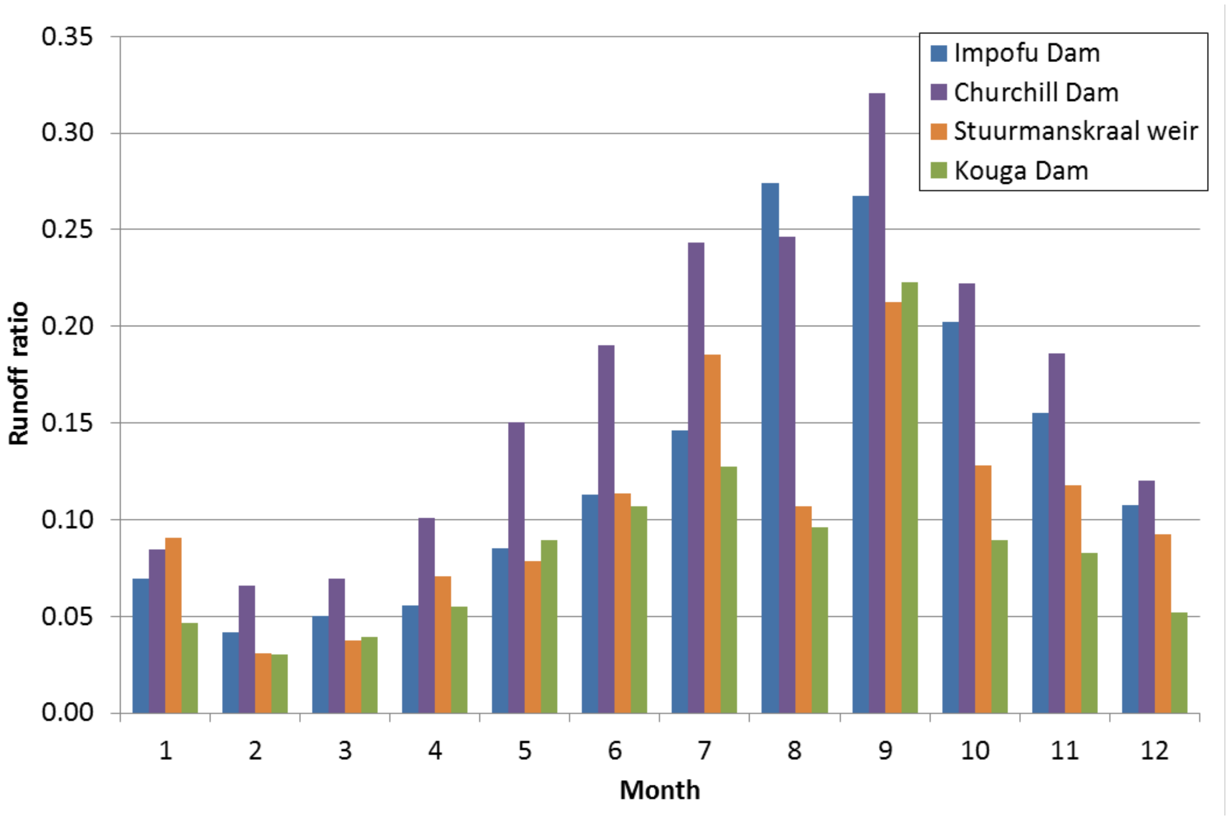

Figure E 8: Monthly average runoff ratios for long-term DWS monitoring points in the BKK catchments

Table E 1: Runoff ratios, baseflow proportions and other hydrometric statistics for flow monitoring points and their contributing catchments (both for the full record at the station and for recent period starting when all the Kromme monitoring sites were established for this project).

Catchment	Area (km^2)	Record period	Start	End	Yrs	Rain (mm)	PET (mm)	Aridity Index (P/PET)	Runoff (mm)	Runoff ratio (Q/P)	Ave. flow (cms)	Ave. % base-flow
Kromme - upper												
Churchill Dam	360	**Full**	**1957-01**	**2017-09**	**61**	**648**	**1335**	**49%**	**130.4**	**20%**	**1.48**	**44%**
		Recent	*2017-05*	*2017-09*	*0.4*	*413*	*872*	*47%*	*10.2*	*2%*	*0.12*	*61%*
Jagerbos (tributary)	3	*Recent (full)*	*2017-05*	*2018-12*	*1.7*	*655*	*1324*	*49%*	*170.3*	*26%*	*0.02*	*51%*
Wit Els (tributary)	18	*Recent (full)*	*2017-05*	*2018-08*	*1.3*	*531*	*1280*	*41%*	*40.1*	*8%*	*0.02*	*14%*
Hudsonvale	152	*Recent (full)*	*2017-05*	*2018-12*	*1.7*	*673*	*1349*	*50%*	*56.3*	*8%*	*0.27*	*42%*
Willowvale	278	*Recent (full)*	*2017-05*	*2018-12*	*1.7*	*667*	*1380*	*48%*	*58.9*	*9%*	*0.52*	*28%*
Kromme - lower												
Impofu Dam	483	**Full**	**1983-07**	**2018-05**	**35**	**611**	**1212**	**50%**	**96.3**	**16%**	**1.48**	**39%**
		Recent	*2017-05*	*2018-05*	*1.1*	*489*	*1231*	*40%*	*26.6*	*5%*	*0.40*	*54%*
Diep Rivier	116	*Recent (full)*	*2017-05*	*2018-12*	*1.7*	*494*	*1370*	*36%*	*8.5*	*2%*	*0.03*	*8%*
Kouga + Baviaanskloof												
Kouga Dam	3,897	**Full**	**1972-01**	**2018-10**	**47**	**477**	**1312**	**36%**	**41.0**	**9%**	**5.07**	**44%**
		Recent	*2017-05*	*2018-10*	*1.4*	*391*	*1205*	*32%*	*17.5*	*4%*	*2.20*	*39%*
Kouga												
Stuurmans-kraal	1,637	**Full**	**1990-04**	**2019-01**	**29**	**390**	**1301**	**30%**	**49.0**	**13%**	**2.72**	**52%**
		Recent	*2017-05*	*2018-12*	*1.7*	*393*	*1293*	*30%*	*25.4*	*6%*	*1.32*	*34%*
Baviaanskloof												
Rooihoek	1,234	Full	2012-03	2018-11	6.7	196	1396	14%	33.2	17%	1.28	39%
		Recent	*2017-05*	*2018-11*	*1.5*	*151*	*1278*	*12%*	*11.5*	*8%*	*0.44*	*17%*
Gannaland (tributary)	9	Full	2012-06	2018-02	5.7	132	1455	9%	10.8	8%	0	2%
		Recent	*2017-05*	*2018-12*	*1.7*	*84*	*1404*	*6%*	*0.0*			
Zaaimanshoek	635	Full	2011-12	2019-02	7.2	206	1523	13%	30.7	15%	0.62	44%
		Recent	*2017-05*	*2018-12*	*1.7*	*141*	*1462*	*10%*	*14.4*	*10%*	*0.28*	*19%*
Joachimskraal	865	Full	2011-12	2019-02	7.2	186	1489	12%	11.9	6%	0.36	39%
		Recent	*2017-05*	*2018-12*	*1.7*	*104*	*1395*	*7%*	*5.6*	*5%*	*0.20*	*14%*

Runoff ratios could only be estimated for the subcatchment monitoring sites for shorter and more recent time periods, however these gave useful insights into patterns of runoff production. The sub catchments monitored in the Baviaanskloof have a 6-7 year record, including major flood events in 2012 (see example Figure E6). The catchment outlet site (Rooihoek) and the confined-valley mid-catchment site (Zaaimanshoek) show runoff ratios of 15-17% in this period, while the mountain tributary site (Gannaland) and wide-valley floodplain site (Joachimskraal) only show 6-8% runoff for the same time period. The Joachimskraal site is downstream of the Zaaimanshoek site, and the contributing catchment compositions in terms of topography, vegetation, and spatially averaged rainfall between Zaaimanshoek, Joachimskraal, and Rooihoek are not very different overall, however the topographic position and valley setting of the monitoring point is. The lower surface runoff ratio at the central wide-valley site may indicate that some water which becomes surface runoff further down the valley is flowing in the subsurface past the Joachimskraal site. A significant proportion of the water leaving the mountain tributaries may also be in the subsurface, potentially accounting for the low runoff at Gannaland. The Gannaland sub-catchment was also drier during the monitored period.

Because the Kromme sub catchments were predominantly monitored in drought conditions in 2017-2018, runoff ratios were also calculated for all the other sites during this period for comparison (Table x). It should be noted that data was not available for all sites for this time period at the time of the this report, and so the Churchill Dam and the Impofu Dam catchment runoff ratios for the recent period should not be compared to other sites as they represent much shorter time-periods. They are just shown to illustrate that runoff ratios were much lower in this period than the long-term average, 2-5% vs 16-20%. The Kromme sub-catchments showed an 8-9% runoff ratio in this period, with exception of the very small, mountain tributary catchment at Jagerbos. This steep rocky tributary showed a 26% runoff ratio due to the stormflow in the September 2018 event (Table E1). Due to equipment failure, this event was not recorded at the Wit Els tributary site. The main valley sites had low runoff ratios despite this event, likely due to depleted catchment storages antecedent to it. During this drought period, the Baviaanskloof main river sub catchments showed similar runoff ratios to those in the Kromme: 8-10% at Rooihoek and Zaaimanshoek. In the Kouga, Stuurmanskraal also had less than half its long-term average runoff ratio during the drought, 6% vs. 13%.

E.3.4 Baseflow proportion estimates

The recursive digital filter algorithm produced estimates of the amount of flow reaching catchment outlets via slower pathways, as demonstrated in Figure E9 with average slow-flow or baseflow proportions given for each site in Table E1. The dam catchment inflow showed a long-term average of roughly 40% of flow coming from slower pathways, rather than storm peaks from surface flow and fast shallow-subsurface flow. This shows that activities that intercept or alter these slower pathways could significantly alter long-term average run-off.

In the recent drought period 2017-2018, the proportional baseflow contributions to total flow went down at the Baviaanskloof sub catchments and at Stuurmanskraal weir by roughly 20% (Table E1). This may seem counter intuitive, however the drought was so severe that rivers were dry or flows were close to zero at many sites, so short flow peaks from the few storms that did occur made up the bulk of the total flow. The storages supplying baseflow were depleted. In the Kromme however, the baseflow proportions at the dams and monitored sub catchments were high, potentially higher than the long-term average as indicated by the Churchill and Impofu Dam records. Although low, the Kromme did remain flowing in this period and the storages supplying baseflow were proportionately less depleted than in the Kouga and Baviaanskloof.

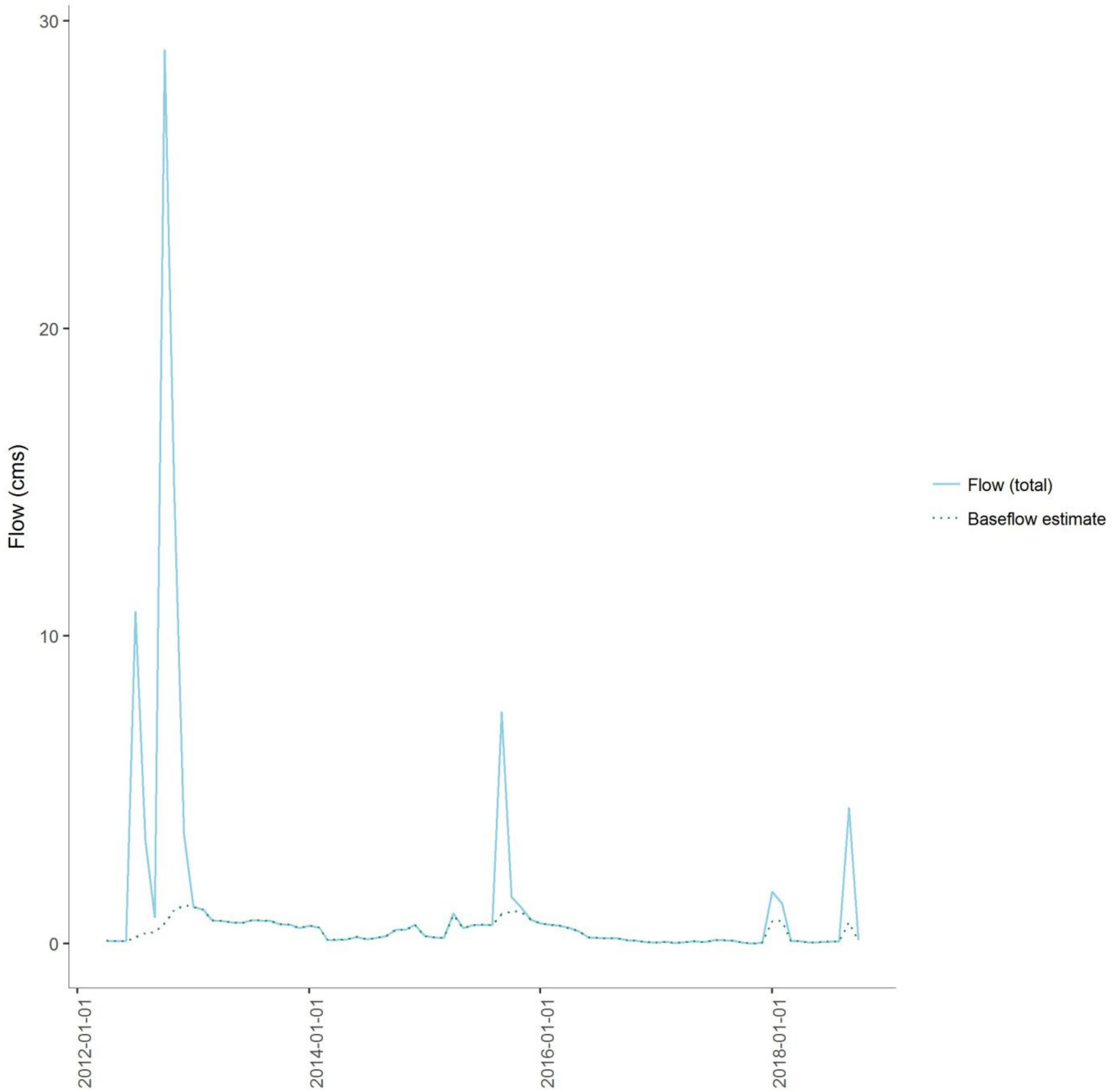

Figure E 9: Example of the monthly flow and estimated baseflow hydrograph for the Rooihoek monitoring site in the Baviaanskloof. The baseflow estimate was produced by applying a recursive digital filter algorithm after Smakhtin 2001.

E.3.5 Recession constant analyses

The range in recession constants between different recession periods at each site illustrates that delayed flows are coming from several different storages with differing drainage rates.

As expected the recession constants for lower flow recession periods were larger than those for higher flow periods across sites. Higher flow, wetter periods, are more likely to have contributions from faster and more ephemeral flow pathways, such as interflow, for which recession constants were on the order of a few days to a week. At the lowest flows, the baseflow is being supplied by slower draining sources. In the Baviaanskloof the maximum recession constants were on the order of a hundred days in the upper and middle catchment sites. Similarly at Stuurmanskraal in the Kouga catchment maximum recession constants were in the order of hundred days. This likely represents drainage from the mountain bedrock aquifers alone, with little contribution from other sources. However the largest recession constants seen at the catchment outlet of the Baviaanskloof (47 days) and the Kouga (20 days) showed that even during the driest periods recorded there was still some contributions from faster draining sources, potentially residual floodplain aquifer contributions. Recession constants for the Kromme and were smaller on average and the maximums were close to 20 days also indicating contribution from a faster draining store such as floodplain storage.

Table E 2: Ranges of flow and recession constants for observation periods at different sites in the BKK catchments (sites listed upstream to downstream)

Catchment	Site	Start date	End date	Flow (cms)			Recession constant, k (days)		
				Mean	Peak	Mean of recessions	Mean	Min	Max
Baviaanskloof	Zaaimanshoek	2011-12	2019-02	0.6	102	3.3	44	2	194
	Joachimskraal	2011-12	2019-02	0.4	100	0.9	48	1	116
	Rooihoek	2012-03	2018-11	1.3	207	3.9	26	2	47
Kouga	Stuurmanskraal	1990-04	2019-01	2.7	414	3.2	16	2	134
	Kouga Dam	1972-01	2018-10	5.1	1,649	16	8	2	20
Kromme upper	Hudsonvale	2017-04	2019-02	0.3	3	0.6	18	8	23
	Willowvale	2017-04	2019-02	0.5	109	0.3	9	3	17
	Churchill Dam	1957-01	2017-09	1.4	577	3.2	8	2	18
Kromme lower	Diep Rivier	2017-04	2019-02	0.03	6	0.6	5	3	3
	Impofu Dam	1983-07	2018-05	1.48	830	7.7	6	4	7

E.4. References

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F. WATER PHYSICOCHEMAL PROPERTY AND NATURAL ISOTOPE SAMPLING

F.1. Introduction

Water physicochemical properties and concentrations of the natural isotopes were sampled in surface water, groundwater, and rain water at various sites across the Baviaanskloof and Kromme catchments to gain information about processes and flow pathways. The solute and isotope concentrations in groundwater reflect the source and mechanism of recharge and the age of the water. The chemistry of the surface water, particularly relatively conservative tracers like natural isotopes, reflects the combination of different water sources producing the streamflow, i.e. surface runoff of rainwater, soil water interflow, fractured rock interflow, groundwater from the floodplain and bedrock aquifers, etc. (Kendall and Caldwell, 1998). Comparing the chemical properties of the rainwater, different groundwater sources, and streamflow at different times can be used to inform hydrograph separation, estimating the varying contributions of different potential sources over time.

Isotope concentrations in groundwater and surface water sources compared to rainfall give information about the amount of evaporation that likely occurred along the flow path to reach the groundwater or stream. Evaporation removes lighter isotopes, leaving heavier ones behind, such that the water from a source subject to significant evaporation is more isotope enriched and may plot below the meteoric water line. Rainfall isotope concentrations can also vary by location and by rainfall event. Events caused by different weather systems will have different signatures. For example rain which originally evaporated from a warmer ocean surface will have more heavy isotopes than those sourced from a cooler surface.

F.2. Methods

Water samples were taken and in-situ physicochemical properties were measured at all the water level sampling sites in the main river channels, tributaries, boreholes, and piezometers as well as groundwater seeps of the Baviaanskloof and Kromme catchments, as described above in Appendix E and shown in Figure E1. Measurement and sampling was done during quarterly field visits in 2017 and 2018, with the exception of the rainfall samples which were obtained from rainfall collectors immediately after events by volunteers from LivingLands.

F.2.1 Physicochemical properties

In situ measurements of temperature, electrical conductivity (EC) and pH were measured quarterly using a YSI Pro-Plus Multi-parameter probe. Water samples were collected and analysed in laboratory for chloride concentrations to compare with the EC measurements.

F.2.2 Natural isotopes

The concentrations of isotopes of oxygen (heavier O^{18} vs O^{16}) and hydrogen (deuterium, heavier H^2 vs H^1) in water are used for the identification of water sources (e.g. groundwater vs. direct rainfall contribution to river flow) The 50 ml samples were kept sealed with no air present and stored at under 4ºC until analyzed. Samples were analyzed for $\delta^{18}O$ and $\delta^{2}H$ composition in the laboratory using the liquid water isotope analyser (Los Gatos Research Inc).

The concentration of the isotopes is expressed as a ratio (equation 1) of the mass balance in relation to the Vienna-Standard Mean Ocean Water (VSMOW).

$\delta(‰) = (R_x/R_s - 1)*1000$ (1)

R_s and R_x represent the concentration in the standard and in the sample respectively.

The global meteoric water line (GMWL) and the local meteoric water line (LMWL) are ratios of heavy oxygen and heavy hydrogen expected in the rainwater before evaporation. Sample concentrations were plotted against the global meteoric line (equation 2) to determine their relationship with the meteoric origin (Nyende, G and Vermeulen, 2013).

Global Meteoric Water Line: $\delta D = 8\delta^{18}O + 10$ ‰ (2)

F.3. Results

F.3.1 Electrical conductivity vs chloride

The presence of chloride in water samples can be attributed to leaching processes, i.e. leaching from rocks, minerals, and possibly saline deposits if sites are coastal. High EC in water can be due to an increase in ion due to increased mineralization. High EC can also be due to runoff from farmlands, sea water intrusions and discharge from industrial areas. EC and Cl can be used to trace flowpaths as well as groundwater and surface water interactions by assessing their variation in different water sources and spatial distribution within a catchment. EC vs Cl plots for Kromme (Figure F1) and Baviaanskloof catchment (Figure F2) are presented.

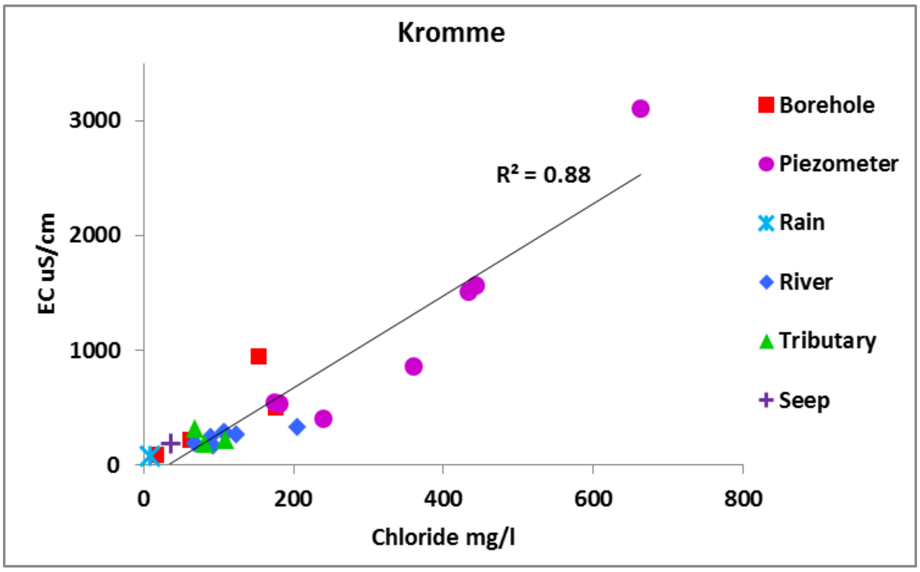


Figure F 1: Comparison of chloride and EC for Kromme

In the Kromme catchment, EC values for surface water, shallow and deep groundwater were 167-326 uS/cm, 406-3101 uS/cm and 88-947 uS/cm respectively and Cl values were 89-205 mg/l, 174-663 mg/l and 17-176 mg/l respectively. EC concentrations were lower in surface water compared to shallow and deep groundwater. Similar to the trend shown in EC, Cl values are low in surface water but highest in shallow groundwater. High EC and Cl values in soil water could be due to mineralization. Most of the deep groundwater and all surface water samples cluster at the bottom left corner implying more or less similar EC and chloride signatures (mixing). This can also be interpreted as surface water being fed by deep groundwater in the catchment or vice versa depending on the elevation differences between the surface and groundwater.

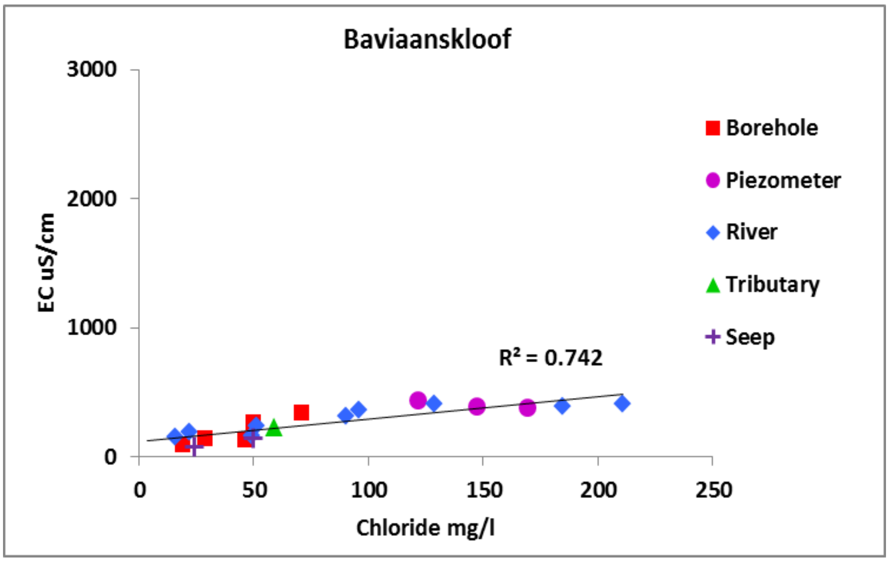


Figure F 2: Comparison of chloride and EC for Baviaanskloof

The Baviaanskloof shows low EC and chloride values in comparison to Kromme in general. EC values for surface water, shallow and deep groundwater were 152-408 uS/cm, 381-437 uS/cm and 94-340 uS/cm respectively and Cl values were 15-184 mg/l, 121-169 mg/l and 19-70 mg/l respectively. Cl concentrations are high in soil water as well as the EC concentrations. This is a similar trend to that in the Kromme catchment attributed to mineralization. EC and Cl concentrations were variable with high concentrations at two midcatchment sites (Zaaimanshoek and Joachimskraal) as well as the catchment outlet. This could be as a result of these sites experiencing different water rock interactions and flow pathways.

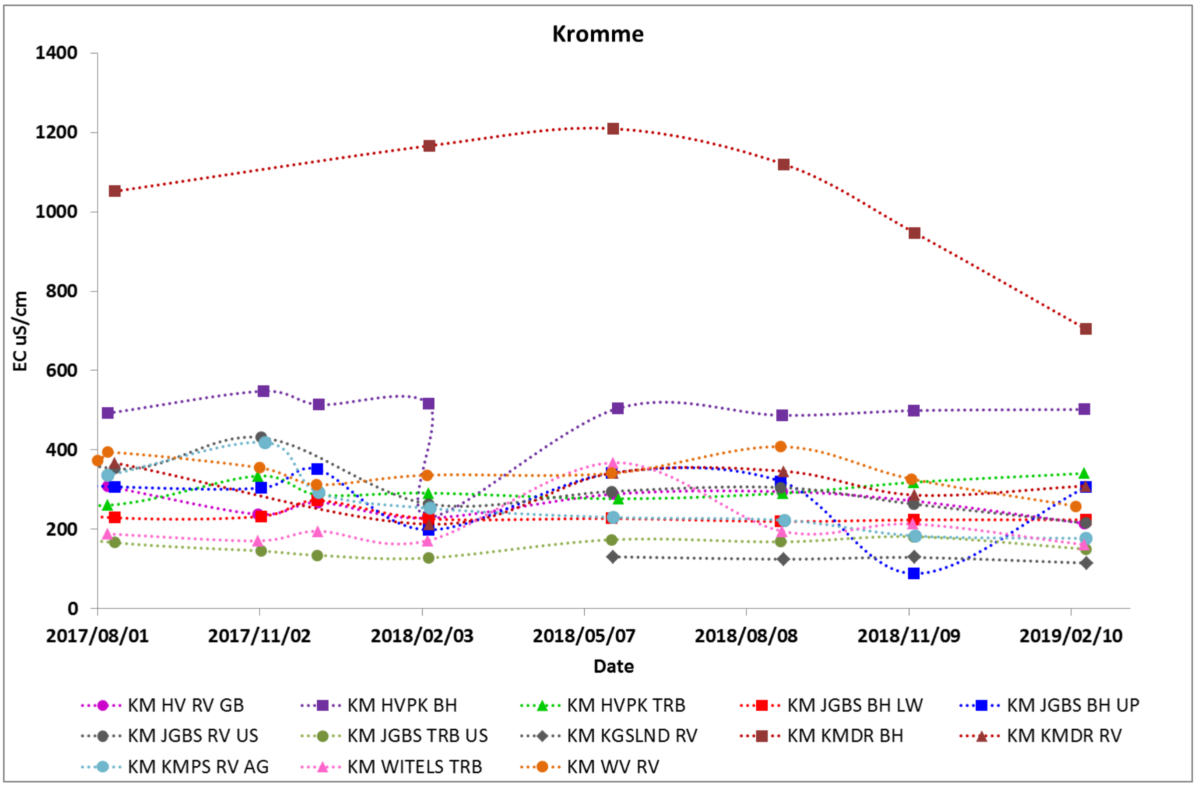


Figure F 3: Electrical conductivity of surface and subsurface water in the Kromme catchment

Electrical conductivity (EC) measurements were done at selected sites in the Kromme catchment. Figure F3 shows results for river, shallow and deep groundwater samples. The EC at the headwater borehole and stream sites Kromdraai (KM KMDR) show big difference between the surface and the groundwater. Water from the stream is much fresher indicating contributions from precipitation whilst the borehole water is very saline. The high EC in the borehole water could be attributed to the geology and rock type where the borehole is located and the differences also indicate that there is probably little contribution from this groundwater source to the stream at the times of sampling.

EC from the other two boreholes in the mid catchment show relatively low EC compared to the Kromdraai borehole. In the majority of samples, the borehole close to the southern mountain range adjacent to a tributary channel (KM JGBS UP) shows higher EC compared to the lower borehole (KM JGBS LW) which is located close to the main river channel. This is not the case for the month of February and November 2018 where the EC of the upper borehole dropped drastically. These fluctuations could be due to dilution following rainfall events.

The Hudsonvale wetland is located roughly half way down the length of the catchment. Two tributaries feeding into the main channel at Hudsonvale were monitored (KM HVKM and KM WITELS TRB). A comparison of EC measurements between the borehole and the tributaries show that the borehole water is more saline compared to the tributaries as well as the main channel at Hudsonvale. This could be due to the geology where the borehole is situated. In February 2018 the borehole had low EC which could be as a result of a response from precipitation as in the case of the upper Jagerbos borehole.

In the main river channel, the EC is highly dynamic whereby in some sections it is high and low in others. This implies that different sections of the river channel are receiving different subsurface source contributions. In general, EC increases from headwaters moving downstream. This could be due to effects of evaporation. As the water flows down the river channel and evaporates from the stream EC concentrations tend to increase.

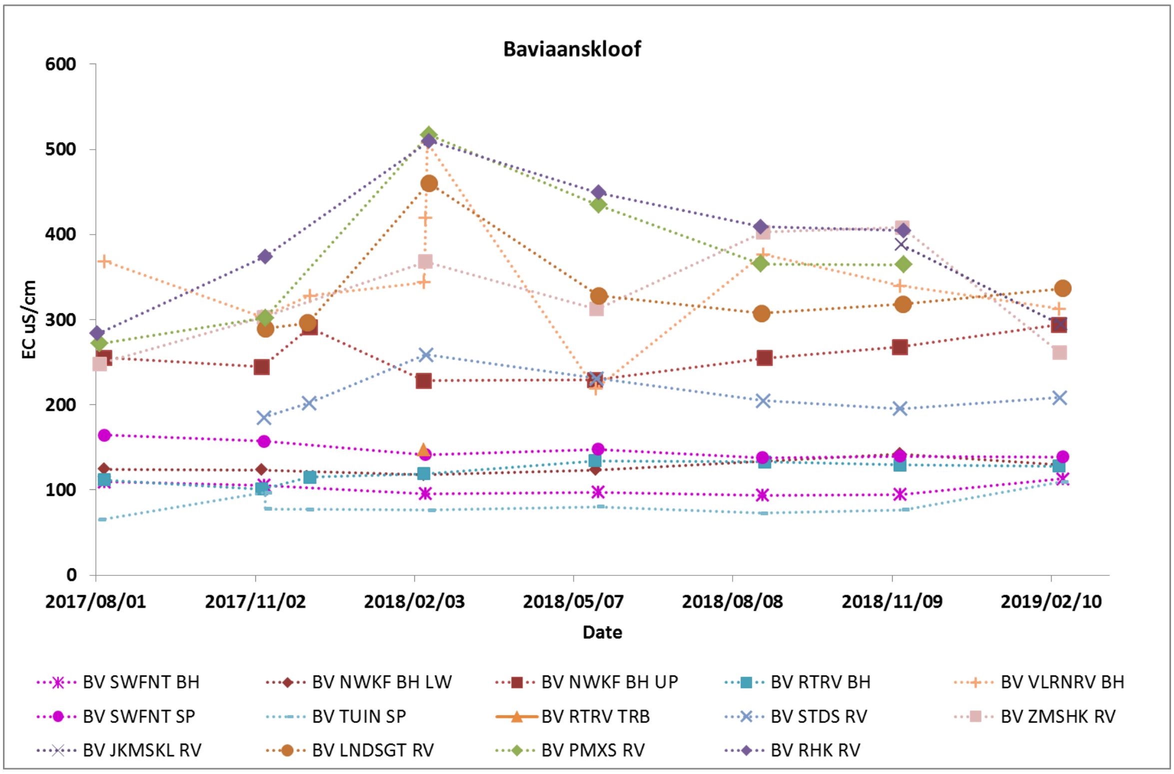


Figure F 4: Electrical conductivity of surface and subsurface water in the Baviaanskloof catchment

The EC in Baviaanskloof catchment (Figure E4) shows a similar trend as the river EC in Kromme. EC increases in the river channel from headwaters to downstream sites therefore the highest EC is recorded at the catchment outlet by Rooihoek. This is also attributed to evaporation effects. All boreholes upstream in the catchment have low EC values implying fresh water compared to surface water in the river channel downstream. Only one borehole upstream has high EC (BV NWKF UP).

A comparison of all boreholes in the catchment show variability in EC values which could be a result of geological properties where they are located.

F.3.2 Natural isotope concentrations

Isotopic signatures for all sampled water types (river, shallow groundwater, deep groundwater, rain and springs) are described in terms of spatial and temporal variability in ^{18}O and deuterium signatures. D-excess values in relation to the Global Meteoric Water Line (GMWL) are also discussed. A D-excess value of 10 plots on the GMWL whilst D-excess values greater than 10 plot above the GMWL meaning the samples are depleted and also indicative of cooler moisture sources and vice versa for values less than 10.

The 2017 isotope samples for both Kromme and Baviaanskloof (Figure F1) exhibit high variability on a temporal scale and less at the spatial scale.

Kromme August 2017 samples show interaction between shallow groundwater and surface water in the main channel at (green circle). There is also interaction at (red) between deep and shallow groundwater, surface water in tributaries and the main channel. One borehole and a tributary plot above the local meteoric water line implying depletion whilst a few samples from shallow groundwater and surface water from the main river plot on the local meteoric water line implying they are of meteoric origin. All samples have d excess values greater 10, which are indicative of cooler sources of origin.

There is no interaction between samples for Baviaanskloof in August 2017 except for one borehole and a seep. D-excess values vary between sampled water sources. Two boreholes (one in the headwaters and one artesian), an artesian seep, one midcatchment river sample and one river sample at the catchment outlet have low D-excess values. This means they are enriched thereby plotting below the GMWL. The rest of the samples are depleted (high D-excess values) and originate from cooler moisture sources.

The November samples show a mixed system implying interaction between surface and groundwater in the Kromme catchment. There is interaction between shallow groundwater, surface water in a tributary and main river (red). There is also a mixed system of all sources (green). A number of samples from all different sources plot above the local meteoric line implying high depletion and a few samples for shallow groundwater and one tributary show meteoric origin implying recharge from precipitation. All samples high D-excess values (originating from cooler sources) except for one upstream piezometer which plots below the GMWL (enriched).

For Baviaanskloof in November 2017 there was no interaction except for one borehole and a tributary which could imply that tributary is being sustained by subsurface contributions originating from the same source where the borehole is located. All samples have high D-excess values (cooler moisture source) hence they all plot above the GMWL except for the rain sample which is evaporated. All the samples plot close to the LMWL and show depletion.

2017 was relatively dry therefore there was not much variation at both spatial and temporal scales.

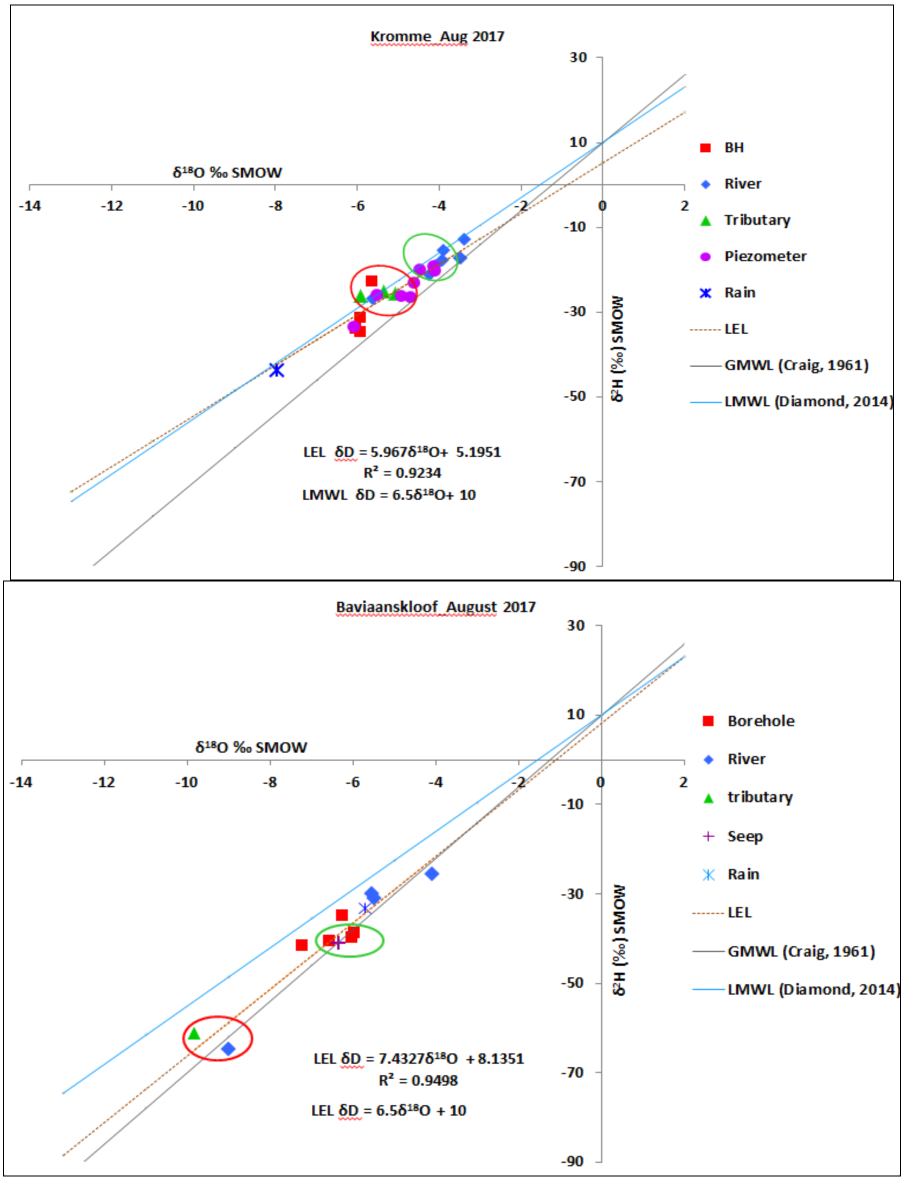
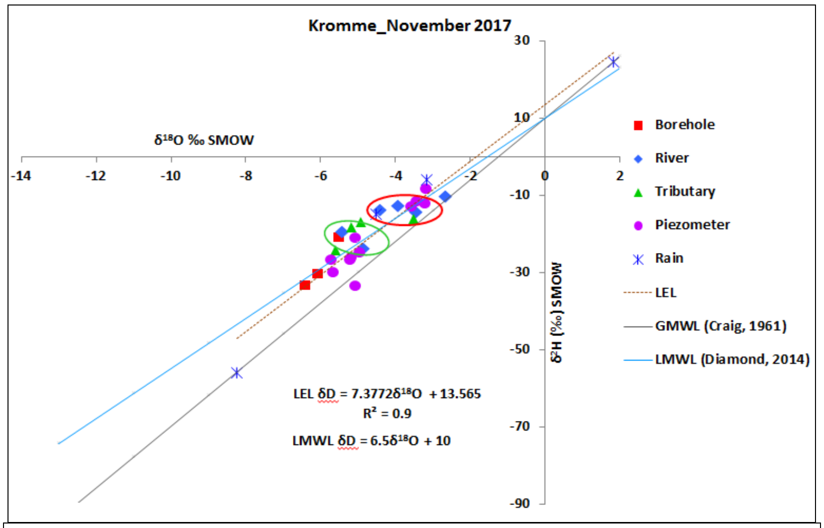
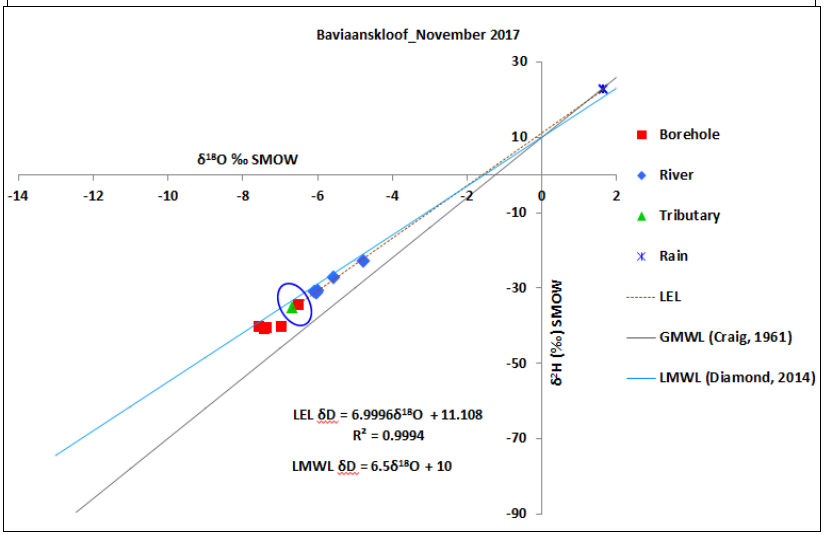


Figure F 5: δ2H (‰) vs δ18O (‰) plot with GMWL and LMWL for Kromme and Baviaanskloof in 2017


Kromme_November 2017
δ18O ‰ SMOW
δ2H (‰) SMOW
Borehole
River
Tributary
Piezometer
Rain
LEL
GMWL (Craig, 1961)
LMWL (Diamond, 2014)
LEL δD = 7.3772δ18O + 13.565
R² = 0.9
LMWL δD = 6.5δ18O + 10


Baviaanskloof_November 2017
δ18O ‰ SMOW
δ2H (‰) SMOW
Borehole
River
Tributary
Rain
LEL
GMWL (Craig, 1961)
LMWL (Diamond, 2014)
LEL δD = 6.9996δ18O + 11.108
R² = 0.9994
LMWL δD = 6.5δ18O + 10

Results for the February 2018 sampling (Figure F 6) show high interaction of all water sources (red) then one borehole, a tributary and the main channel also interact (green). Mixing of samples is an indication of one source feeding the other hence showing temporal connectivity. There is one depleted rain sample plotting above the LMWL. A few groundwater, river and tributary samples plot on the local meteoric water line showing recharge. The majority of February D-excess values are high (cooler moisture source) therefore plot above the GMWL except for two river samples (one upstream at Kromdrai and one downstream at Willowvale) and one midcatchment piezometer which are enriched.

In Baviaanskloof there is no indication of mixing as samples are not clustering close together. There are no samples plotting on the meteoric line therefore implying the February samples are not of meteoric origin. This means there was no significant contributions from rainfall events to influence the isotope signatures in all sampled sources. In February 2018, both catchments have d excess values greater than 10 implying cooler moisture sources except for the rainfall sample and one tributary that were enriched.

In May 2018 (Figure F 6) there is mixing between river samples and shallow groundwater in Kromme (green) implying that one source may have been losing to the other during the time of sampling. There was also surface and groundwater interaction between deep and shallow groundwater and all surface water sources sampled (red). This implies a mixed system and hydrological connectivity of the different sources. One borehole plots at the local meteoric line and various other samples plot close to the line implying meteoric origin therefore, recharge. One rain sample and two samples from sites midcatchment (one piezometer and one river sample) have a D-excess value 10 meaning they plot on the GMWL. The majority of samples are depleted (cooler moisture sources) with D-excess values greater than 10 except a few river samples, piezometer and one rain sample. Variations in d excess can be due to variability within rainfall events and/or kinetic fractionation.

In Baviaanskloof, there is evidence of mixing of groundwater, rain and river water samples (green). The fountain sample plots on the local meteoric line implying recharge. The samples are depleted therefore plot above the GMWL (D-excess greater than 10), also implying the samples are from cooler moisture sources.

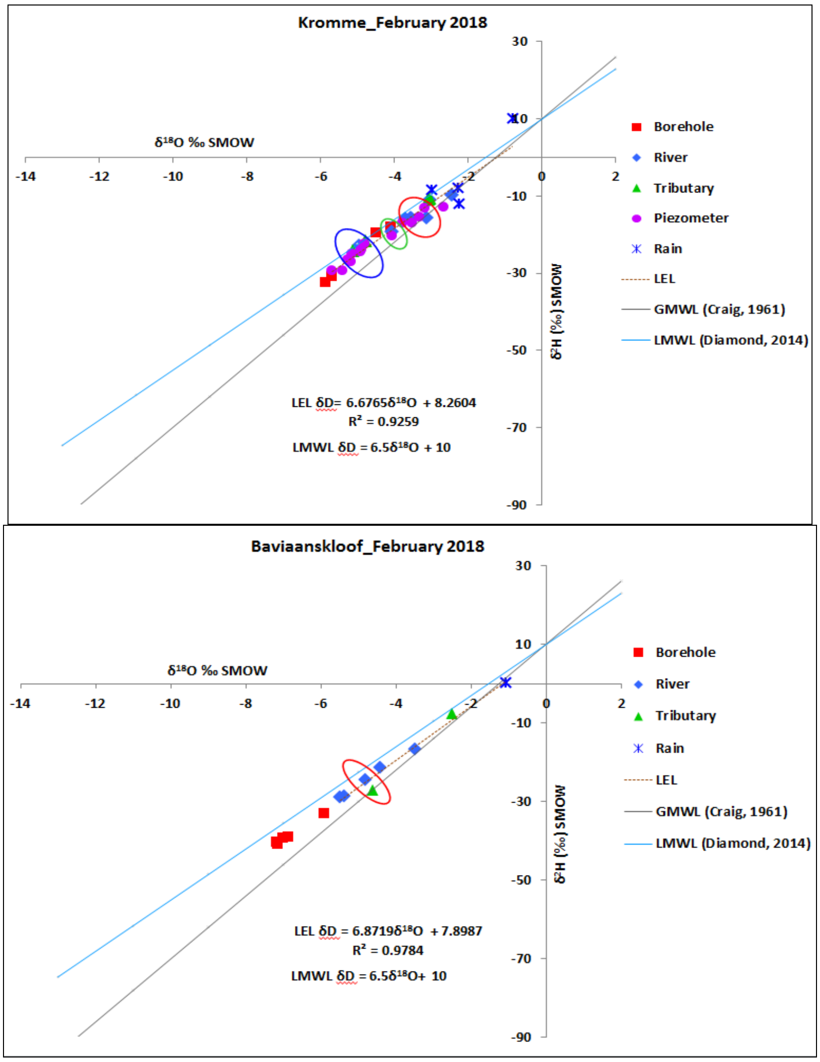
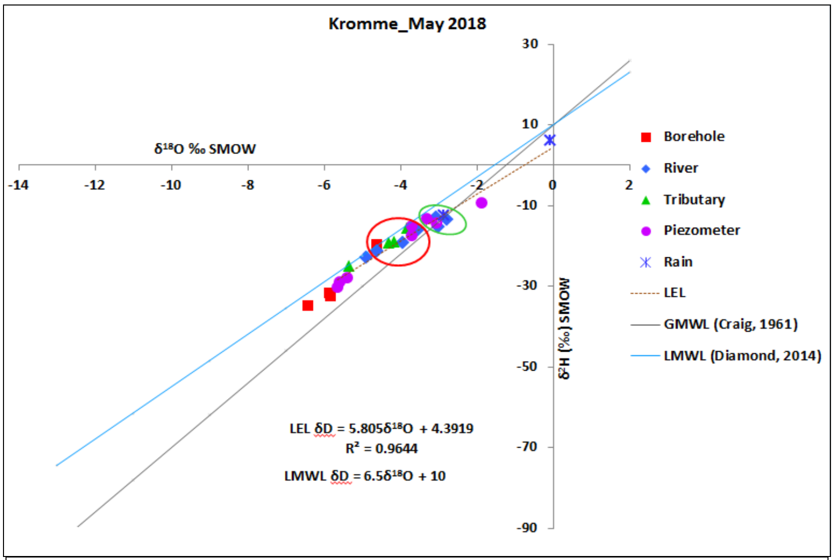
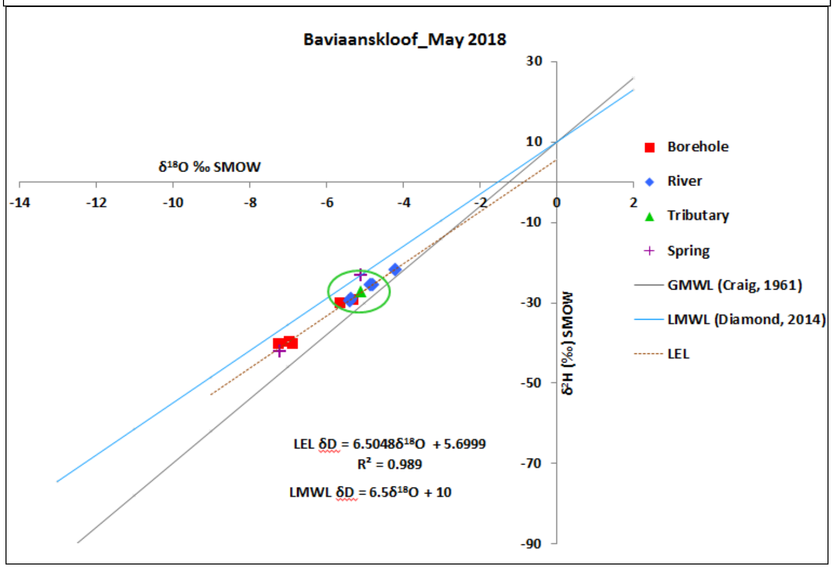


Figure F 6: δ2H (‰) vs δ18O (‰) plot with GMWL and LMWL for Kromme and Baviaanskloof in February and May 2018


Kromme_May 2018
δ¹⁸O ‰ SMOW
δ²H (‰) SMOW
Borehole
River
Tributary
Piezometer
Rain
LEL
GMWL (Craig, 1961)
LMWL (Diamond, 2014)
LEL δD = 5.805δ¹⁸O + 4.3919
R² = 0.9644
LMWL δD = 6.5δ¹⁸O + 10


Baviaanskloof_May 2018
δ¹⁸O ‰ SMOW
δ²H (‰) SMOW
Borehole
River
Tributary
Spring
GMWL (Craig, 1961)
LMWL (Diamond, 2014)
LEL
LEL δD = 6.5048δ¹⁸O + 5.6999
R² = 0.989
LMWL δD = 6.5δ¹⁸O + 10

In August 2018 (Figure F 7), Kromme samples (top left) show high interaction. There is interaction of shallow and deep groundwater, rain and river water (green). In comparison to the May results, the system is still well mixed. There is also interaction between shallow groundwater, surface water from a tributary and some main river samples (red). The majority of river samples show meteoric origin with D-excess values of 10. Two samples are enriched (sea sample and one midcatchment piezometer). The rest of the samples have D-excess values greater than 10 implying cooler sources of origin therefore plotting above the GMWL.

In Baviaanskloof, there is interaction between rain water, groundwater (borehole and spring) and surface water (green). The red circle focuses on similar signatures between a tributary and a few river samples. The d excess values are all greater than 10 implying cooler moisture sources.

In November 2018 (Figure F 7), the Kromme samples cluster along the local meteoric water line implying meteoric origin and recharge. There was a big flood a few weeks prior to this sampling making it more probable for more samples to be of meteoric origin. A few samples plot above the local line showing depletion. Both groundwater and surface water samples interact (green) showing that the system is still well mixed. D-excess values are all greater than 10 implying cooler moisture sources similar to the August samples.

In Baviaanskloof, there is high depletion of the spring sample whilst all the other samples plot close to the local line showing a possibility of recharge. The tributary and some main river samples are still clustering showing a relationship between these sources. Similar to Kromme, all samples have D-excess values greater than 10 (cooler moisture source).

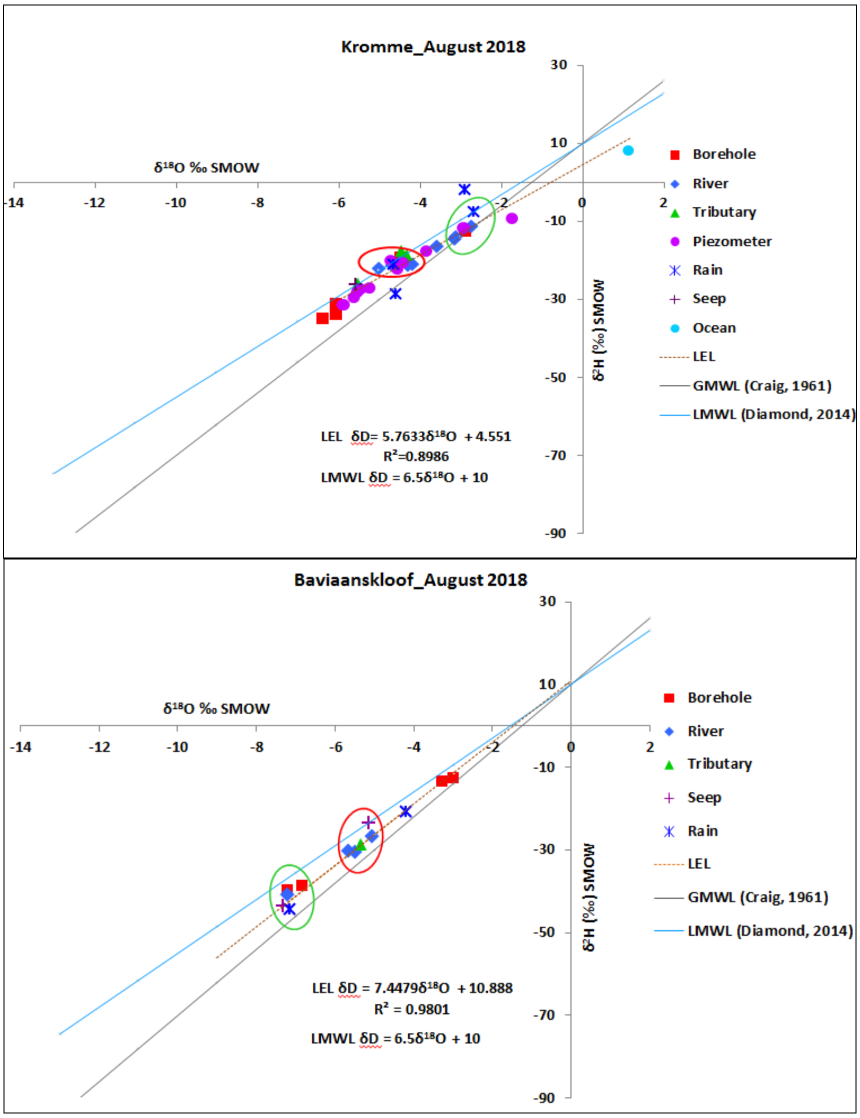
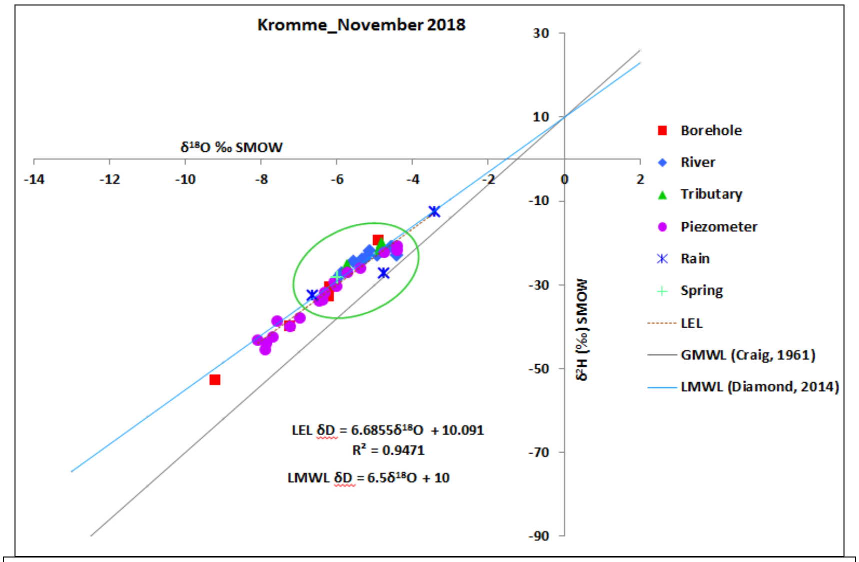


Figure F 7: δ2H (‰) vs δ18O (‰) plot with GMWL and LMWL for Kromme and Baviaanskloof in August and November 2018


Kromme_November 2018
δ¹⁸O ‰ SMOW
δ²H (‰) SMOW
Borehole
River
Tributary
Piezometer
Rain
Spring
LEL
GMWL (Craig, 1961)
LMWL (Diamond, 2014)
LEL δD = 6.6855δ¹⁸O + 10.091
R² = 0.9471
LMWL δD = 6.5δ¹⁸O + 10

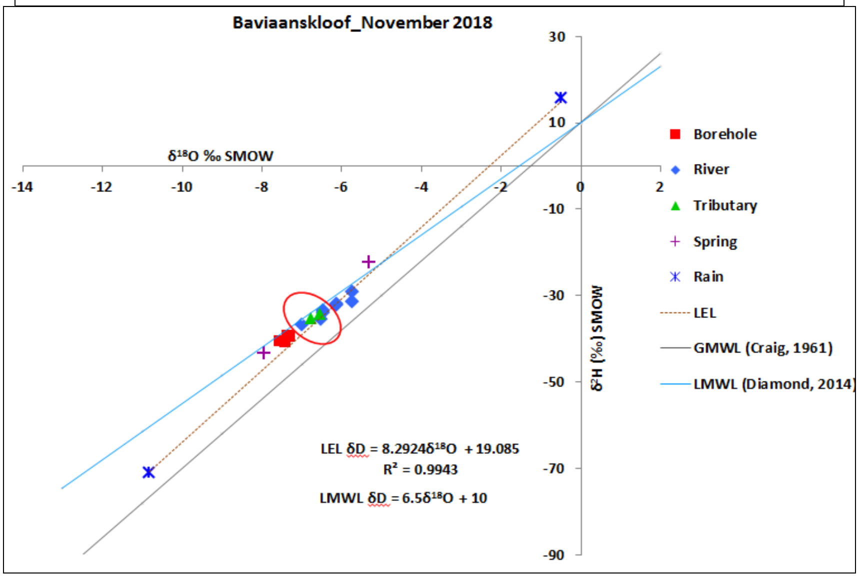

Baviaanskloof_November 2018
δ¹⁸O ‰ SMOW
δ²H (‰) SMOW
Borehole
River
Tributary
Spring
Rain
LEL
GMWL (Craig, 1961)
LMWL (Diamond, 2014)
LEL δD = 8.2924δ¹⁸O + 19.085
R² = 0.9943
LMWL δD = 6.5δ¹⁸O + 10

Table F 1: Discharge and percentage contributions of rain and groundwater to surface flow

Site	Type	Catchment	Date	Discharge	O18_River	O18_GW	O18_Rain	Rain %	Gw %
Wit Els	Tributary	Kromme	2017/11/01	0.0300	-3.51	-6.41	1.83	1.1%	98.9%
Hudsonvale	Main River	Kromme	2017/11/01	0.0910	-3.91	-6.08	1.83	2.5%	97.5%
PK Jagerbos	Tributary	Kromme	2017/11/01	0.0003	-5.6	-6.08	1.83	0.0%	100.0%
Willowvale	Main River	Kromme	2017/11/03	0.0760	-4.41	-5.5	1.83	1.1%	98.9%
Kompanjies	Main River	Kromme	2017/11/05	0.0090	-5.42	-5.92	1.83	0.1%	99.9%
Willowvale	Main River	Kromme	2018/02/05	0.3110	-2.42	-4.48	-2.28	29.1%	70.9%
Wit Els	Tributary	Kromme	2018/02/06	0.0050	-3.04	-4.08	-2.28	0.3%	99.7%
Hudsonvale	Main River	Kromme	2018/02/06	0.1630	-3.50	-5.70	-2.28	10.5%	89.5%
PK Jagerbos	Tributary	Kromme	2018/02/06	0.0020	-4.77	-5.70	-2.28	0.1%	99.9%
Kompanjies	Main River	Kromme	2018/02/07	0.1400	-4.95	-5.87	-2.28	3.6%	96.4%
Willowvale	Main River	Kromme	2018/05/22	0.0240	-3.07	-4.60	-2.86	2.1%	97.9%
Willowvale	Main River	Kromme	2018/08/27	0.0720	-2.72	-2.87	-2.66	5.1%	94.9%
Wit Els	Tributary	Kromme	2018/08/28	0.0140	-4.45	-6.38	-4.64	1.6%	98.4%
Hudsonvale	Main River	Kromme	2018/08/28	0.0270	-4.17	-6.04	-4.64	3.6%	96.4%
PK Jagerbos	Tributary	Kromme	2018/08/28	0.0050	-5.50	-6.04	-4.64	0.2%	99.8%
Kompanjies	Main River	Kromme	2018/08/29	0.0160	-4.66	-6.04	-4.64	1.6%	98.4%
Willowvale	Main River	Kromme	2018/11/10	0.1660	-4.55	-4.89	-3.44	3.9%	96.1%
Wit Els	Tributary	Kromme	2018/11/11	0.0100	-4.84	-9.21	-3.44	0.8%	99.2%
Hudsonvale	Main River	Kromme	2018/11/11	0.1110	-5.12	-6.17	-3.44	4.3%	95.7%
PK Jagerbos	Tributary	Kromme	2018/11/11	0.0040	-5.71	-6.17	-3.44	0.1%	99.9%
Kompanjies	Main River	Kromme	2018/11/12	0.0870	-5.95	-6.22	-3.44	0.8%	99.2%
Zaaimanshoek	Main River	Baviaanskloof	2018/02/09	0.0020	-5.37	-7.17	-1.06	0.1%	99.9%
Zaaimanshoek	Main River	Baviaanskloof	2018/08/25	0.0430	-5.47	-6.84	-4.23	2.3%	97.7%
Zaaimanshoek	Main River	Baviaanskloof	2018/11/14	0.1070	-6.46	-7.54	-0.50	1.6%	98.4%
Rooihoek	Main River	Baviaanskloof	2018/02/11	0.0720	-3.49	-7.17	-1.06	4.3%	95.7%
Rooihoek	Main River	Baviaanskloof	2018/11/15	0.0320	-5.73	-7.54	-0.50	0.8%	99.2%

Using discharge and ^{18}O values for groundwater and rain, a two component hydrograph separation was done to get an estimate of percentage contributions from groundwater and precipitation to surface water (Table F 1). Differences in discharge values for the different monitored sites (upstream, midcatchment and downstream points in main river channel and mountain tributaries) were also assessed.

The two component hydrograph separation shows that for both the Kromme and Baviaanskloof catchments, surface water is sustained to a larger extent by groundwater. In terms of surface flow, the Kromme river has higher flow compared to its contributing tributaries (WIit Els and PK Jagerbos) These Kromme tributaries also have low flow volumes compared to flow upstream of the catchment (Kompanjies). However, the tributary from the Tsitsikamma side (Wit Els) has more flow compared to the tributary from the Suuranys side. This is anticipated as the Tsitsikamma side receives more rainfall compared to the Suuranys.

Surface flow increases downstream therefore, Willowvale has the highest flow volumes compared to Hudsonvale (mid catchment) and Kompanjies (upstream). Willowvale is also expected to have higher flows as it is downstream therefore, receives sustained flows from a large catchment area. At all monitored sites, there was an increase in flow volumes in February 2018. This did not follow a significant rainfall event but the high flow volumes could be attributed to time of sampling after a rainfall event when the research team was at the sites.

In Baviaanskloof, flows were measured at Zaaimanshoek (mid catchment) and Rooihoek (downstream). In February 2018, Rooihoek had more flow compared to Zaaimanshoek but in November 2018, Zaaimanshoek had more. The low flow volumes at Rooihoek in November could be as a result of channel transmission losses therefore less water was reaching the catchment outlet as surface flow.

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G. SOIL MOISTURE DYNAMICS ACROSS VEGETATION TYPES IN THE WILLOWVALE, KROMME FLOODPLAIN SITE

G.1. Introduction

The Willowvale site presented an opportunity to monitor soil moisture and shallow groundwater across multiple vegetation types in the Kromme floodplain in close spatial proximity to on another (dense black wattle tree stand, palmiet wetland, and grassland). The different cover type sites can be assumed to experience very similar rainfall and temperature as well as adjacent streamflow and groundwater inputs from the upper catchment and surrounding mountains. Differences between the sites may largely be attributed to the differences in vegetation cover.

G.2. Methods

Soil moisture dynamics were monitored at three locations at the Willowvale floodplain site in the Kromme catchment (Figure G 1) using hourly-logging DFM capacitance probes. The monitoring points varied in vegetation cover: dense wattle stand, an area cleared of wattle with recovering palmiet, and an area cleared of wattle now with grass cover patch. The soil moisture probes are 600 mm long with six sensors at 100 mm intervals.

Soil samples were collected in all areas where soil moisture probes and piezometers were installed for texture and particle size analyses to infer hydrological properties.

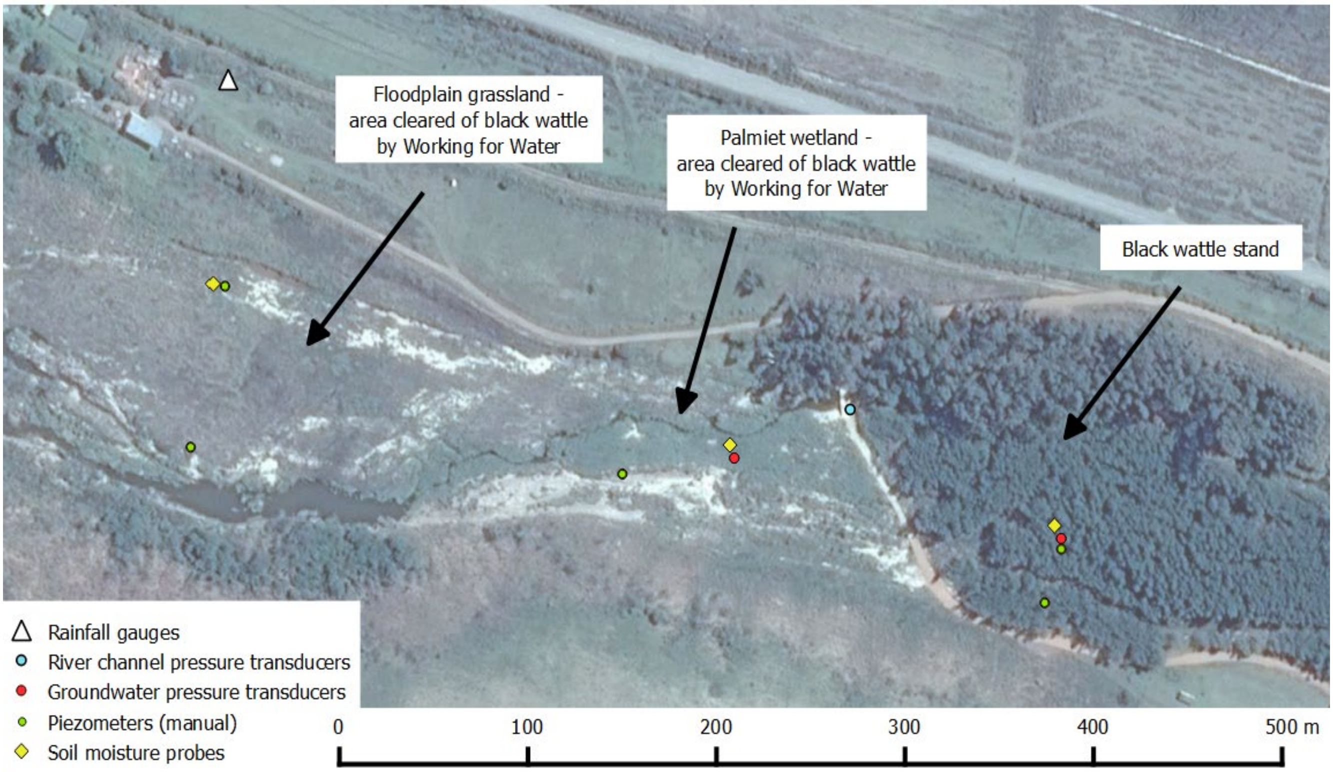

Figure G 1: Willowvale monitoring sites in three different vegetation types in close proximity to one another

Results

The soil moisture patterns logged across the three vegetation types at the Willowvale floodplain site in the Kromme catchment from August 2017-08 to February 2019-02 showed differing patterns. All 3 sites are loamy sand therefore differences can be attributed to the vegetation types and local subsurface contributions.

G.2.1 Grassland site

At the grassland site (Figure G 2), the deeper sensors, 40, 50 and 60 cm, generally showed higher moisture compared to the shallow sensors. This indicates the presence of shallow groundwater in the area. The adjacent piezometer indicated a water table deeper than 2 m for most of the manual monitoring dates, but it is unknown whether or not the water table was higher in between sampling dates. The water table was closer to the surface at nearby sites. The 30 cm depth sensor showed the lowest moisture content which could be an indication that the active root zone is 20 cm and 30 cm from the surface.

All sensors were quick to respond to rainfall events, although the sensors in the active root zone have smaller peaks compared to the deep sensors. Sensors at 10 cm, 40 cm, 50 cm and 60 cm have high peaks, but from August 2017 to November 2017, the peaks for the 3 deepest sensors were higher than that at 10 cm. This could be the result of some local subsurface contributions (rising groundwater table) whereas the sensor at 10 cm only responded to direct precipitation surface inputs.

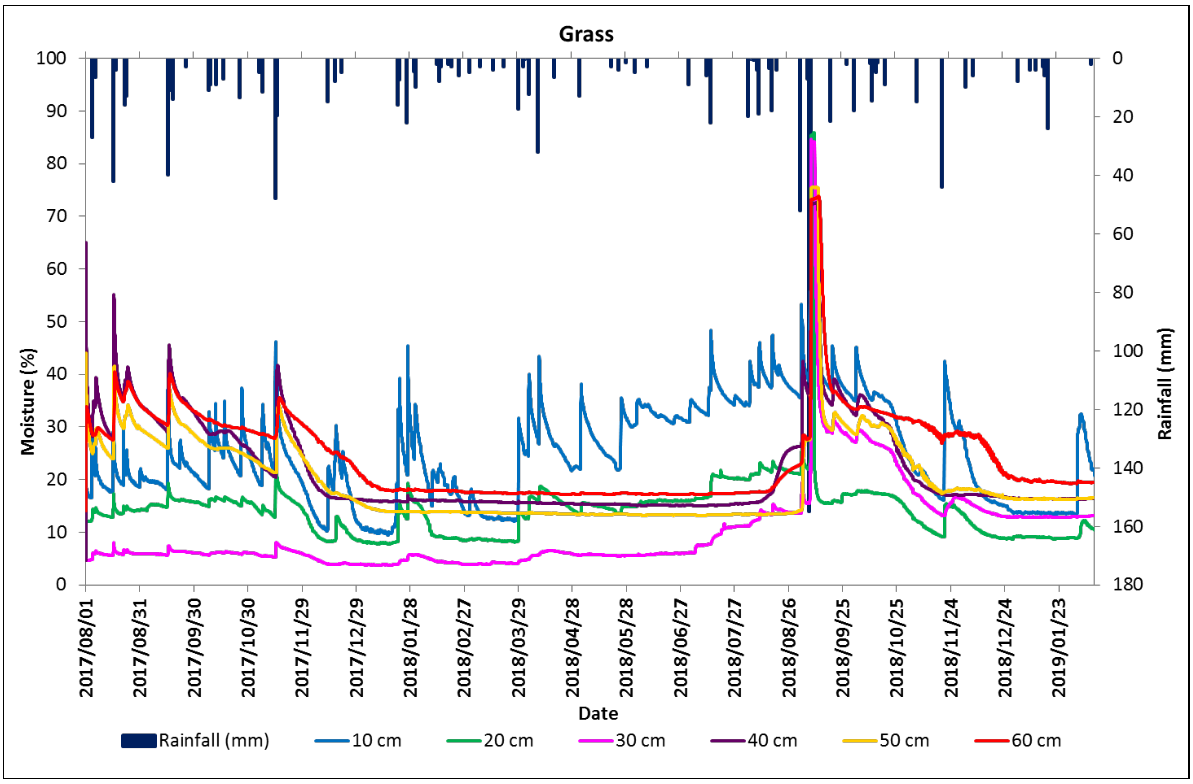

Figure G 2: Subsurface soil moisture dynamics at the grass site

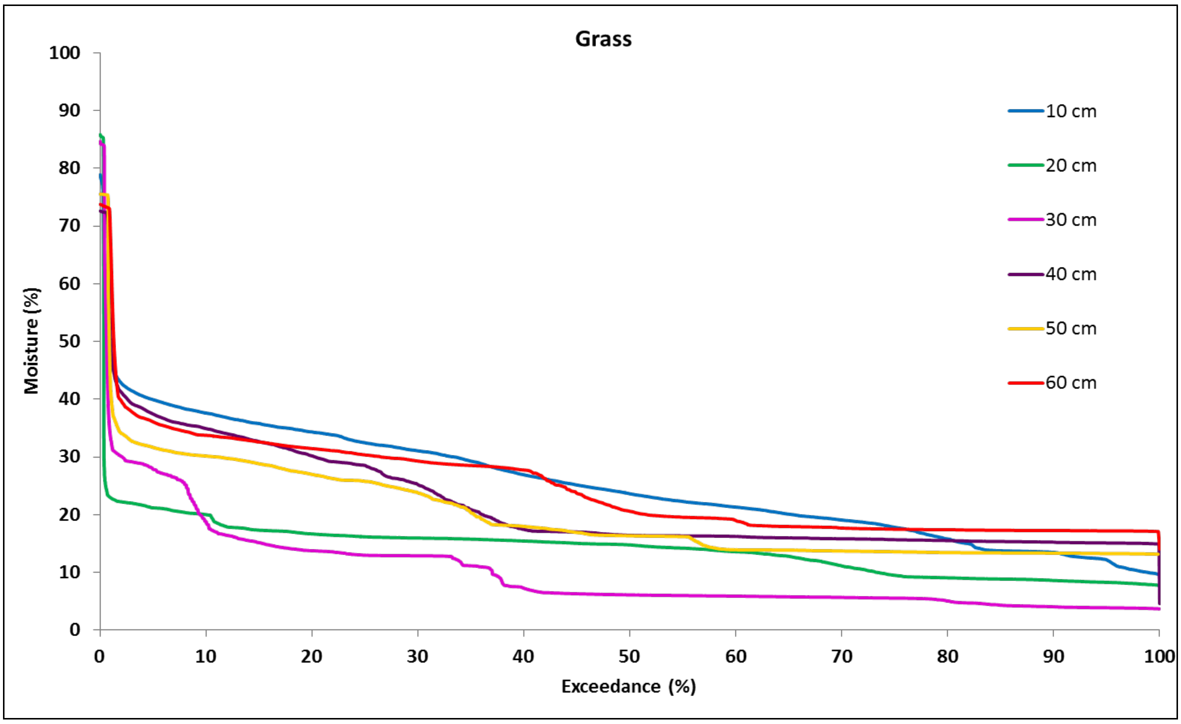

Figure G 3: Exceedance curves for subsurface soil moisture dynamics at the grass site

From November 2017 to August 2018, the 3 deepest sensors did not respond to all rainfall events but maintained constant moisture levels. This could be due to direct precipitation not infiltrating to the deeper layers as it gets used up by roots in the shallow layers, especially in hot summer periods. However, the deeper sensors may have also maintained their moisture due to local subsurface contributions.

During the September 2018 flood, all sensors responded to the storm, however, the 20 cm sensor had the least moisture (potentially active root zone). The sensors at 30 cm, 40 cm, 50 cm and 60 cm receded gradually with the deepest sensor retaining more moisture than the rest.

Following November 2018 and January 2019 rainfall events, only the 2 shallow sensors responded whilst all the other sensors had slight to no response at all, similar to the previous year's pattern at this time. The rainfall events were smaller (under 30 mm) than those when all sensors peaked and the season may also have an impact on percolation.

The percentage exceedance curves (Figure G 3) show that the shallow sensor (10 cm) and the 3 deepest sensors maintained higher percentages of moisture compared to the sensors in the root zone.

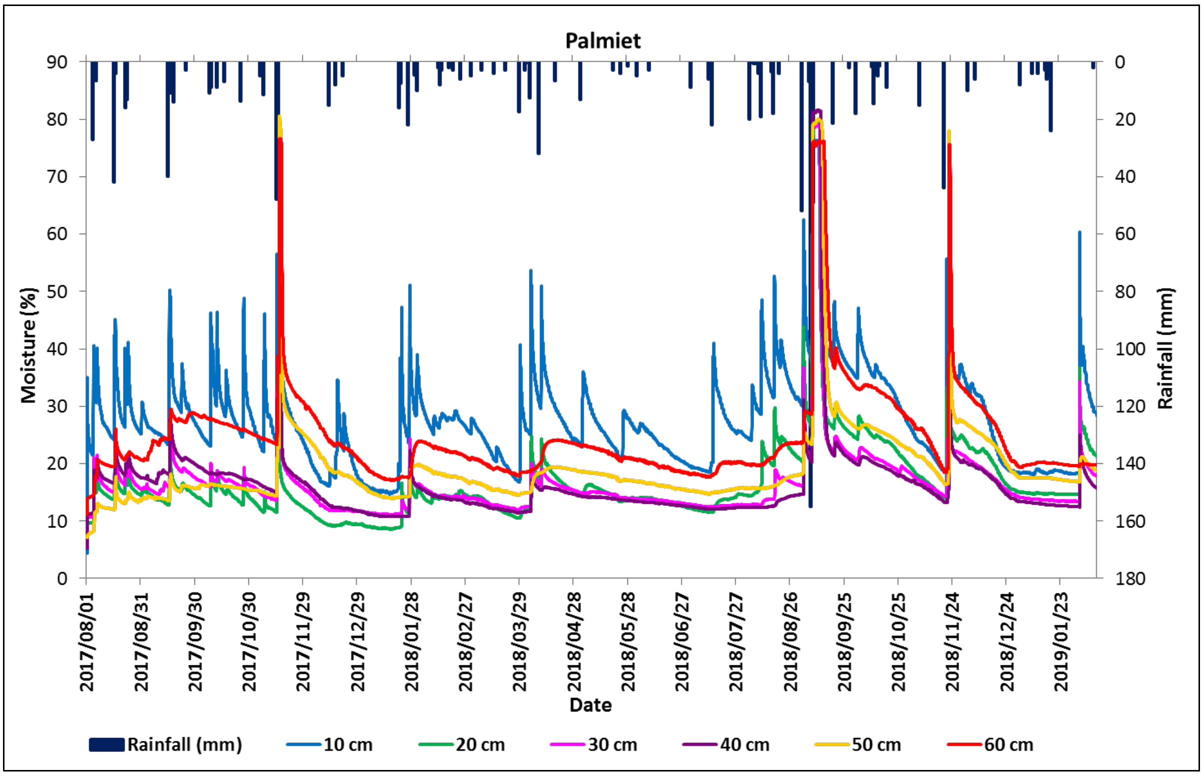

Figure G 4: Subsurface soil moisture dynamics at palmiet site

G.2.2 Palmiet site

At the palmiet site (Figure G 4), the shallow sensor shows more moisture compared to the majority of the other sensors, but the main difference between the palmiet and the other sites, is that the deep sensor shows high soil moisture which rises over the sampling period. This shows the presence of shallow groundwater in this area, not seen at similar depths in the wattle stand (Figure G 6). There could also have been increased local recharge in the palmiet area during flood flows after these storm events. Palmiet's dense surface cover and above-ground rhyzome root system slows down water velocity thereby promoting recharge to groundwater. The large flood would also likely lead to a general lift in the floodplain groundwater table.

Analysis of lags, rates of saturation and drainage after storm events gives an indication of water loss through transpiration and possible contributions through subsurface flows. All the sensors respond to rainfall events, although the peaks are not big which could be as a result of canopy interception from the dense cover. During the recession periods after rainfall events, the moisture recession is gradual compared to the other two sites.

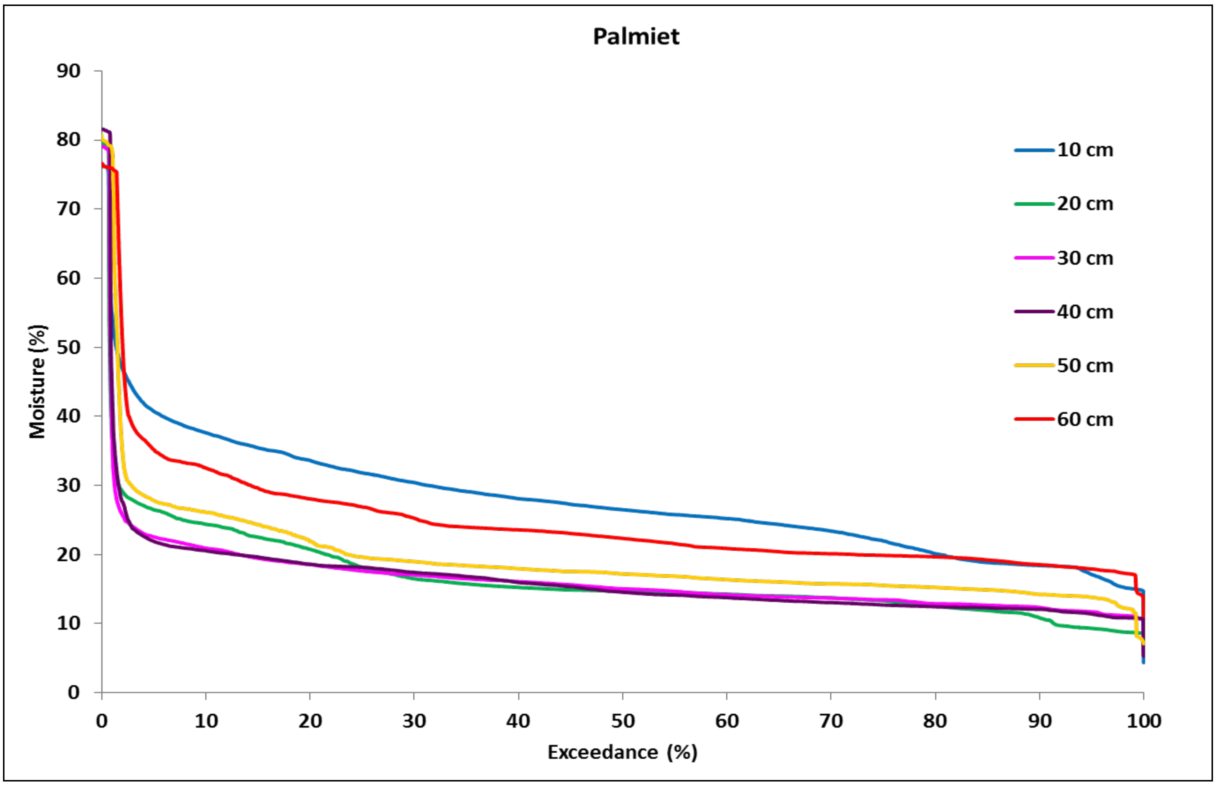

Figure G 5: Exceedance curves for subsurface soil moisture dynamics at the palmiet site

The percentage exceedance (Figure G 5) curves show that the shallow and deepest sensors retain the most moisture whilst the region from 20 cm to 50 cm shows slight differences. Sensors at 30 and 40 cm show similar patterns in their water retention characteristics.

G.2.3 Wattle site

The soil moisture at the wattle site (Figure G 6) shows the greatest moisture at the shallowest sensor (10 cm). The other 5 sensors show lower moisture which could be attributed to water use by the wattle trees. All sensors have quick responses to rainfall events. In some events, only the 2 shallow sensors responded whilst the region from 30 cm to 60 cm maintained their low moisture.

The recession at the wattle site is almost as quick as the time to peak. A comparison of the 3 sites show that the recession rates at the wattle site are much faster compared to the palmiet and grassy site. This could be an indication of the rapid water use by the black wattle trees and/or very fast drainage. The wattle site moisture only receded slowly after the large September 2018 flood. In January 2019 events, only the shallow sensors responded whilst the deeper sensors maintained their moisture levels. The percentage exceedance curves show that the shallow sensor had more moisture whilst the 40 cm sensor had the least.

In general, the groundwater table rises across the area following large rainfall events in the Kromme from August to November 2017 and September 2018. The difference in the depth to water table between these nearby sites is likely due to greater transpiration by the wattle trees.

Exceedance curves (Figure G 7) shows that the soils lose and retain moisture at more or less the same rate with the shallow soil layers retaining a bit more than the rest which could be attributed to ground litter and possible the absence of tree or grass roots in the shallow layers.

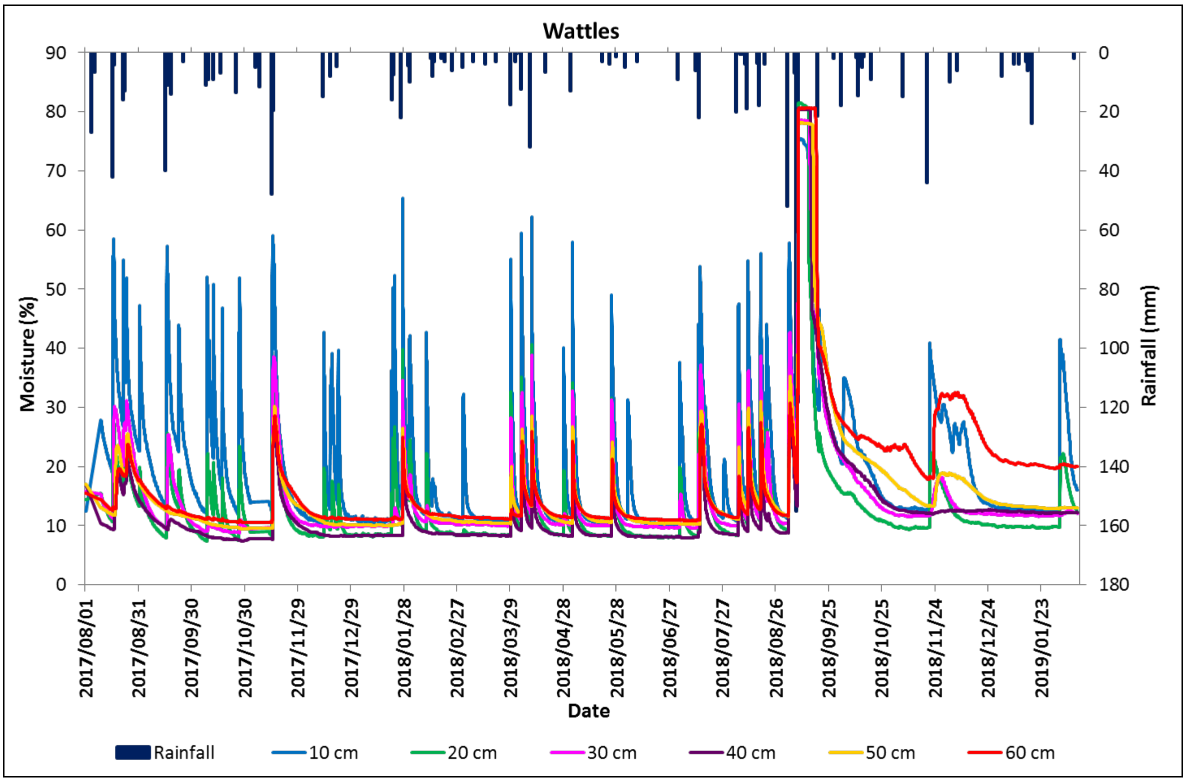

Figure G 6: Subsurface soil moisture dynamics at wattle site

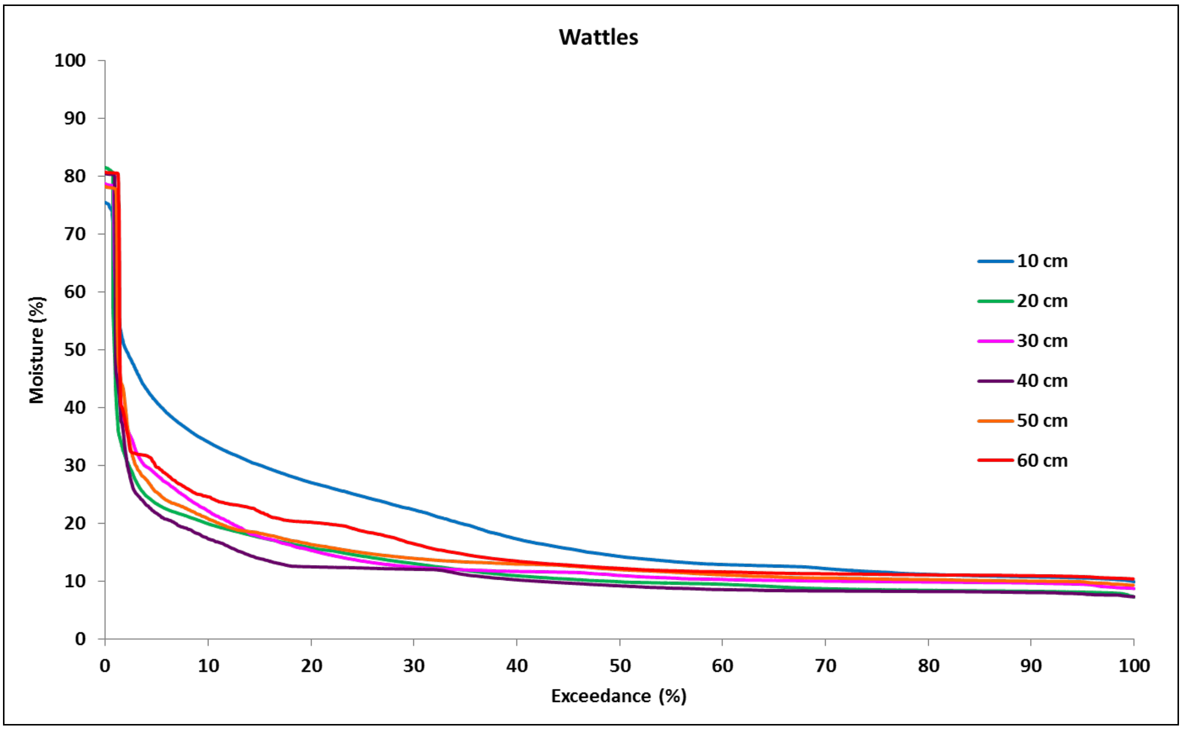

Figure G 7: Exceedance curves for subsurface soil moisture dynamics at the wattle site

H. MODELLING SOFTWARE ASSESSMENT AND SELECTION

There are many catchment modelling software programmes available, either as commercial products, free-ware, or accessible via academic institutions. Using available modelling software, rather than designing and programming a model from scratch, greatly reduces the time and programming skills needed to complete the project and maintain the model after the project period, but does place limitations on the structure of the model used.

Different available software programmes require the model of the catchment to take on certain structures and represent hydrologic processes in different ways. Most programmes do include multiple options spatial discretization and process algorithms, but some provide more options than others. Many programmes use similar governing equations and algorithms for hydrologic or hydraulic processes (e.g. applying Manning's equation for surface flow), but implement them at different spatial scales or allow different levels of connectedness between modelled units, which changes the real meanings and likely values of the parameters in the equations.

A selection of modelling software programmes which are commonly used in South Africa or internationally were considered for use in this project:

- Pitman / WRSM (Hughes, 2004; Pitman, 1973)
- ACRU (Schulze, 1986, 1995)
- SWAT (Arnold et al., 1998)
- MIKE-SHE & MIKE-11 (DHI, 2014; Refsgaard and Storm, 1995)
- HEC-HMS & HEC-RAS (USACE-HEC, 2010)
- 3Di (Delft Technological University, Deltares, and Nelen & Schuurmans)

These were initially compared based on a few eliminating structural criteria in order to short-list packages for more detailed comparison as shown in Table H1.

Two modelling software programmes were short-listed, primarily differentiated by their flow routing and spatial scale options, calculation of flood extents, and groundwater levels:

1. MIKE-SHE/MIKE-11 (a coupled system of MIKE-SHE hydrologic and MIKE-11 hydraulic modelling systems – hereafter simply referred to as MIKE-SHE), and
2. 3Di

MIKE-SHE was chosen over 3Di based on its representation options for subsurface flows and its licensing options, as 3Di requires a subscription and employment of the Deltares team to have full control over scenario set-ups and runs in the model.

Table H 1: Short-listing modelling systems based on structure and output criteria

Modelling system	**Developer / Custodian / Reference**	**Spatial discretization***	**Short-listing criteria**				
			Model effects of land-cover change	**Explicit conside-ration of river channel shape or capacity**	**Dynamic, two-way, SW – GW** exchange**	**Calculates extent of flooded area**	**Calculates GW depth**
Pitman	IWR - Rhodes University, & University of Witwaters-rand (Pitman, 1973)	Sub-catchment	yes – indirect parameterization	can add routine for overbank flood redistribution	yes	no #	(could estimate from GW storage)
ACRU	BEEH - UKZN, (Schulze, 1994)	HRU within sub-catchment (no catena for surface flow)	yes	can add routine for overbank flood redistribution	no	no #	(could estimate from GW storage)
SWAT	US Dept of Agriculture & Texas A&M, (Arnold & Allen, 1996)	HRU within sub-catchment (not catena)	yes	can add routine for overbank flood redistribution	no	no #	(could estimate from GW storage)
HEC-HMS (+HEC-RAS)	US Army Corps of Engineers (USACE)	HRU within sub-catchment (not catena)	yes	yes - when coupled	no	yes - when coupled	no
MIKE-SHE/ MIKE-11	Danish Hydrologic Institute (DHI), (Refsgaard & Storm, 1995)	Gridded OR HRU (catena or not) within sub-catchment	yes	yes	yes	yes	yes
3Di	3Di Foundation	Gridded	yes	yes	yes	yes	yes

***Definitions:**
HRU - hydrologic response unit - areas with similar vegetation, soils, slopes, geologies which are expected to have similar hydrologic responses to climate;
catena - sequence of connected land units or HRUs along a flow path (e.g. plateau/crest, hillslope, valley floor), over which flows are routed. If HRUs are not considered in a catena, runoff from each HRU is routed directly to the stream.
** **SW – GW** – surface water – groundwater
# Can use flow outputs of a hydrologic model as inputs into a hydraulic model, such as HEC-RAS or MIKE-11, to calculate the spatial extent of a flood event. The disadvantage of coupling to an external model when looking at longer-term flow patterns is that the infiltration of floodwater into the floodplain material is not included in the hydrologic model.

The two South African modelling software programmes, Pitman and ACRU, provide advantages such as:

- Greater support and familiarity with local institutions
- Free use and access
- Lower computational burden compared to more complex gridded models

The process algorithms included in these two programmes are quite similar, but they have different structural options. Both calculate canopy interception as a function of rainfall and a vegetation specific parameter; infiltration as a function rainfall reaching the ground, the antecedent soil moisture, and soil properties; surface flow reaching channels as infiltration and storage excess which is lagged; percolation to groundwater as a function of soil moisture and soil properties; baseflow as a function of groundwater storage; evapotranspiration as a function of demand, vegetation type, and available soil moisture.

The Pitman modelling programme allows two vegetation types per sub-catchment, however inclusion of additional irrigated area, wetland units, and impervious area consideration pushes this up to five. In ACRU, areas can be broken up into many linked sub catchments representing different land cover types. The surface flows from each of these units is assumed to directly reach a stream unit in models built in ACRU, but the subsurface flows can be routed downslope.

Both programmes had drawbacks in terms of process representation that led to their exclusion. They were excluded from further detailed analyses here for the following reasons (summarized in Table H 2):

- Do not include surface flow routing across different land cover types in a catena (Pitman & ACRU)
    - In both models surface runoff is routed to the river channel with a lagging function, however there is no explicit link between this lagging and the spatial arrangement of vegetation and geomorphic types along a hillslope. This means it is difficult to directly determine the impacts of the configuration of land types (e.g. impact of natural vegetation buffer areas or unchannelized alluvial fans) on surface flow.
    - When surface flow across the landscape is relatively unimportant compared to subsurface, this becomes less important. ACRU allows routing of subsurface flows between land units in a series before reaching a channel. In Pitman these flows are lumped.
- Do not calculate the extent of overbank flooding (Pitman & ACRU).
    - NB: Both modelling programmes can approximate some flow regulation processes associated with overbank flooding by inclusion of an optional off-channel wetland routine. The routines are similar for both programmes: a channel segment is given a specified capacity and when modelled flow exceeds this, the excess is allocated to a wetland unit that is conceptualized similarly to a dam. The wetland unit has a specified volume, volume-surface area relationship, and storage related drainage function to determine outflow to a river channel. In ACRU the wetland routine includes soil moisture accounting for the area of the wetland unit that is not saturated.
        - The floodplain areas of the BKK catchments could be conceived using these wetland routines to capture some of the flood attenuation effects, but this would not allow the routines associated with irrigated agriculture to be applied to the same areas.
- Do not calculate groundwater elevations in multiple locations (Pitman & ACRU)
    - Both programmes can estimate an average groundwater elevation across a subcatchment unit.
- Do not include channel transmission losses (ACRU only)
- Do not include groundwater pumping (ACRU only)

Table I 2 Summary comparison of the Pitman, ACRU, and MIKE-SHE models

	Pitman	ACRU	MIKE-SHE
Pro	• Free • Common in SA • Batch run facility (calibration) • Farm dam routine • Dynamic subsurface – surface water connection • External irrigation demand calculation needed (e.g. SAPWAT)	• Free • Common in SA • Catena routing of subsurface flow • HRU structure facilitates land cover change scenarios • Farm dam routine • In-built means of estimating sub-daily peak-flow	• Free to researchers, discounted to DWS • Support in SA • Highly flexible structure – catena routing and gridded options • Coupled surface and groundwater modelling (gridded) • Flood extents • Distributed groundwater depth • Irrigation application options & source links
Con	• Daily model exists, but less tested – monthly not give peaks • Lumped structure complicates parameterization of land cover scenarios • No catena routing • Lumped groundwater depth • No flood extent estimation	• No batch run facility • No surface catena routing • No groundwater abstraction?? • No channel transmission losses	• Software license payment • Complex – learning curve & computing power • Representation of farm dams more complex

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