AN INTEGRATED APPROACH TO ASSESSING AND IMPLEMENTING ECOLOGICAL WATER REQUIREMENTS

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

RATIONALE

South Africa has a rich history of research on Ecological Water Requirements (EWR), even before the development of the National Water Act (Act 36 of 1998, NWA) introduced concepts such as the Ecological Reserve. However, with the advent of the NWA there were numerous challenges in terms of the human resource capacity and training to implement these concepts effectively within Integrated Water Resource Management (IWRM). North-West University launched a Masters programme in EWR in 2016 to implement an Ecological Water Requirements curriculum (Wepener, 2016), which was the culmination of 20 years of EWR curriculum development. Even with this curriculum being available, there has been a lack of formal training and capacity building within the EWR field in recent times, with particular reference to socio-economic integration that often lacked in depth. As such, this project relates to that interface of providing postgraduate training in EWR while still trying to advance the science behind EWR.

The implementation of EWR in IWRM has been lacking, largely due to the lack of capacity identified but also in some regards due to the lack of methods and research on how to integrate the EWR within existing water resource management strategies. Integration, in the context of this project, was defined as the technical integration of driver and responder data together with the stakeholder vision for a catchment using a holistic method. This method has the capability to include riverine, wetlands and groundwater information and to determine what the risks to achieving the catchment vision or endpoints are. Therefore, this project used a case study catchment to look at integration and implementation of EWR using a holistic methodology. Due to dynamic climatic changes, an environmental water requirement should be more flexible and adaptive in the future. All too often, the methodologies and management measures have been too rigid to be responsive to dynamic aquatic ecosystems. Therefore, an integrated approach based on the Relative Risk Model (RRM) proposed by O'Brien and Wepener (2012) and O'Brien et al. (2018) is potentially a way forward to improve EWRs for aquatic ecosystems in South Africa, both in the integration of socio-ecological endpoints and in improved implementation of EWRs. It must be noted, that it is proposed that this RRM be used as an integrated framework for riverine, wetland and groundwater ecosystems and not to replace existing methods for each aquatic ecosystem type. The existing methods to assess EWRs still provide valuable information that is needed in the RRM to define the relationships to the socio-ecological endpoints identified as important. The RRM method would be an inclusive and participatory method for the management of water resources in a specific catchment.

The selected case study was the Mooi River in the Vaal River catchment, originating in the Gauteng and North West Provinces. This is a small but complex catchment with numerous activities resulting in an impact on the Mooi River. These activities include dense urban and rural developments, agriculture (mostly crop farming), and mining (mostly gold mining). Other impacts on the Mooi River include discharge of poorly treated wastewater while the three impoundments (Klerkskraal, Klipdrift, Boskop and Potchefstroom Dam) also affect the Mooi River. This project dealt with the following problem statements as a baseline: a) human resource capacity in EWR is limited in South Africa; b) general water-related expertise in South Africa, especially within certain government departments, is declining; c) little fundamental research on EWRs in South Africa has been done, especially related to integrated technical approaches; and d) water governance issues surrounding EWR implementation and integration are often experienced. The following rationale and problem statements were used to set the four main aims for the project:

AIM 1: Ecological Water Requirement training and skills development
To strengthen research and training in Environmental Water Requirements (EWRs) utilising the Masters Programme in Environmental Management with specialisation in EWRs at the North-West University.

AIM 2: Technical integration
Advance the technical integration of EWRs using science-based methodologies. The focus here is the integration of the various existing methods into a framework that will potentially allow better EWR implementation.

AIM 3: Mooi River case study
To demonstrate the implementation and the integration of EWRs by means of a case study. For this purpose, the Mooi River within the Vaal River Catchment was selected as the case study catchment.

AIM 4: Water related skills development
Develop and strengthen water related skills within students participating in the Masters in Environmental Management with specialisation in Ecological Water Requirements.

METHODOLOGY

The methodologies for the three main research outcomes based on the aims previously highlighted are briefly explained below. The focus was on the EWR training and development, the technical integration and the use of the Mooi River case study as illustration of the methodology.

Ecological Water Requirement training and skills development (Aim 1 and 4)

The training and skills development of the students were facilitated through the Masters in Environmental Management with specialisation in Ecological Water Requirements at North-West University. The students registered for three modules:

- Management of Ecological Drivers in Aquatic Ecosystems
- Management of Ecological Response in Aquatic Ecosystems
- Research module in EWR (any topic in EWR applicable to Mooi River or more general).

This Masters utilises various experts and professionals from the EWR and water resources sectors in South Africa. The duration of the course is two years with the ultimate goal to equip the students with the necessary skills to function efficiently and professionally in the water resources management sector in South Africa.

Technical integration (Aim 2)

The review of existing methodologies used in EWR and EWR integration in South Africa highlighted the different methods that are available for the different components. However, the holistic, regional-scale, probabilistic assessment method within the Relative Risk Model (RRM) approach (O'Brien and Wepener, 2012; O'Brien et al., 2018) was considered to be a promising method to assess a complex socio-ecological system. The method uses a regional-scale ecological risk assessment framework that is able to deal with multiple stressors to social and ecological endpoints and still be able to address ecosystem dynamism (O'Brien et al., 2018). Bayesian belief networks are incorporated into the RRM to address uncertainty explicitly. The RRM methodology that was applied in the Mooi River case study consisted of 10 steps:

Step 1: Vision exercise
Step 2: Mapping and data analyses
Step 3: Risk region selection
Step 4: Conceptual model
Step 5: Ranking scheme
Step 6: Calculate risks

Step 7: Uncertainty evaluation
Step 8: Hypotheses establishment
Step 9: Test hypotheses
Step 10: Communicate outcomes

Mooi River Case Study (Aim 3)

The catchment that was used for the case study is the Mooi River catchment in the Vaal River. The headwaters of the Wonderfonteinspruit tributary originates in Krugersdorp, while the mainstem Mooi River originates north of Potchefstroom in the Boons region. The other significant tributary is the Loopspruit that originates to the east of Fochville. It is a complex catchment which is highly utilised with numerous anthropogenic impacts. These impacts include mining, agriculture, rural and urban developments and discharges of poorly treated wastewater. A thorough review of the available ecological and socio-economic conditions within the catchment was conducted. The review is compiled through the gathering of published and grey literature on the catchment for the different individual student projects. The socio- and resource economics studies were conducted using a desktop level socio-economic classification and valuation for the Mooi River sub-catchment. The Prime Africa® Ecosystem Services Capital (Eco-CAP$_{es}$) was utilised as a standard for classification.

RESULTS AND DISCUSSION

The results from each aim as identified previously are presented in the following sections.

Ecological Water Requirement training and skills development (Aim 1 and 4)

Two of the main aims of this research project were to build capacity in EWR within the water resources management sector in South Africa. This was achieved through the Masters in Environmental Management in EWR at North-West University. Thus far, 19 students have received training through their participation in this research project and their research dissertation forming part of the case study on the Mooi River in the Vaal River Catchment.

Upon the successful completion of the course the students will have:

- a useable knowledge of the relevant methods and procedures used within EWRs to solve practical and theoretical problems, specifically related to the ecological drivers and responders in aquatic ecosystems;
- the ability to address challenging and complex aquatic ecosystems problems and these issues are addressed within EWRs, and

- have specialist knowledge and understanding regarding EWRs and be able to engage with – and critically discuss practises on national and international environmental and sustainability challenges.

Even though the degree at NWU only started in 2016, 38 students have already enrolled for the programme (19 of these funded through this research project). Although the programme was originally developed to train employees of the Department of Water and Sanitation, only 33% of students have been from this government department. The majority of students are from other government departments, local government departments and independent consultants. However, students that have been part of this programme have indicated the value that it has provided for their development within the water resources management sector in South Africa. The results from AIM 2 and AIM 3 have already been incorporated within the learning material of the Masters course, especially in using an applied case study to practise and implement various methodologies throughout the theoretical and practical components of the course.

Technical integration (Aim 2)

The RRM model was applied in the case study catchment during the project. A stakeholder workshop was held to discuss the catchment vision as well as various social and ecological endpoints that would be important for water resource management in the catchment. Overall, 12 endpoints were selected for further analyses and implementation in the Mooi River catchment. Of these 12 endpoints, seven were social endpoints while there were five ecological endpoints. All available information on the aquatic resources of the Mooi River catchment was analysed and the data were captured for analysis within the RRM. The catchment was divided into five risk regions (RRs) to develop the RRM and to demarcate water resource management regions. The following risk regions were identified based on the impacts, river condition, river morphology and land use in the catchment:

- RR1 = Upper Mooi River
- RR2 = Wonderfonteinspruit
- RR3 = Mooi River downstream of Wonderfonteinspruit to Loopspruit confluence
- RR4 = Loopspruit
- RR5 = Mooi River downstream of Loopspruit

The Mooi River conceptual model was developed based on the various social and ecological endpoints identified from the stakeholder consultation. These models need to be tested and validated further using the available data and uncertainty identified in the conceptual models. The various scenarios identified during the stakeholder consultation are specific hypotheses that will need to be tested in future to determine the risk of failure due to water resource management failure in the Mooi River catchment. These models and risks need to be communicated to the stakeholders in the catchment to ensure further participation in the water resource management of the Mooi River catchment.

According to Arthington et al. (2018), innovative integrated methods are required to provide meaningful management recommendations for the sustainable utilisation of complex aquatic ecosystems coupled with changing environmental and societal futures. This study demonstrates that the RRM methodology indeed provides such an innovative approach allowing for the selection of relevant socio-ecological and socio-economical management objectives.

Mooi River Case Study (Aim 3)

All of the results from the case study were applied to the conditional probability tables of the RRM model. The conditional probability tables are used to explain and define relationships between sources, stressors, and the various social and ecological endpoints. The following ecological and socio-economic aspects were identified as the main drivers of water resources management in the Mooi River.

Ecological aspects

- A major source of water to the Mooi River catchment are the various springs that feed the Mooi River, i.e. Wonderfonteinspruit and the Loopspruit, with the Gerhard Minnebron, Bovenste Oog and Turffontein Spring contributing the most to the water supply.
- The Mooi River catchment is classified as a Water Resource III – highly utilised catchment.
- There is only one EWR site in the entire Mooi River catchment that was utilised for setting of the Ecological Reserve.
- The Present Ecological Status in the catchment is generally a D Ecological Category.
- The Ecological Importance and Sensitivity in the catchment varies but is generally found to be moderate to high, depending on the position in the catchment. The lowest EIS is reported from the Wonderfonteinspruit.
- The quantity and quality Resource Quality Objectives have been set for and the Reserve has been gazetted for the catchment.

Socio-economic results

- The population density influenced the Vulnerability Index, with the denser RR2 and RR3 having the lowest vulnerability. This is due to greater access to water through service providers.
- The results showed that RR1 was more rural and relied primarily on boreholes for water and as such was highly vulnerable to impacts on water resources.
- The social wellbeing indicated similar results with RR1 having the highest percentage of the population falling below the threshold for social wellbeing. In contrast, RR3 and RR4 had the highest social wellbeing that corresponded to access to piped water, formal houses, education and a higher income.
- Water provisioning was the major service provided by the ecological infrastructure – both for industry and communities.
- The results indicated that the water economy (municipal and agriculture) was estimated at R571.5 million per annum.

RECOMMENDATIONS

This project has focussed primarily on education through integration of different aspects within EWRs and the resulting research outcomes from the student projects. Based on the learning process related to EWR the following recommendations can be made:

- Ensure faster uptake of EWR training in the Department of Water and Sanitation.
- Continuously update EWR learning material when newer research methods and ideas come along.
- Implement the recommendations that have emanated from the student research projects on the Mooi River catchment.
- Further testing of the RRM is needed within the Mooi River catchment to complete various endpoints identified during the stakeholder engagement process.
- The Mooi River Catchment has a significant rural population that utilises natural aquatic ecosystem resources. This resource value is not captured within the formal economy and it is vital to capture these environmental externalities to improve ecosystem value assessment and the RRM.
- The spatial distributions identified in the Vulnerability Index and social wellbeing scores should be explicitly accounted for when managing resources in the Mooi River Catchment.

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LIST OF ABBREVIATIONS

Eco-CAP$_{es}$	Ecosystem Services Capital Tool
EWR	Ecological Water Requirements
DAFF	Department of Forestry and Fisheries
DEA	Department of Environmental Affairs
GDP	Gross Domestic Product
GVA	Gross Value Add
Ha	Hectare
IDP	Integrated Development Plan
NWA	National Water Account
RR	Hydrological Risk Region
SANBI	South African National Biodiversity Institute
StatsSA	Statistics South Africa
SWS	Social Wellbeing Score
VI	Vulnerability Index
WRC	Water Research Commission
WWTW	Wastewater Treatment Works

1 INTRODUCTION AND OBJECTIVES

1.1 Motivation

The development of the National Water Act (Act No 36 of 1998 – NWA) led to the introduction of new concepts such as the Reserve and Classification of water resources (Wepener, 2016). These concepts were generally recognised as being revolutionary and ground breaking in terms of being included within legislation to manage water resources. Even before the promulgation, the then Department of Water Affairs and Forestry realised that the implementation of the new act would require retraining and education of their own officials as well as officials from other government departments, non-governmental organisations and the private sector. This education initiative was imperative if Integrated Water Resource Management (IWRM) would be achieved by the NWA. The specific needs of this training and education was identified by United Nations Educational Scientific and Cultural Organisation (UNESCO) and the World Meteorological Organisation (WMO).

These assessments led to the formation of numerous training modules that have been developed since 1998. The development of all the various modules were finalised into an Ecological Water Requirements curriculum in 2016 (Wepener, 2016). Even though all of these modules were developed over a 20-year period it did not adequately solve the skills and human resource capacity needs identified in 1998. The reason for this is probably a complex interaction of the socio-economic and political climate of South Africa in the last 20 years. This lack of adequate development of human resources have led to the inadequate and fragmented implementation of EWRs in South Africa. Furthermore, it led to a lack of knowledge transfer through capacity building with the end result being many hindrances to water resource management (Wepener, 2016). In turn, water resource management have not been able to address issues such as equity, environmental sustainability, efficiency, social and economic development and the eradication of poverty (Wepener, 2016).

The EWR methodologies currently in use that relate to the specialist scientific aspects of Reserve determinations, have been developed both locally and internationally over many years, using specialist knowledge and experience in both water resource and aquatic ecology functioning (DWAF, 2007). These methodologies have been adapted where necessary to suit South African requirements and to incorporate the latest information and available knowledge. However, much still needs to be done to refine these methodologies (DWS, 2017). However, implementation remains a key area of concern which requires more research and reflection on previous implementation frameworks.

Even though South Africa has a rich history in the determination and research in EWRs, it is still not widely implemented and effective in water resource management. In particular, there was a need to critically reflect on many aspects such as governance and technical integration of components. Governance related to the implementation of EWR within management and departmental structures are often problematic. Issues related to mandates and accountabilities of different stakeholders who is implementing EWRs are often unclear; especially related to the monitoring and reporting on compliance, imbedding EWRs in infrastructure projects and accounting for the Reserve in WUL.

Furthermore, the development and training of human resources within the EWR sector has also been lacking. Thus, the need for research and training in EWR has been an ongoing focus of the WRC and the Department of Water and Sanitation (DWS), dating back to the late 1990s. Most recently, in March 2016 a new tutored masters in EWR was launched by the WRC with support from the DWS, with the NWU positioned as the first institution to champion the particular degree. At the launch, the initiative was strongly supported by the Director General (DG) of DWS, also in light of South Africa's commitment to Goal 6 of the recently adopted United Nations (UN) 2030 Sustainable Development Goals (SDG), which states, "To ensure availability and sustainable management of water and sanitation for all".

This project used a case study to implement EWR training and research. A case study provides the opportunity to test training and research methods in a real and complex system. The rationale is that should the training and research prove effective within the case study, it can be applied on a larger scale for further testing and development. The Mooi River catchment was identified as an ideal case study because it provides sufficient complexity to test the governance, technical integration and implementation of EWR dimensions, while also being a strategically important catchment area, for various towns, mining operations, agricultural practises and rural communities. Learning from this catchment for EWRs will provide valuable insights for other catchments in the country that have similar complex scenarios The Mooi River is also a very important tributary of the Middle and Lower Vaal River catchments that support a significant agricultural development that depend on the quality of water exiting the

Upper Vaal catchments. As a disadvantage, the Mooi River could not consider integration of the freshwater and estuarine ecosystems; however, this has already been considered in Vezi et al. (2020). Considerations of the economic impact of water are central to both Integrated Water Resource Management (IWRM) and EWRs. Decisions around water allocation should be based on an integrated understanding of the catchment and different water users.

The concept of "integrated" in this project comes from the use of EWR within the Integrated Water Resources Management paradigm. The definition of IWRM, according to the Global Water Partnership, is the "the process of coordinating conservation, management and development of water, land and related resources across sectors within a given river basin, in order to maximise the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems." (Agarwal et al., 2000). When looking at the process for EWR determination (details in section 3 below), it is evident that integration is often encountered throughout the process. Some examples of this include:

- Integration of ecological drivers into an EcoStatus.
- Integration of ecological drivers and responders to determine flow-duration covers and preferences for biota.
- Integration between ecological and socio-economic concepts into the catchment vision.
- Integration of EWRs and Reserve's within IWRM and water resource management.
- Integration of wetlands, groundwater and riverine systems into an integrated catchment management strategy.

These examples illustrate how important the integration of data in various stages of the EWR process is, often with different data and information formats. This is especially true within the technical integration of driver and responder data. Since there is so many different areas of integration within the EWR process, it is important to define the "integration" that the current project focussed on. In the context of this project, the integration was focussed on the technical integration of driver and responder data, integration of stakeholder vision into EWRs, and utilising a holistic method that have the capability to include wetlands, groundwater and riverine information in one Relative Risk Model (RRM) to determine whether catchment vision or endpoints are achievable.

1.2 Problem statement

The motivation provided a background on where EWR has come from and some of the key challenges that its implementation has experienced in South African water resources management. Based on the project motivation and history of EWR in South Africa, we can currently highlight the following problem statements that are characterising water resource management and specifically EWRs in South Africa:

a) Human resource capacity in EWR is limited in South Africa.
b) Little fundamental research is being completed on EWRs in South Africa, especially on integrated research approaches.
c) General water related expertise in South Africa, especially within certain government departments, are declining.
d) Governance related issues surrounding the implementation of EWRs.

As mentioned previously, these problems are not exhaustive and many other issues can be highlighted in EWR implementation. These include issues such as monitoring and reporting on compliance (both for the Reserve and RQOs), development of water allocation schedules that account for the Reserve and EWRs, operating rules for impoundments and many more. However, for the purpose of this project we focused on the highlighted problem statements to determine the project aims.

1.3 Project aims

The rationale for this application relates to the interface postgraduate training and research in Ecological Water Requirements (EWRs). The project was divided into four research aims so that this project could add and start to address the various problem statements highlighted in the previous section. Therefore, the aims of the project were as follows:

- To strengthen research and training in Environmental Water Requirements (EWRs);
- To further develop and strengthen water related skills through the EWR masters programme at NWU;
- To advance the technical integration of EWR components using a science based methodology together with improved integration of social and ecological endpoints;

- To demonstrate the implementation of the integration of EWRs by means of a case study; and

2 HUMAN CAPACITY DEVELOPMENT

2.1 Introduction

Research has shown that one of the key problems with the implementation of EWRs is that of capacity within the water resources sector (Stoffels et al., 2018). This relates both to doing the necessary fundamental research to determine EWRs but also to implement the EWRs on a daily basis within water resources management of a country. In South Africa, various publications have highlighted human capacity and skills development as a major hindrance to the implementation of EWRs as well as IWRM in South Africa. This includes publications from the Department of Water and Sanitation (DWS, 2017) as well as research reports from the Water Research Commission (Palmer and Munnik, 2018).

Numerous projects have initiated programmes to bridge this gap in capacity and skills, including the current Masters in Environmental Management with specialization in Ecological Water Requirements at the North-West University. This programme is based on a curriculum specifically designed to meet the needs of DWS, practitioners, and other water related agencies within South Africa (Wepener, 2016). This programme has been running from 2016 at the North-West University and has been successful in implementing a curriculum for EWR that had been published by the Water Research Commission (Wepener, 2016). However, the knowledge and tools utilized within EWR or internationally ecological flows (e-flows) are growing every year resulting in newer methodologies and techniques available.

The first aim of this research project was to build capacity in EWRs within the water resources management sector in South Africa. This was achieved through the theoretical component of the Masters in Environmental Management in EWR as well as the research component of the qualification. Thus far, this research project has supported 19 students in this qualification through the case study on the Mooi River in the Vaal River Catchment. The following section provides a brief overview, aims and objectives of each student's project. Further details on the research project can be accessed through the North-West University Library Institutional Repository (https://repository.nwu.ac.za/) utilizing the student name and project title.

2.2 Student project summaries

<u>Impacts of urban land use on the surface water resources of the Mooi River Catchment – Mr Samuel Maliaga (DWS)</u>

Urbanisation is a common phenomenon witnessed in most parts of the world. Population growth together with industrialisation, wealth creation and improved mobility have resulted in the irrevocable transformation of previously rural land into housing developments and the more intensive development of urban fringe areas. As this urban fabric is formed, it gives rise to a host of environmental impacts. In the context of effective urban resource planning and management, the impacts of urban land use on the water resources is seen as one of most critical (Goonetilleke and Thomas, 2003). Urbanisation results in the removal of vegetation and the replacement of previously pervious areas with impervious surfaces and the introduction of pollutants. Anthropogenic structures such as irrigation canals, wells, reservoirs, dams, and paved roads also shape the natural catchment landscapes. Urbanization, amongst other things, affects surface water dynamics, stream geomorphology, biogeochemistry, and stream ecology (Sun and Caldwell, 2015).

Impacts on water quality are primarily caused by the following: significant production of pollutants and reduction of retention capacity of catchments as a result of increased impervious surfaces. Urban waters often contain pharmaceuticals such as antibiotics, analgesics, narcotics, and psychotherapeutics, pesticides, metals, pathogenic microbial populations, and organic pollutants (Bowden et al., 2015). A combination of changes to the physical habitat and altered water quality is the major impact of urban storm water runoff. As the storm water flows over the drained surface, pollutants will be incorporated through various physical and chemical processes and deposited in surface water bodies. The source from which the storm water runoff is derived is one of the most important factors which will influence its pollutant composition and consequently the impact and risk.

In an effort to mitigate the adverse impacts of urbanisation, the current approach by authorities is the adoption of structural and regulatory measures. Structural measures commonly include the provision of detention basins, wetlands and pollutant/sediment traps. Regulatory measures are often in the form of restrictive zoning, demarcation of buffer strips and the imposition of limits on storm water quantity and quality exports from an urban development (Goonetilleke et al., 2005).

The appropriate management of urban storm water runoff and streamflow has significant socio-economic and environmental effects. Therefore, it is imperative that this continuous urban growth is wisely managed and innovative strategies are adopted to ensure the protection of surface water resources, especially in cities under development. This research aimed to determine the impacts of urban land use on the surface water resources of the Mooi River Catchment in Potchefstroom. The objectives for the project were as follows:

- To identify the types of urban land use activities in Potchefstroom.
- To determine the impacts of urban land use activities on the surface water quality.
- To identify the sources of surface water pollution.
- To determine the impacts of urban land use on surface water quantity.
- To identify the activities that impact on surface water quantity.

Fish and habitat present ecological state in the Mooi River catchment in the North West Province – Ms Mosima Tele

Natural disturbances such as floods, droughts, or fires and anthropogenic activities such as agriculture and mining affect the rivers (surface water) (Rashleigh et al., 2009) to an extent that they have a detrimental impact on fish species (Kock and Schoonbee, 1980). The effect also results in loss of habitats and biodiversity, due to sedimentation and invasion of alien plants and fish such as largemouth bass (Walmsley and Mzuri, 2002). Roux et al. (2002) noted that under certain environmental conditions a river ecosystem may be transformed to an extent that new equilibrium assemblages may occur (Rashleigh et al., 2009). Fish have been used extensively in river health monitoring in South Africa. However, in certain catchments there is a lack of information on fish communities especially hard working river catchments like the Mooi River which resulted in lack of ecological information. The discharge of mine and agricultural water into the Mooi River contributed to increased metals (Van Aardt and Erdmann, 2004), potentially affecting the fish community negatively.

This research will benefit the stakeholders of the Mooi River as it will give an indication of the PES, indicate compliance or non-compliance against the Resource Quality Objectives (RQO) of the Vaal water management area and it will also outline the measures to be taken to improve the PES. The aim of the project was to determine the fish present ecological state using the FRAI model and compare the results with the Vaal WMA RQOs. This was achieved though the following objectives:

- To determine the variety and abundance of fish species in the Mooi River.
- To determine their response to physico-chemical, hydrology and geomorphology.
- To assess the fish integrity (category) of the Mooi River using FRAI and compare the results with the Vaal WMA RQOs.

Assessing macroinvertebrate response in the Mooi River catchment within an ecological water requirement framework – Ms Zafika Nyongo

Physico-chemical monitoring of water resources is the norm in pollution control and water quality management throughout the world (Palmer *et al*., 2004). According to DWAF (1996), general and special standards for a selected range of individual variables have to be met as end-of-pipe criteria. This method, however falls short because it is difficult to accurately model concentration-duration due to the time-intervals of collecting water samples. Patchy distribution of sites, and a limited range of variables analysed are some of the additional factors that can make physico-chemical monitoring incomplete.

One method to assess aquatic ecosystems is through biomonitoring. A lack of resources makes it impossible to analyse all physical and chemical constituents at once, and thus biological indicators are used. Macroinvertebrates have their own unique environmental requirements and a change in water quality variables and in the extent of pollution will have a positive or negative influence on taxa, depending on the sensitivity of the organism (Dallas and Day, 2004). This characteristic makes macroinvertebrates an indispensable component of any resource directed study associated with mining activities (Venter et al*.,* 2013). Most rivers in the North West Province have been found to be impacted by human activities (DWS, 2014; RHP, 2007b), including the Mooi River catchment. The RQOs for the Upper Vaal (Mooi River catchment) state that in terms of water quality, nutrients and salts must be decreased for ecosystem condition and that the river must not be toxic to aquatic organisms (DWS, 2005). The Mooi River catchment area forms part of the Upper Vaal water management area. The catchment has been the sole water source for Potchefstroom since 1842 (Van der Walt et al., 2002). The area includes polluted areas such as the far West-Rand of Gauteng Province, where the Wonderfonteinspruit tributary originates, contributing pollutants associated with mining activities (Venter et al*.,* 2013). According to the Department of Water and Sanitation (2014), informal settlements, agricultural activities and dysfunctional sewage treatment plants are also some of the pollution sources and are partly responsible for the increased nitrogen and phosphate levels in the catchment. Therefore, the aim of this study was to conduct an assessment on the aquatic macroinvertebrates in the Mooi River catchment using ecological water requirement methodologies. This was achieved through the following objectives:

- Determining the Macroinvertebrate Response Assessment Index (MIRAI) (Thirion, 2007) using data from detailed aquatic biodiversity surveys from 2014-2016.
- Integrating the MIRAI results within a wider EWR framework and assessing the impact of scenarios on the MIRAI.
- Analyse functional macroinvertebrate community characteristics (described by biological traits and categories).

Using riparian and wetland vegetation responses in the Mooi River catchment within the RDM process – Ms Joyce Ngobele

Life history characteristics of plants can have an important effect on the trajectory of a riparian primary succession. Initial colonization of bare sediment in riparian environments is accomplished primarily through a combination of wind and water dispersal, although animal dispersal may bring a more diverse set of propagates to a site over time (Kalliola et al., 1991, Galatowitsch et al., 1999). Soil seed banks contribute to vegetation dynamics along lake or reservoir shore lines and along margins of confined rivers (Keddy and Reznicek, 1986).

Throughout the world, riparian habitats have been dramatically modified from their natural conditions because of the array of ecological goods and services provided by the natural riparian ecosystems (Naima and Decamps, 1997), also due to frequent and intense disturbances of the ecosystems either naturally or human influences. Therefore, their conservation and restoration have become the focus of many land and water managers and conservation authorities. Riparian vegetation can stabilize sediments in former reservoir pools, perhaps also reducing down-stream sediment transport that can harm aquatic ecosystems (Bednarek, 2001). Riparian species vary in their tolerance levels of high sedimentation rates (Hupp, 1998).

The changes and disturbances of the riparian vegetation, such as human influences, invasive alien plants and environmental changes, create problems for the conservation of the system. In most cases, riparian vegetation is now threatened due to irrigation farming along the river, reduced flow by the construction of dams and livestock. Riparian vegetation is sometimes affected by fluvial processes such as flooding and deposition of alluvial soil, which typically support a distinctive flora that differs in structure and functions from adjacent terrestrial vegetation (Gregory et al., 1991; Naiman et al., 1993; 2005; Tang and Montgomery, 1995; Prach et al., 1996, Naiman and Decamps, 1997).

Other scholars have indicated that urbanization is one of the drastic and dynamic global human alterations of ecosystems (Grimm et al., 2001, Pickett et al., 2001). It has found to have some drastic effects on the ecology of the riparian area because it changes the hydrological conditions, which could lead to hydrological drought by lowering of the water table which in turn lowers soil, vegetation and pollutants functions. Grimm et al. (2001) mentioned riparian zones are sources rather than sinks for nitrate in urban watershed and are regarded as some foci for human nature interactions and can serve as catalysts for ecological and socio-economic revitalization in urban ecosystems.

Riparian vegetation fulfils or influences various important ecological functions in relation to aquatic habitats, such as reducing the impact of flooding on the surrounding areas, provision of food, moderation of stream water temperature through evapotranspiration and shading, providing a buffer zone that filters sediments and controls nutrients and stabilization of stream banks (Barling and Moore, 1994; Hood and Naiman, 2000). Riparian vegetation also provides a corridor for the movement of biota (Naiman and Decamps, 1997) and serves many important roles for humans because they can serve as a catalyst for ecological and socio-economic revitalization in ecosystem (Kemper, 2001).

The role of riparian vegetation for upland systems has recently received a little attention. However, there are different contributing factors that are negatively affecting the riparian vegetation, the floods of 2000 stripped most the riparian vegetation in rivers and transformed most of the highly dense vegetation to a sparsely vegetated state (Parsons et al., 2006, Parsons et al., 2007). Though there are other factors that are contributing to the transformation of the riparian vegetation such as anthropogenic activities, grazing and browsing, animal footpaths, alien invasive plant species and any other environmental condition, the transformation during the 2000 flood in South Africa more especially in the Sabie River in Kruger National Park, was more intense than any other environmental change (i.e. alteration of certain vegetation structures) observed in the last two decades (Parsons et al., 2006, Parsons et al., 2007) It was further mentioned that the flood caused an environmental damage of approximately R73 millions of damage within the Kruger National Park (Dept. of Public Works, 2000).

Subsequently, transformation on riparian vegetation should be investigated accurately to determine the root course because riparian vegetation such as reeds and other herbaceous species form part of the integral part of the ecosystems, which act as pioneering species which create a suitable environment for the establishment of trees and other plant species (Van Niekerk and Heritage, 1993). Tremendous research undertaken in the last two decades have focused on the role of riparian vegetation as a source of energy and matter for the aquatic vegetation (Hynes, 1995, Decamps, 1984; Naiman and Decamps, 1997). Riparian vegetation can control and regulate allochthonous inputs from the upland drainage basin and the river itself (Schlosser and Karr, 1981; Brinson et al., 1984; Peter John and Correll, 1984).

However, the Mooi River has very little information in relation to riparian vegetation changes. Therefore, this study investigated the present ecological status of riparian vegetation, riparian vegetation changes or responses and implications towards the Resource Directed Measures processes (RDM) in the Mooi River catchment. Therefore, a thorough investigation to determine the present ecological status of the Mooi River catchment was required. Thus the aim of the project was to determine the present ecological status of the riparian vegetation in comparison to the reference condition. This aim was achieved with the following objectives:

- To determine present ecological status of the riparian vegetation in comparison with reference conditions.
- To map, assess and analyse trends of Riparian Vegetation changes for the past years.
- To rank, rate and weight Riparian Vegetation changes.
- To quantify and compare the magnitude of changes between the reference conditions and present ecological conditions.

Quantification of the impacts of pollution on the water resources within the Mooi River Catchment – Ms Xolile Dube

South Africa is a water scarce country with many water resources drying out as a result of climate and mismanagement. Very little rains are experienced in most parts of the country leaving many rivers dry thus affecting livelihoods since in most cases rains are the sources for rivers. Today there are many cities worldwide facing water shortages. Industries and the agricultural sector depend on water for their processes (Halder and Islam 2015). It is estimated that the demand for water in South Africa will be more than the available natural supply in the 21st century (Ncube, 2015).

The Mooi River Catchment is known to provide farmers with water for irrigation, for mining activities and other agricultural purposes, wastewater discharges do take place in tributaries of the Mooi River and the same resource is being used for drinking water purposes by communities located within the study area. There are a number of human activities that result into poor water quality. The issues are mainly the impacts on water quality by the metal concentration from the mines, the nutrients from the farmers and wastewater discharges. Treated wastewater can pose risk to the environment and to human health (LaBrie, 2016). Harwood et al. (2000) mentions the faecal pollution from the non-human and human sources as one of the major contributing factors towards the degradation of water quality in both developed and developing countries.

Many studies have revealed that South Africa’s rivers are continuing to deteriorate in terms of quality and quality. The Water Research Commission indicated at the Implementing Environmental Water Allocation Conference in Port Elizabeth that some rivers in South Africa show a huge decline in water quality (SAPA, 2009). One of the major water quality issues associated with the wastewater treatment plants and their discharges is the release of high concentrations of nutrients, nitrogen and phosphorus (LaBrie, 2016). These nutrients are known for their serious eutrophication effects in water resources. Another potential threat to water quality is the presence of metal contaminants in the treated effluent (LaBrie, 2016), as well as emerging pollutants of concern. The following research questions were identified for this project:

The main aim of the study was to determine if there are potential impacts on the water quality of the Mooi River Catchment due to the sewage treatment plants. The objectives identified to achieve the aim were to:

- To determine the effects of discharged treated water on the physico-chemical and microbial characteristics of Mooi River and its tributaries.
- To determine the impacts of potential pollution on the suitability of water for drinking purposes.
- To determine the extent of change in water quality from 2015 to 2018 at a single historical water quality monitoring station of the Mooi River

<u>Investigating the value of water in the Mooi-River catchment – Carl Schoeman</u>

A number of socio-economic challenges is prevalent in the world (Taylor and Buttel, 1992) as well as in South Africa which ultimately impacts upon exploitation of natural resources and sustainable development (Ostrom, 1999). A global challenge exists in sustainably managing water resources along with continued economic growth (Cohen, 2006). This challenge is addressed in developed countries through the setting of regulatory requirements to tax the use of or impacting of water resources. This regulatory process enables the generation of tax revenue, which is then applied to sustainably managing water use, impacts and further ensuring sustainable economic development can continue (Maila et al., 2018). In developing countries, this approach however is not very successful due to weak economies leading to low income for sustainable development.

South Africa, as a water scarce, developing country, has taken note of the potential impact on sustainable water resource use and has followed suite in setting regulatory requirements to enable a fiscal management approach for water resources management in an effort to address these (Pillay, 2001). A weak economy has however prevented the approach from being successful and has led to an ever-increasing debt incurred by the South African government. This results in under-spending in the water sector, which in turn ultimately leads to environmental degradation, which must then be rectified by the government (or costs passed on to water users). An investigation towards alternative management measures is required to firstly ensure that environmental impact making actions are internalised into the economy, and secondly that socio-economic challenges in South Africa are simultaneously addressed.

As South Africa is a country still developing (Kinzig et al., 2013), the exploitation of natural resource is the main driver of the economy and this poses a challenge of developing sustainably. Policy and decision makers in South Africa have set goals towards economic growth and protection of natural resources to enable sustainable development for the country (Kinzig et al., 2013). A fine balance is required between development and protection of resources and this poses another challenge based upon legislation for the protection and exploitation of water resources.

An investigation of the current management practices should be undertaken (Core-econ.org, 2017) to gain insight and simplify these for more practical implementation. Firstly, focus must be placed on decisions affecting the water resources in terms of the marginal costs and marginal benefits (Roach et al., 2015). For example, the choice is not to be made between having clean or polluted drinking water but rather between the levels of pollution that can be accepted in terms of the required or expected use of the water resource. A way in which to address this is by comparing the expected financial fiscal costs with the financial benefit of exploitation. Secondly, to determine the required outcome (Dreze and Stem, 1987) to ascertain the required actions to reach the desired outcome. This however requires a value to be placed on environmental aspects such as protection, utilisation and development (Pearce, 2001). The evaluation and financial cost estimating process is however complicated as no generally accepted market price is readily available on environmental goods even though it has been attempted (Costanza et al., 1998). The determination of a monetary value is further complicated when social realities are considered, i.e. the allocation of resources (efficiency) versus the distribution of income (equity) from using these resources and the process to determine it (Moynihan and Titley, 2000).

Legislative policies must consider the manner in which the various groups will be impacted on (Dreze and Stem, 1987); how the current use will affect future generations or how it will affect greater community including neighbouring countries or the global community. Therefore, the study of applied socio-economic principles is required in South Africa in order to understand and effectively guide the development and management of natural resources in a sustainable manner (DEA, 2011). It must be considered that the outcome obtained might not be desirable for all communities (Social Affairs. and United Nations / Department of Economic., 2013), for example the redistribution or allocation of water usage rights and that this could pose a further challenge on managing environmental resources.

The Water Pricing Strategy for South Africa makes provision for water not subjected to pricing, which includes water usage for permissible use, basic human needs, ecological sustainability and international obligations (Pricing Strategy). It further provides for funding of water resource management. Even though the pricing strategy is in place, the exact financial cost of water supply and use is not accurately considered in South Africa.

Water usage and flow data is reasonably available and therefore a financial value can be applied to the movement of water through a system. The system considered in this research will be the Mooi River catchment with the aim of determining the financial cost of water and further considerations required for informing catchment planning, management and policy setting. Recently, a report published for the Water Research Commission (Maila et al., 2018) has set forth an approach to determine the financial accounting of the Water Management Areas (WMA). The aim of the report, as simplified, was to develop an accounting framework from where further comprehension of water accounts could be gained and maintained in order to influence water resources management.

The Mooi River catchment is home to a number of water use activities which require management in terms of the National Water Act. Water use charges for these activities are set in accordance with the Pricing Strategy as set out by DWS. The Pricing Strategy provides a framework from where the use of water resources could be charged for on a formal basis. This includes the use of water resources, be it natural or from government distribution systems, the cost of supply and management thereof. The Pricing Strategy however does not take into account, by setting the charge for water use, the actual cost of water as a whole through the requirements of maintaining and replacing distribution and treatment infrastructure. Further does not account for the water quality and quantity and how this should in essence affect the value allocated to water usage. The Mooi River catchment and water resource related transactions will be investigated in this case study to review the possibility of incorporating the aspects not taken into account by the Pricing strategy into the decision-making process. No research formally addresses the estimation of the value and actual cost of water in the Mooi River Catchment.

The aim of the investigative research was to estimate the value of water in the Mooi River Catchment based upon a number of variables affecting the perceived valued. Further to review the aspects affecting the value to set a business case for a cost benefit analysis. The following objectives were set for the proposal.

- Baseline assessment of the catchment to characterise the local water economy.

- Development of a water resource benefits balance to detail water transactions.
- Describe the value of water transactions in a structured manner.
- Analyse the water transactions through an appropriate risk assessment methodology.
- Make recommendations on management implications based on the findings.

A critical perspective of Ecological Water Requirement (EWR) governance within the Mooi River Catchment – Ms Lethabo Ramashala (DWS)

The world is growing in awareness that fresh water supplies are vulnerable to human activities and that water resources need to be managed in an integrated and systematic manner to ensure that they can continue to meet the current and future needs (Falkenmark, 1989; Biswas, 1993; Gleick, 2000). A decade after the Integrated Water Resources Management (IWRM) approach, it is clear that the full potential of IWRM have not yet being realized. Ecological Water Requirement (EWR) is one of the components within the IWRM and needs to be protected to ensure sustainable economic value, goods and services. Due to its complexity as a result of different stressors, the Mooi River catchment needs proper EWR governance which seems to be lacking. This could be attributed amongst other, to inadequate attention being paid to ensuring that appropriate governance systems are in place. There appears to be differences in the understanding of what constitutes good governance (Schreiner and Hassan, 2011; WWC, 2000). For example, the lack of consensus on a guiding ethic for water policy has led to fragmented policies and incremental changes which do not benefit anyone (Gleick, 2000).

South Africa, like any other developing country advocates for IWRM, however, it took a long time after the drafting of the Constitution before the integrated management of water resources could be initiated and realised. Since South Africa is semi-arid and experiences increasing variability in droughts and flooding events, due to climate change, it is important to have strong and well-functioning governance arrangements. For example, the governance and decision-making around water quality and quantity, as important components of EWR, becomes particularly important. Anecdotal evidence suggests the following governance challenges facing EWR as part of IWRM in South Africa:

- Fragmented and uncoordinated decision-making between spheres and within government.

- Complexities between DWS, Water Institutions, Local Government, Provincial and Districts municipalities.
- Confusing / unclear mandates between DWS (NWA) and Local Government (By laws) as well as Catchment Management Agencies (CMAs)
- Varying interpretations of mandates.
- Overlapping mandates.
- Gaps in mandates (Agricultural activities such as piggeries).

The above governance challenges vary in different catchments. A particular catchment where serious water governance challenges exist is the Mooi River Catchment. For this reason, this catchment provides an ideal case study for exploring governance challenges related to EWR. Based on its dolomitic formations which hinders development due to fear of sink holes and historic mining liabilities such as the Acid Mine Drainage and mine water decant. In order to address the latter problem statement, the following research questions were set:

a) Main research question: What are the main challenges for governance of EWRs in the Mooi River Catchment (Chapter 5)?
b) Sub-research questions:
    - What is the current governance mandate related to EWR as described in policy and legislation (theoretical framework based on literature review – Chapter 3)?
    - What are the views of different stakeholders in the Mooi River Catchment on the challenges for EWR governance mandate (testing the theoretical framework through interviews – Chapter 4)?

<u>The effect of illegal dumping on surface water quality using diatoms as a bioindicator – Ms Kelly Lourens</u>

Illegal dumping is not just a local environmental problem in South Africa but a problem worldwide (Abel, 2014). The effects caused by illegal dumping are not only limited to where the location of the dumping is, but extends rather to a much greater footprint (Abel, 2014). Some of the effects caused by illegal dumping include health, social, environmental and economic impacts (Abel, 2014; Brandt, 2017). The current local governing by-laws on illegal dumping were found to be highly fragmented and out-dated and are very seldom properly enforced by the local municipalities (Abel, 2014). There is a great need for these by-laws to be updated and properly enforced and for raising public awareness on the seriousness of the risks and penalties associated with illegal dumping, such as fines and/or even imprisonment for those found guilty (Abel, 2014).

As the human population increases, the consumption levels increase which places considerable pressure on the waste management services of the country, resulting in a lack of municipal service delivery in certain areas, which contributes to the increase in events of illegal, dumping. Studies have shown that illegal dumping is more common in the rural communities where there is very limited access to basic services such as potable water, sanitation services and municipal waste collection (Mihai et al., 2015). This study aims to assess the impact that illegal dumping has on the water quality, through the use of diatoms as a bioindicator of the health of the aquatic ecosystem. This study also aims to identify the current gaps found within the waste management legislation regulating these activities. Diatoms are as primary producers that play a significant ecological role in the aquatic ecosystems with their dynamic position at the bottom of the trophic food web (Dalu and Froneman, 2016). Their specific environmental requirements make them sensitive to any change within an environment and therefore they are regularly used in aquatic studies to assess the anthropogenic impacts and the ecosystem health of the aquatic system (Dalu and Froneman, 2016). The study will be conducted at several surface water bodies within the Ikageng and Promosa suburbs of Potchefstroom in the North-West Province of South Africa. These water bodies form part of a larger drainage system which drains into the Mooi River which is a very important water resource as it is the only water supply of Potchefstroom (Van der Walt et al*.,* 2002). These surface water bodies play an important role in these suburbs as these waters are used by the surrounding community for growing their crops, fishing and in certain areas even used as drinking water.

This study aimed to assess the impact that illegal dumping has on the surface water quality by using diatoms as a bioindicator. The following objectives were identified for the project:

- To compare the results from the physical and chemical water quality variables measured for each site.
- To determine the change in the diversity of the diatom communities at each site sampled as an indicator of the change in the water quality due to the illegal dumping present at each site.

- To assess whether the illegal dumping within Ikageng and Promosa area has an impact on the water quality within the area of which the community is dependant.
- To review and identify the gaps within the waste management legislation regulating these activities.

<u>Identification of flood risks and their implications for insurance companies: A case study of Potchefstroom, South Africa – Ms Lethabo Maebana</u>

In terms of mortality and economic damages floods account for destruction and damage of approximately a third of disasters originating from natural hazards (Kok and Barendregt, 2004). Anthropogenic activities that may lead to increased flood risks are; intensified land-use, river regulation measures and the emissions of greenhouse gases which results in the changing of the global climate. According to Hung and Hwang (2003), flood trend analyses has shown that significant floods and associated disasters and losses increased significantly over the past decades, a trend expected to further increase in frequency and severity in future.

Potchefstroom is a town located on the periphery of the North West Province of South Africa and is mainly drained by two tributaries of the Vaal River, namely, the Loopspruit and the Mooi River (Annandale and Nealer, 2011). The Mooi River is a perennial river which is led by several strong dolomitic springs and is regarded as the most significant water resource for the town. The town of Potchefstroom's drinking water is mainly abstracted from the Boskop Dam which forms part of the Mooi River catchment (Annandale and Nealer, 2011). The rainfall in Potchefstroom is erratic with a mean annual rainfall of 600 mm per annum and most of the rainfall occurs from October to April. The least amount of rainfall with an average of 6 mm occurs in July and the most precipitation occurs in January with an average of 109 mm. The climatic conditions are comprised of hot summers and cool winters, with average daily temperatures of 29°C and 16°C respectively. (Weather Bureau, 1988).

Over the recent years, temperature changes and rainfall patterns have had significant effects on the intensity and the occurrence of disasters related to climate in the North West Province. Flooding, together with sewer flows, as a result of an increase in heavy precipitation events, are some of the effects that have indicated the climate sensitivity related to weather disasters (Climate Support Programme – Vulnerability Assessment

(Report for North West Province), 2015)). Although several studies have been undertaken around on the Potchefstroom area, which focused on the chemical-, biological and physical features (Barnard et al., 2013; Van der Walt et al., 2002; Venter et al., 2013), none of these studies have looked at the identification of flood risks their implications on insurance companies in Potchefstroom.

The main aim of this research was to identify flood risks and their implications for insurance companies in Potchefstroom. In order to achieve the main aim of the research the following objectives are defined:

- Determine the extent to which flood risks have been identified for Potchefstroom.
- Identify various sectors which are affected by floods in Potchefstroom.
- Investigate the local constraints flood risk impact on insurance.
- Make recommendations in improvement of the relationship between floodplain management authorities and the insurance industry

<u>Macro-invertebrate communities and water quality related to WWTW effluent in Gauteng – Mr Neal Neervoort</u>

South African domestic, industrial and commercial waste is treated by various wastewater treatment plants across South Africa. These wastewater treatment plants operate on a daily limit depending on the size and capacity of the plant. According to Snyman et al. (2006), more than half of the plants experience problems with flow balancing, secondary treatment, maturation ponds and chlorination. As the treated effluent from the water treatment plants are discharged in the receiving aquatic environment the water treatment plants should comply with certain water use licence conditions stipulated in the licence. The major sources of pollution include domestic and industrial wastewater discharges, mining, surface runoff and agrochemicals (Murray et al., 2005). The wastewater treatment plants monitor water quality on a daily basis which includes the chemical and biological indicators. Aquatic bio-monitoring is monitored on a seasonal basis to ensure that the effluent does not deteriorate the ecological state (EC) from the reference and/or resource quality objectives set out for the catchment. Tafangeyasha and Dube (2008) state that the SASS indices provides a better measurement of water quality since they integrated seasonal changes in rivers, whereas chemical analysis only reflect the condition of the river water at the time which the samples are taken. The aquatic bio-monitoring entails the use of the

SASS 5 method as per the River EcoStatus Monitoring Programme (REMP) to monitor the aquatic macro-invertebrate assemblage. Part of REMP is to monitor the habitat associated with macro-invertebrates present within an aquatic ecosystem. Based on the research done by Menezes et al. (2010), the habitat templet concept and using a species-abundance table as well as species-traits table, it is possible to obtain a functional image of the study system and detect pollution impact. Doledec et al. (1999) highlighted that an ideal biomonitoring tool – generic in terms of geographic application, specific in terms of stressor identification, reliable and derived from sound theoretical ecological concepts – is possible to obtain using benthic macroinvertebrate ecological and biological traits, as an alternative to the traditional taxonomy-based approaches. The question is that if adequate habitat is available for these macro organisms why is certain pollutant tolerant taxa more prevalent downstream of certain wastewater treatment works. Macroinvertebrate of the family Chironomidae and Tubificidae are considered to be tolerant to organic pollution (Wenn, 2008). The multi-variate approach will assist in taking the chemical water quality into consideration when looking at the macro-invertebrate assemblages to determine if certain taxa are more prevalent to certain water quality constituents (organics or inorganics) and if the constituents are due to a certain process used by the wastewater treatment works or due to problems experienced within the process.

The aim of this study was to assess the effect of wastewater treatment work effluent on macro-invertebrate community structures using a multi-variate statistical and trait-based approach. The objectives that were selected to achieve the aim included the following:

- Determine the water quality upstream and downstream of various wastewater treatment works in Gauteng.
- Determine the aquatic macro-invertebrate diversity upstream and downstream of various wastewater treatment works in Gauteng.
- Assess the impact of water quality on the macro-invertebrate communities using various multivariate and trait-based approaches.
- Determine if the water quality and macro-invertebrate assemblages are based on certain water treatment processes used at the different wastewater treatment works.

Feasibility study of the introduction of the grass carp, Ctenopharyngodon idella, into the Boskop Dam – Mr Louis Noemdoe

The Boskop Dam is situated in the North West Province, 20 kilometres outside Potchefstroom. It forms part of the relatively small (3000 hectares) Boskop Dam Nature Reserve. It was constructed in 1959 for domestic use and irrigation. The dam is an angling haven and also the primary source of drinking water supply to Potchefstroom. Over the years macrophytes (such as water grass) and reed growth had a diminishing effect on the capacity of this impoundment. The natural sediment build-up and the organic material from the land use upstream are the main contributing factors to the eutrophication. In order to stop the process, the grass carp (*Ctenopharyngodon idella* Val.) can be introduced as a biological weed controller. Introduction of a species must be carefully considered because it may have benevolent or malevolent consequences for the existing ecological state of the dam (McDowell, 1986; Vooren, 1972). Stott (1977) states four reasons for grass carp introduction into the United Kingdom (1) bringing in a plant-eating fish to reduce the growth of water plants, (2) to make use of plant material as a food resource, (3) addition of an active, fast growing species to the angling sport and (4) to use the fish as a biological weed control agent.

There are a few difficulties that has to be considered when the grass carp is introduced. Gulland (1971) reports on the conservatism of anglers. It is important to consider the view of anglers. In general, there is a risk of introducing parasites and diseases, especially infectious diseases, not common to the water body (Kennedy, 1975). Musselius and Strelkov (1986) discuss the trouble with a parasitic cestode, *Bothriocephalus gowkongensis*, in detail. On the other hand, the risk can be mitigated with artificial breeding of the grass carp (Stott, 1977). Species behave unpredictably if introduced in a foreign environment. Climatic conditions (Pentelow and Stott, 1965), increase in water temperature (Opuzynski, 1971) and diet change associated with growth (Shireman and Smith, 1983) and size determine grass carp appetite and plant selectivity (Cudmore and Mandrak, 2004). Apart from problems with natural breeding outside its native habitat, the extreme case of overgrazing may lead to unnecessary plant destruction (Dibble and Kovalenko, 2009). It is obvious that a rather unique form of eutrophication occurs in the Boskop Dam and that the remedy for it is not a simple one.

The aim of this study was to assess the feasibility of introducing the grass carp, *Ctenopharyngodon idella,* into the Boskop Dam as a biological control of aquatic weeds. The various objectives that were established to achieve this aim included:

- Evaluate three methods of removal of aquatic weeds from impoundments.
- Determine, with examples, what was done elsewhere to remedy the problem.
- Provide a biological synopsis of the grass carp and grass carp in South Africa.
- Determine the impact of grass carp introduction on the ecology and what special biota are there to protect.
- Speculate on the long term economic and ecological cost if there is no rehabilitation.

Impact of impoundments on the water quality in the Mooi River Catchment – Mr Senzo Nyembe

Wei et al. (2008) says that impoundments in the twentieth century emerged as one of most important, visible tools and infrastructure for management of water resources. These impoundments play a vital role in the economic and social development in areas they are located in. Large impoundments provide important services such as electricity generation, attenuation for industrial usage, recreational activities, ecological services and human consumption. Wei et al. (2008) further says impoundments play a vital role in water supply to communities and emphasizes the role impoundments play in flood control. Mao et al. (2005) studied the detailed effects on hydrodynamics and hydrological characteristics and nutrient transportation when dam projects are developed. Sulphide formations and anoxic conditions were observed in a newly developed dam in Greece by Albanakis et al. (2001). This clearly demonstrates that impoundments could affect the quality between upstream and downstream river reaches.

The Mooi River Catchment has four impoundments, namely Potchefstroom Dam, Boskop Dam, Klerkskraal Dam and Klipdrift Dam. The dams are located in the Upper Vaal Catchment in quaternary C23H, C23G, C23J and C23F respectively. Rivers that these dams are located onto are Mooi River, Wonderfonteinspruit and Loopspruit. The Mooi river catchment is characterised by several upland activities that have a direct impact on the water quality of the area. Mines are one of the key upstream activities. These activities discharge pollutants to the Wonderfonteinspruit which eventually feeds into the Mooi River. According to Venter et al. (2013), the Wonderfonteinspruit and the Boskop Dam are fed with polluted water originating from the mines. Coetzee et al. (2006) confirmed that Boskop Dam has a high mineral content coming from the mine effluents. Other upland activities that contributes to water quality ranges from petrol stations, airport, agriculture, sanitation, gypsum processing to hospitals and cemetery. Rodrigues and Pacheco (2003) concluded that cemeteries may contribute in the contamination of ground water. Watts and Torbet (2009) say that if Gypsum is found in soil it reduces soluble phosphorous and these impacts could be traced on ground water. These activities bring about various pollutants into the system. Wastewater treatment is found in almost all the four impoundments and this could be contributing more pollutants to the Mooi River Catchment. Moolman et al. (1999) emphasizes that waste disposal systems and sanitation puts pressure on water resources in areas where they are found. Magagula et al. (2006) says that not all wastewater treatment work functions optimally in this catchment and this results in levels of phosphorous inputs to the catchment being high.

The aim of the research was to determine the impact on water quality of the Klerkskraal Dam, Klipdrift Dam, Boskop Dam and Potchefstroom Dam on the Mooi River and the Loopspruit. The objectives that were set for this project were as follows:

- Determine the upland activities with their direct impact on water quality.
- Analyses of the dam inventory (i.e. biophysical analysis of each impoundment).
- Determine water quality upstream and downstream of each impoundment.
- Compare key changes in the physio-chemical water quality for each dam and downstream river reach.
- Determine whether the water quality is currently complying with the Resource Quality Objectives (RQO) for the catchment.

The impacts of irrigation by industrial effluent on the groundwater resource in Zwelitsha-King Williamstown, Eastern Cape – Ms Khathutshelo Ravele (DWS)

The clothing industry is the second largest polluter in the world, second only to oil. Textile mills generate one-fifth of the world's industrial water pollution and use 20,000 chemicals, many of them carcinogenic, to make clothes (CleanbyDesign, 2012). Da Gama Textiles is a large manufacturer of bleached, dyed and printed fabrics and it was constructed in 1946. The manufacturing facilities comprise a large single textile mill in Zwelitsha, King Williamstown, in the Eastern Cape Province. The company employs a diverse mix of manufacturing technologies including weaving, washing, bleaching, dyeing, printing, heat treatments and others, many of which require steam for their operation. Groundwater contamination is frequently associated with the use of wastewater from industrial sources such as Textile and Tanneries.

The greatest water quality problem in the Buffalo River catchment area is the discharge of effluent from wastewater treatment works and industries around Zwelitsha-King Williams Town. The Da Gama Textile factory has caused significant pollution of the Buffalo River, resulting in the widespread death of fish. This disaster occurred when holding dams over-flowed during periods of intense rain (CES, 2003). Several water quality issues in the Buffalo River basin have been investigated in previous studies. Reed and Thornton (1969) found that the major source (± 61%) of salinisation originates from natural geological weathering, while ±27% came from industrial origins (textile and tannery). Textile effluent contains high concentrations of water colorants, dissolved salts, organic wastes, insecticides, pesticides, chemical wastes, alkalis, sodium and detergents (Buckley et al*.,* 1983). The textile effluent at Da Gama is initially contained in evaporation ponds, and is then sprayed onto land adjacent to the Mlakalaka tributary, from which much of the effluent runs directly into the Buffalo River and infiltrate to the groundwater (O'Keeffe et al., 1996). The effect of the run-off from these irrigated lands has not been quantified. DWAF (1999) estimated that 88% of the salt load entering the river from other than natural sources originate from the factories.

Groundwater contaminated by textile effluents, has impact on agriculture irrigation, drinking utilities, soil and agricultural systems (Bharti, 2007). So, it is essential to assess the status of industrial effluent and distribution and dispersion of heavy metals in the environment of the vicinity of industrial area before discharging and to prevent and control of groundwater pollution. Water pollution due to the dyeing industry is the matter of great concern since large quantity of effluent is discharged into the water bodies. The dye effluent contaminates the surface and groundwater, thereby, making it unfit for irrigation and drinking (David and Ranjan, 2014). The dye effluent contains certain chemicals that could be toxic, carcinogenic or mutagenic to living organisms. Previous studies have demonstrated that wastewater irrigation does not only affect the quality but may decrease soil hydraulic conductivity and infiltration rate.

There are studies that have been done on the effects of industrial/textile wastewater on the nearby Buffalo River and not on the receiving groundwater resource (O'Keeffe et al., 1996). The main aim for this study was to determine the impacts of irrigation with industrial wastewater (Da Gama Textile) on the groundwater quality in Zwelitsha-King Williamstown. The objectives for this study was to:

- To investigate the historical and current water quality status of the surface water of the Buffalo River.
- To investigate the current industrial wastewater quality from the textile industry.
- To assess the influence of the industrial wastewater on the groundwater quality by comparing background water quality with the current water quality.

<u>Assessment of the extent of agricultural activities impact on the different water uses in Mooi River – Ms Lillian Siwelane (DWS)</u>

The Mooi River system currently faces a serious challenge due to anthropogenic activities such as agricultural activities and others (Venter et al., 2013). In the Northwest region where Mooi River is located, approximately 62% of surface water has been allocated to the Agricultural Sector, this water use generates surface runoff which contains pollutants such as pesticides, herbicides and other chemicals. These pollutants find its way into ground and surface water resources through point source and diffuse source discharges (Pelser, 2006). The headwaters of the Mooi River are at the northern parts of Potchefstroom close proximity of town of Koster and then flows southerly where it confluences with the Vaal River. The Mooi River runs through towns of Potchefstroom, Westonaria, Oberholzer, Fochville and Carletonville until it confluences with the Vaal River near the border of Free State, approximately 15 kilometres of Stilfontein.

The Mooi River catchment consist of three sub catchments namely the Wonderfonteinspruit (north eastern reach), Mooi River proper (northern reach) and Loopspruit (eastern reach). There are various dams along Mooi River and these are Donaldson, Klipdrift, Boskop and Potchefstroom dams. The Mooi River Catchment borders Gauteng Province in the upper section of West Rand and the lower part of the catchment is within the Northwest Province. According to the DWAF (2007), the upper reaches of the Mooi River Catchment is dominated by gold mining activities, comprising tailing dams, mine dumps, sand dumps and rock dumps which together contribute significantly to the poor water quality of this river system. Farming activities dominates the lower Wonderfonteinspruit, the Northern sub catchment is dominated by crop farming and cattle grazing, and the eastern subcatchment (Loopspruit) is dominated by crop farming and grazing lands.

Since the year 1842 Mooi River has been the sole supply of water for Potchefstroom town. From the late 1950's and early 1960's the quality of water has gradually deteriorated in the Boskop and Potchefstroom Dams which are known as the reservoirs for drinking water supply for Potchefstroom town and both dams are located within the Mooi River system (Van der Linde et al., 2002)

The citizens of Potchefstroom town are faced with a serious problem of bad taste in the water and most of them are resorting to buying bottled water and others are even installing water purification systems in their homes (Kankeu et al., 2016; Mulovhedzi, 2016). Several studies were conducted in the Mooi River and most of them are focusing on the impact of mining activities that are occurring in the area. Agriculture is one of the anthropogenic activity that is contributing to the deterioration of water quality in the Mooi River (Venter et al., 2013). According to Labuschagne (2017), agricultural activities run offs and abattoirs wastewater are some of main sources of organic pollution within the catchments of Mooi River (Van der Linde et al., 2002) study proposed a development of an integrated management plan which will assist in the filling the gaps in the knowledge and understanding of Mooi River. Furthermore, this writer recommended further studies which will gather more information on Mooi to assist in the quantification of pollution sources.

Recreational water uses are categorised into three groups namely, full contact (swimming and diving), intermediate contact (water skiing, canoeing, angling, paddling and wading) and non-contact (picnicking and hiking along water bodies DWAF (Department of Water Affairs and Forestry 1996). In the Mooi River catchment the Boskop Dam is known to be used for recreational and conservation activities by the surrounding communities, however due to the thick reeds that are growing along the banks of the dam shoreline angling is currently restricted (Department of Water and Sanitation 2015). Although the situation has a potential to restrict other secondary use of the dam to a point that the economic potential of the dam and access by the users may be compromised, Boskop Dam remain a well-known destination for recreational activities. Also within the Mooi River itself, Tlokwe (2010) reports that secondary activities such as angling and general recreational activities are widely undertaken by users. The aim of this study is therefore to provide insight into the extent of the impacts of agricultural activities on both domestic and recreational water uses in the Mooi River system and the environment.

The aim of this study was to quantify and determine the extent of the impact of agricultural activities mainly on domestic and recreational water use of the Mooi River. The objectives of the study were to:

- Analyse and compare the water quality trends in the Mooi River catchment with guidelines for domestic and recreational water use.
- Analyse the historical and current water quality trends and determine its compliance to resource quality objectives (RQO'S) with relevance to the different use components of the resource (i.e. domestic, recreational, aquatic environment).
- Investigate the types of recreational water use activities that are practiced within the Mooi River catchment.
- Recommend best practices for agricultural activities based on water quality guidelines.
- Recommend safe recreational activities which should be practiced within Mooi River catchment.

River flow response to change in climate in the Mooi River – Ms Nelisiwe Vilakazi (DWS)

Water resources, food security, health, infrastructure, together with its ecosystem services and biodiversity face a major risk in South Africa as a result of climate change (WIREs, 2014). This includes the Nama Karoo biome, the Indian Ocean coastal belt, the Fynbos biome, the Forest biome and the grassland biome (it's the biome most under threat due to climate change). The issue of food security due to impacts of climate change is largely becoming a cause of concern, not only in South Africa but in other parts of the world as well; this was also noted by Masipa (2017). The DEA (2017) mentions that South Africa is already experiencing serious effects of climate change in the agricultural sector and has resulted in increased agricultural produce prices and food shortages. WIDER (2016) further note that the risk of irrigation demand and runoff due to climate change significantly varies across South Africa; dry regions are expected to become drier and wet regions are expected to get wetter (flooding). The USAID (2016) also note that disasters associated with droughts, floods, and waterborne diseases are likely to increase due to increased variability in rainfall as a result of climate change. It is further mentioned that the achievement of economic development goals is compromised due to predicted increase in sea levels, floods and extreme heat events as this will damage infrastructure.

Quaternary C23H is within the Vaal Water Management Area; it is located in the North West Province in South Africa, with Potchefstroom as the main industrial hub. The catchment is 451 km^2 (WRC, 2018). The main river in C23H is the Mooi River with Potchefstroom Dam as its major impoundment with a full supply capacity of 2.03 Mm^3. Upstream of Potchefstroom Dam lies the Boskop Dam with a capacity of 21 Mm^3 which was built in 1959 to meet the need for increased water demand; it has canals on the left and right banks of Mooi River which transport water for agricultural supply (Annandale and Nealer, 2011). The City of Potchefstroom's water is stored and discharged from the Boskop Dam into a canal that is 12 km in length and transported to the city's purification plant which is located right next to the inflow of Mooi River to the Potchefstroom Dam. Upstream (5 km) of Boskop Dam is the Gerhard Minnebron Eye with a flow rate of 60-80 Mℓ per day; it is the largest natural spring in the Southern hemisphere (Annandale and Nealer, 2011). According to Van der Walt et al. (2002), from 1842, Mooi River has been the main source of raw water in Potchefstroom and the town has since been dependant on it.

DWAF (2002) noted that in C23H, agriculture accounts for most water use with 40% requirements for irrigation. With respect to the latter statement, it is of paramount to investigate how runoff of Mooi River responds to climate change as it is the main source of water in the catchment as this has the potential to affect food production and development. According to Manase (2010), most studies regarding the impacts of climate change have been conducted in developed countries while only a few have been conducted in developing countries, especially in Africa. He noted that South Africa is at risk of being affected by the extreme rainfall variability due to lack of sufficient knowledge on climate change, limited adaptation resources and incapacity to regulate river and stream flow. Developed countries on the other hand are less vulnerable yet investments are made to understand climate change and predicting its impact, including strategies for adaptation and mitigation. Literature has noted that there is no doubt that the availability and use of water resources in southern Africa will be impacted by climate change (Matondo et al., 2005; Yamba et al., 2011).

WIREs (2014) mentioned that mechanisms controlling inter annual and decadal variability studies have been the main focus of the South African Earth Systems Science (ESS) programme and recently, what the effects of climate change on these mechanisms would be. One report from the United States regarding climate change impacts, mentioned that comprehension of the global climate system is necessary for understanding changes in climate and their impacts. These causes and changes have been comprehensively documented in different reports by the US Climate Change Science Program and the Intergovernmental Panel on Climate Change (Karl et al., 2009). The United States has invested more than 20 billion dollars in global change and climate change research through the U.S. Global Change Research Program, making it the largest scientific investment in the world (USGCRP, 2009).

The aim of this study was to investigate the response of the Mooi River flow regime to changing climatic patterns. The objectives of the study were to:

- Gather river flow data, rainfall data and temperature data from the Mooi River catchment from as far back as data is available
- Analyse river flow, rainfall and temperature trends at various flow gauging stations
- Compare river flow trends with temperature and rainfall trends

<u>Quantification of the impacts of mining (including tailings) on the groundwater resources of the Mooi River Catchment – Ms Kulanyane Maponya (DWS)</u>

The Mooi River catchment in particular the Wonderfonteinspruit (WFS) has been the subject of a larger number of studies regarding significant pollution sources, generally attributed to mining in the area (Barnard et al., 2012). The principle aquifer under consideration is the dolomitic aquifer of the Malmani subgroup which has been compartmentalised by several north-south trending syenite dykes of Pilanesberg age (Hodgson et al., 2001). Groundwater moves rapidly in large volumes through large solution cavities in the dolomites. This groundwater flow, along with the Wonderfonteinspruit, forms a continuous link between the mining areas. These areas may warrant special protection due to the very valuable groundwater resource that they contain. Due to the dolomites which occur across the area, problems have been experienced with water in the mines. Consequently, the mines pump out large volumes of water from the compartments to dewater the dolomites. Enslin et al. (1967) showed that rainfall recharge of the system was equal to the average annual flow of springs issuing from the dolomite. Mine waste disposal has allowed significant leachate to infiltrate the dolomite. In some mines, it will discharge into the karst aquifer thus adding an additional pollution load. Water polluted by leachate from mine dumps, so called acid mine drainage, shows characteristically high sulphate concentration and high dissolved salts (Hodgson et al., 2001). This relationship and high recharge of groundwater from surface streams are relatively unique in this area and are due to the karst topography (Hodgson et al., 2001). The Boskop Dam, the receiving water body for the Wonderfonteinspruit, shows deteriorating quality (Barnard et al., 2012). Conditions exist for uranium to be transported in solution in these waters (Winde, 2010).

The dolomites of the Far West Rand comprise one of South Africa's most important groundwater resources. This study addresses the impact of mining and tailings on the groundwater resource of the Mooi River Catchment by utilization of three case studies the decanting of karst aquifers, the uranium pollution and the recharge of voids leading to the acid mine drainage that will discharge into the Mooi River Catchment. In light of the problem statement project aimed to address the following research question: To what extent are the impacts of mining and tailings evident on the groundwater resources of the Mooi River Catchment?

Evaluating the Implementation of Diatom Indices in the River EcoStatus Monitoring Programme and Testing the Method in the Mooi River – Ms Nobubele Boniwe (DWS)

The National Water Act recognises that water is a scarce and valuable resource and that water resources should be managed in a sustainable manner. In order to effectively manage water resources, proper monitoring is required and Section 137 of the National Water Act (Act 36 of 1998) mandates the establishment of national monitoring systems (DWAF, 1998).

The Department of Water and Sanitation being the custodian of water resources in the country established a biomonitoring programme called the River Health Programme (RHP) which is currently known as the River EcoStatus Monitoring Programme (REMP). The programme formed part of the National Aquatic Ecosystem Health Monitoring Programme (NAEHMP) that was designed to monitor and report on the ecological health of the river ecosystems of the country (Hohls, 1996). The development and design of the programme was established at the national level and the actual implementation was intended to take place at the provincial or regional level. The implementation manual with detailed description of procedures to be followed in assessing and monitoring river ecosystems was developed (DWAF, 2008). The monitoring programme intended to make use of biological organisms such as the macro-invertebrates, riparian vegetation, fish and diatoms as indicators of the water quality of the river ecosystems instead of directly measuring the water quality variables. The biological organisms in a river ecosystem are more exposed to all water quality variables found in a system and can therefore give an indication of the health or ecological status of that system (DWAF, 2008).

The diatoms when compared to other bio-indicators respond rapidly and can accurately highlight water quality changes (De La Rey et al., 2008). The application of diatom indices was regarded as challenging and it did not straight away form part of the national biomonitoring programme (Taylor *et at*., 2007c). Later, there were conducted studies examining the effectiveness of diatom-based indices in assessing the water quality or ecological status of river ecosystems. Taylor et al. (2007b) investigated the effectiveness of indices that were established in other countries in determining the water quality of the Vaal and Wilge Rivers. The Specific Pollution Sensitivity Index, Biological Diatom Index, Generic Diatom Index and Eutrophication and Pollution Index showed a high correlation with measured physico-chemical variables. It was proven that the indices were suitable for indicating water quality changes and can be used in most water resources of the country.

The standardised method for collecting, slide preparation and analysis of diatoms was formally described and documented (Taylor et al., 2007a). The effectiveness of indices was also assessed in the river ecosystems of the Crocodile West and Marico Water Management Area and they were proven useful in reflecting the water quality and were recommended to form part of the national biomonitoring programme (Taylor et al., 2007c). The application of diatom based indices for biomonitoring was further proven to be useful even in semi-arid areas (Holmes and Taylor, 2015). Later, Harding and Taylor (2011) developed the South African Diatom Index which included endemic diatom species that were not recognised by the indices of other countries. The development of the index elevated level of accuracy in water quality assessments.

One of the challenges affecting the application of the diatom-based indices was lack of capacity and training due to limiting financial resources (Dalu and Froneman, 2016). Despite the challenges diatoms remain indisputably good indicators of water quality. However, from the time they were introduced in the biomonitoring programme till now there's still uncertainty in terms of the extent to which the indices have been utilised. The implementation plan was clear but the actual implementation of diatom indices to ensure integrated results remains unclear.

The aim of the study was to evaluate the implementation of the diatom-based indices in the REMP and furthermore to test the method in the Mooi River. In order to achieve this aim, the following objectives was identified:

- Review the application of existing diatom-based indices.
- Review the implementation of diatom-based indices in the national REMP.
- Application of the diatom-based indices in the Mooi River National REMP site (field testing).

2.3 Water related skills development

The project used the existing curriculum for EWR (Wepener, 2016) and implemented that within an academic framework to develop and increase human resources capacity within the water resources management sector in South Africa. In addition, the students were mentored by industry professionals during the various modules in the Masters course to increase their knowledge as well as their network. The masters course also allowed networking with their peers that were attending the coursework. The two modules (Management of Ecological Drivers in Aquatic Systems and Management of Ecological Responders in Aquatic Systems) provided foundational knowledge that will allow the students to compete and excel within the water sector in South Africa. In brief the outcome skills that the students were measured against were as follows:

- Demonstrate specialist knowledge and understanding to engage with and critique research and practices relating to global and national perspectives on environmental and sustainability challenges; including all relevant environmental management and governance instruments.
- The ability to evaluate current processes of knowledge production in relation to ecological water requirements and to choose appropriate processes of enquiry for the area of specialisation.
- A command of relevant methods and procedures required to solve practical and theoretical problems related to ecological water requirements and specifically ecological drivers in aquatic systems.
- The ability to address complex and challenging problems in relation to ecological water requirements and ecological drivers in aquatic systems, and to understand and contextualise their findings.

- Demonstrate the ability to operate within the ethical requirements of water management and governance.
- Demonstrate the ability to access, process and manage information related to ecological water requirements and to communicate their findings in academically appropriate ways.
- Candidates exhibit the potential to act as leaders and experts in the field of water management and governance.
- Self-regulated learning and responsibility for academic and professional development with cognisance of their ethical responsibility.

In presenting this masters course at North-West University, there has been 38 students admitted to the program (19-funded by this project). Since its inception, 12 have already graduated with their degrees while a further eight should graduate by March 2020. However, one of the concerns with the program has been that there has been little uptake of Department of Water and Sanitation employees in this training programme. It is only approximately 33% of students that are from DWS while the other 66% is made up out of consultants, other government departments and semi-government companies such as Joburg Water and Randwater. It is especially unfortunate since the curriculum was created with the continued development and education of DWS employees as a main driver for the content.

The Masters in Environmental Management in Ecological Water Requirements are now firmly entrenched within the Masters programs that the Unit for Environmental Sciences and Management at the North-West University are presenting. The information generated from this current project has also been incorporated within the course content and in future will potentially drive EWR research in South Africa. An overview of these master's courses can be found at the following links:

- Overview video: https://www.youtube.com/watch?v=9OWR-EX-Q8A
- Brochures: http://natural-sciences.nwu.ac.za/unit-environmental-sciences-and-management/environmental-management

3 LITERATURE REVIEW – ECOLOGICAL WATER REQUIREMENT

3.1 Existing methods of EWR

3.1.1 Methods for different aquatic ecosystems:

Water resources in South Africa are mainly comprised of wetlands, rivers, estuaries, and groundwater. As each of these systems function differently and comprises of different ecosystem components, different methods for assessment of the EWR had to be developed and used for each. Table 1 provides a summary of the major determinants for each water resource type.

Table 1: Type of water resource and the main determinants of each of the water resources.

Type of water resource	Main determinants
Rivers	Flow
Lakes	Water level
Wetlands	Persistence of surface water and water level; soil water (especially seeps), i.e. hydropedology
Groundwater	Water level, outflow, and rate of recharge
Estuaries	Flows for maintenance of salinity gradient, inflow requirements, and mouth condition

The following documents are the main reference/s for each ecosystem type for the EWR methods used in South Africa:

<u>Rivers</u>: DWAF (2008), DWAF (1999), DWAF (2003), Hughes (2004), Hughes and Louw (2010), King and Pienaar (2011), Griffin et al. (2014).

<u>Wetlands</u>: Rountree et al. (2012) = only used for Rapid Reserves and specific wetland types. More work is needed to undertake targeted EWR studies on wetlands.

<u>Estuaries</u>: Adams (2012); DWAF (2008). DWAF (2010)

<u>Groundwater</u>: DWAF (1999); Flanagan et al. (2006); Parsons and Wentzel (2006).

3.1.2 Basic tasks of an Ecological Water Requirement Study

There are a few basic steps or tasks that are required to complete an Ecological Water Requirement study. This information is based on the proposed structure by O'Keefe (2009). The different tasks are presented in Table 2 below:

Table 2: Basic tasks for specialists in different disciplines that should be completed during an environmental flow assessment and implementation (O'Keefe, 2009).

<u>Stage A: Scoping</u> Assess the area of interest, to try to identify issues of particular importance, and to draw up an initial plan for the assessment.
STAGE B: PREPARATION FOR THE ASSESSMENT WORKSHOP **Task 1: Initiate EWR assessment (level of detail, define methodology, appointment of the specialist team)** **Task 2: Zone the study area** Identify reaches of the study river in which physical and ecological conditions are likely to be similar **Task 3: Habitat integrity** Assess the condition of the area of interest by classifying sections of the river in terms of how much they have been modified from natural conditions. **Task 4: Site selection** Select sites within the study area for detailed analysis based on: ease of accessibility; habitat diversity; sensitivity of habitats to flow changes; suitability for modelling; proximity to a flow gauging site; representation of conditions in the river zone; and critical flow locations. **Task 5: Surveys and measurements** These surveys are intended to augment information and fill in gaps that have not been covered in previous studies: • ***Biological surveys* –** To identify flow-sensitive species and define their seasonal habitat requirements in terms of current velocity, depth, substrate type and wetted perimeter. • ***Hydraulic survey and analysis* –** To provide the link between ecological habitat requirements and flows. • ***Hydrological analysis* –** To check that the recommended flows are within reasonable limits of flows experienced in the river, and is therefore a check on the realism of the process, rather than a motivation for recommended flows. • ***Geomorphological survey* –** To assess the sources and types of sediment in the river, analyse the channel morphology in terms of the geomorphic features and their stability, and predict the consequences of changing flows on the sediment input-output and therefore the channel shape and substrate types.

- ***Water quality analysis –*** To assess possible problems related to flow modification and to identify point and diffuse runoff impacts.
- ***Social survey –*** (1) To identify people who are directly dependent on a healthy riverine ecosystem (e.g. subsistence fishermen, farmers, withdrawers of domestic water, and anglers) and (2) to consult with all stakeholders and identify preferences for the management objectives for the river.

Task 6: Ecological and social importance and sensitivity

Define the priority of the area of interest from an ecological perspective (e.g. number of sensitive and rare species, the resilience of the system to human disturbance, importance as a migration route).

Task 7: Define reference conditions

Define the reference (usually natural, unmodified) physical, chemical and ecological conditions as a baseline against which to judge how much the river has been modified.

Task 8: Define present ecological status

Define present ecological, physical, chemical and ecological status based on available data and expert judgement.

Task 9: Define environmental objectives

Define the most appropriate environmental objectives given the nature of the system, and priority uses.

STAGE C: EWR WORKSHOP

Decide upon flow recommendations (including wet and dry season base flows, and floods) using inputs from all of the specialists. Decisions should be made considering all of the identified environmental objectives.

STAGE D: NEGOTIATION

Task 1: Hydrological yield analysis

Calculate the likelihood of being able to maintain the environmental flows and supply the user needs, in wet and dry years.

Task 2: Scenario analysis

Provide the basis for negotiations and decisions where there is insufficient water to meet all requirements.

Task 3: Decision

STAGE E: IMPLEMENTATION AND COMPLIANCE MONITORING

This culminating step in the process lasts indefinitely. Methods of implementation depend on the availability of storage structures, inter-basin transfers, or potential for demand management on any specific river. Initiate long-term monitoring and refinement of flow requirements.

3.1.3 Methods and levels of confidence

The level of the EWR and confidence required for the catchment will determine what methods will be used as well as the confidence of the study. In catchments where the EIS is low, the socio-economic importance is low as well as little threat for future use, a low confidence study would be acceptable. However, in catchments with high EIS and socio-economic importance and large proposed developments, a high confidence EWR is required. This will also determine what the data requirements of the specific study will be. A Reserve or EWR study can range from a desktop assessment to a comprehensive assessment (Table 3). The duration will be from a day for the desktop to two years for the comprehensive assessment that will result in a very low to medium – high confidence level respectively. It has to be noted that in practice, time and funding play a significant role in the confidence and method used within EWR determinations.

Table 3: Methods and level of confidence for Reserve Determinations

Method	Hydrological Requirement	Duration	Indication of possible confidence
Desktop	WR90	1 day	Very Low
Rapid	Site specific monthly data	2 days	Low
Intermediate	Daily data	12-24 weeks	Low-Medium
Comprehensive	Daily data	12-24 months	Medium to High

Irrespective of the level of the assessment, there are general minimum data requirements for each of the various components that will be included in the assessment. A summary of these data requirements are provided in Table 4.

Table 4: Minimum data set required for each component of a typical EWR determination (Wepener, 2016). Table is for rivers and groundwater – estuaries and wetlands were not included in this table.

Component	Minimum data set
Habitat Integrity	The minimum data set for an assessment of habitat integrity would include the following components. • General information on land use in the catchment. • General information on the hydrological character of the river, i.e. general information on the extent of water abstraction and flow regulation. • Videography, or at least low-level aerial photography, for the section of the river under investigation. • Some water quality information, or an informed judgment on the water quality as related to the structure and functioning of the aquatic ecosystem. • Some information on the aquatic biota or at least an informed opinion on the attributes of the biota in the river section.
Ecological Importance and Sensitivity	Information on the presence of rare, endangered or unique species in the river (principally vertebrates, but including riparian plants and aquatic invertebrates). There should also be sufficient information to make at least an approximate evaluation of the biodiversity of the system, and to estimate the sensitivity (or fragility) of the biotic and abiotic components of the system. An estimate is also required of habitat diversity, the importance of the study area as a migration route, and the presence of conserved areas within or adjacent to the study area.
Hydrology	A daily time series of observed flow data measured at, or close, to each site. The data set should be sufficiently long to represent the range of conditions (wet and dry extremes) that naturally occurred. If the observed data represent a flow regime greatly modified from natural, then it may be necessary to simulate parallel data sets of natural and present day conditions.
Hydraulics	An absolute minimum data set would be one stage measurement at an appropriate low flow, plus the stage of zero discharge. An acceptable data set would be three such stage measurements distributed over the low flow range of interest, plus the stage of zero discharge and some flood-related data.

Component	**Minimum data set**
	An ideal data set would be six data points over a good distribution of discharges, plus the stage of zero discharge and some flood-related data.
Geomorphology	A minimum data set would be derived from the following activities: A desktop study to identify sediment source areas within the catchment; and complete a reach analysis of the river's long profile, based on map and video analysis. Site visits to: verify the reach analysis; survey and classify the channel morphology; identify significant features on the channel cross-sections; survey bed and bank material; survey the types and distribution of hydraulic biotopes. An extended series of field data collection activities could consist of the following components: extension of field surveys within the time frame for the application; repeated surveys of hydraulic biotopes at different discharges; refinement of medium to high flow stage-discharge relationships. Additional desk studies using available data: studies of aerial photographs to assess channel change at each site; magnitude-frequency studies of relative bedload transport based on theoretical bedload equations. Long-term field monitoring: field studies of channel dynamics and long-term channel change; bedload monitoring.
Water quality	The data required for the Workshop are: the physical and chemical water quality conditions associated with the current flow regime; how these conditions change seasonally and yearly; where appropriate, similar data for the system in the non-impacted state. The suites of variables for which data are required, are listed below. Data on those variables shown in bold are essential. Data on the other variables will provide useful additional information. • System variables: pH; water temperature; dissolved oxygen (DO). • Non-toxic constituents: electrical conductivity (EC) or total dissolved solids (TDS); TSS; base cations (sodium, potassium, calcium, magnesium); other constituents such as sulphate, silica and total alkalinity (TAL). • Nutrients: total phosphorus (TP); soluble reactive phosphate (SRP); total nitrogen (TN); nitrate; ammonia (proportion of ionised to unionised); nitrite; total organic carbon (TOC).

Component	Minimum data set
	• Toxic constituents: metal pollutants; pesticides; any other toxins likely to occur in the system.
Vegetation	The minimum data set for a site comprises the data collected during a single visit in the dry season. The data describe the species composition and cover of the dominant and emergent vegetation in the different vegetation zones along one complete transect. However, single transects provide no indication of within-site variability, and give data of unknown reliability for monitoring purposes. On the transect, the exact locations of zone boundaries are related to fixed known points, and the magnitudes of flow that would inundate these points are established. The different levels of inundation typical of wet and dry season flows are illustrated.
Aquatic invertebrates	The basic data set will be drawn from a survey of the invertebrate fauna of all habitats at all sites, with the animals identified to family level or to more detailed levels. This data set is used to assess the present state of the river, and to recommend flows which will maintain or improve the river according to the Environmental Management Class and objectives.
Fish	A minimum data set would consist of recent historical records of fish species occurring in the river, and a fundamental understanding of the flow-related habitat requirements of the most sensitive species or life history stages. If no or insufficient historical data are available, at least one fish survey should be conducted in each designated geomorphological zone in the study area. This survey should be conducted at the selected sites towards the end of the low flow season, as this usually represents the most critical period for fish survival.
Groundwater	A large amount of geohydrological information is available with which to develop a conceptual understanding of the geohydrological characteristics and functioning of a system. The National Groundwater Database (NGDB), national scale geohydrological maps and regional scale geohydrological maps currently being produced by DWAF represent important sources of information. These may be supplemented with other readily available information (rainfall data, geological maps, and WR2005 data), to produce the minimum information required to provide a low confidence geohydrological input into the assessments.

3.1.4 Water Quantity in Rivers

Historically various methods have been developed to determine the water quantity that is needed for river ecosystems. These methods can basically be summarised in four types of methods: hydrological, hydraulic/habitat rating, habitat simulation and holistic approaches. A summary of these types of methods are briefly provided together with key literature and specific methods that have been used.

Hydrological (Tennant or Montana method)

This is one of the earliest methods that have been applied for water quantity assessments. It is a simple and rapid method (Desktop approach) with minimal data requirements (Tennant, 1976). The method uses summary statistics from the hydrological data sets (e.g. a percentile from the annual flow duration curve) to set "a minimum flow" for the river. This is normally done for the dry season to ensure, for example, adequate dilution of pollutants or sufficient habitat for fish. This method also sets a range of acceptable variation in flow throughout the year. The minimum flow that is required for the aquatic environment to be sustainable is then expressed as a percentage of the mean annual flow. Different percentages are then used for the wet and dry season.

The Tennant (or Montana) method has been developed following extensive field observations of habitats that are used by fish communities (Tennant, 1976). The method was developed in the United States of America and is applicable for all stream sizes in both warm and cold climates. This method is suitable for reconnaissance assessment but it can be upgraded with local input and professional judgement. The disadvantages of hydrological methods are that it only takes into account flow data (normally monthly data) and that it is region specific. The method does not address the dynamic nature of the flow regimes in rivers, i.e. flow variability or specific flow events. The method is not sensitive towards the nature of individual rivers and the relationship that exists between the flow and the aquatic ecosystem state is poorly established (Wepener, 2016).

Hydraulic / habitat rating methods

This type of method is based on the development of the various relationships between habitat and discharge. The most widely used method is the Wetted Perimeter Method. The hydraulic variables that are measured for this method include the wetted perimeter, wetted width or depth. These are measured at one or more cross-sections at representative sites of a river as well as over a range of flows. This is then seen as a surrogate for the ecological data on habitat. The values can then be plotted against the discharge and thresholds are found when the slope of the curve changes. The assumption of the method is that when the flow drops below the threshold, there will be a change in the habitat quality which will in turn affect the aquatic ecosystem and the ecological integrity of the system. Advantage of this method is that it uses river-specific data and that it allows precise hydraulic relationships to be described. Disadvantages of the method is the common assumption that the chosen thresholds will have ecological significance.

Habitat simulation (Instream Flow Incremental Method)

These methods link hydraulic relationships found within a river with extensive (sometimes not extensive) data on the habitat requirements of aquatic plants and animals in the same river. The most widely used method is the Instream Flow Incremental Method. Hydraulic data from many cross-sections are used to compile a description of the representative river sites in terms of the hydraulic habitat that are present. This is also compiled over a range of different flow scenarios. These descriptions are then linked to known hydraulic-habitat requirements of animals or plants in the system. An output is provided graphically of the amount of habitat available for the species at any given flow scenario. These relationships can then be used to identify the optimal flows that the selected species requires. The advantages of these methods include the strong ecological links as well as the quantitative outputs that it provides. These are invaluable in the negations over the amount of water needed in a system. However, the disadvantages include the complexity of the method, the focus of the method on the habitat of the selected species without considering other environmental requirements, the preference of aquatic species over riparian species and the focus on low flows without including the importance of flood events in the system.

Holistic approaches (Building Block Methodology)

These methods are the most advanced and also rapidly growing range of methods in the global context. These methods generally address all part of the river ecosystem and all parts of the flow regime. Holistic approaches are essentially structured data and information management tools that require and use hydrological, hydraulic, sedimentological, geomorphological, chemical, thermal, botanical (aquatic, marginal and riparian plants), zoological (fish, invertebrates, plankton, water birds, other wildlife), and microbiological data to compile an understanding of the river and develop a consensus prediction of how it would change with flow changes.

These methods are useful in developing countries as it is possible to assess the impact of changing flow conditions on subsistence users and can provide economic information on compensation for resources lost for example downstream of new impoundments. When subsistence use is present, the anthropological, socio-economic and resource economic data can be used to predict the implications for people of the changing river. These methods can make use of any relevant data, knowledge or local wisdom. It can also incorporate discipline specific methods if it is needed to derive the relationships that could be needed for any predictions.
Advantages of these methods include that they contribute toward national aquatic ecosystem databases that ultimately enhance the understanding of the rivers. These methods also allow rapid methods to be derived from the full scale methods following prior applications. The disadvantages include the higher cost of the large multi-disciplinary teams needed to function optimally over at least one annual hydrological cycle to gather the river specific data. A summary of the different types of environmental flow methodologies based on King et al. (2000) are presented in Table 5. In the following section the major methodologies used in South Africa are presented in more detail.

3.1.4.1 Building Block Method (King et al., 2000)

The Building Block Method (BBM) has been applied in South Africa since the early 1990's to determine EWRs but the DRIFT and habitat flow stressor response (HFSR) methods have been more widely used in recent times. The method includes the assessment of the habitat integrity, the ecological importance and sensitivity, and also the consequences of the different flow scenarios. This method takes around 8-12 months to complete with a reasonable confidence. The BBM method relies on the best available knowledge and expert opinion.

One of the key components of the methods is a workshop (i.e. specialist meeting) that is attended by all the scientists within the specified fields of expertise. The aim of the workshop is to provide a consensus decision on the recommended flow regime that is required to maintain a river in a desired state. The workshop is used to determine the flow magnitudes, timing and duration. The focus is on the natural flow regime of the river, i.e. perennial or non-perennial; magnitude of base flows in the dry and wet season; magnitude, timing and duration of floods in the wet season; and small pulses of higher flow, or freshets, that occur in the drier months. Attention is then given to which flow features are considered most important for maintaining or achieving the desired state of the river, and thus should not be eradicated during development of the river’s water resources. The described parts of each flow component are considered the building blocks that create the EWR, each being included because it is understood to perform a required ecological or geomorphological function. The first building block, or low-flow component, defines the required perennial or non-perennial flow regime of the river, as well as the timing of wet and dry seasons. Subsequent building blocks add essential higher flows.

Table 5: Summary comparison of the different types of environmental flow methodologies (King et al., 2000).

Type	Ecosystem components addressed	Data needs	Expertise	Complexity	Resource intensity (time, cost, technical capacity)	Resolution of output	Flexibility	Appropriate level of application
Hydrological	Non-specific	Low (primarily desktop): measured or simulated hydrological record	Manipulate hydrological date	Low	Low	Low	Low	Reconnaisance level planning
Hydraulic-rating	General aquatic habitat	Low-medium (desktop and limited field): measured or simulated hydrological record; one or a few hydraulic variables from a cross-section	Manipulate hydrological data; perhaps some hydraulic modelling	Low-medium	Low-medium	Low	Low	Low-conflict water-resource allocations
Habitat-simulation	Aquatic habitat for selected species	Medium-high (desktop and field): measured or simulated hydrological record; many hydraulic variables at many cross-sections; habitat data for selected species	Advanced hydrological and hydraulic modelling; specialist ecological expertise on habitat requirements of selected species	Medium-high	High	Medium-high	Medium	Water allocations for high conservation areas where in-channel habitat is main concern
Holistic	Whole aquatic and riparian ecosystem; can include groundwater, wetlands, floodplains, estuary, delta, and subsistence users	Medium-high (desktop and field): measured or simulated hydrological record; many hydraulic variables at many cross-sections; biological data on flow-related habitat requirements of wide range of species	High: advanced hydrological, hydraulic, and habitat modelling; chemical and thermal modelling if possible; specialist expertise on all ecosystem components; social and economic expertise as required	Medium-high	High	High	High	Developed and developing countries; Flow management in any size river, including ones of high strategic or conservation importance; dam de-commissioning and river rehabilitation

3.1.4.2 Habitat Flow Stressor Response (Hughes, 2004; Hughes and Louw, 2010)

The habitat flow stressor response method uses the principles of ecological risk analysis (ERA) (Suter, 1993) to evaluate the ecological consequences of modified flow regimes. The method does this by using an index of flow-related stress. This method is limited to the quantification of the low flow requirements of rivers and alternative approaches are required to determine the high flow requirements. The "stress" on the flow-dependent biota refers to the discomfort or damage suffered due to the changes in discharges in the system. The severity of stress likely to be caused by any modified flow regime is judged by how much it is increased or decreased from natural levels. Relationships are translated into a stress 'regime' (a description of a time series pattern of stress, similar to a flow regime) for any flow regime, in terms of magnitude, frequency and duration. The Habitat Flow-Stressor Response method was designed to consistently capturing the specialist knowledge on the relationship between flow, hydraulic habitat and the responses of instream biota. The stressors, flow hydraulics and associated habitat changes are related to biotic responses in terms of abundance, life stages, and persistence.

The advantages of this method is that it addresses the magnitude, frequency and duration of effects, it allows for gradual changes and it does not use assumed thresholds. The disadvantages of the method include that it is labour intensive and that it focuses on the stress responses from only the low flow conditions and does not include high flows.

3.1.4.3 DRIFT (Brown et al., 2006; 2013)

The DRIFT method predicts the effects of successive flow reductions on a range of indicators and develops a database of thousands of individual consequences and their severity. The method is also able to include social and economic costs and benefits in the assessment. DRIFT is a scenario-based interactive approach in which a database is created that can be queried to describe the biophysical consequences of any number of potential future flow regimes (scenarios). Within DRIFT, component-specific methods are used by each specialist to derive the link between river flow and river conditions (biophysical), or between changing river conditions and social and economic impact (socio-economic).

The central rationale of DRIFT is that different aspects of the flow regime of a river elicit different responses from the riverine ecosystem. Thus removal of part or all of a particular element of the flow regime will affect the riverine ecosystem differently than will removal of some other element. Furthermore:

- It is possible to identify and isolate these elements of the flow regime from the historical hydrological record.
- It is possible to describe the probably biophysical consequences of partial or whole removal or a particular element of the flow regime, in isolation.
- Once these biophysical consequences have been described, it is possible to combine them in various ways to describe the overall impact on river conditions of a range of potential flow regimes.
- Once the potential changes in river conditions have been described, it is possible to describe their socio-economic implications.

There are eight main activities in DRIFT (post data collection):

- Preparation of the hydrological data and derivation of summary statistics.
- Linkage of the hydrological statistics to cross-sectional river features at a number of representative river sites.
- Reduction of different flow components in a structured series, and description of the biophysical consequences.
- Entry of the consequences into a custom-built database.
- Querying the database to describe the changes in river conditions caused by one or more potential flow regimes (scenarios).
- Identification of the social impacts of each scenario.
- Calculation of the economic cost of compensation and mitigation for each scenario.
- Calculation of the impact on system yield for each scenario.

The specialists that will be included in each project will depend on the requirements of the specific project. Generally, the biophysical specialists will include the following disciplines: hydrology, hydraulics and physical habitat, water quality, geomorphology/sedimentology, botany, macroinvertebrate ecology and fish. In certain cases, the project might require specialists in aquatic parasites, algae, aquatic and semi-aquatic mammals, birds, and herpetofauna. The specialist team for the socio-economic study is also generally project specific but it can include specialists in sociology, anthropology, public health, animal health, resource economics, scheme economics and public participation.

3.1.5 Water Quality EWR methods

The assessment of the water quality has received a fair amount of attention in the past. However, the main method is the DWAF (2008) that is still in use. These methods are discussed in detail in the DWS (2017) as well as the report in Griffin et al. (2014).

3.1.6 Technical integration

Every catchment has various water resource types such as rivers, lakes, wetlands, estuaries and groundwater; however, to adequately manage these different types, there is a need for EWRs to be integrated and managed together. The key to the management is integrated water resource management, i.e. dealing with the catchment and the drainage as an interrelated system but that still considers the water needs of all the stakeholders in the catchment. Integrated assessment of water resources involves: water quality *and* quantity; surface *and* groundwater, and rivers, lakes, wetlands *and* estuaries. A holistic approach is required on the part of the specialists who are undertaking both the Reserve determination and the associated public participation process (Wepener, 2016). There are a few different integration measures that are important components of EWRs in South Africa. Each of these integrations are briefly discussed below.

Integration of Surface Water Quantity and Quality EWRs (King et al., 2000)

In the RDM approach water quality and quantity are assessed independently and then integrated. The integration provides the decision maker with information on instream water quality conditions under a variety of flow scenarios. This is typically done using a database and model which relates instream concentrations and flow.

Matching of River and Estuary EWR Results (Adams et al*.,* 2004)

Previously the results as a percentage of MAR for the downstream river EWR site (i.e. closest to the estuary) were compared to the estuarine flow requirement results. The comparison usually indicated a marked difference in requirements, mostly a much larger requirement for the estuary. The estuary and river results were provided as different outputs and were therefore not comparable as a percentage of the MAR. Estuaries are driven by both catchment-derived runoff and seawater intrusion, unlike rivers, which are only influenced by catchment-derived runoff. The responses to stressors such as decreased freshwater flows are therefore vastly different between estuaries and rivers.

In estuaries, river inflow patterns (i.e. water quantity) do show strong correlation with important hydrodynamic and sediment characteristics, such as state of the mouth, amplitude of tidal variation, water circulation patterns and sediment deposition/erosion. However, the relationships between these characteristics and river inflow are generally not linear, but often rather complicated to interpret, owing to the influence of the sea. The manner in which these characteristics are influenced by river flows is often also not the result of a single flow event, but rather that of characteristic flow patterns occurring over weeks or months.

Marked differences exist between the chemistry (or water quality) of river water and seawater, particularly in terms of system variables (e.g. salinity, temperatures, oxygen levels, pH and suspended solids) and nutrients (e.g. nitrate, ammonium, phosphate). As a result, river inflow also has a strong influence on water quality characteristics of estuaries (in addition to the water quality of river inflow). The water quality characteristics along the length of the estuary therefore are often driven by the quantity of river water entering the estuary during that period.

In the RDM approach the river water quantity and quality results are used as input flow scenarios for the estuary assessment. The river state is compared with that of the estuary and changes are made to the EWR model to supply the results in the correct format to the yield modeller. The matched flow regime as modelled will then result in the desired EC for river and estuary. If the results are significantly different then a scenario is provided that will supply Reserve scenarios to the river or estuary with an associated description of the consequences on either.

Matching of Wetland EWR Results with River and Groundwater EWRs (Rountree et al., 2012)

Integration of wetland results has not been extensively tested but in most cases a similar approach to that described for the estuaries would apply for valley bottom wetlands. Wetlands such as wetland flats and pans are wetlands where groundwater plays a key role and in such cases wetlands merely reflect the condition of the groundwater resource. Whilst such wetlands could be monitored as an indicator of the groundwater resource, the Reserve quality and quantity components would need to be assessed by a dedicated Groundwater Reserve study. Modifications of the river EWR methods for floodplains have been undertaken as part of EWR studies where floodplain sites were encountered: i.e. floodplains dictate the flood requirements of rivers. In the case of wetland seeps, no EWR is typically set but rather EcoSpecs (a descriptive management objective).

Matching of Surface and Groundwater EWR Results (Parsons and Wentzel, 2006)

The role of groundwater in sustaining rivers, lakes, wetlands, estuaries and the marine environment have been acknowledged in the literature. In addition to addressing the groundwater components of RDM, one of the key roles of a geohydrologist in the RDM process is to provide insight to other specialists about how the groundwater system functions and the role it plays in supporting other components of RDM. For example, groundwater plays a key role in sustaining many wetlands. If Resource Quality Objectives for groundwater are set without considering the requirement of a wetland that is groundwater driven, the RQOs may be altogether ineffective for protecting that wetland.

The integration of the groundwater component requires an understanding of the hydrological processes that are associated with the generation of base flows in the river. If the groundwater is targeted for use this would affect the base flow contribution to surface water systems and in particular, rivers. The groundwater assessment would then have to take into account the low flow requirements of the river. River base flows are not normally quantified on the basis of any assumed hydrological process they are merely the low amplitude, high frequency component of the total flow regime. Unfortunately, the relationship between surface water and groundwater are not always clearly understood. A newer research field called hydropedology have also emerged that links surface and groundwater interactions with the study of soil water and its movement.

3.2 Assessment of existing method

A recent study by DWS (2017) looked to review all the methods used in Resource Directed Measures in South Africa and how widely they were applied. Table 6 provides a summary of these results for the EWR process.

Table 6: Identified tools used in EWR and the Reserve Determination studies and how often they have been applied (adapted from DWS, 2017).

Step	Action	Method / Tool	Frequency rating
3.1 Driver information	1. Generate hydraulic information for EWR sites	HABFLOW.	Very High: Used for all EWRs Rapid II and higher since about 2007.
	2. Generate natural and present day discharge time series at nodes and EWR sites (ideally with surface-groundwater interaction)	• Water Resource Yield Model (WRYM).	• Very High: Used for most water resource systems in RSA.
		• Water Resource Planning Model (WRPM)	• High: All large water resource systems simulated with WRYM.
		• WReMP – (Water Resources Modelling Platform).	• Low.
		Other tools: • The Daily Dam Model (DDM) is applied to perform a daily time step spill analysis of dams.	• Medium: Used in three studies.
		• Fish River Seasonal EWR method.	• Very Low – Used in Fish River (Namibia) as part of joint SA study.
	5. Water quality: Obtain information specific to EWR sites, high priority estuaries and wetlands (where relevant)	• DWAF (2008c). Data collection/processing step.	• Very High.
		• RapidMiner (for data quality assessment – to assist in refining the conceptual model of the catchment).	• High
3.2 BHNR	Match quaternary catchment with refined population data	GIS Based Analysis tool.	Very High – used in all studies
3.3.1: Ecological Water Requirements - Rivers	2. Apply EcoClassification (detailed approach)	• FRAI (Level IV EcoClassification) (Kleynhans, 2007).	• Very High: Since 2004 in all EWR studies.
		• MIRAI (Thirion, 2007, Thirion 2016).	• Very High: Since 2004 in all EWR studies

Step	Action	Method / Tool	Frequency rating
		• GAI IV (2006 version – Rowntree and du Preez, 2006).	• High: Since 2007 in all EWR studies.
		• GAI III (2006 version – Rowntree and du Preez, 2006).	• Low.
		• GAI (Rowntree, 2013). •	• Very Low – update of 2006 GAI in use as the standard.
		• Potential Bed Material Transport (PBMT) (Dollar and Rowntree, 2003)	• Very High – used in many studies since 2002.
		• (VEGRAI (IV) (Kleynhans et al., 2007).	• Very High: Since 2007 in all EWR studies.
		• VEGRAI (III) (Kleynhans et al., 2007). •	• High: Since 2007 largely for river health practices. •
		• IHI (Kleynhans et al., 2009). •	• Very High: In use for detail studies since 2007. •
		• IHI (Kleynhans, 1996, ver2).	• Very High: Original method and now updated.
		• EcoStatus model (Kleynhans and Louw, 2007).	• Very High: Used since 2007 in all EWR studies
		• EIS (2009, site based) (DWAF, 1999a; Louw and Koekemoer (eds), 2010).	• High: Used since 2009.
		• EIS (1999) (DWAF, 1999a).	• Very High: used since 1999 but now obsolete
		• EIS (2014 – PESEIS) (DWS, 2014b).	• Very high (SQ level for SA).
		• PAI model (Kleynhans and Louw, 2007; DWAF, 2008c)	• Very High: used since 2007 for most EWR studies.
		• Desktop Reserve tool for water quality of rivers.	• High: Only used by P Wade.

Step	Action	Method / Tool	Frequency rating
		• Tool for Ecological Aquatic Chemical Habitat Assessment (TEACHA – Jooste, 2007)	• Very High – currently not in use due to software issues.
		• Diatom Ecological Reserve protocol (Koekemoer and Taylor, 2008), SA Diatom Assessment Protocol (DAP) (Taylor et al., 2007a;b) and OMNIDIA software (LeCointe et al., 1993).	• Very High: Used since 2004 in most rivers where EWRs undertaken.
	3. Set EWRs for relevant ECs	• Habitat Flow Stressor Response (HFSR) (O'Keeffe et al., 2002; Hughes and Louw, 2010).	• Very High (consistently used since 2000 for most EWR studies.
		• Downstream Response to Imposed Flow Transformation (DRIFT; King et al., 2003).	• High (mostly used in Western Cape and Lesotho).
		• Fish Invertebrate Flow Habitat Assessment (FIFHA – part of HFSR) (Kleynhans and Thirion, 2016 in press).	• Very Low (recently developed).
		• Fish Flow Habitat Assessment (FFHA – part of HFSR).	• High: Developed in 2009 – may be replaced by FIFHA.
		• Building Block Methodology (BBM – King and Louw, 1998).	• Very High but now obsolete.
		• Revised Desktop Reserve Model (RDRM – Hughes et al., 2013).	• Medium: Extensively used for desktop assessments and for all studies to produce EWR rule. Currently under revision.
		• Desktop Reserve Model (DRM – Hughes and Hannart, 2003).	• Very High: Extensively used since development for all desktop assessments and production of EWR rule.
3.3.2: Ecological Water Requirements - Estuary	2. Apply EcoClassification	• Estuarine Health Index – see DWAF (2008b) (or any updates thereof).	Very High: Used in all Estuary EWR studies since 1999.
		• Estuarine Importance Index (DWAF, 2008b); Turpie et al. (2012).	

Step	Action	Method / Tool	Frequency rating
	4. Set EWRs (undertaken during Integrated Step 4)	• DRIFT (Brown et al., 2013; 2006; King et al., 2003)	• Very Low: Only used on St Lucia.
		• Method for setting EWRs described in DWAF (2008b) (or any updates thereof).	• Very High: Used in all EWR studies apart from the above.
3.3.3: Ecological Water Requirements - Wetlands	1. Determine dominant wetland HGM type	• Classification system for wetlands (Ollis et al., 2013).	• Low
		• Wetland types in DWAF (2007).	• Low
		• Rountree and Batchelor (2013).	• Medium
	2. Determine appropriate level of RDM study for wetlands	Guideline for RDM assessment level (DWA, 2012).	Low: Few wetland Reserves have been undertaken in SA.
	3a. Validate PES of priority wetland RUs	**All wetlands:** • WET-Health (MacFarlane et al., 2007).	• High
		• Water Quality: Malan et al. (2013), but refined in Malan and Day (2012).	• Low
		• Wetland IHI (DWAF, 2007).	• High
		• Diatoms: Koekemoer and Taylor (2013).	• Medium
		Pans: Invertebrates: Pan macro-invertebrate Assessment Method (Farrel, unpublished)	• Very Low
	3b. EIS of priority wetlands	Rapid EIS method (Appendix A3 in Rountree and Kotze (2013).	High
	3c. REC of priority wetlands	REC determination guidelines – Section 4.3 in Rountree et al. (2013).	Low (few wetland Reserves undertaken in RSA).
	4. Determine EWR (or other RDM) to achieve REC	**Desktop Reserve Determination:** • Pans – Rainfall-inundation method – Rountree (2013a).	• Very low

Step	Action	Method / Tool	Frequency rating
		Rapid Reserve determination: • Pans – Rountree et al. (2013); Kotze and Walters (2013) and Koekemoer and Taylor (2013).	• Medium
		• Unchannelled VBs, Channelled VBs, and floodplains – Mallory (2010).	• Medium
		• Mallory (2013); Jordanova (2013); Birkhead et al. (2007); Kotze and Walters (2013); Koekemoer and Taylor (2013) and Rountree (2013b).	• Low
		Intermediate Reserve Determination: • Channelled VB Wetlands – Mallory (2010, 2013); Jordanova (2013); Birkhead et al. (2007) and Kotze and Walters (2013).	• Low
		• Seepage wetlands: Hydrus (Šimůnek et al., 1999); PyTOKAPI (Sinclair and Pegram, 2013) and SPRING (Konig, 2011).	• Very Low
		Comprehensive Reserve Determination: • Lakes – DWAF (1999b).	• Low. Applied on five lakes associated with the Mhlathuze system.
		Floodplains – Standard river EWR approaches.	Medium – Only few large wetlands done by this method.

3.3 EWR determination: Implementation challenges

There have been numerous comments on the many implementation challenges and opportunities to improve methods and tools. However, these can mainly be summarised by the following list:

- Flow dominated methods and thinking.
- Integration of all protection methods.

- Implementation of EWR within management frameworks and governance structures.
- Continued method development and standardization.
- Monitoring and feedback into decision-making processes.
- Clearly defined roles and responsibilities for the implementers and monitoring agency
- Buy in from stakeholders in the catchment.

In various research reports (Palmer and Munnik, 2018) mention was made of the challenges to implementation. The success stories (identified in Palmer and Munnik, 2018) have mostly been as a result of a champion consistently pushing the agenda of ecological water and integrated water resource management. Palmer and Munnik (2018) provide some research on various aspects that influence the implementation of EWRs in South Africa.

Newer methodologies such as the RRM and PROBFLO framework are integrating multiple objectives from both ecological and social aspects to approach sustainable river management. In developing countries especially, the challenge for sustainable freshwater ecosystem management lies in satisfying consumptive and non-consumptive uses. The sustainable use of these resource uses lies at a very complex interface of ecological and social science (Martin et al., 2014). Therefore, successful implementation requires a mix of ecological theory with social science methods that is a collaboration between ecologists, biologists, geomorphologists, economists, catchment planners and any other non-technical stakeholders (Martin et al., 2018).

In the implementation phase of environmental water management, the institutions and processes linking the stakeholders and the governance that manages the water allocation process are vitally important (Horne et al., 2017). The literature on the legal, regulatory and organizational tools for water allocation and management of environmental water is growing (Godden, 2010; Foerster, 2011; Pahl-Wostl et al., 2013), but very little of this literature has been incorporated in the main body of environmental water literature (Horne et al., 2017). According to the OECD (2015), many of the crises in water management in the past have fundamentally been a crisis of governance. One of the critical factors for environmental water to be successful, is that it needs strong institutions that underpin accountability, transparency and is able to support efficiency, efficacy and legitimacy of environmental water management (O'Donnell and Garrick, 2017). Increasing volumes of environmental water will make the institutions and governance and the roles they play very important for the continued growth of environmental water management (Horne et al., 2017).

In a review by Poff (2018) it is mentioned that water management must build on the rigorous predictive science, past successes and a realistic appreciation that the aquatic ecosystems are highly altered and non-stationary. These aquatic ecosystems are also increasingly found in human-dominated landscapes (Arthington et al., 2018). Poff (2018) indicates that the challenge is to “develop the capacity to more confidently state under what circumstances flow interventions will be successful and resilience can be achieved.” One of the important considerations is what flow variability pattern we are aiming for. Attaining historical flow variability is often unrealistic due to the changing baseline conditions as a results of permanent changes in climate and other environmental shifts (Acreman, 2014; Arthington et al., 2015, Humphries and Winemiller, 2009; Poff, 2018). The resilience in our systems are often also unknown, especially how this is influenced by flow variability. Therefore, any new tool or framework needs to ensure that management of environmental water needs to include a broad range of waterbody types, robust management endpoints and be cognisant of the various environmental, social, economic and political constraints (Arthington et al., 2018).

In Arthington et al. (2018) a review was made of the recent advances in environmental flows science and water management with the focus on what innovation is needed within the Anthropocene. This article looked at the scientific challenges and areas where future exploration is needed in environmental water assessments. The major scientific challenges were:

a) Advanced understanding and quantification of ecological processes and social-ecological outcomes from delivery of environmental flows
b) Improved understanding of complex hydrological interactions
c) Quantify/predict the interaction between hydrology, sedimentary processes, geomorphology, hydraulics, temperature and ecological variables
d) Improve understanding of spatial variability and cumulative catchment effects
e) Account for extreme events and non-stationarity
f) Quantify, stochasticity and uncertainty

In addition to the scientific challenges, Arthington et al. (2018) also highlights the following areas where the advancement of environmental water management could be made:

a. Include additional waterbody types in water allocation strategies
b. Expand measurement of ecological responses to flow to reflect system dynamics
c. Embrace cultural and heritage values as well as ecosystem services
d. Account for water scarcity and ecological drought
e. Sustainable water resource development in intact catchments
f. Apply a tiered approach to environmental flow assessment
g. Active management of environmental water

Each of the following sections will provide information on aspects related to the integration and implementation of EWR in South Africa. The sections will deal with human capacity development, governance, technical integration as well as implementation of all of the previous sections within integrate water resource management (IWRM) in South Africa.

3.3.1 Human capacity development

A recent publication by Stoffels et al. (2018) looked at how science can support the management of riverine flows. This study highlight the important roles scientists play within water resource management. Stoffels et al. (2018) highlighted the following four roles that scientists need to fulfil to support ecological flow management:

a) Monitoring and evaluation of ecosystems to support scientifically defensible reporting of outcomes, and to reduce uncertainty through adaptive management.
b) Modelling to support spatial and temporal projections of ecosystem change under different flow scenarios, resulting in more effective management decisions; improved causal inference about flow effects; identification of threats to the efficacy of flow management; and scaling flow response dynamics to broader spatial extents.
c) Fundamental research, resulting in improved outcomes through the identification of non-flow management interventions that work in synergy with environmental flows and improved understanding of the ecological limitations of current policy.

d) Decision science, leading to more defensible environmental flow decisions and more efficient use of resources.

In the research by Stoffels et al. (2018), the authors also identify barriers to the implementation of these roles. One of the key findings from this research was that current research efforts on EWR is often ad hoc in nature and thus making it difficult to move the science forward. To overcome this problem, Stoffels et al. (2018) suggests the following four solutions to these problems. Research programmes on EWR must be:

a) Developed at a basin or regional scale to ensure science supports decisions at multiple scales
b) Developed as a collaboration between all stakeholders to ensure that sciences investments remain aligned with decisions problems
c) Recognize the need to build and maintain technical capacity within all four roles

3.3.2 EWR Implementation in the Mooi River Catchment

The governance of EWRs within the Mooi River catchment was investigated to determine how the methods described in the sections have been imbedded within the processes and mandates of the various municipal, local and national government departments responsible for water resource management. Interviews will be completed with various levels of government officials at the various departments in the Mooi River catchment. Interview questions will preliminary consist of the following statements / questions:

- Basic understanding on EWR within the Integrated Water Resources Management looking at anthropogenic activities?
- What is considered good governance towards EWR implementation?
- How to achieve collaboration and coordination on EWR governance (Leadership, Control, Management and Planning) to ensure its effectiveness and sustainability?

These interests can be broadly defined in Figure 1. It also includes all the sectors of society playing a role in IWRM in South Africa.

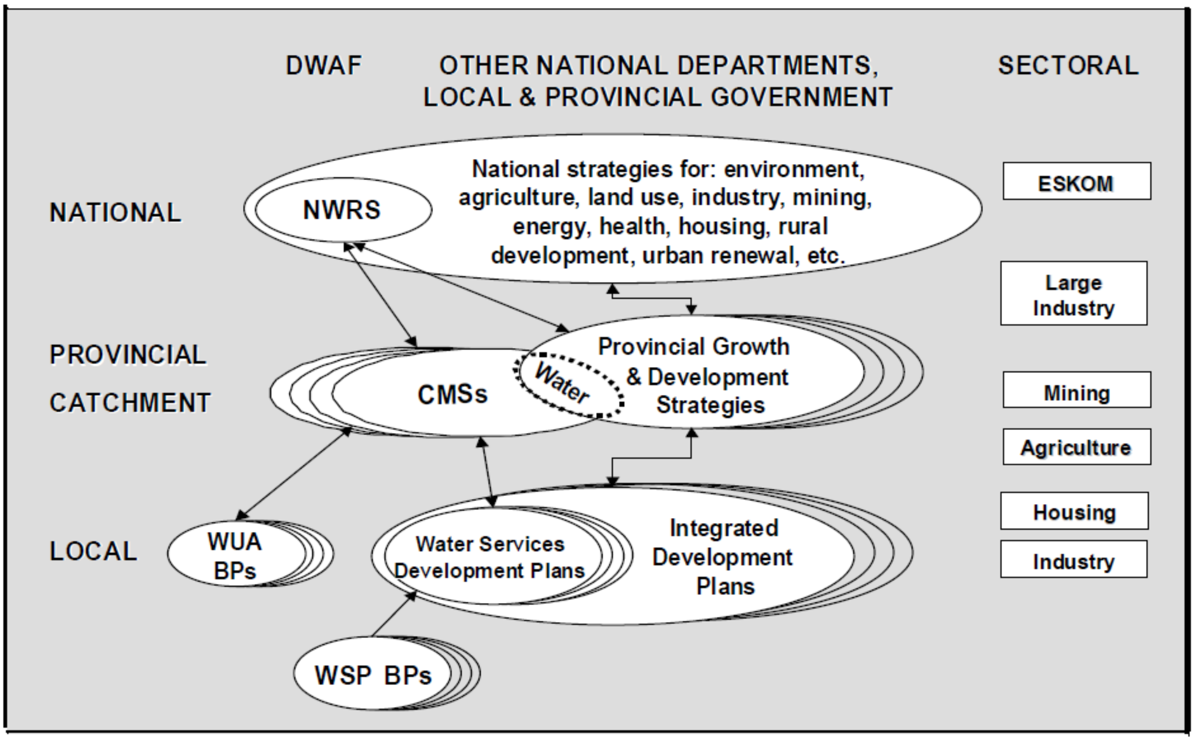

Figure 1: Interrelationships between spheres of government and sectors of society in South Africa from a water resource management perspective (source NWRS (2004)).

Already in 2006 research by the WRC indicated that the challenge of implementation of ecological water requirements deal with the shared responsibility of managing South Africa's water resources. To overcome this, stakeholders from public / government institutions must create cooperation and interaction between departments so that services can be efficiently provided. This cooperation needs to happen both at the policy-strategy level as well as the operational-implementation level. Historically, poor cooperation between the various institutions have resulted in the inefficient use of scarce water resources and also in various disputes (Mamabolo, 2012).

Furthermore, a study on the procedural efficiency of water use licences in 2017 (Myburgh, 2017) identified various inefficiencies within the licensing system. Although not part of the EWR process, outputs from EWR studies need to feed into water use license requirements. The inefficiencies were as follows:

a) Inadequate management of human resources within the department
b) A lack of clearly defined and well managed communication systems
c) Complex manual administrative processes
d) Uncoordinated process management
e) A lack of process awareness

f) No post approval feedback loop exists to allow continual improvement based on results
g) A lack of procedure for cooperative governance
h) A lack of expertise and guidance for the compilation of licenses
i) A lack resources for decision-making

3.3.3 Technical integration

The integration of information generated through EWR specialist studies represent different ecosystem components and as such need to be integrated to determine the final water requirements for a specific system.
The following integration points are important as pointed out in the DWS (2017) study:

- Integration of ecological responses – EcoStatus.
- Integration of ecological responses with ecological drivers.
- Socio-economic integration throughout EWR approach = Stakeholder engagement must happen throughout the process (DWS, 2017).
- Integration of other ecosystems, i.e. groundwater and wetlands.

Integration happens throughout the various tasks or processes that are used to determine the EWR of an ecosystem. In South Africa, various frameworks or processes have been used in IWRM and specifically in the resource directed measures for the management of riverine ecosystems. In Figure 2, the generic task structure that needs to be completed by the various specialists involved with an ecological water requirement study. It comprises five stages with various tasks that need to be completed during each stage.

Within the resource directed measures approach, there are three different frameworks that are implemented, i.e. resource classification, Reserve determination and resource quality objectives. All of these frameworks have been implemented in catchments within South Africa to determine the Reserve; however, the resource quality objectives have only been gazetted in selected catchments due to various procedural and methodological problems in their development. This is especially true in the case of wetlands, groundwater and to some extent estuarine systems.

Much of the last 20 years of the National Water Act being in force, research has dealt with the development of the methods to determine the Reserve and resource quality objectives. Therefore, very little research has gone into the actually implementation of this. In certain cases, such as the Sabie River and Crocodile River (Palmer and Munnik, 2018), the implementation of the Reserve has been fairly successful. This was achieved with much energy spent on involving stakeholders within the whole process of determining the amount of water the river and people need in the catchment.

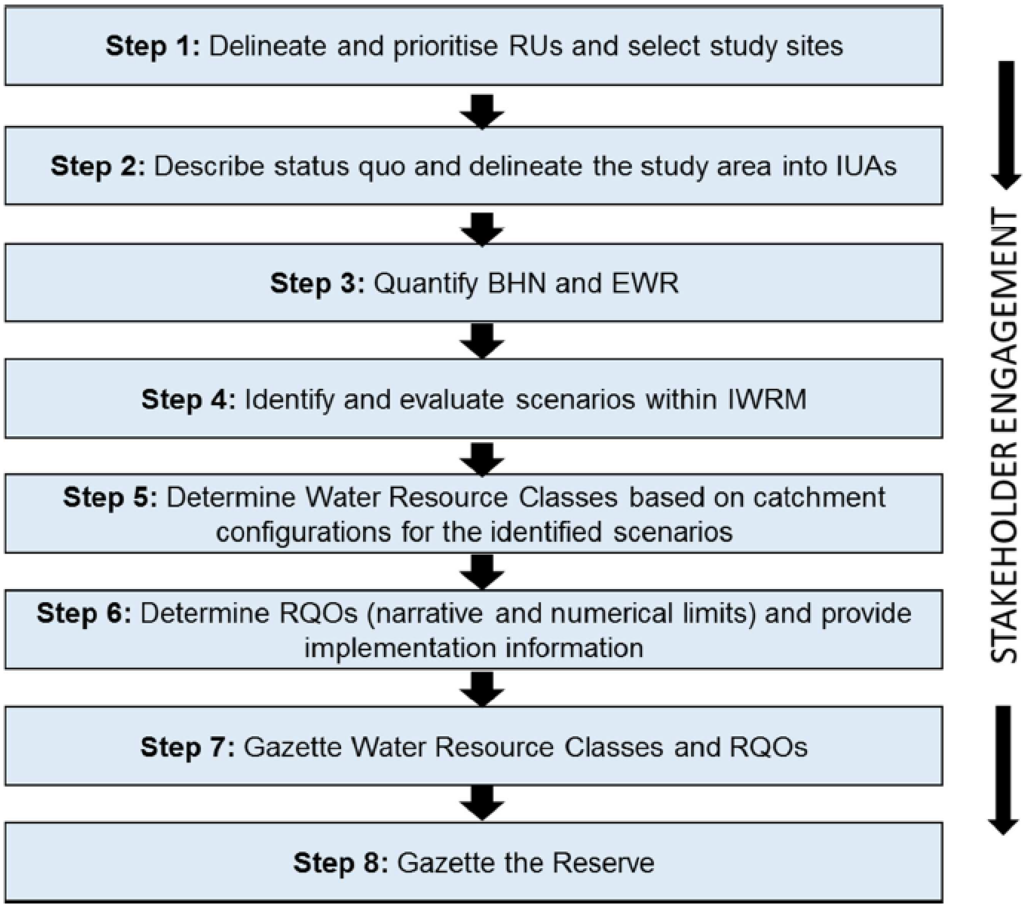

Figure 2: Integrated framework for the operationalization of the Reserve from the National Water Act (From DWS, 2017).

As operationalization of the resource directed measures have been quite problematic, it was decided to devise an integrated framework (Figure 2) to increase the implementation within water resource management in South Africa. The integrated framework is a combination of the frameworks for the classification, Reserve determination and resource quality objectives as presented in Figure 3. The flow diagram in Figure 3 uses the various colours to indicate where each step is taken up into the integrated framework. It is important to note that stakeholder engagement should be included throughout the integrated framework so that stakeholders are well informed of the processes occurring within the water management in their catchment.

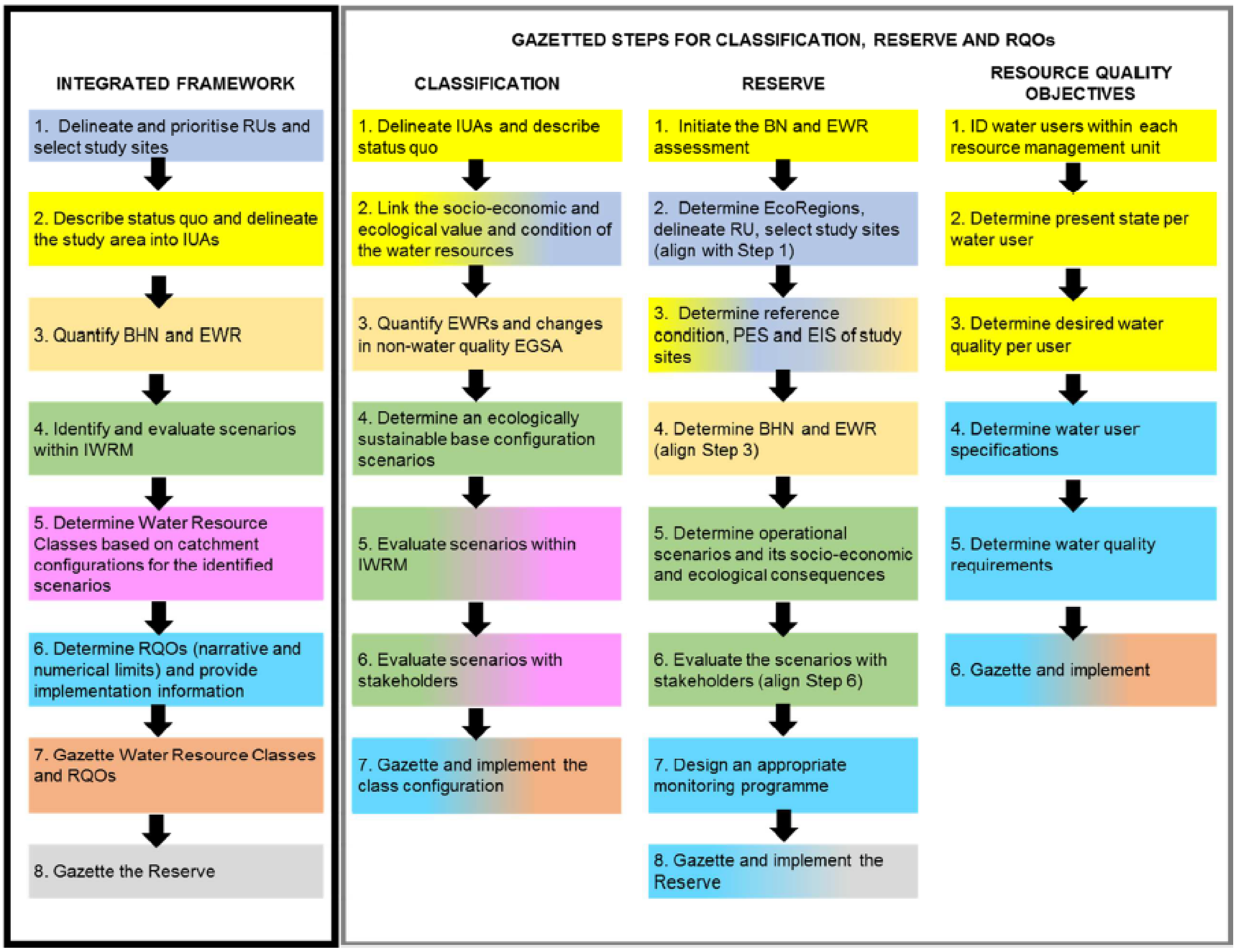

Figure 3: Flow diagram illustrating how the gazetted steps for Classification, Reserve and RQO are incorporated in the Integrated Framework (taken from DWS, 2017).

A recent study by Kennen et al. (2018) indicated that technical and sophisticated methods leads to the improvement of the environmental water science, but it often results in outcomes that are not easily interpretable and therefore does not lead to a positive influence of management decisions. Therefore, ecological water scientists need to be able to translate the results from the various modelling methods into easily interpretable tools and guides. These tools will then be easier to implement with stakeholders to encourage their active participation in IWRM. This is especially important with the growing water demand and droughts that South Africa has experienced and where we need stakeholders and managers to be proactive in implementing alternative water allocation scenarios (Kennen et al., 2018).

The traditional environmental flow methodologies used mainly hydrological and ecological data to determine the amount of water needed in rivers to sustain a desired ecological condition and human well-being (Martin et al., 2014). Newer methodologies have recognized the importance to include the socio-economic aspects to be inclusive and participatory in the management of the water resources. However, many of these complex hydro-ecological tools do not have a structured approach to incorporate data from socially relevant sources into the methods (Martin et al., 2014). The need to include socio-economic data is often extremely important when multiple objectives need to be achieved within a water management system. Martin et al. (2014) approached environmental flows from a social-ecological system (SES) perspective. The SES is an aggregation of linked social (e.g. institutions, property rights, behavior) and ecological (e.g. environmental resources) subsystems (Berkes and Folke, 1998), which integrates important information from these subsystems by establishing relationships between ecological and social conditions.

Martin et al. (2014) proposed a flexible framework that uses a social-ecological systems approach to include multiple flow-related objectives to reflect biophysical sustainability and societal preferences. This research conceptualized the freshwater social-ecological system as a hierarchy of human and environmental domains (Martin et al., 2014). This was followed by a stepwise procedure that assessed flow-related vulnerabilities of the important ecosystem attributes, address their feedbacks, and translate these assessments to a common classification for comparative analyses so that it can guide holistic flow management decisions.

This framework extends a SES approach so that it integrates various types of data into the environmental water field (Figure 4). The aim of Martin et al. (2014) was to provide a systematic account of relevant water data from relevant domains of a freshwater SES. This was followed up by a way to use the data so that it can assist in integrated environmental water studies and decision-making. The framework of Martin et al. (2014) consists of the following six steps:

1. Identify the target scenario and define objectives;
2. Determine relevant domains of the freshwater SES;
3. Identify target social-ecological attributes from relevant SES domains;
4. Assess flow-related vulnerabilities of the attributes through expert opinion and/or data analysis;
5. Address feedbacks among system attributes;
6. Classify the data and integrate using decision support techniques.

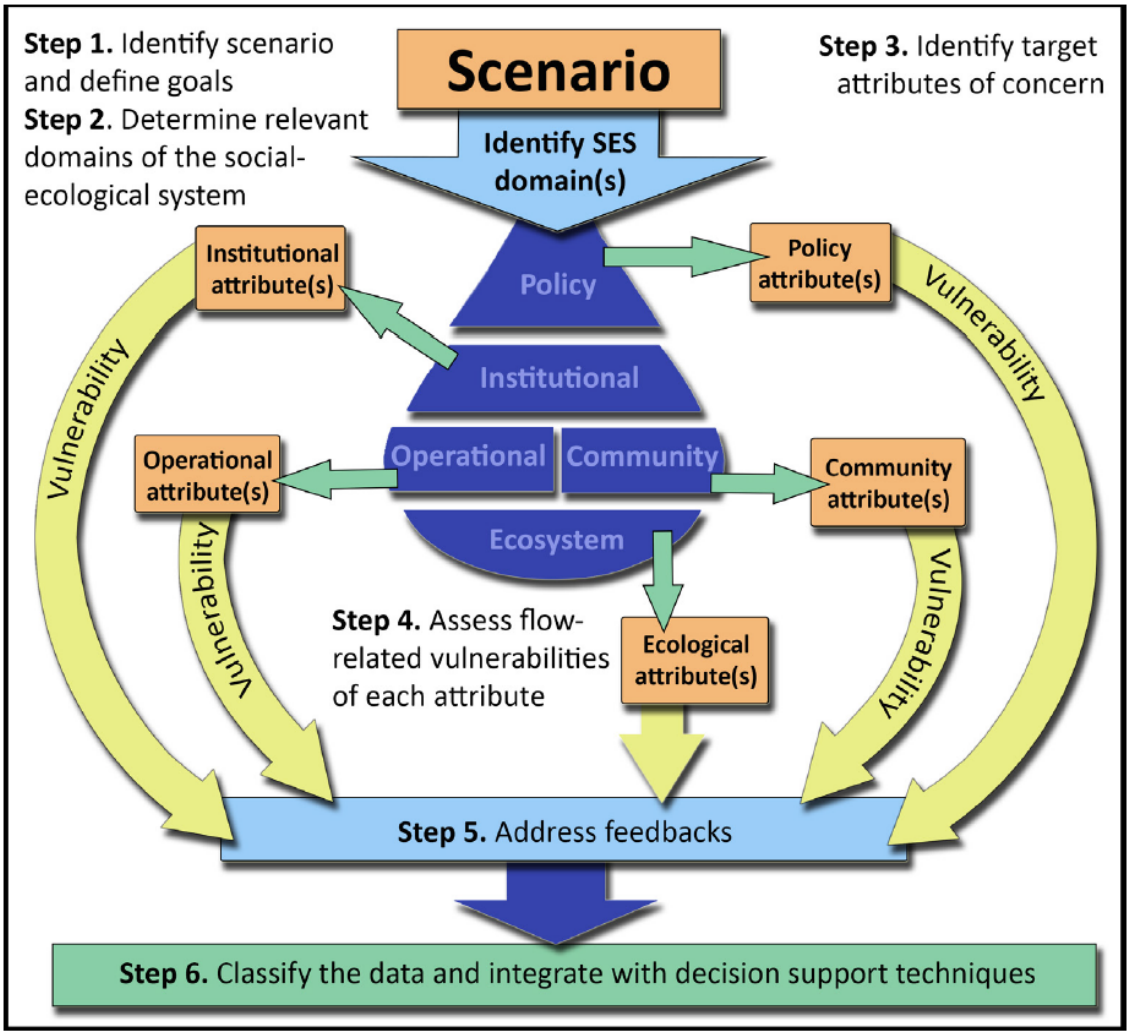

Figure 4: Hierarchical representation of a social-ecological systems approach to flow management. (From Martin et al., 2014).

In South Africa, Palmer and Munnik (2018) also advocated the use of a social-ecological systems approach to integrated water resource management. These authors argued that we should move to an approach called Adaptive integrate water resource management to deal with all of the various issues South Africa faces in regards to its water resources.

More recent approaches to environmental water have started to focus on basin-scale or regional assessments. This has been necessary as the water resource management activities have changed rapidly with increases in dams, diversions, retention and reuse (Arthington et al., 2018). These regional-scale methods (both hydrological and ecohydrological) has the ability to support ecological risk assessment and the identification of priority actions for environmental water (flow) and river restoration actions (Arthington et al., 2018).

These increased research activities have led to newer approaches and more robust, dynamic and predictive methods in environmental water science. These methods have started to include the measurements of process rates (e.g. birth rate, colonisation rate) and species traits (e.g. physiological requirements, morphological adaptations) as well as ecosystem states (e.g. species richness, assemblage structure) as the variables that represent the ecological responses to flow variability and allocation of environmental flows (water) (Arthington et al., 2018). Many of the advantages of traits-based approached have only recently become evident as environmental science and management struggles with shifting climatic and hydrological regimes (Poff et al., 2017). This will potentially lead to species replacements within similar functional guilds or groups.

One of the first more holistic approaches, was the ecological limits of hydrological alteration (ELOHA) proposed by Poff et al. (2010). This approach makes use of both the scientific process as well as the social process (Figure 5) to determine ecological water (flows). The scientific process has four general steps while the social process is also managed throughout the scientific process to provide societal input for the project. It is a process that can be adjusted and adapted if needed based on the monitoring data gathered. One of the major drawbacks of our current approaches to ecological water requirements in terms of the integrated framework, ecological reserve, classification and resource quality objectives (Figure 2 and Figure 3) is that no explicit feedback loop is built into the framework. Although it is assumed that monitoring should happen of especially the resource quality objectives, there are no official way to amend RQOs and ecological reserves of catchments. This is especially important in light of climate and hydrological changes experienced at present as well as for future water resource management scenarios. Monitoring, environmental flows (water) and objectives must be dynamic to respond to changes in both the ecological infrastructure as well as changes in societal objectives.

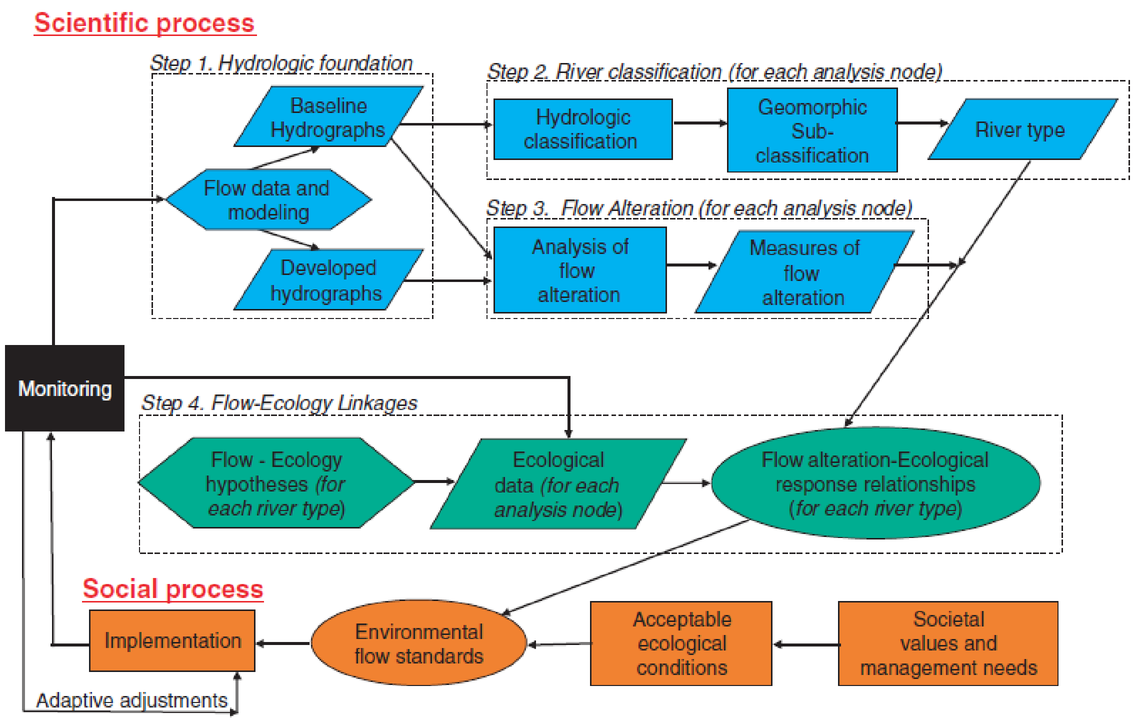

Figure 5: The ELOHA framework comprises both a scientific and social process. Hydrologic analysis and classification (blue) are developed in parallel with flow alteration-ecological response relationships (green), which provide scientific input into a social process (orange) that balances this information with societal values and goals to set environmental flow standards. This paper describes the hydrologic and ecological processes in detail, and outlines the scientist's role in the social process. From Poff et al. (2010).

Recently, Bond et al. (2018) also described an alternative method called a state-and-transition framework. This aims to translate alternative sequences of specifically floodplain inundation events into dynamic ecological responses within the floodplains. This approach integrated historical flow sequences and ecological conditions into a model that is able to predict the dynamic responses of the biological component within the floodplain, at any point in the future (Bond et al., 2018). The framework was specifically designed for floodplain vegetation but it can be applied to various aquatic organisms that respond to flow. Furthermore, it is able to explore the impacts of any other factors that could influence the floodplain biological community, i.e. salinity, grazing, climatic variability and climate change (Bond et al., 2018).
Text

In South Africa, a method was developed by O'Brien et al. (2018) that is a holistic, regional-scale, probabilistic assessment that includes flow and non-flow drivers of change in a social-ecological context. The method uses a regional-scale ecological risk assessment framework that is able to deal with multiple stressors to social and ecological endpoints and still be able to address ecosystem dynamism. Recently, this method has also been using Bayesian belief networks. Therefore, this method is a holistic environmental flow assessment framework using a relative-risk model and Bayesian belief networks in a transparent probabilistic modelling tool that addresses uncertainty explicitly (O'Brien et al., 2018) (Figure 6).

The RRM method is able to evaluate the socio-ecological consequences of historical, current and future water resource use scenarios and generate environmental water (flow) requirements at a regional spatial scale (O'Brien et al., 2018). The method was tested in two case studies in Africa namely the Senqu River in Lesotho and the Mara River catchment in Kenya and Tanzania. In both case studies the evidence-based outcomes were able to facilitate informed environmental management decisions, with trade-off considerations in the context of social and ecological aspirations. Therefore, the RRM methodology can contribute to the adaptive management of water resources and contribute to the allocation of resources for sustainable utilisation while still addressing the protection of water resources. The 10 steps of the RRM methodology are presented in Figure 6 for the various case studies.

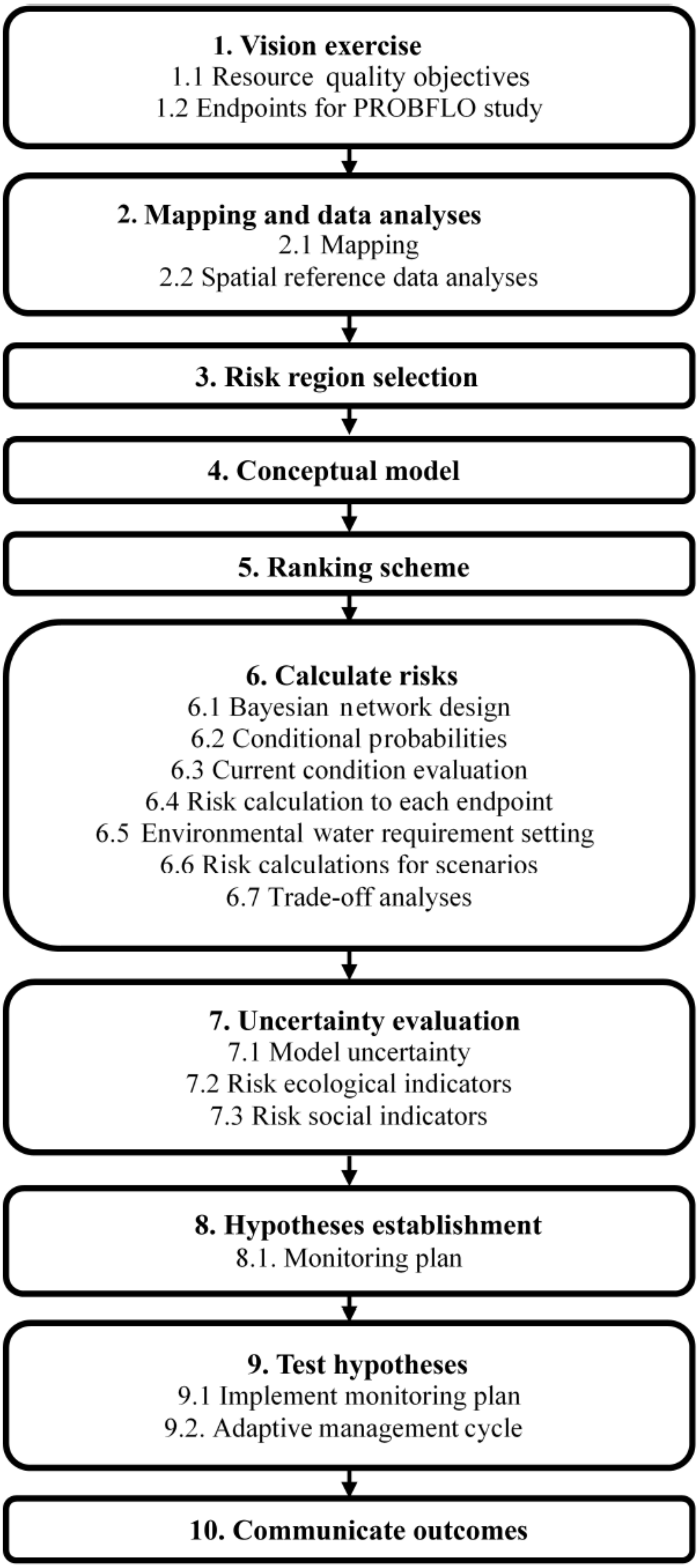

Figure 6: The 10 procedural steps of the RRM methodology (from O'Brien et al., 2018).

4 SOCIO-ECONOMIC CLASSIFICATION AND VALUATION OF THE MOOI RIVER CATCHMENT

4.1 Introduction

The North West University approached Prime Africa to conduct a desktop level socio-economic classification and valuation for the Mooi River sub-catchment. The Prime Africa® Ecosystem Services Capital (Eco-CAP$_{es}$) was utilised as a standard for classification. The process involved the classification of key hydrological Risk Region (RR) identified by the project team (Figure 7).

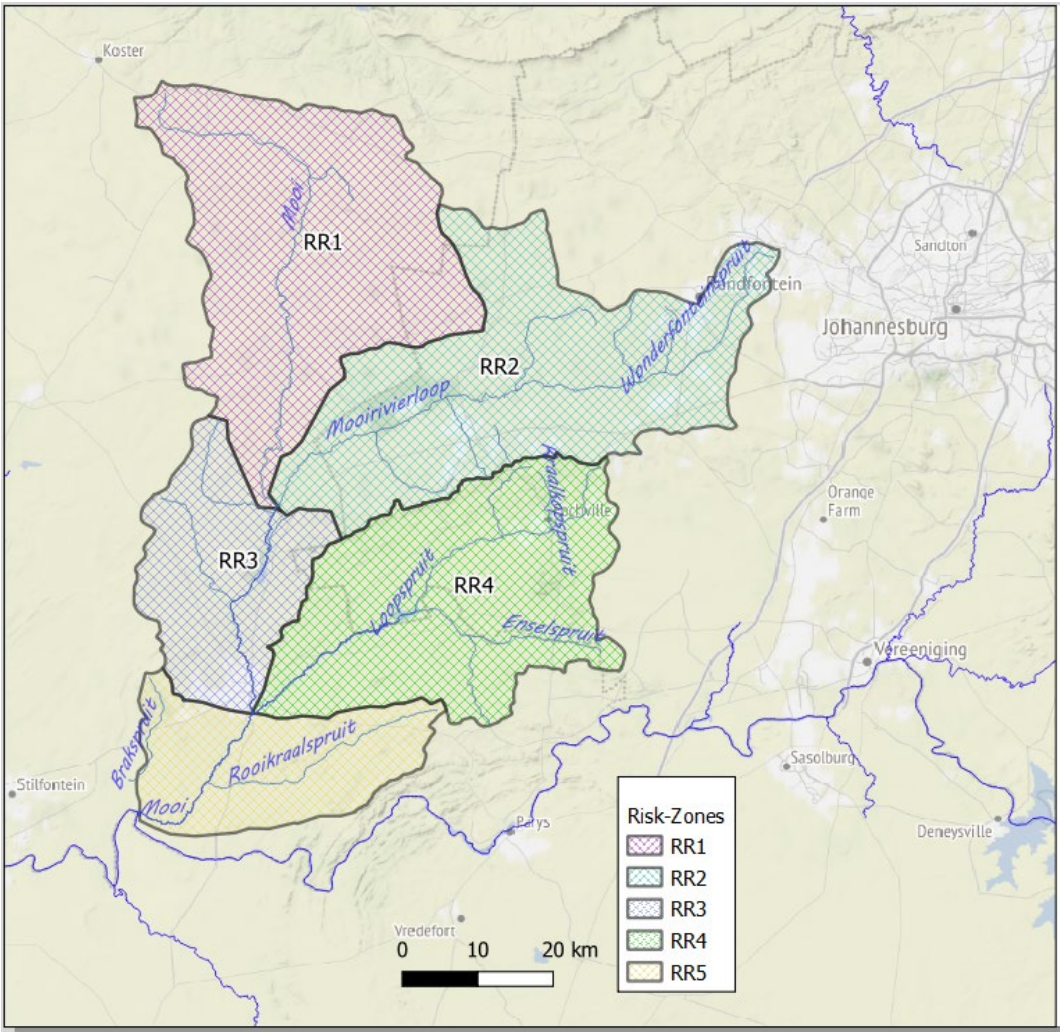

Figure 7: Locality of the Mooi River sub-catchment and categorised Risk Zones.

The following indicators were used to classify the zones:

- Population and demographic information obtained from StatsSA;
- Indicators of social vulnerability (education, employment, access to services) obtained from StatsSA;
- Ecological infrastructure (protected areas, freshwater ecosystems) obtained from SANBI;

- Land cover classification (latest land cover data, DAFF agricultural data) obtained from SANBI and DAFF; and
- Local economic drivers (latest land cover data, municipal IDP's and StatsSA).

The outputs of this report represent a chapter that:

1. Classifies the broad socio-economic baseline of the target catchment (Section 4.2; Appendix 1 and 2);
2. Broadly identifies regions of relative socio-economic vulnerability to negative impacts on water resources (Section 4.2; Appendix 3);
3. Broadly maps out ecological infrastructure and socio-economic drivers and conditions towards identifying the flow of key ecosystem services (Section 4.3);
4. Demonstrates the total economic value of water in the catchment (Section 4.4);

The assessment was based on available documented information and no site visits, field work or additional data collections were undertaken to verify or update the available information.

4.2 Socio-Economic Baseline

The Mooi River catchment is situated in the upper regions of primary hydrological catchment C within the Vaal Water Management Area (WMA). The sub-catchment includes quaternary catchments E, F, G, H, J, K and L within tertiary catchment C23. The Risk Zone collated sub-catchment region straddles two provinces, five district and 8 local municipalities (Table 7; Figure 8). Major cities and towns in the identified RR's include Randfontein, Westonaria and Fochville in the East, Potchefstroom and Klipdrif in the South, Carletonville in the centre and Mathopestad in the North West (Figure 8). The key economic drivers in the catchment are mining, manufacturing, agriculture, financial, trade and community services (Government Services) (Table 7).

Table 7: Municipal demarcations within the risk regions in the Mooi River catchment and associated data from municipal Integrated Development Plans (IDP). * Percentages of economic sectors not available.

Province	District Municipality	Local Municipality	Key Economic Sectors (GVA) (Latest IDP)
Gauteng	West Rand	Mogale City*	Mining services, transport, energy, manufacturing, tourism, Agriculture (Mogale City IDP 2019)
		Rand West	Mining (54%), Manufacturing (10%), Community Services (10%), Finance (8%), Trade (6%) (Rand West IDP 2016)
		Merafong	Mining (25%), Trade (21%), Finance (14%), Community Service (13%), Manufacturing (7%), Construction (6%) (Merafong IDP 2016)
	Sedibeng	Emfuleni	Manufacturing (26%), Finance (22%), Community Service (22%), Retail (11%), Transport (8%) (Emfuleni IDP 2019)
	City of Johannesburg	City of Johannesburg*	Financial services, Trade and logistics services (Primary), agriculture, mining and manufacture (Secondary) (CoJ IDP 2019)
North West	Bojanala	Rustenburg	Mining (>70%), Finance (7%), Trade (7%), Transport (4%), Community Service (4%) (Rustenburg IDP 2019)
		Kgetlengrivier*	Agriculture, Tourism and Small-scale mining and Manufacturing (Kgetlengrivier IDP 2017)

Province	District Municipality	Local Municipality	Key Economic Sectors (GVA) (Latest IDP)
	Dr Kenneth Kaunda	JB Marks (Ventersdorp/Tlokwe)	Key sectors are Mining, Manufacturing and Agriculture (Rural and Commercial) (JB Marks IDP 2018) Historically in Tlokwe LM- General Government Services (29%), Finance (21%), Community Services (14%), Manufacturing (10%) (Tlokwe IDP 2011)

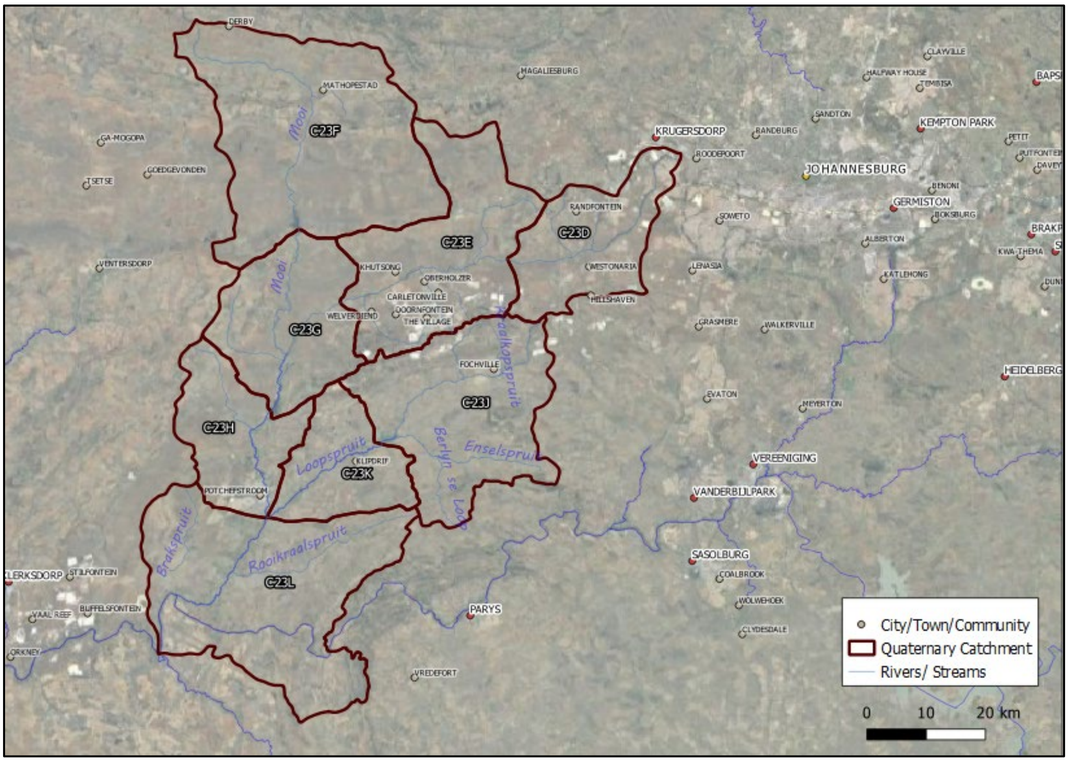

Figure 8: Overview of location of quaternary catchments, cities, towns and rivers in the Mooi River sub-catchment

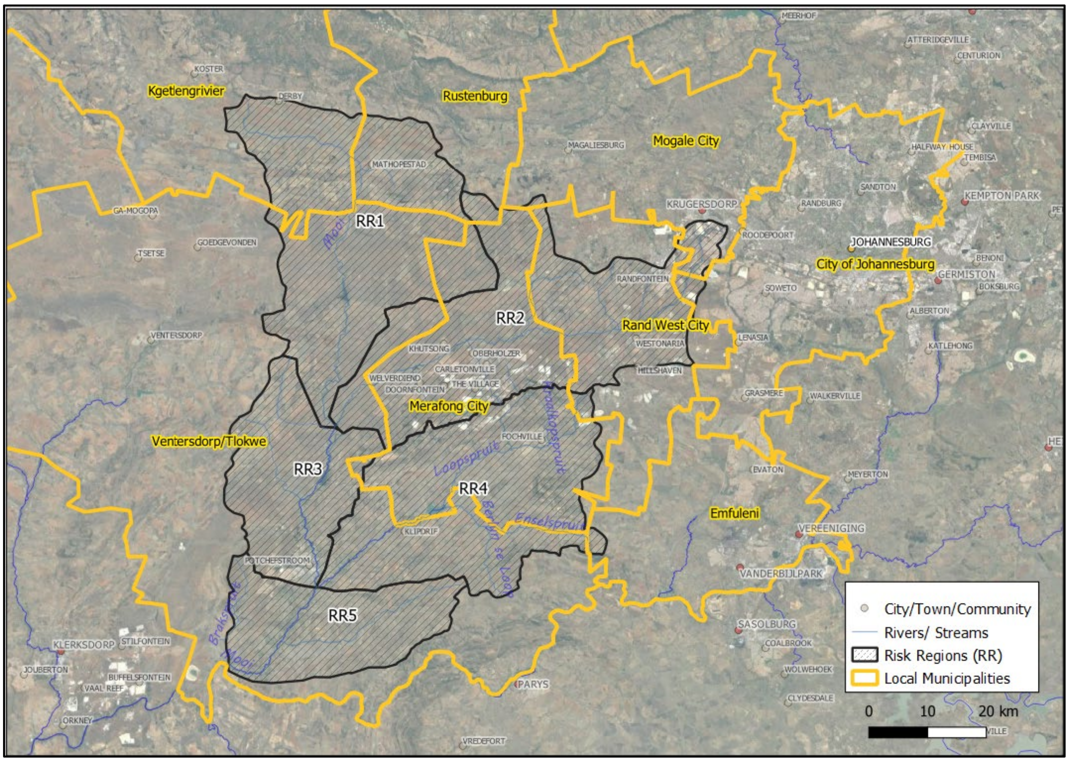

Figure 9: Distribution of Risk Regions across local municipalities in the Mooi River Catchment

Population in the focal region (as of Census 2011) equates to over 745 000 with the vast majority (504 000) residing in the East (RR2) towards the urban landscape of the Johannesburg region (Westonaria, Randfontein and Carletonville) and a smaller proportion (100 000) in the West (RR3) towards Potchefstroom (Figure 9). The relative population density within each RR similarly shows RR1 and RR5 to have the lowest density per capita at 0.104 and 0.014 km^2 /Capita respectively (Figure 10).

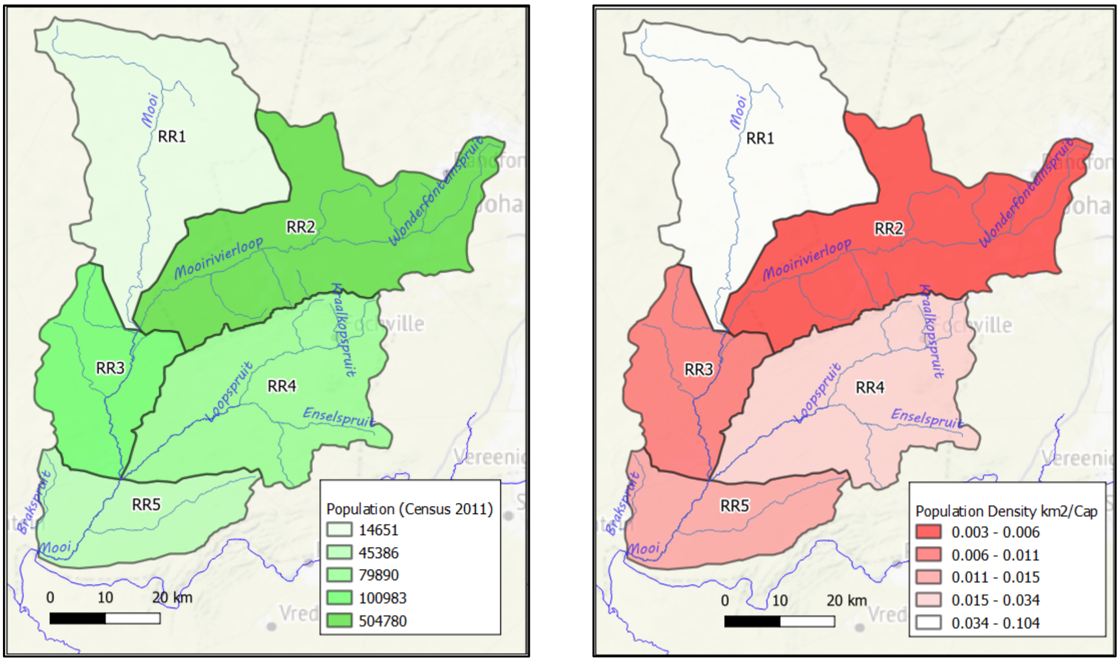

Figure 10: Population and population density (km^2/Cap) per Risk Zone in Mooi River sub-catchment (Census 2011)

Unemployment is observed to increase in developed urban regions including RR2 and RR3 that include the greater Johannesburg and Potchefstroom regions but also the agriculturally focussed RR5 (Figure 11). RR5 also displays the highest percentage of households earning below the minimum wage (<R3 800 /a).

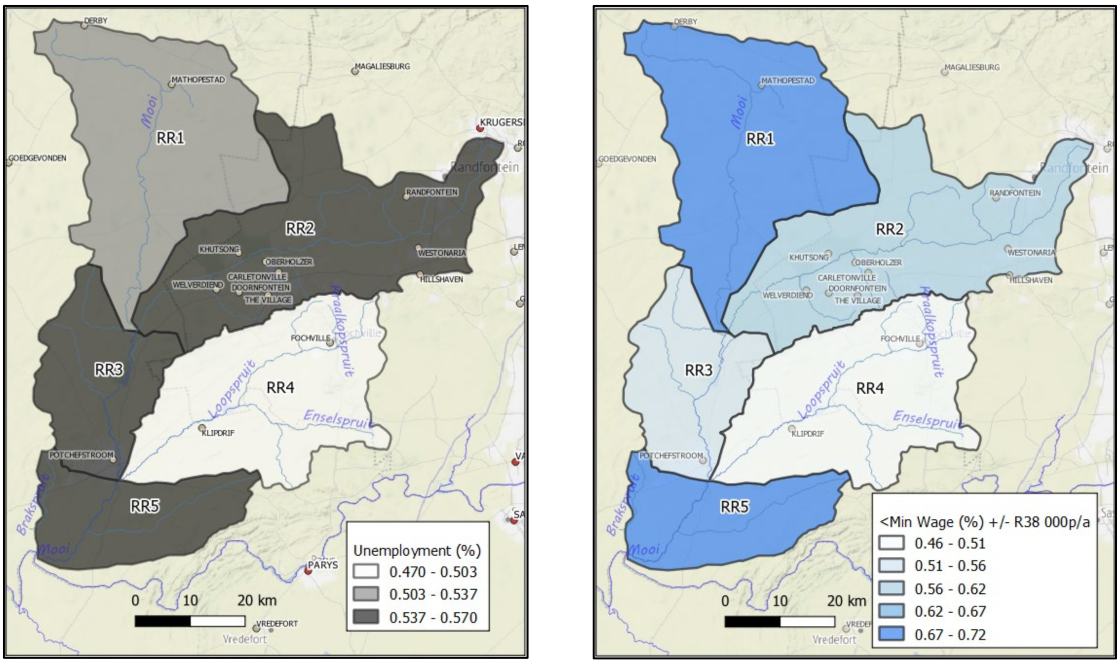

Figure 11: Unemployment and households earning less than minimum wage (% population) per Risk Zone in Mooi River sub-catchment (Census 2011)

Please see appendix 1 for detailed population and demographic data per RR.

4.2.1 Land Cover Analysis

Land cover analysis indicates urban regions (4% of cover in the catchment) largely associated with the greater Johannesburg region (predominantly RR2) and the regions associated with the city of Potchefstroom (Figure 13). The catchment is predominantly characteristic of natural or undeveloped land (64%) and cultivated (29%) regions (Figure 13). Of the cultivated land, approximately 89% is formally cultivated annually, 5% pivot irrigation and both smallholdings and old unused farmland representing 3% (Figure 14). The land cover analysis reiterates the large role the agricultural sector plays in the region. Surface water is represented by a range of rivers and streams as well as scattered wetlands and dams throughout the region. Sub-surface water potential is relatively high from a South African context with ground water potential of greater than 5 l/s being observed throughout much of the catchment (Figure 12).

Please see Appendix 2 for results data tables land cover, cultivated field type data per RR.

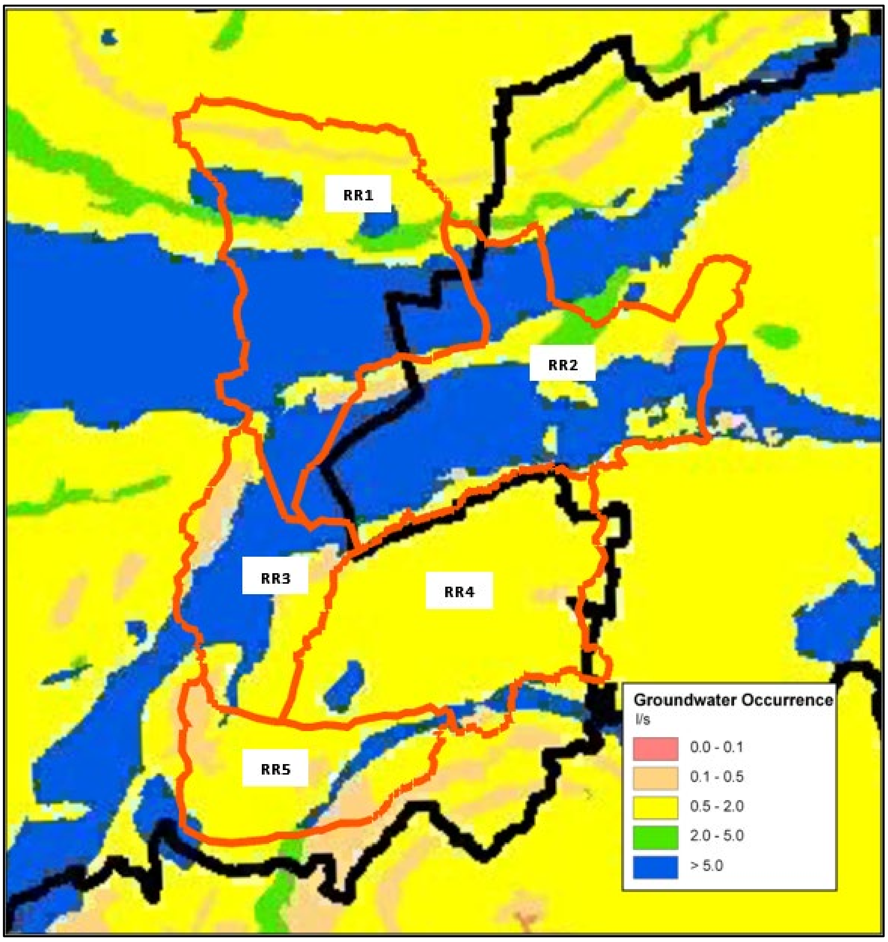

Figure 12: Groundwater occurrence across the Mooi River Catchment (DWS)

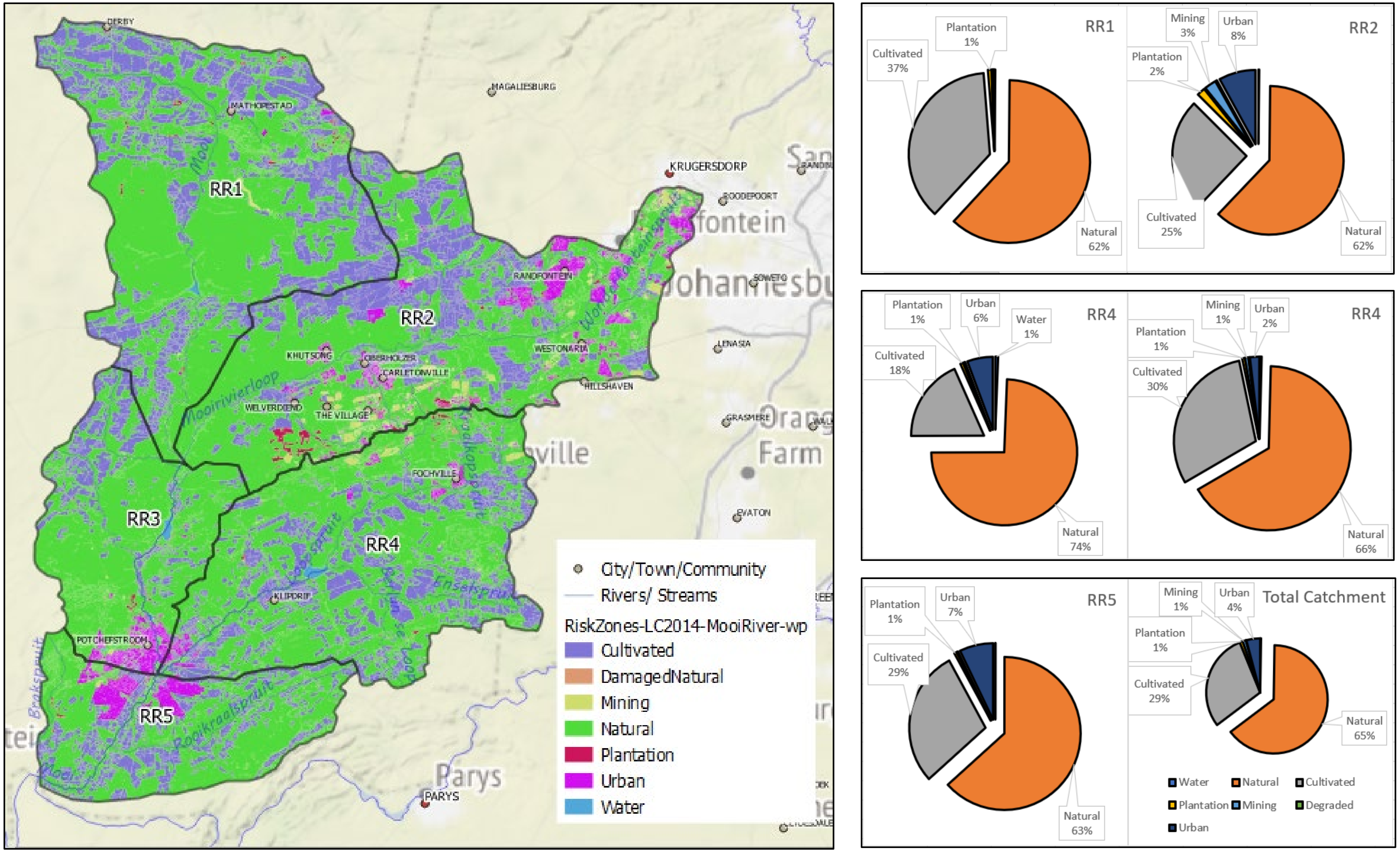

Figure 13: Land cover (DEA 2013/14) in the Mooi River sub-catchment

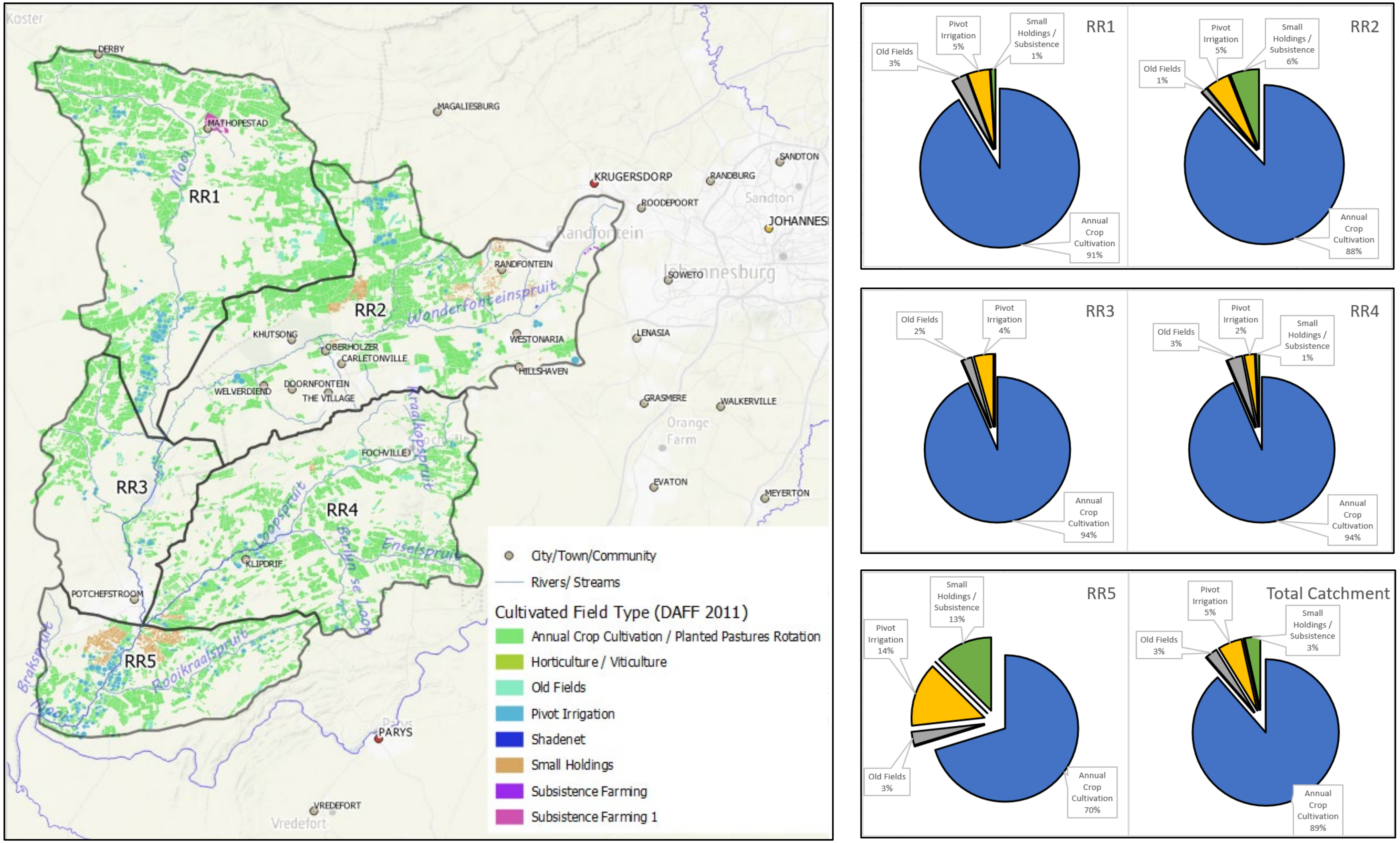

Figure 14: Cultivated field types in the Mooi River sub-catchment (DAFF 2011)

4.2.2 Socio-Economic Vulnerability and Opportunity

A valuable representation of socio-economic vulnerability and opportunity in terms of the effective management of catchments is the Vulnerability Index and Social Wellbeing Score (Eco-CAP$_{ES}$, 2018). These measures are both represented as a percentage population along a predetermined threshold.

The Vulnerability Index represents the percentage of the population that relies on water sources other than regional or local water services as their primary source of water. These sources include boreholes, springs, rivers, dams and water tankers of which if, through various development scenarios, are impacted on, will result in impacts to the livelihoods of communities that rely on them. It is no surprise that the Vulnerability Index follows similar patterns to that of population density along with extent of land transformation (being highest in RR's 2 and 3 in the greater Johannesburg and Potchefstroom region). Greater urban transformation in these regions has resulted in a greater percentage of populations having access to water through service providers. Conversely the rural relatively undeveloped characteristics of RR1 show the populations being highly vulnerable to impacts on water resources (Figure 15). Over half (62%) of the population residing within RR1 relies primarily on boreholes as their primary source of fresh water where much of the population (94%) residing in RR2 receives water directly from a water service provider (Figure 15).

The Social Wellbeing Score (SWS) represents the weighted percentage of the population within each RR that falls above a minimum measure of wellbeing (as per Eco-CAP$_{ES}$ 2018). The index represents the relative wellbeing in terms of access to sanitation, water services, level of employment, education and dwelling type. Similarly, to the Vulnerability Index, RR1 represents greatest percentage population in the catchment that falls under the threshold for social wellbeing (i.e. RR1 has the lowest SWS) (Figure 16). RR3 and RR4 have the highest SWS which is a result of these regions having the highest percentage population having access to piped water, formal housing, education and receiving income greater than minimum wage.

Although there is greater economic development and population densities in RR2, the influx has likely resulted on a trade-off in overall wellbeing (i.e. perhaps overcrowding and reduced access to services). High level of unemployment (56%) certainly plays a role in reduced wellbeing in the region. It is crucial that the spatial distribution of VI's and SWS's must be accounted for to ensure social needs are accounted for when managing the resources in the catchment.

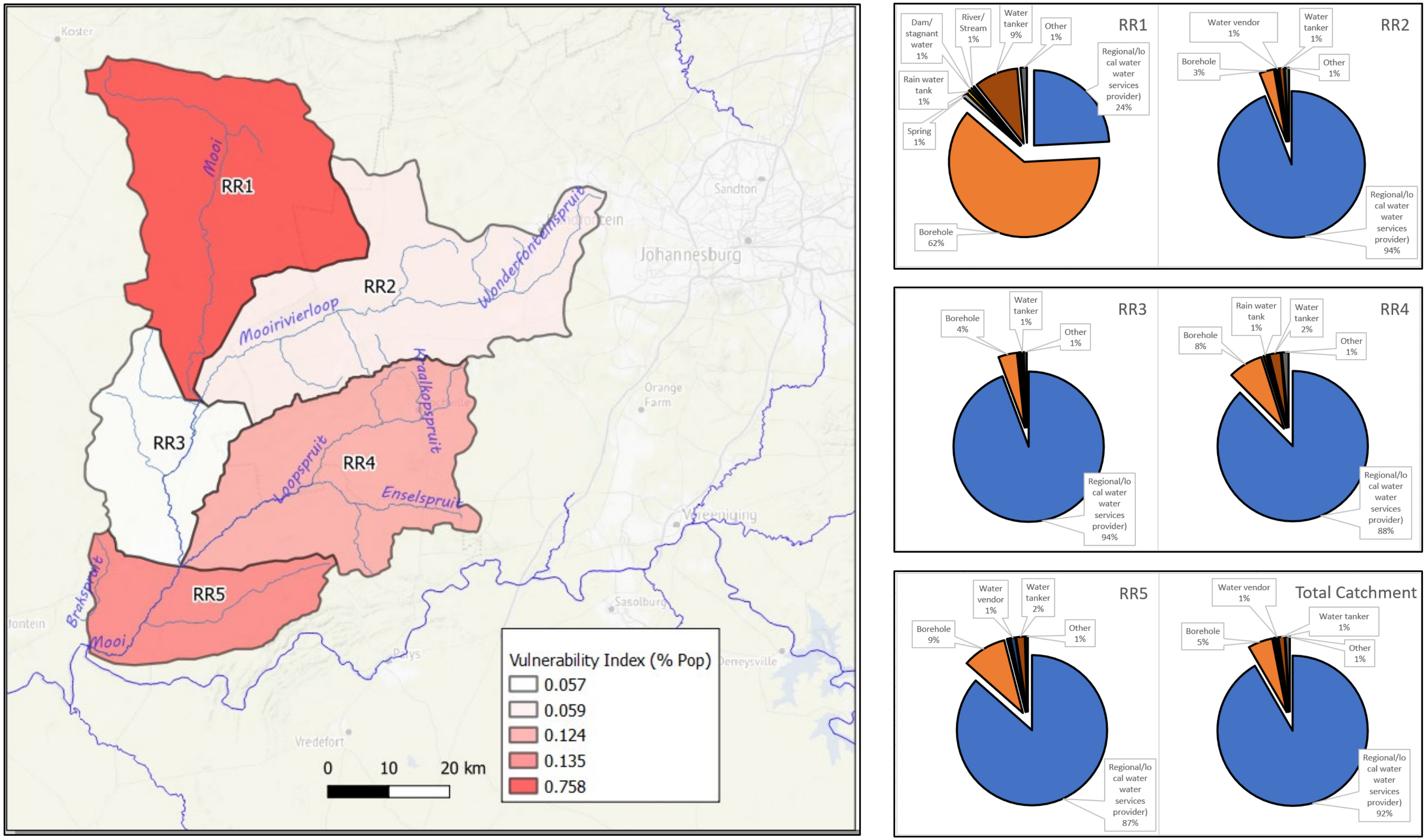

Figure 15: Vulnerability Index per Risk Zone in Mooi River sub-catchment and percentage representation of the population's primary water source (Census 2011; Eco-CAP$_{ES}$ 2018)

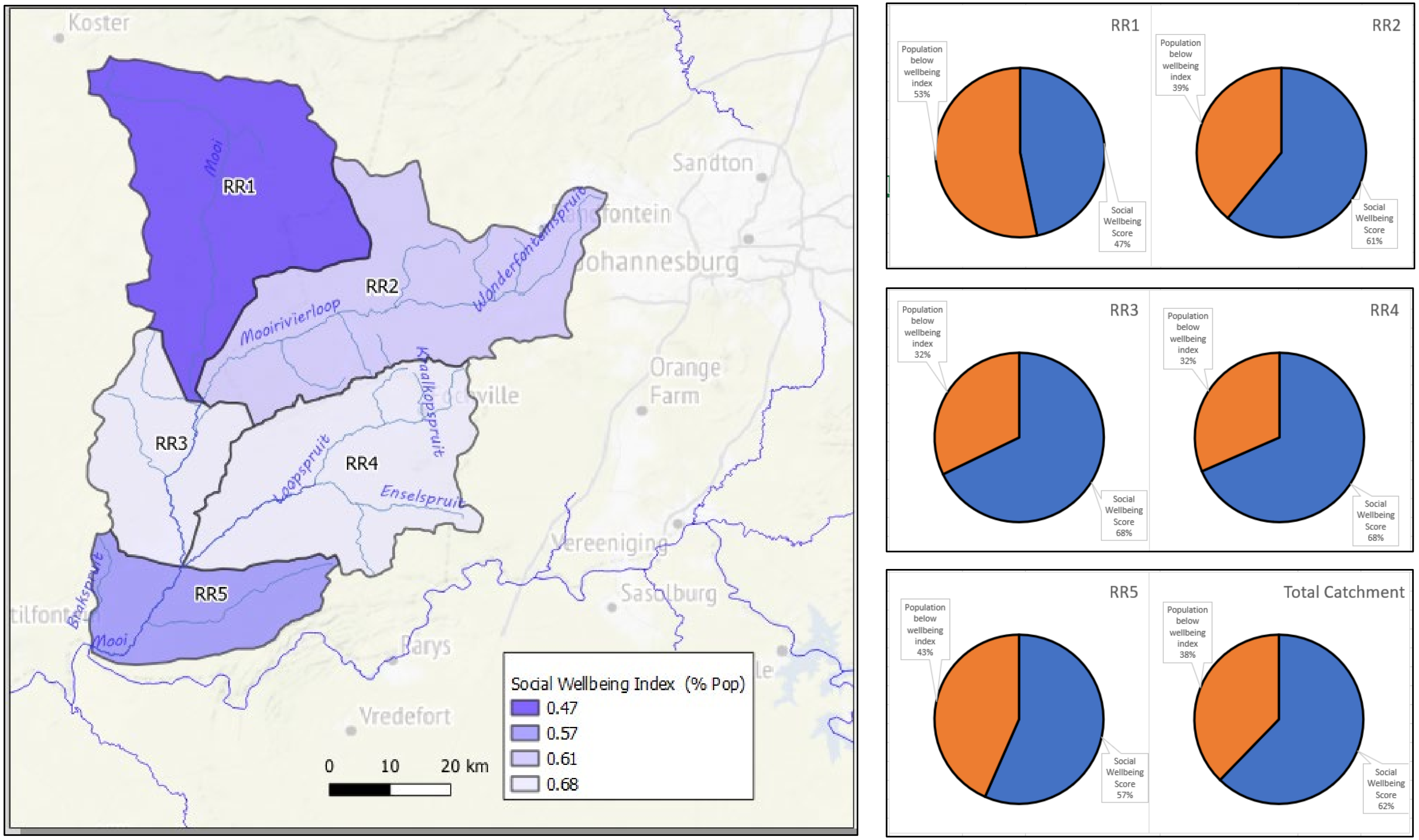

Figure 16: Social Wellbeing Score per Risk Zone in Mooi River sub-catchment (Census 2011; Eco-CAP$_{ES}$ 2018)

4.3 Ecosystem Service Assessment

An ecosystem service mapping exercise was conducted to demonstrate the ecological value chains flowing from ecological infrastructure to beneficiaries in the catchment. The exercise utilises the ecosystem service framework that has been adapted from the Millennium Ecosystem Assessment (MEA 2010) and The Economics of Ecosystems and Biodiversity (TEEB 2013). The development of ecosystem service frameworks has arisen from the realisation that natural biodiversity and its associated ecosystem services can no longer be treated as inexhaustible and free 'goods' and their true value to society as well as the costs of their loss and degradation, need to be properly described and extent understood (TEEB 2010, de Groot et al. 2012).

The information obtained through the socio-economic and ecological classification of the catchment provides an input into the analysis. The results indicate that the presence of specific ecological infrastructure, in this case waterways, wetlands and aquifers, provide various ecosystem services either directly or indirectly to beneficiaries (Table 8). The flow of natural benefits from ecological infrastructure to beneficiaries is dependent on the quantity, extent and condition of ecological infrastructure and in turn the characteristics of beneficiaries, i.e. the flow of benefits from aquatic ecosystems will be greater for industries that are highly reliant on water or rural communities that rely on ecosystems for their livelihoods.

The ecosystem services mapping exercise of the Mooi River catchment shows various degrees of aquatic ecosystems such as rivers and streams, wetlands and aquifers that provide a range of provisioning, regulating and cultural services. The major service provided to all RR's is the water provisioning service, providing both industry (driven by the high extent of irrigated land) and communities (driven by high densities of subsistence farming, and communities directly reliant on natural sources for water) with benefits of fresh water (Table 9). The large extents of undeveloped land what are characteristic of each RR provide opportunities for collection of raw materials, food and to a likely degree, medicinal plants as well as grazing for livestock. These provisioning services benefit the RR's with higher densities of rural communities (i.e. RR1). The presence of protected areas (Vredefort Dome Nature Reserve and private reserves) and recreational sites (such as Boskop and Klipdrif dam) contribute to the cultural value held by beneficiaries of which ecotourism, recreational, educational and inspirational services are provided by the catchment (Table 9). The water provisioning service has been identified to be a major contributor to beneficiaries in the catchment and therefore has been included in the valuation step done below.

Table 8: Ecosystem Services provided by ecological infrastructure in the Mooi River Catchment.

Ecosystem Services (TEEB 2013)		Description	Ecological Infrastructure and associated services		
			Waterway	Wetland	Aquifer
Provisioning Services	Food	Sustainably produced/harvested crops, fruit, wild berries, fungi, nuts, livestock, semi-domestic animals, game, fish and other aquatic resources, etc.	x	x	
	Fresh Water (Water quantity)	Ecosystems play a vital role in the global hydrological cycle, as they regulate the flow and purification of water. Vegetation and forests influence the quantity of water available locally	x	x	x
	Raw materials	Sustainably produced/harvested wool, skins, leather, plant fibre (cotton, straw, etc.), timber, cork, etc.; sustainably produced/ harvested firewood, biomass, etc.	x	x	
	Medicinal resources	Ecosystems and biodiversity provide many plants used as traditional medicines as well as providing the raw materials for the pharmaceutical industry. All ecosystems are a potential source of medicinal resources	x	x	
Regulating Services	Climate/climate change regulation	Carbon sequestration, maintaining and controlling temperature and precipitation	x	x	
	Water quantity regulation	Flood control and Drought Mitigation	x	x	x
	Water purification & waste management	Decomposition/capture of nutrients and contaminants, prevention of eutrophication of water bodies, etc.	x	x	
	Erosion control/ Soil stability	Maintenance of nutrients and soil cover and preventing negative effects of erosion (e.g. impoverishing of soil, increased sedimentation of water bodies)	x	x	
	Biological control	Ecosystems are important for regulating pests and vector borne diseases that attack plants, animals and people. Ecosystems regulate pests and diseases through the activities of predators and parasites. Birds, bats, flies, wasps, frogs and fungi all act as natural controls.	x	x	
Supporting Services	Habitats for species	Habitats provide everything that an individual plant or animal needs to survive: food; water; and shelter. Each ecosystem provides different habitats that can be essential for a species' lifecycle. Migratory species including birds, fish, mammals and insects all depend upon different ecosystems during their movements	x	x	
	Maintenance of genetic diversity	Genetic diversity is the variety of genes between and within species populations. Genetic diversity distinguishes different breeds or races from each other thus providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial crops and livestock. Some habitats have an exceptionally high number of species which makes them more genetically diverse than others and are known as 'biodiversity hotspots'	x	x	
Cultural Services	Landscape & amenity values	Amenity of the ecosystem, cultural diversity and identity, spiritual values, cultural heritage values, etc.	x	x	
	Ecotourism & recreation	Hiking, camping, nature walks, jogging, skiing, canoeing, rafting, recreational fishing, diving, animal watching, etc.	x	x	
	Educational values and inspirational services	Language, knowledge and the natural environment have been intimately related throughout human history. Biodiversity, ecosystems and natural landscapes have been the source of inspiration for much of our art, culture and increasingly for science.	x	x	

Table 9: Ecosystem service mapping of risk regions in the Mooi River catchment (Please note: The ecosystem service mapping exercise has been conducted at a desktop level and inferences have been made based on the catchment classification. To improve accuracy of the ecosystem service assessment, in situ investigations will be required.

Risk Region (Area Ha)	Ecological Infrastructure (Ha; Flow m³/a)	Protected Areas Extent (Ha)	Vulnerability Index (VI) and Social Wellbeing Score (SWS) (Figure 15; Figure 16)	Key Economic Sectors and Municipal Contribution	Economic Features	Relative Flow of Ecosystem Services (TEEB 2013): Food	Fresh Water	Raw Materials	Landscape Values	Ecotourism & Rec	Edu & Inspiration
RR1 (152 383) 62% Undeveloped Land	Waterway - Mooi River - Klerkskraal Dam Wetlands - 3 067 Ha Aquifer - Ave. >5 l/s	Somerville Private NR (2 726 Ha) Fred Coetzee Private NR (2 398 Ha)	Pop: 14 651 VI – 75.8% SWS – 47%	- Mining, - Manufacturing, - Agriculture, - Tourism, - Trade, (Rustenburg IDP 2019, Rural and Commercial, JB Marks IDP 2018)	Cities/ Towns - Mathopestad, Derby Land Use - Irrigated Land: 2 589 Ha - Annual Crops: 51 889 Ha - Informal Crops: 563 Ha - Mining: 374 Ha	Higher	Higher	Higher	Higher	Medium	Medium
RR2 (154 510) 62% Undeveloped Land	Waterway - Mooirivierloop - Wonderfonteinsspruit Wetlands - 2 643 Ha Aquifer - Ave. >5 l/s	Abe Bailey NR	Pop: 504 781 VI – 5.9% SWS – 61%	- Mining, - Trade, - Manufacturing, - Community Services, - Finance, (Rand West IDP 2016) (Merafong IDP 2016)	Cities/ Towns/ Infrastructure - Randfontein, Carletonville, Westonaria - Flip Human, Oberholzer, Khutsong, Welverdiend and Hannes van Niekerk WWTW Land Use - Irrigated Land: 1 831 Ha - Annual Crops: 32 721 Ha - Informal Crops: 2 188 Ha Mining: 3 983 Ha	Lower	Higher	Lower	Medium	Medium	Medium
RR3 (67 714) 74% Undeveloped Land	Waterway - Mooi River - Boskop Dam Wetlands - 719 Ha Aquifer - Ave. >5 l/s	Boskop Dam NR	Pop: 100 984 VI – 5.7% SWS – 68%	- Mining, - Manufacturing, - Agriculture (Rural and Commercial) (JB Marks IDP 2018)	Cities/ Towns/ Infrastructure - Potchefstroom - Tlokwe WWTW Land Use - Irrigated Land: 530 Ha - Annual Crops: 11 388 Ha - No Informal Crops - Mining: 175 Ha	Lower	Higher	Lower	Lower	Medium	Lower
RR4 (128 628) 66% Undeveloped Land	Waterway - Loopspruit - Enselspruit - Klipdrif Dam Wetlands - 1 509 Ha Aquifer - Ave. 0.5-2 l/s	Vredefort Dome (1 823 Ha) UNESCO World Heritage Site	Pop: 79 891 VI – 12.4% SWS – 68%	- Mining, - Manufacturing, - Agriculture (Rural and Commercial) (JB Marks IDP 2018)	Cities/ Towns/ Infrastructure - Fochville - Kokosi and Wedela WWTW Land Use - Irrigated Land: 833 Ha - Annual Crops: 33 299 Ha - Informal Crops: 267 Ha - Mining: 850 Ha	Medium	Higher	Medium	Medium	Medium	Higher
RR5 (63 396) 63% Undeveloped Land	Waterway - Mooi River - Rooikraalspruit Wetlands - 884 Ha Aquifer - Ave. 0.5-2 l/s	Vredefort Dome (16 579 Ha) UNESCO World Heritage Site	Pop: 45 387 VI – 13.5% SWS – 57%	- General Government Services (29%), - Finance (21%), - Community Services (14%), Manufacturing (10%) (Tlokwe IDP 2011)	Cities/ Towns - Agricultural activities: Potchefstroom Land Use - Irrigated Land: 2 857 Ha - Annual Crops: 14 189 Ha - Informal Crops: 2 547 Ha - Mining: 105 Ha	Medium	Higher	Medium	Medium	Medium	Higher

4.4 Total Economic Value of Water in the Catchment

Agriculture, Mining, Manufacturing, Trade and Finance are the key economic sectors in the Mooi River catchment (Municipal IDP's for JB Marks, Merafong City, Kgetleng River, Rustenburg and Rand West[1]). This diversity of economic activities is expected in a catchment represented by such a mosaic of land use types and intensities such as urbanisation, mining, agriculture, rural communities and undeveloped natural regions.

Although comprehensive data on water use in the focal catchment is limited, it was possible to make useful inferences based on fragmented current and historical information. The total water use in the catchment is observed to be (at minimum) 74.8 mil m^3/a (Table 10).

Table 10: Water use in the Mooi River Catchment

Water Use Category		Volume (mil m^3/a)	Reference / Source
Municipal water (HH, Commercial, Industry)		**31.9**	Financial Census for Merafong City, Potchefstroom and Randfontein Local Municipality (2006)
Irrigation Water		**42.9**	Water allocation to irrigated land in the Mooi River Catchment (C23) (DWS 2009)
	Formal Water Scheme	18.7	Irrigation for Tertiary catchment C23 (WRC 1990)
	Other Irrigation	24.2	
Other (Agricultural HH, Industry)		**-**	Negligible due to net positive contribution from mining industry (WRC 1990)
Estimated Water Use		**74.8**	

Water use in the Mooi River catchment can be subdivided into three categories:

1. Municipal use: Providing water for households (rural and urban), commercial and industrial sectors as well as internal municipal use;
2. Agricultural use: Raw water being utilised for the irrigation of crops;

[1] Specific mmunicipalities were selected that best represent the economics of the Mooi River catchment

3. Other Use: Other uses include agricultural households and industries that utilise raw water.

Based on the financial census for Merafong City, Potchefstroom and Randfontein Local Municipality a significant amount of water, approx. 32.3 mil m^3/a, is allocated municipalities (Financial Census 2006)[2] (Table 10).

The greatest extent of land use in the catchment is agriculture with over 90% of land being utilised for dryland agriculture. An area of 8641 ha (5%) of land is under pivot irrigation, which draws an average of 42.9 mil m^3/a (DWS 2009) (Table 10). There are three formal irrigation schemes in the catchment including Klerkskraal, Boskop and Lakeside dams of which account for 44% of the water used in irrigation (WRC 1990).

Other water use includes agricultural households and industries. The only major industry found in the catchment is mining (predominantly gold mining) which is chiefly situated along the watershed between RR2 and RR4. The nature of gold mining processes results in a net positive contributor of water to the catchment (through dewatering) of which has been observed in the catchment (WRC 1990). Agricultural household water use is expected to be negligible compared to the municipal and agricultural use in the catchment.
The size of the water economy in the catchment can be calculated through financially quantifying total sales to end users. In the Mooi River catchment, these sales are specifically made up of municipal sales and raw water sales to irrigation schemes.

Table 11: Municipal Sales of Water in the Mooi River catchment

Municipality	Municipal Sales (R/a 2017)	Reference
JB Marks LM	89 576 000	NWPG 2019
Rand West LM	221 881 000	GPG 2019
Merafong City LM	258 526 000	GPG 2019
Total	569 983 000	

The total water sales by key municipalities to end-users is R570.0 mil (Table 11). The average price of water sold to irrigation schemes is R0.0358 or 3.58c (Vaal Tariffs 2018/19) resulting the total sales by the irrigation sector being R1.536 mil/a.

[2] The collation of data was based on the location of major cities, towns and communities within the study region.

The size of the water economy in the Mooi River catchment is therefore estimated at R571.5 mil/a.

Although the price paid for water represents a direct market value of water, this price does not represent the value of water as a contributing factor to the economy, i.e. this value is not inclusive of additional natural services provided by the hydrological cycle to the catchment (for example precipitation that may contribute to agricultural output but is not captured in water pricing).

This value is representative of the contribution of sectors that are reliant on the provisioning of water by natural systems. The typical method of quantifying this value is through the use of a production functions whereby water use throughout economic sectors is assessed against their economic contributions. A study of this nature however falls outside of the scope of this study. Alternatively, a high-level indicator used to demonstrate this value is the GDP contribution per unit of water for the catchment.

The GDP contribution of all sectors in the Mooi River Catchment were quantified and related back to the GDP contribution per unit water used. Please note, this approach in no way states that all sectors utilise water, but rather infer that if all water supply to the region were to be lost, there would be no economic output within the region. To this end based on GDP/Capita (StatsSA, 2017) the total GDP contribution in the Mooi River catchment falls in the order of R77.4 bil/a (Table 12). The GDP contribution per unit water translates to R1029/m^3 or R1.029 per litre which is significantly larger than the market price of water. The relatively high values show a high economic reliance on water services. The high value is more evident during times of water scarcity as can be seen to impact economic activities in the region.

Table 12: GDP contributions per sector and value contribution in the Mooi River Catchment (StatsSA 2017)

	North West	**Gauteng**	**Total Mooi River Catchment**
Population (RRs)	161 022	584 672	745 693
GDP/Cap (R) (StatsSA 2017)	77 089	111 171	
GDP (mil R/a)	12 413	64 999	77 412

The values demonstrated above underestimate the true value of water to the economy as other ecosystem services (as demonstrated in Table 10) have not been included. As an example, the catchment has been shown to have a significant rural population of who receive natural benefits from associated ecosystems of which are not captured in the formal economy yet provide a range of provisioning and cultural services to beneficiaries. It is vital that the value of environmental externalities is considered when managing these regions.

5 ECOLOGICAL OVERVIEW OF THE MOOI RIVER CATCHMENT

5.1 Introduction

The Mooi River catchment is part of the Vaal River Water Management Area and is situated in the western region of the Gauteng Province and in the North West Province (Van der Walt et al., 2002). There are two major tributaries of the Mooi River namely the Wonderfonteinspruit in the northeast and the Loopspruit in the southeast (Van Veelen, 2009; Merafong City Local Municipality, 2014; Tlokwe City Council, 2014). The Mooi River catchment covers a total area of approximately 1 800 km^2 and has a relatively flat topography as the altitude ranges between 1520 to 1300 m above mean sea level (DWA, 2009; Tlokwe City Council, 2014). The catchment contributes approximately 55.8% of the total runoff of surface water into the Mooi River (Van der Walt et al., 2002). A major source of water to the Mooi River catchment is the various springs that feed the Mooi River, Wonderfonteinspruit and the Loopspruit, with the Gerhard Minnebron, Bovenste Oog and Turffontein Spring contributing the most to the water supply (Tlokwe City Council, 2014).

The Mooi River origin is situated in the Boons area, after which it flows into three impoundments namely the Klerkskraal Dam, Boskop Dam and Potchefstroom Dam. The Loopspruit origin is in the Fochville area and it is fed mostly by springs as well as excess water from various mines (Figure 17). There are two major impoundments on the Loopspruit namely the Klipdrift Dam and the Modder Dam. The Wonderfonteinspruit headwaters are situated in the Krugersdorp region in Gauteng. These systems feed into the Donaldson Dam in Randfontein, where after the river is pumped in a 1 m diameter pipeline for approximately 32 km to Carletonville (DWS, 2014; Hamman, 2012; Tlokwe City Council, 2014). The pipeline ensures three dewatered dolomitic compartments (Oberholser, Venterspos, and Bank) remain dry and water is not recirculated in these compartments.

The Wonderfonteinspruit confluence with the Mooi River can be found upstream of the Boskop Dam (approximately 10 km) meanwhile the Loopspruit confluence with the Mooi River is located downstream of Potchefstroom near the sewage treatment plant (Tlokwe City Council, 2014). The Mooi River then flows to its confluence with the Vaal River system which is approximately 20 km downstream from Potchefstroom (Tlokwe City Council, 2014). The Vaal

River then flows in a westerly direction where the dependence is mainly for agriculture as well as small rural towns. The Vaal River then joins the Orange River near Douglas in the Northern Cape.

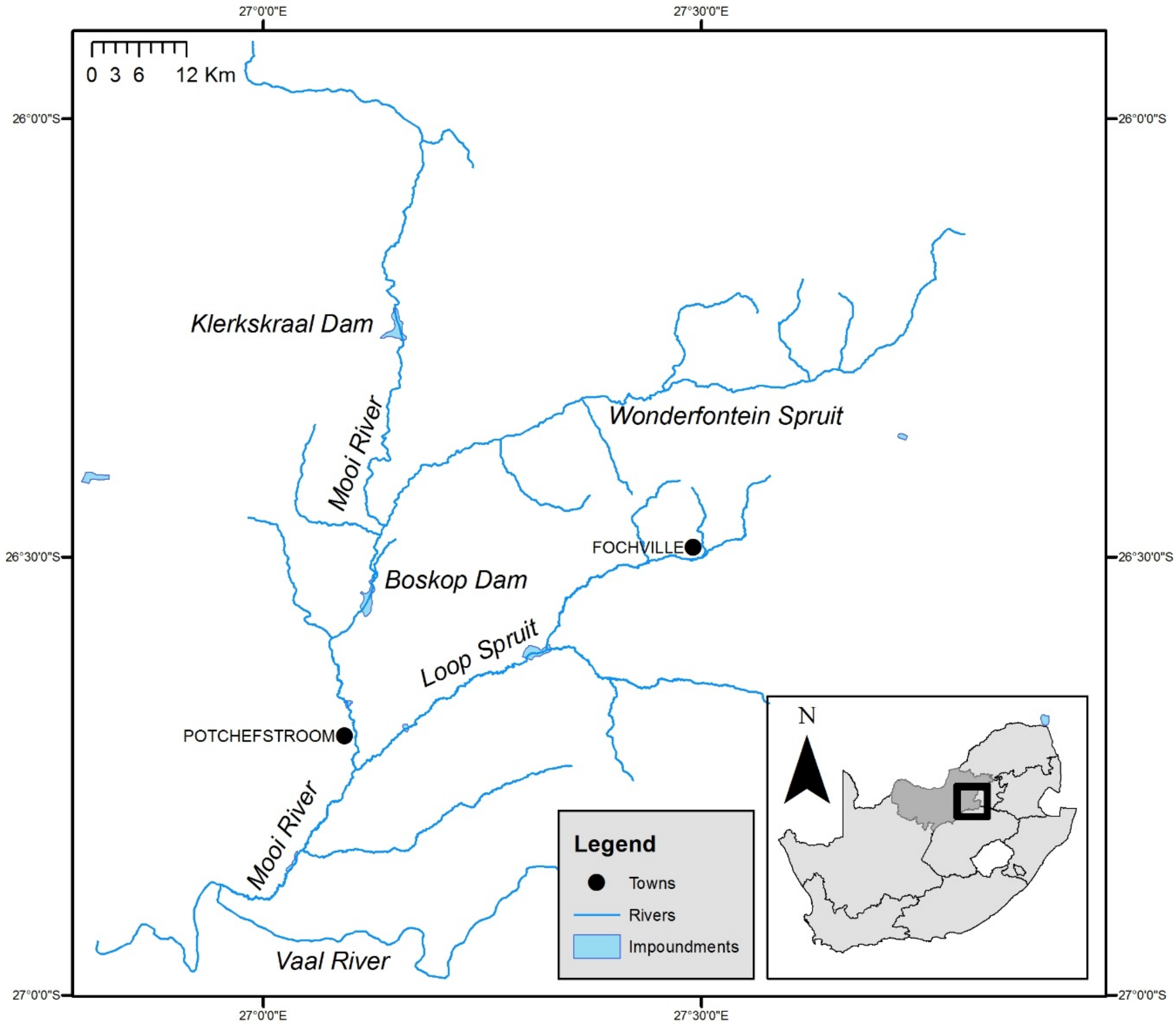

Figure 17: The Mooi River catchment indicating the various major tributaries, impoundments and urban areas in the catchment.

The Mooi River Catchment falls in the Vaal River Water Management area (Figure 18), in secondary catchment C2, and tertiary catchment C23. There are eight quaternary catchments that form the Mooi River catchment (Figure 18).

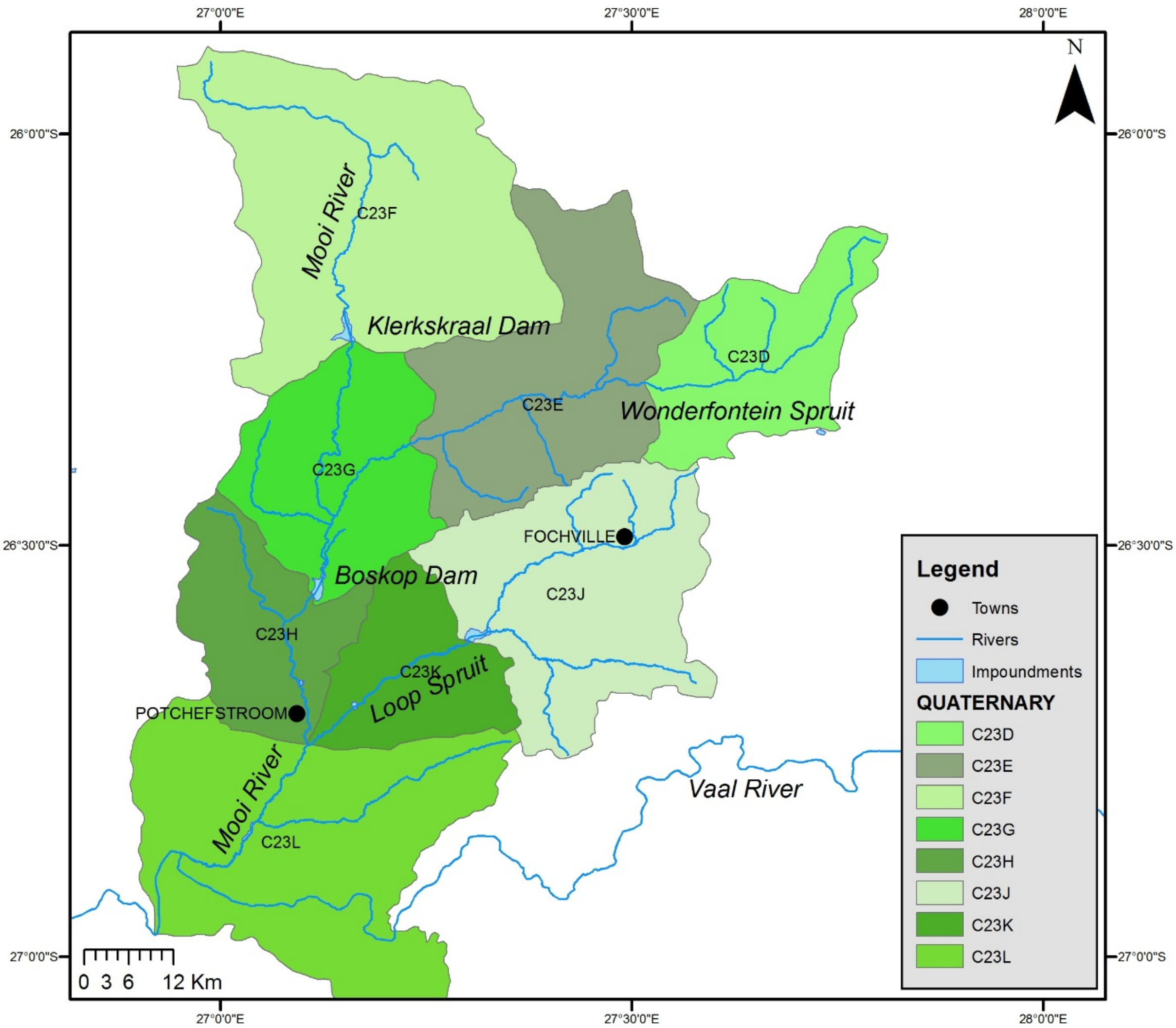

Figure 18: The quaternary catchments of the Mooi River catchment (DWS RQIS data layer).

5.2 Climate

The Mooi River receives annual rainfall of approximately 680 mm; however, the average evaporation potential in the catchment is 1 650 mm (Van der Walt et al., 2002). The mean temperatures ranges from > 32°C in the summer to -1°C in the winter months. Frost is also a common occurrence in the winter season (Cilliers and Bredenkamp, 2000). The catchment is situated in the Highveld Ecoregion (Ecoregion Level 1) and there are three different level 2 ecoregions situated in the catchment (Figure 19) (Kleynhans et al., 2005). However, the majority of the catchment is only situated in two of these ecoregions.

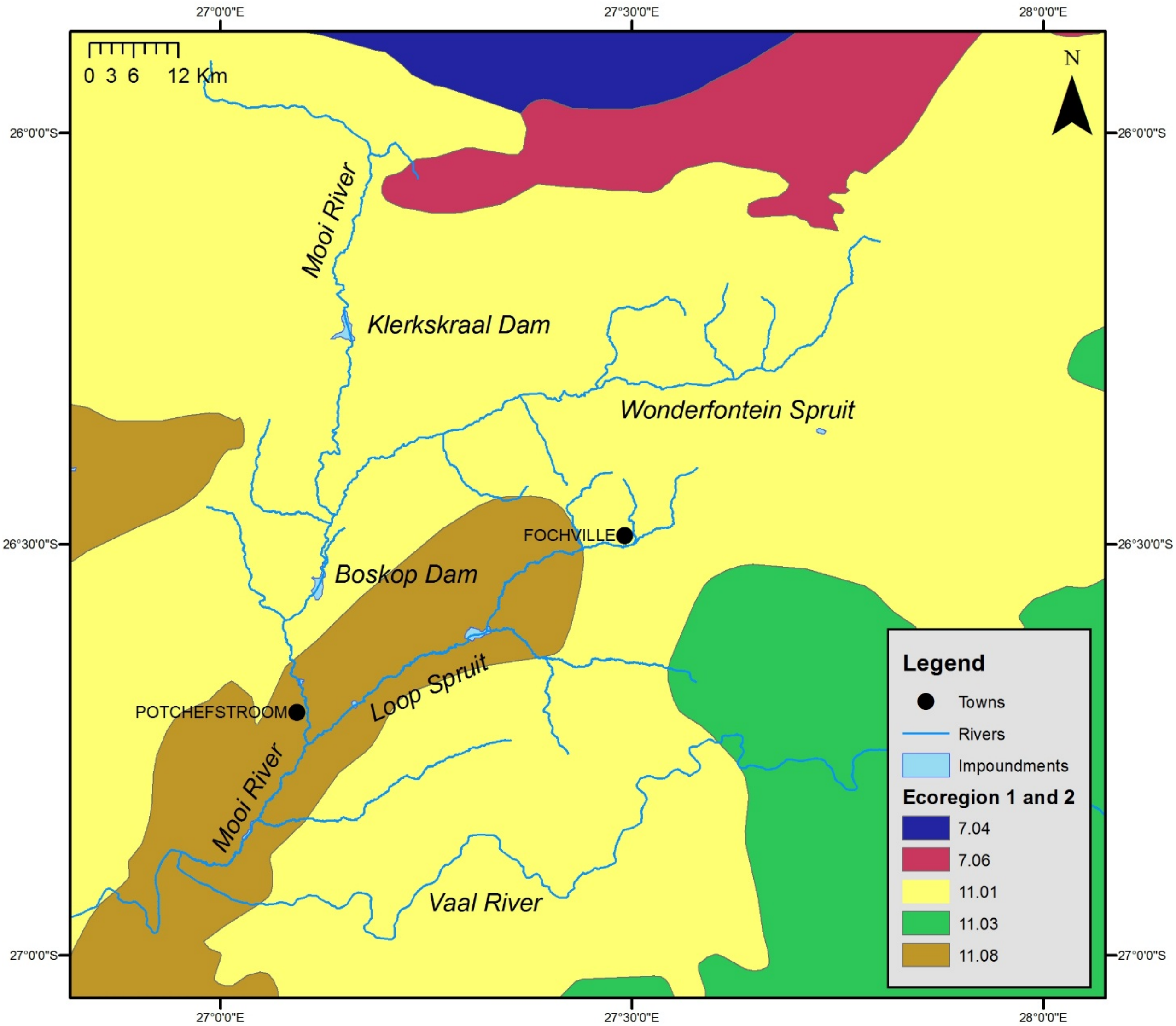

Figure 19: Map of the Mooi River catchment indicating the level 1 and level 2 ecoregions that can be found within the catchment (DWS RQIS).

5.3 Geology

The geology in the area is dominated by dolomite and there are major gold mining operations across the upper reaches of the catchment (Barnard et al., 2013; DWA, 2009; DWS, 2014).

5.4 Anthropogenic activities

The main anthropogenic activities in the catchment including mining, informal settlements, urban areas and agriculture. The Mooi River catchment has some of the richest gold reserves in South Africa (Gauteng Department of Agriculture and Rural Development, 2011; Tlokwe City Council, 2014). There are also numerous informal settlements surrounding the various urban areas and it includes Kokosi, Khutsong, and Green Park (DWS, 2014). The agricultural activities in the catchment include livestock, irrigation and crop farming (Barnard et al., 2013; DWS, 2014). There are also some industrial and recreational water use that is concentrated around Potchefstroom and Boskop Dam. The land cover assessment from 2009 are indicated in Figure 20.

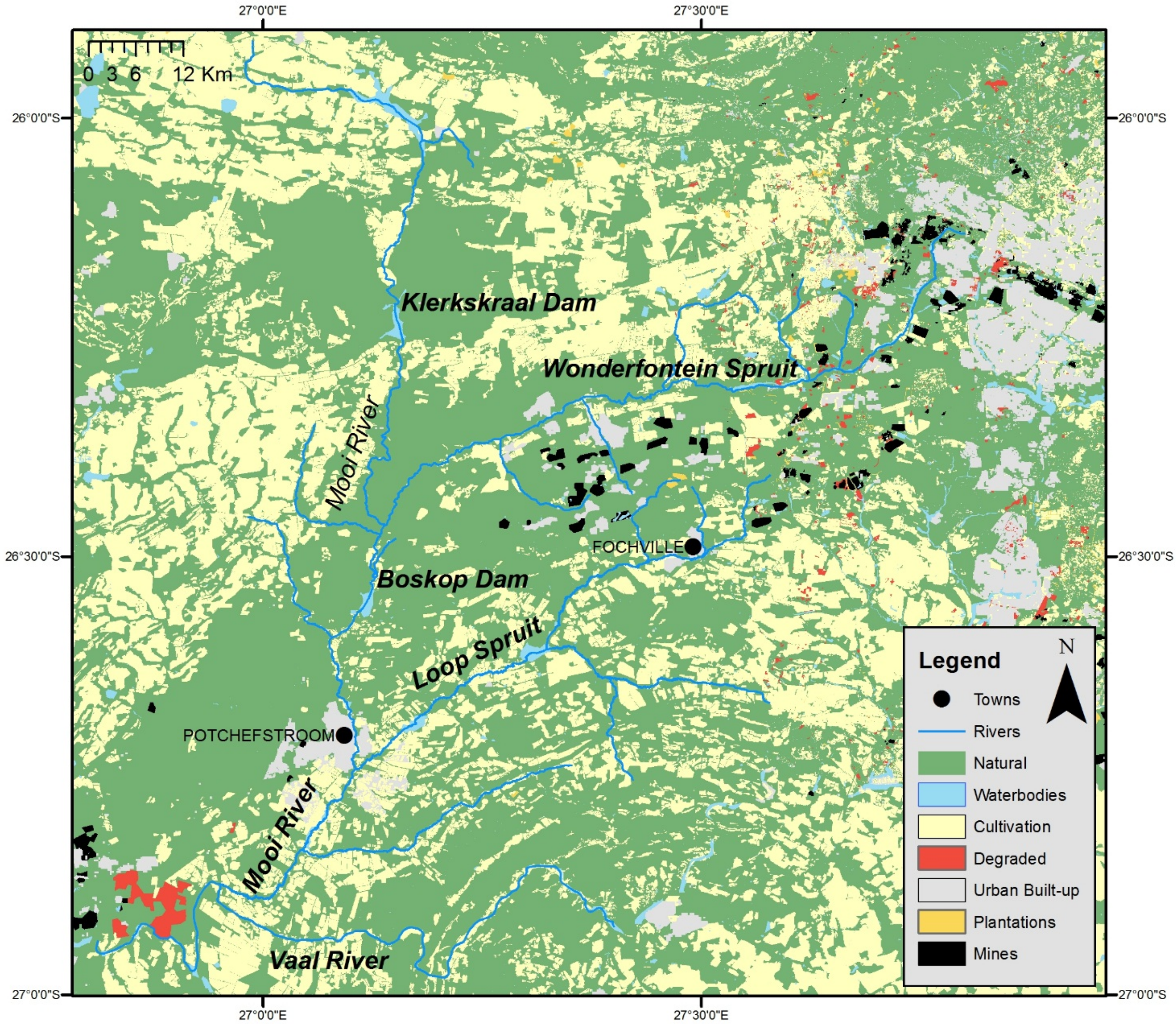

Figure 20: The land cover situation in the Mooi River catchment based on the 2009 Land Cover assessment.

5.5 Aquatic Ecosystems in the Mooi River catchment

The majority of the aquatic ecosystems in the catchment relates to the major river systems as described previously, i.e. Mooi River, Wonderfonteinspruit and the Loopspruit. However, there are also wetland ecosystems and ground water systems that are important from both a water quantity and quality aspects. The wetland vegetation that are most dominant in the catchment are either Dry Highveld or Mesic Highveld Grassland (Figure 21) (Driver et al., 2011). These types are dominated by different vegetation groups in the various areas in the catchment. The vegetation types in the hillier areas of the catchment are generally variations of Central Bushveld vegetation.

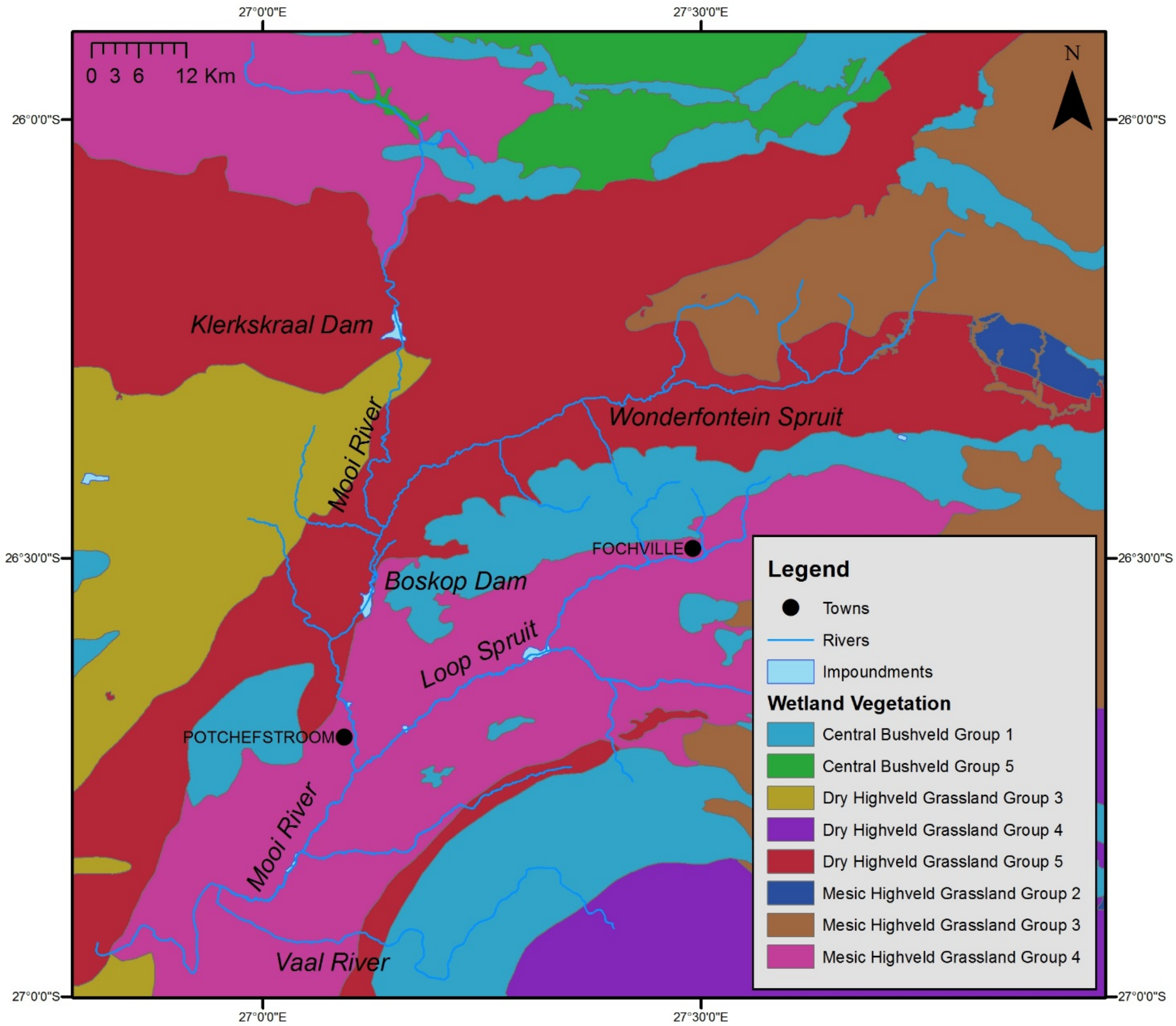

Figure 21: Wetland vegetation (NFEPA data layer) of the Mooi River catchment (Driver et al., 2011).

The wetland types that can be found in the Mooi River catchment are highlighted in Figure 22; however, the largest areas of wetland found within the catchment are floodplain wetlands, and channelled valley bottoms. There are also various seeps and depressions in the catchment; many of these are temporary systems due to the arid nature of the region.

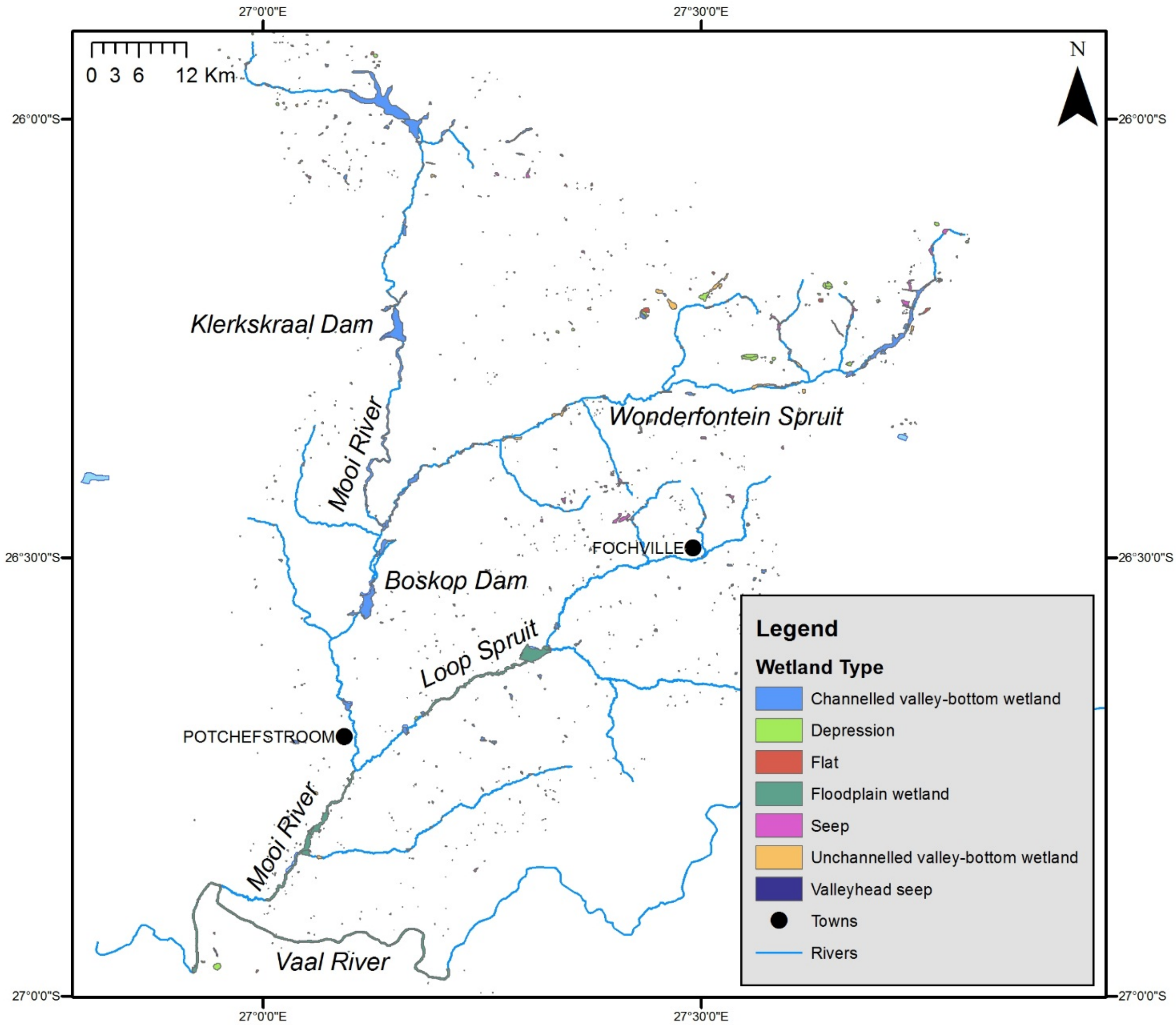

Figure 22: Map of the Mooi River catchment indicating the various wetland types that can be found within the catchment (Driver et al., 2011).

The National Freshwater Ecosystem Protected Areas (NFEPA) was completed during early 2011 and the goal of the project was determining strategic spatial priorities for conserving freshwater ecosystems and supporting sustainable use of water resources (Driver et al., 2011). This does not mean that the rivers cannot be used for human needs but that the rivers should be supported by good planning, decision-making and management so that human use does not impact on the river ecosystem condition. The project outputs are in the form of numerous maps indicating different categories with their own management implications. These categories include river FEPA's (Freshwater Ecosystem Protected Areas) and associated sub-quaternary catchments, wetland FEPA's, wetland clusters, fish support areas and associated sub-quaternary catchments, fish sanctuaries, phase 2 FEPA's and associated sub-quaternary catchments and upstream management areas (Driver et al*.,* 2011).

River FEPA's were determined where rivers are currently in a good condition (Ecological Category A or B) and it is possible to achieve biodiversity targets. These quaternary catchments should remain in a good condition if biodiversity goals are to be met, as well as to ensure the sustainability of water resource use. The river FEPA also refers to the catchment land use as the surrounding land use and tributaries should be managed so that the good condition in the river reach can be maintained. The upstream management areas refer to catchments where there are downstream FEPA's and therefore the upstream human and land use activities should be managed to maintain the ecological category downstream (Driver et al*.,* 2011). Fish support areas are defined as fish sanctuaries that are not in a good condition (A or B ecological category) or if the catchments are important for migration of threatened or near-threatened fish species. The management of fish support areas is similar to river FEPA's in this case as there are an endangered fish species present. The ecological condition should remain in the current condition or if it is not in a good condition, management measures should be employed to increase the ecological condition. Driver et al*.* (2011) recommended various management measures that deals with water quantity, water quality and habitat, as well as biota that should be implemented. The Mooi River catchment are comprised of upstream support areas as well as fish support areas (Figure 23).

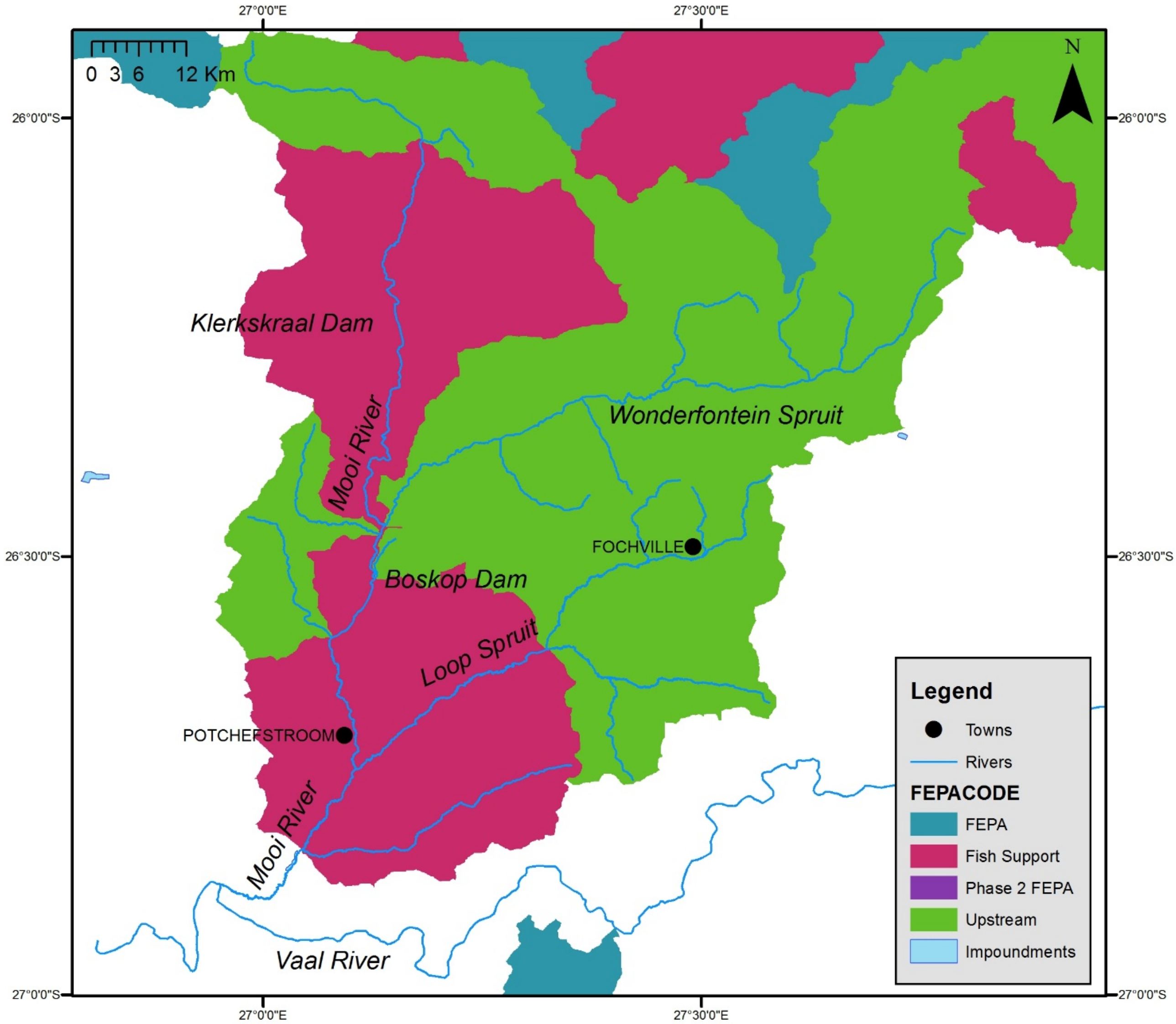

Figure 23: Map of the Mooi River catchment indicating the Freshwater Ecosystem Protected Areas (FEPA) that are found within the various quaternary catchments (Driver et al., 2011).

5.6 Present Ecological State and Ecosystem Importance and Sensitivity

A summary of present ecological state and ecosystem importance and sensitivity are presented in Table 13 below for the Mooi River Catchment. In the DWS (2014) project to assess the PES-EIS of the catchment, 25 sub quaternary reaches were assessed. The PES category varied from Ecological Category E to Ecological Category C. However, the predominant PES found was Ecological Category D. The ecological importance was generally found to be moderate while the ecological sensitivity was found to be moderate to high. In most sub quaternary reaches the recommended category for management should be an Ecological Category C or an Ecological Category B.

Table 13: Present Ecological State and Ecosystem Importance / Sensitivity in the Mooi River and its tributaries (DWS, 2014).

SQ REACH	SQR NAME	PES CATEGORY MEDIAN	MEAN EI CLASS	MEAN ES CLASS	LENGTH km	STREAM ORDER	DEFAULT EC
C23D-01313	Wonderfonteinspruit	E	MODERATE	LOW	28.0	1.0	C
C23D-01339	Rietfonteinspruit	E	LOW	LOW	16.5	1.0	D
C23D-01343	Middelvleispruit	D	MODERATE	LOW	11.2	1.0	C
C23D-01365	Wonderfonteinspruit	C	MODERATE	MODERATE	4.0	2.0	C
C23D-01384	Wonderfonteinspruit	E	LOW	LOW	19.0	2.0	D
C23E-01368	Mooirivierloop	E	LOW	LOW	12.8	2.0	D
C23E-01378	Mooirivierloop	D	MODERATE	LOW	11.6	2.0	C
C23F-01189	Mooi	D	LOW	LOW	10.3	1.0	D
C23G-01250	Mooi	D	MODERATE	HIGH	61.7	2.0	B
C23G-01406	Mooirivierloop	E	LOW	MODERATE	21.5	2.0	C
C23G-01551	Mooi	D	MODERATE	HIGH	1.4	3.0	B
C23G-01558	Mooi	D	MODERATE	MODERATE	7.5	3.0	C
C23H-01575	Mooi	E	MODERATE	HIGH	9.9	3.0	B
C23H-01653	Mooi	D	MODERATE	MODERATE	21.8	3.0	C
C23J-01487	Loopspruit	D	MODERATE	MODERATE	16.6	1.0	C
C23J-01494	Elandsfonteinspruit	D	MODERATE	MODERATE	15.7	1.0	C
C23J-01507	Kraalkopspruit	C	MODERATE	HIGH	10.6	1.0	B
C23J-01523	Loopspruit	C	HIGH	MODERATE	23.2	2.0	B
C23J-01543	Loopspruit	D	MODERATE	MODERATE	8.1	2.0	C
C23J-01615	Enselspruit	E	MODERATE	MODERATE	12.1	2.0	C
C23J-01669	Enselspruit	D	MODERATE	MODERATE	26.1	1.0	C
C23J-01699	Berlyn se Loop	C	MODERATE	HIGH	17.0	1.0	B
C23K-01579	Loopspruit	D	MODERATE	HIGH	37.0	3.0	B

SQ REACH	SQR NAME	PES CATEGORY MEDIAN	MEAN EI CLASS	MEAN ES CLASS	LENGTH km	STREAM ORDER	DEFAULT EC
C23L-01759	Mooi	D	HIGH	HIGH	16.3	4.0	B
C23L-01768	Rooikraalspruit	D	MODERATE	MODERATE	40.6	1.0	C
C23L-01827	Mooi	D	HIGH	HIGH	19.0	4.0	B

5.7 Resource Quality Objectives: Mooi River Catchment

The Resource Quality Objectives (RQO) for the Upper Vaal River catchment was published in the Government Gazette in April 2016. The following requirements were set for the Wonderfonteinspruit:

River Quantity RQOs: No river quantity RQOs were set for the WFS. Therefore, the increased water that would be decanted into the Wonderfonteinspruit will not impact on RQOs for water quantity.

Water Quality RQOs: There are numerous water quality RQOs that have been set. These include three main categories – nutrients, system variables and metal concentrations. The water quality RQOs for the following constituents are as follows:

- electrical conductivity < 111 mS/m.
- phosphate < 0.125 mg/L
- nitrates / nitrites < 4 mg/L.
- fluoride < 3.0 mg/L; aluminium < 150 µg/l;
- arsenic < 130 µg/L;
- cadmium (hard) < 5 µg/L;
- chromium (VI) < 200 µg/L;
- copper (hard) < 8.0 µg/L;
- mercury < 1.7 µg/L;
- manganese < 1300 µg/L;
- lead (hard) < 13.00 µg/L;
- selenium < 30 µg/L;
- zinc < 36 µg/L;
- chlorine < 5.0 µg/L;
- Endosulfan < 0.2 µg/L and
- Atrazine < 100 µg/L.
- Uranium (U) is set at < 15 µg/L.

Aquatic Ecology RQOs: The aquatic ecology RQO for the ecosystem components have been set at an Ecological Category of D (> 42) for instream habitat, the macroinvertebrate community and the fish community. The overall recommended ecological categories for the WFS have also been set at a D category.

Descriptive RQO:

- Instream habitat must be in a largely modified or better condition to support the ecosystem.
- Instream biota must be in largely modified or better condition.
- Flows must be in largely modified or better condition. Low flows must be suitable to support the ecosystem functions.
- Water quality:
    - The nutrient concentrations must be decreased for ecosystem condition and other users.
    - Salt concentrations must be at levels that do not threaten the ecosystem and are suitable for users.
    - The river water must not be toxic to aquatic organisms or be a threat to human health. Uranium must be at acceptable levels

River Riparian Zone Habitat

- The riparian zone must be in a largely modified or better condition. Riparian Zone Habitat Integrity category ≥ D (≥ 42)
- Riparian vegetation must be in a largely modified or better condition. Riparian EcoStatus category: ≥ D (≥ 42)
- Low and high flows must be in a largely modified or better condition. Hydrological category ≥ D (≥ 42)

Klerkskraal Dam Resource Quantity

The descriptive RQO is: “Dam levels must therefore be maintained at levels sufficient for irrigation releases as well as for protection of ecosystem function downstream”.
Flow releases: Vaal RE-EWR2 in C23G; VMAR = 37.7x106 m^3; REC = D*. (Releases from Klerkskraal Dam monitored by C2H006.) Details can be found in Table 14.

Table 14: Numerical limits for water quantity for Klerkskraal Dam.

Maintenance low flows (m^3/s) (Percentile)		Drought flows (m^3/s) (Percentile)
Oct	0.12 (70)	0.106 (99)
Nov	0.12 (70)	0.109 (99)
Dec	0.12 (70)	0.106 (99)
Jan	0.128 (60)	0.108 (99)
Feb	0.155 (60)	0.124 (99)
Mar	0.153 (50)	0.115 (99)
Apr	0.16 (60)	0.12 (99)
May	0.154 (60)	0.116 (99)
Jun	0.154 (60)	0.118 (99)
Jul	0.146 (60)	0.113 (99)
Aug	0.143 (60)	0.112 (99)
Sep	0.137 (70)	0.113 (99)

Resource quality objectives: Impoundment water quality

The following RQOs for water quality have been set for both the Klipdrift Dam in the Loop Spruit and the Boskop Dam in the Mooi River:

Nutrients: The Klipdrift Dam system is currently eutrophic and must be improved and then maintained in a mesotrophic state. Phosphate ≤ 0.025 mg/L P (Klipdrift Dam: 95th percentile = 0.031 mg/L). Nitrate and nitrite ≤ 1.00 mg/L N (Klipdrift Dam: 95th percentile = 0.11 mg/L).

The Boskop Dam system nutrient concentrations must be maintained such that the system is in a mesotrophic state. Phosphate ≤ 0.025 mg/L P (Boskop Dam 95th percentile = 0.006 mg/L). Nitrate and nitrite ≤ 1.00 mg/L N (Boskop Dam: 95th percentile = 0.3 mg/L).

Salts: The Klipdrift Dam salt levels must be maintained at concentrations where they do not impact negatively on the ecosystem. Electrical conductivity ≤ 85 mS/m. The 95th percentile = 102 mS/m.

System variables: The Boskop Dam pH of the water should not negatively impact on ecosystem function. pH_max * ≥ 8.8 (95th percentile = 8.7); pH_min * ≤ 5.9 (95th percentile = 8.1).

Toxins: The Klipdrift Dam must avoid cyanobacteria blooms and the dam must be maintained in a mesotrophic state. Chl-a: phytoplankton* ≤ 20 µg/L. No data for 95th percentile.

Resource quality objectives: Groundwater

The following RQOs for the groundwater aquifers have been set:

RU71-RU73: Medium to long-term water trends should not show negative decline or deviation from the natural trend. Indicator will be: Depth to Groundwater Level according to Groundwater Monitoring Guidelines. Numerical limits are as follows:

- RU71 Water level fluctuations around the average site water level should not exceed 13.8 m.
- RU73 Water level fluctuations around the average site water level should not exceed 4.2 m.
- RU72 Water level fluctuations around the average site water level should not exceed 7.16 m.

5.8 Ecological Reserve

The Ecological Reserve for the Vaal River catchment was gazetted on 21 December 2018 in the government gazette. It is based on the Reserve Determination that was completed and implemented since 2009. The Reserve for the Mooi River at the EWR site is presented in Table 15 below. It describes the PES, EIS and TEC together with the ecological and basic human needs Reserve based on the MAR.

Table 15: Proposed Reserve for the Mooi River at the EWR site. The EWRs to protect the aquatic ecosystem and the BHN requirements are include.

Quaternary Catchment	Water Resource	PES	EIS	TEC5	MAR (MCM)[1]	Reserve[2] (%MAR)	Ecological Reserve [3](%MAR)	Basic Human Needs Reserve[4] (%MAR)
C23G	Mooi River – RE-EWR2	D	Low	D	37.7#	19.061	19.05	0.0106

1) MAR is the Mean Annual Runoff (# Based on natural flow at the EWR site MAR).
2) The Reserve is the total requirement that accounts for both the Ecological Reserve and the Basic Human Needs Reserve (BHN).
3) Ecological Reserve requirement represents the long term mean based on the MAR. If the MAR changes, this volume will also change.
4) Represents the BHN requirement as a percentage of the MAR. Basic human needs includes the population directly reliant on rivers,
streams and springs for water supply (derived from 2011 Census data)

6 REGIONAL RISK METHODOLOGY FOR THE DETERMINATION AND INTEGRATION OF ECOLOGICAL WATER REQUIREMENTS IN CATCHMENT MANAGEMENT

The previous sections have highlighted various methodologies to approach environmental water in South Africa and also the rest of the world. Following on from the initial methodologies, most researchers working with environmental water agree that an approach that incorporates the social aspect of water resources are vitally important (Palmer and Munnik, 2017). The inclusion of stakeholders in the process makes it all the more likely that it will succeed as there is buy-in from the various stakeholders.

It is also evident that much more research is needed in this field, especially changing ecosystems due to climate change. Therefore, an environmental water requirement should be more flexible and adaptive in the future. All too often, the methodologies and management measures have been too rigid to be responsive to dynamic aquatic ecosystems.

Therefore, an integrated approach based on the Relative Risk Model (RRM) proposed by O'Brien and Wepener (2012) and O'Brien et al. (2018) (Figure 24) is potentially a framework to improve EWRs in South Africa for aquatic ecosystems in South Africa. It must be noted that it is proposed that this methodology be used as an integrated framework for riverine, wetland and groundwater ecosystems. This methodology would be supplementary to existing methods and provide a methodology for integration of both social and ecological endpoints in the management of aquatic ecosystems. The ten steps of the RRM is discussed briefly here together with the information generated for the specific step in the Mooi River Catchment.

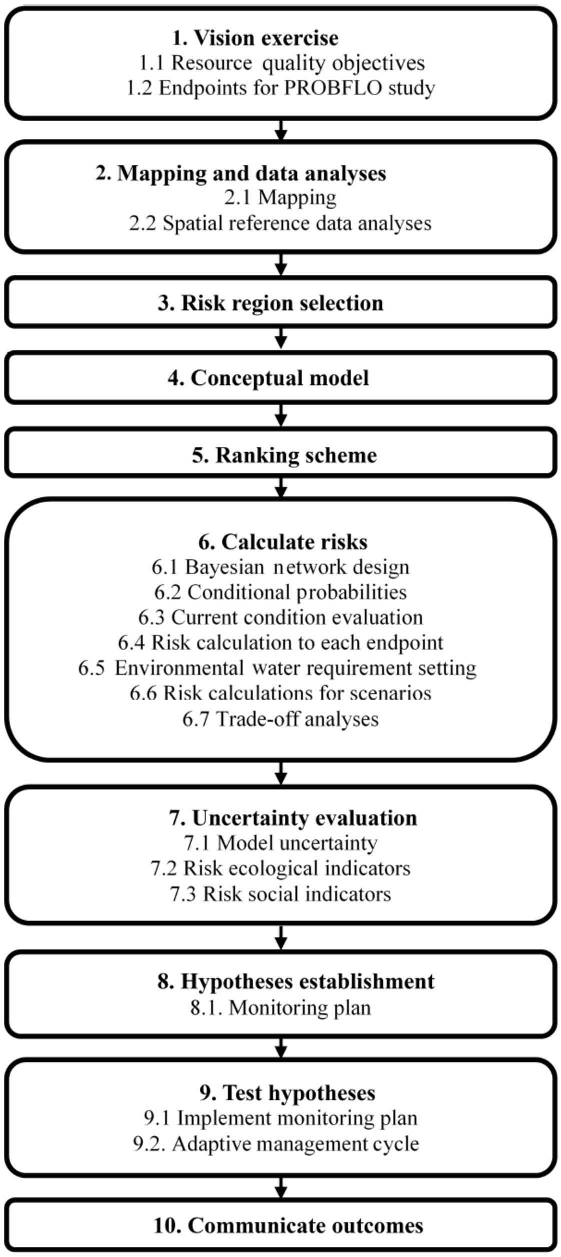

Figure 24: **The ten procedural steps of the Relative Risk Method (from O'Brien and Wepener, 2012; O'Brien et al., 2018)**

6.1 Vision exercise

This is the initial determination of the importance of the specific catchment and what the clear water resource management objectives are for the catchment. The clarity of the catchment vision is extremely important to ensure that it is able to direct the use and protection of water resources (O'Brien et al., 2018). The development of a catchment vision can follow numerous approaches but as the Mooi River catchment already has defined resource quality objectives (RQOs) that have been gazette. In addition, the Mooi River has been assigned a Management

Class III, indicating the river is a well-used catchment. As seen in previous sections, the RQOs provide narrative and numerical description of various ecosystem components that are important for the balanced use and protection of water resources in the Mooi River catchment.

A visioning exercise was held together with numerous stakeholders from the Mooi River catchment (Table 16) on 12 July 2019. The stakeholders were composed of staff from the NWU, local and district municipal offices, Sibanye-Stilwater mining, provincial Department of Water and Sanitation and a Non-Governmental Agency (Federation for Sustainable Environment). The workshop aim was to define what is important in the catchment and what the various endpoints could be for water resource management in the catchment.

Table 16: Attendees for the vision exercise workshop held on 12 July 2019 in Potchefstroom.

Number	Name	Affiliation
1	Matthew Burnett	University of KwaZulu-Natal
2	Gordon O'Brien	University of KwaZulu-Natal
3	Wynand Malherbe	North-West University
4	Victor Wepener	North-West University
5	Francois Retief	North-West University
6	Chris van Niekerk	North-West University / Boskop Yacht Club
7	Artimissia Monjane	North-West University
8	Jurie Potgieter	North-West University
9	Theuns de Klerk	North-West University
10	Mariette Liefferink	Federation for Sustainable Environment
11	Simone Liefferink	Sibanye Stilwater
12	Thuli Letseka	JB Marks
13	Ntombi Rikhotso	JB Marks
14	David Tebene	DWS
15	Noah Lechelele	JB Marks
16	Dorcas Mokopu	Dr Kenneth Kaunda District Municipality
17	Mashilo Kabedi	Department of Water and Sanitation
18	Lukas Esterhuizen	JB Marks
19	Ms Candice Mendle	Dr Kenneth Kaunda District Municipality
20	Gadifele Kock	Dr Kenneth Kaunda District Municipality
21	Ruth Pule	JB Marks
22	Portia Chawane	Department of Water and Sanitation

Number	Name	Affiliation
23	Victor Nkuna	Department of Water and Sanitation
24	Matseba Ephraim Mogale	Department of Water and Sanitation

The workshop managed to determine numerous endpoints that are important within the catchment and how the Mooi River is used as a resource. There was a distinction made between ecological and social endpoints. As the catchment has been classified as a Water Resource Class III, it is expected that in many risk regions the social endpoints would be important. Ecological endpoints on the other hand is important as it is able to inform us about ecological functioning and provisioning of resources needed for many of the social endpoints. The 12 endpoints (not in any order of importance) that came up during the workshop are summarised in the following section.

6.1.1 Social endpoints

1. The river should be **MAINTAINED** for cultural and recreational activities and pose no risk to human health. These are activities such as baptism and swimming. This endpoint is a constitutional right. This is especially true within RR2.
2. There has to be an **INCREASE** in recreational and sport angling in the catchment.
3. There should be an **INCREASE** in other recreational activities such as sailing and canoeing for example.
4. Subsistence agriculture should be **MAINTAINED** – livestock watering and subsistence agriculture.
5. There should be an **INCREASE** in fisheries within the catchment so that it can contribute to regional governmental food security plans. Subsistence fisheries or angling is already present in certain impoundments.
6. The raw water for basic human needs should be **MAINTAINED** based on the population size.
7. There should be **NO** outbreaks of waterborne diseases such as *E. coli* and other pathogens.

6.1.2 Ecological

1. The Mooi River catchment should **MAINTAIN** productivity and assimilative capacity of rivers and wetlands.
2. The aquatic ecosystems should **MAINTAIN** connectivity for aquatic animals.

3. The Mooi River catchment should **MAINTAIN** refugia for regional fish spp. Due to the fish support areas as identified in the Freshwater Ecosystem Protected Area.
4. The habitat of springs and eyes within the Mooi River catchment should be **MAINTAINED** for potential endemic diversity. Furthermore, it will then comply with RQOs and REC for the biophysical nodes.
5. The Mooi River ecosystem should be **MAINTAINED** in an Ecological Category of D as specified by the RQOs.

6.1.3 Scenarios

The RRM, once populated, are able to critically evaluate and model scenarios for the catchment. These scenarios can be based on future water availability, environmental planning, mine closures or any scenario that might be deemed important within the specific catchment. In the workshop the participants were asked about future development in the catchment and various scenarios are presented for evaluation in the RRM. These scenarios did consider some existing plans for mine closure and water availability in the Mooi River catchment.

- Scenario 1: A past outlook and what the catchment would have looked like pre-development; especially for the ecological endpoints.
- Scenario 2: A present scenario looking at the risk of failure in meeting the social and ecological endpoints identified in the previous section.
- Scenario 3: A future scenario with complete mine closure and no mitigation measures in place. The Wonderfonteinspruit diversion pipeline will stay in place to protect dolomitic aquifers.
- Scenario 4: A future scenario with partial mine closure together with reclamation and rehabilitation and reclamation measures in place.
- Scenario 5: New mining activity scenario based on existing permits and plans that are in place for the next 5 years.
- Scenario 6: Resource use diversification scenario ~ Agriculture development scenario (flow reduction and increases in water quality issues)
- Scenario 7: Excessive growth in urban areas.
- Scenario 8: Increased demand for inland fisheries and fish consumption in the catchment.
- Scenario 9: Ecological scenario to improve the aquatic ecosystem from an Ecological Category of C/D (including wetlands) to an Ecological Category B.
- Scenario 10: A science based updated RQOs for the Mooi River Catchment.

6.1.4 Sources of stressors

The workshop identified the following stressors as having a significant impact on the Mooi River Catchment:

- Alien plants and animals
- Mines
- WWTW
- Communities (Informal as well as urban)
- Agricultural water use – especially in the main stem Mooi River.

These impacts have all been studied throughout the various student projects and previous research indicated in the ecological outline of the Mooi River catchment. The results of these various studies will feed into the conceptual model and ranking of impacts in the following sections and steps of the RRM.

6.2 Mapping and data analyses

This step requires the detailed mapping of the catchment under investigation together with the gathering of all data and spatial data for the catchment. This includes data such as ecosystem condition, ecosystem type, sources of stressors, habitats, and impacts. In addition, source-stressor exposure and habitat/receptor to endpoint pathways/relationships should be spatially referenced where possible (O'Brien et al., 2018). It is also important to determine what uncertainty is present within each of the data sets included for the catchment. The variety of spatial, ecological and socio-economic data that have been utilized in this section have been presented in section 4 and section 5.

6.3 Risk region selection

During this step, combinations of the management objectives, source information and habitat data were used to establish geographical risk regions that can be assessed in a relative manner (Landis, 2004; O'Brien and Wepener, 2012). The outcomes of the framework will depend on the available spatial scale identified during this step while each outcome can be based on multiple temporal scenarios associated with alternative management options (O'Brien et al., 2018). It is important that each risk region incorporate appropriate sources, stressors, habitats and endpoints for the study. It is also possible to assess the downstream effects of source on the risk regions downstream or even the upstream connectivity requirement for migratory fish (O'Brien et al., 2018). The Mooi River catchment will be the case study for the approach (Figure 25).

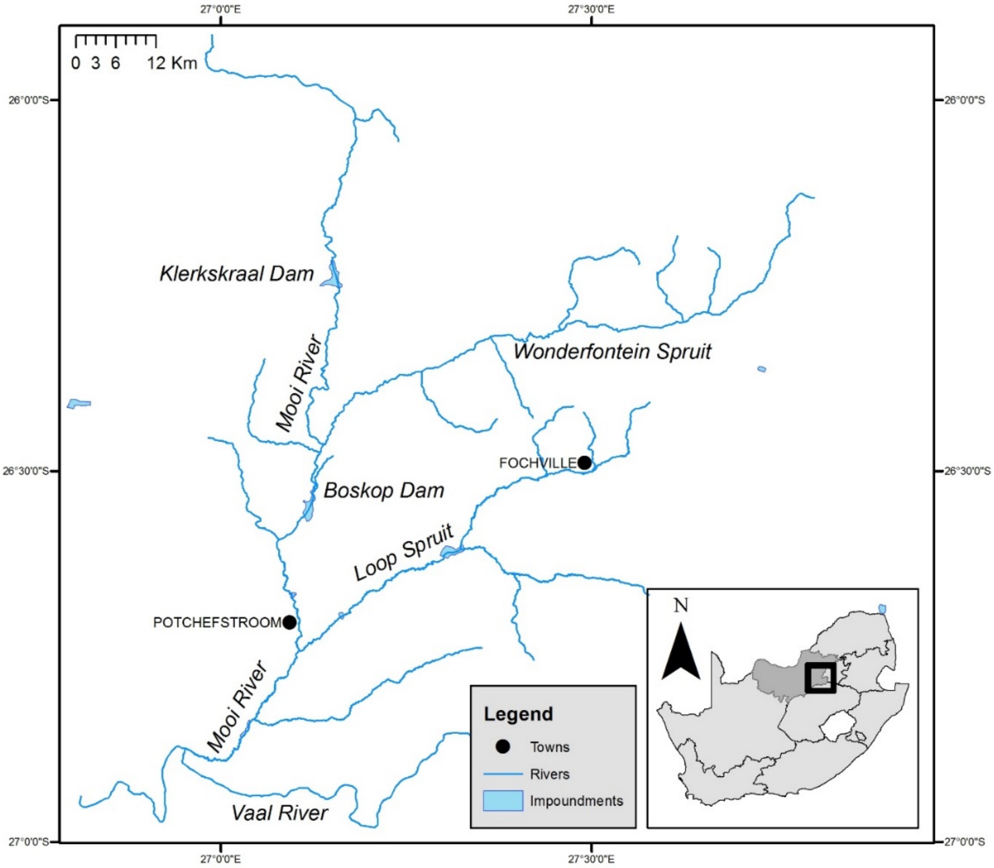

Figure 25: The Mooi River catchment indicating the various major tributaries, impoundments and urban areas in the catchment.

The demarcation of the risk regions for the study was based on the catchment vision, social endpoints and ecological endpoints that were discussed at the stakeholder workshop for the Mooi River. In general, the quaternary reaches of a catchment are mostly used individually or grouped for risk regions as most spatial data can be related to that management framework. The workshop discussed the various important aspects (sources, stressors, endpoints) within each of the catchments to determine the most valuable risk regions. The outcomes from each risk region can later directly relate to the ecosystem or water resource classification (O'Brien et al., 2018). Therefore, the following risk regions were identified for the implementation of the RRM (Figure 26):

- Upper Mooi River (RR1)
- Wonderfonteinspruit (RR2)
- Mooi River downstream of Wonderfonteinspruit to Loopspruit confluence (RR3)
- Loopspruit (RR4)

- Mooi River downstream of Loopspruit (RR5)

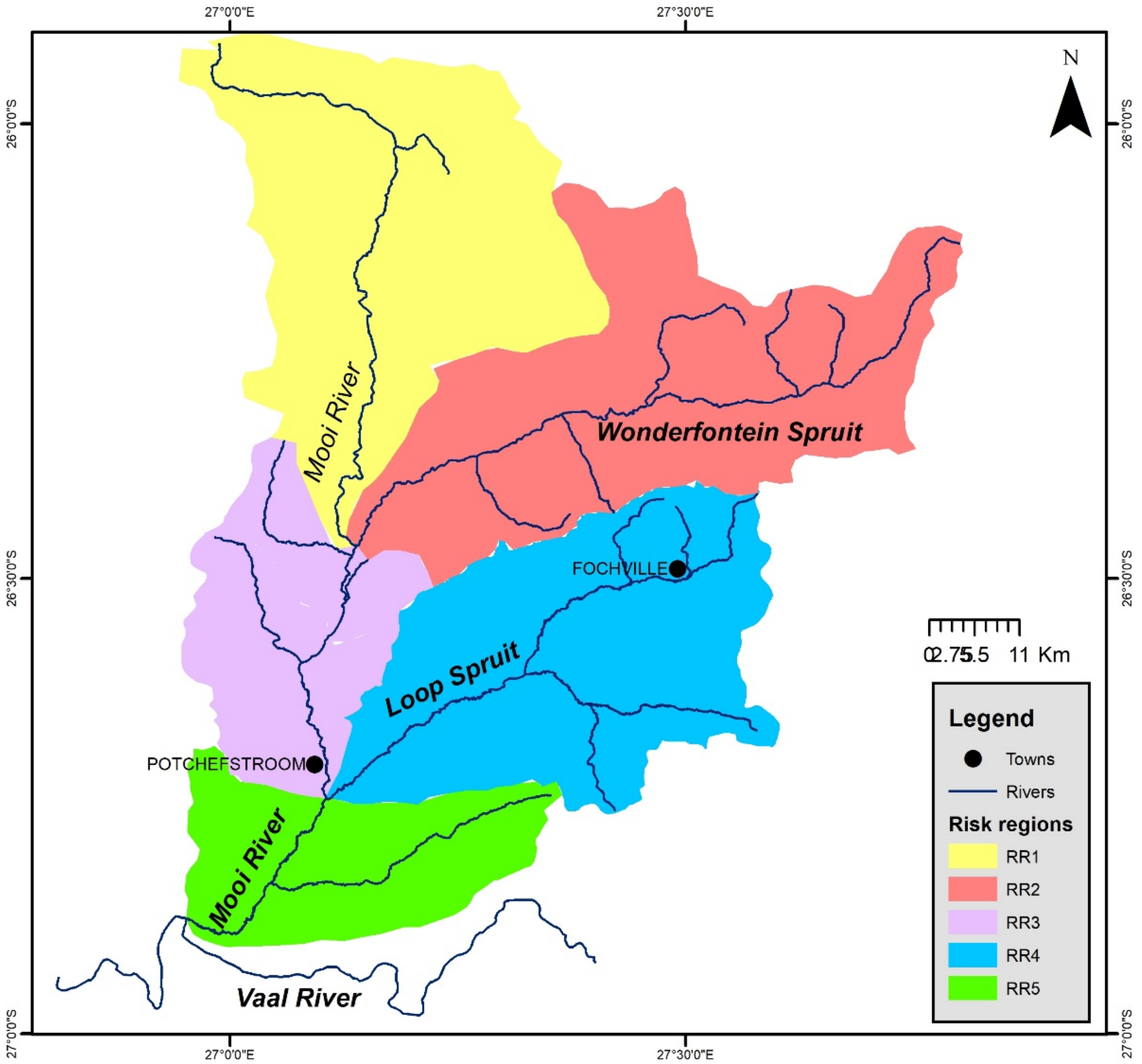

Figure 26: Risk regions identified for the Mooi River Catchment.

6.4 Conceptual model

The conceptual model is set up to determine and map the relationships between all of the sources, stressors, habitats and impacts to the selected endpoints for the RRM study. The expert should include but is not limited to hydrologists, geomorphologists, ecologists, ecosystem services expert, social scientists and resource economist (O'Brien et al., 2018) to develop a realistic model for the endpoints. The conceptual model should be as holistic as possible and include flow and non-flow related variables in a spatial-temporal context. Experts constructing the conceptual model should be familiar with the social-ecological process and be able to translate that into probable cause and effect variables and relationships of sources to stressors to multiple receptors in relation to their impacts on the selected endpoints (O'Brien et al., 2018). The various social and ecological endpoints were identified through the stakeholder workshop. Two of these models are presented here to visualize one ecological and one social endpoint. In Figure 27 the Bayesian Network model for the "Fish for Human Consumption" is presented and in Figure 28 the Bayesian Network model for "maintaining the aquatic ecosystem in a D ecological category". In these Bayesian networks the exposure (Green and Yellow blocks), effect (Pink blocks) and endpoints (Blue blocks) are presented for the specific model endpoint. The yellow block "Fish_River_Habitat" is the exposure child node as it is dependent on the "Fish_Riv_VD1" (velocity depth profile for the river) and the "Fish_Riv_Cover" (cover habitats present in the river). The conditional probability tables (CPT) that are used to derive the fish habitat are based on field data capturing the habitat present at the specific site. These CPTs then determine what habitat is available for fish; when the pollution levels that could be toxic to fish ("Fish_Toxic" = pink block) and that is present in the river is combined with the fish habitat, the daughter node indicating the probability that fish needed for human consumption is under threat is determined ("FFH_Env_Threat"). However, the risk to fish for human consumption is only realized if there are people wanting to fish in the system ("Fish+poten").

In short, Figure 27 and 28 is a model of each endpoint that was determined or selected. The model then captures how the ecological and social systems (both quantitatively and qualitatively) will affect the endpoint as well as the specific components in these socio-ecological systems that drive or could potentially drive the selected endpoints.

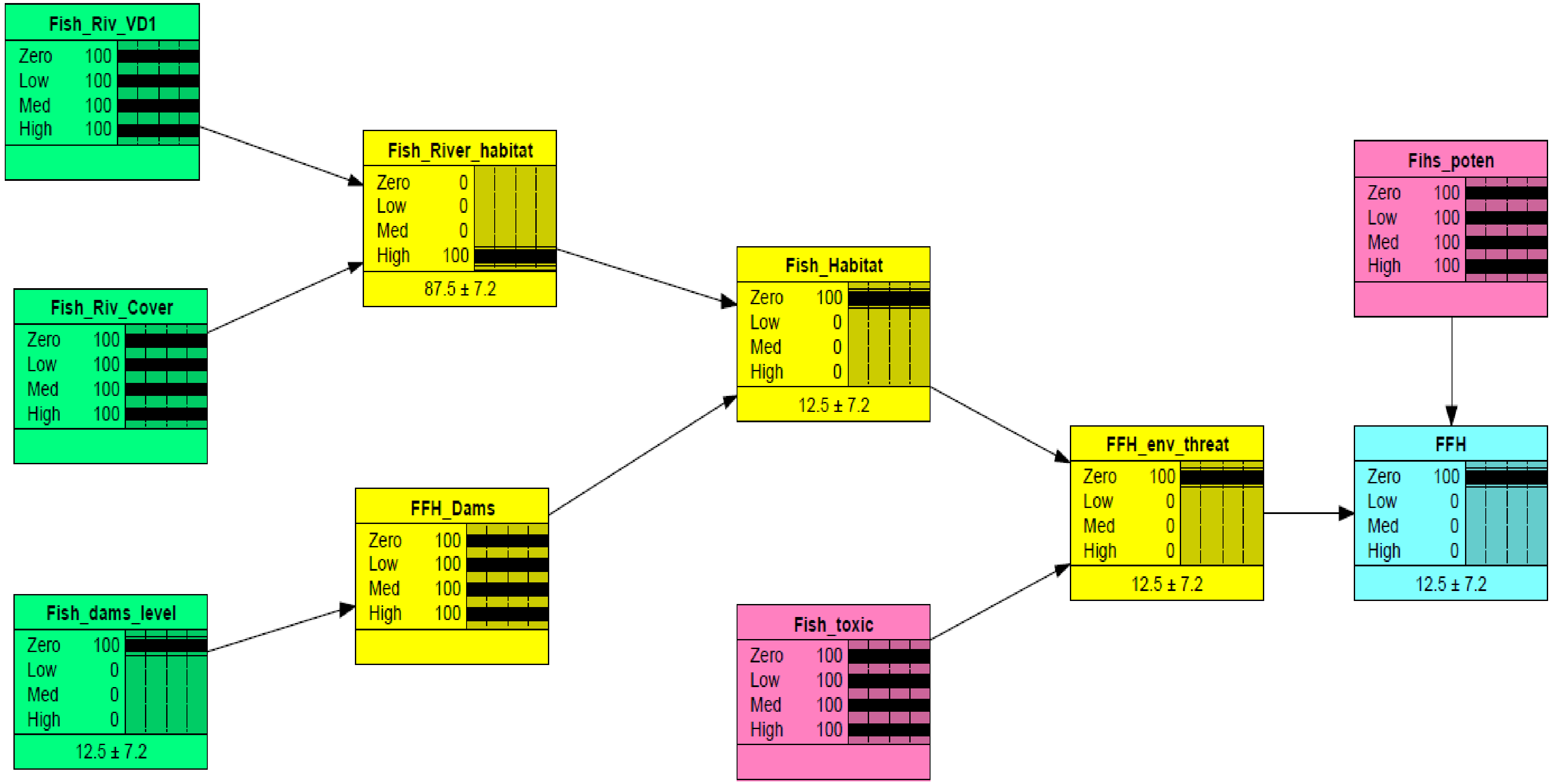

Figure 27: Bayesian Network belief network for the Fish for Human Consumption social endpoint identified through the stakeholder consultation.

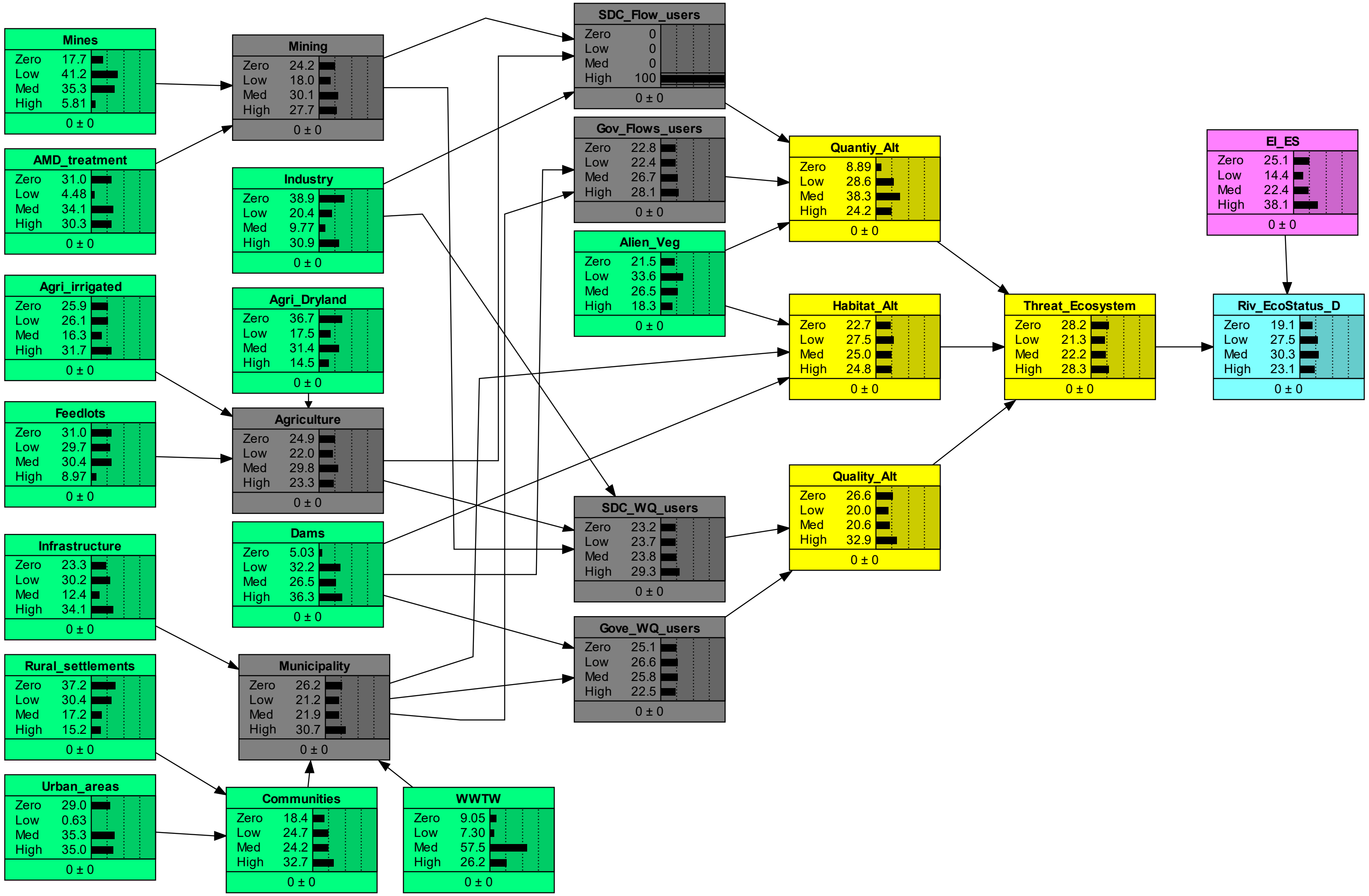

Figure 28: Bayesian Network belief network for the ecological endpoint "Maintain EcoStatus for the Mooi River at an ecological category of D."

6.5 Ranking scheme

The multiple data sources that have been identified in Chapter 4 and Chapter 5 was utilized for each of the parent nodes in Figure 27 and Figure 28. The data was ranked with a non-dimensional rank so that it is possible to compare the multiple data sources. The RRM makes use of four states and it is designated as zero, low, moderate and high before it is combined in the BN-RRMs (O'Brien et al., 2018). Each of these nodes in Figure 27 and Figure 28 was based on known information of the Mooi River catchment.

6.6 Calculate risks

In this step all of the multiple data sources from the social and ecological aspects are incorporated into the network design, probabilities and risk calculation. There will be seven sub-steps (O'Brien et al., 2018) within this phase, i.e.

a. Bayesian network design
b. Conditional probabilities
c. Current condition evaluation
d. Risk calculation to each endpoint
e. Environmental water requirement setting
f. Risk calculations for scenarios
g. Trade-off analyses

The relative risk scores calculated for various scenarios are also calculated during this step (O'Brien et al., 2018) and the different scenarios can be evaluated in an easy to understand format, i.e. probability curves. Furthermore, through an integration of the various social and ecological endpoints, one probability score can be calculated for comparison to the overall achievement or risk of the various scenarios that were identified. This is a vital step as it allows decision makers to visually compare different management options and thus, potentially improve decision-making in the water resources management sector.

6.7 Uncertainty evaluation

The uncertainty for each data source as highlighted in the previous steps should be evaluated in this step to ensure best practice in ecological risk assessment is maintained (O'Brien et al., 2018). This will include the uncertainty associated with the model, the risk to ecological indicators and the risk to social indicators. All aspects of uncertainty throughout the whole BN-RRM process should be evaluated including the objectives, endpoint selection, availability and use of evidence, expert information and model uncertainty. The uncertainty for each data source will initially become the drivers of the hypotheses in the next section. The refinement of uncertainty will lead to improved risk prediction and decision-making regarding EWRs and water resource management.

6.8 Hypotheses establishment

In this step, suitable hypotheses based on the social and ecological endpoints and their network relationships need to be determined. These hypotheses can be either field or laboratory experiments depending on the relationship (O'Brien and Wepener, 20102; O'Brien et al., 2018). This step and the testing of the hypotheses are the adaptive management approach followed within the framework as the improvement of the understanding of the various social-ecological risk relationships will lead to revisiting outcomes and re-evaluating approaches used to manage environmental water (O'Brien et al., 2018).

In this RRM framework (O'Brien and Wepener, 2012; O'Brien et al., 2018), these adaptive management principles acknowledge the social-ecological systems that are being assessed are dynamic and the limited understanding of these processes leads to many assumptions being incorporated. Therefore, in some cases the outcomes need to be amended based on the uncertainty before decisions can be made. If possible, assumptions need to be rigorously tested and as early as possible in the process to minimize the uncertainty (O'Brien et al., 2018). According to Lee (2004), the adaptive management processes should:

a. be informed by iterative learning about the conceptual model relationships;
b. consider and respond to earlier management successes and failures; and
c. increase present-day socio-ecological system resilience that can improve the ability of EWR (water resource) management to respond to the threats of increasing resource use (Lee, 2004).

The scenarios identified in section 6.1.3 have been converted to hypotheses regarding water resources management in the Mooi River catchment. These hypotheses will be utilized in future student projects to generate additional information for the RRM of the Mooi River. Some of the potential hypotheses based on the scenarios and available data are as follows:

Hypothesis 1: The current water resource use in the Mooi River Catchment is not sustainable and RQOs will not be attained.

Hypothesis 2: Increased fish consumption in the Mooi River catchment will lead to increased risk due to contaminated fish species being consumed.

Hypothesis 3: Agricultural diversification would place the Mooi River water resources under an unacceptable risk due to unsustainable water use.

Hypothesis 4: The future risk to social and ecological endpoints would be unacceptable with current water resource management measures.

6.9 Test hypotheses

This step is where the relationships highlighted in the RRM are tested to determine if the risk projections were accurate. These monitoring programmes, preferably long-term, will ultimately aim to improve the understanding of conceptual model relationships (O'Brien et al., 2018). This step will implement the agreed upon monitoring programme that is based on the endpoints used within the BN-RRM. There will be an adaptive management cycle in this step where the RRM can be revised based on the information generated during the monitoring programme.

The aim in the Mooi River Catchment will be that students registered on the Masters in Environmental Management with specialization in EWR at NWU will implement and test the various hypotheses generated through the RRM method. The results of each of these hypotheses will then feed into the conditional probability tables to improve the risk predications. Furthermore, this will also help to refine the conceptual model were needed as additional information over time becomes available. Ultimately, this will lead to improved monitoring and assessment of EWR and water resource management in the Mooi River Catchment.

6.10 Communicate outcomes

These types of frameworks are determined for the water resource managers and stakeholders so that the system can be more effectively used and / or protected. The information management needs have to be generated by robust, best scientific practice methods in a transparent, clear and concise format. This information is needed so that the consequences of water resource use options can be evaluated both from a social and an ecological viewpoint. The communication step is vitally important as it is this information that water resource managers will base their decisions, taking into account the uncertainty associated with the RRM (O'Brien et al., 2018). Ultimately, the information generated from this framework must be easily understood to facilitate management decisions.

7 DISCUSSION OF APPLICABILITY AND IMPLEMENTATION OF THE METHODOLOGY IN SOUTH AFRICAN WATER RESOURCE MANAGEMENT

7.1 Water resources management – freshwater

A few studies have used RRM for various approaches since O'Brien and Wepener (2012) published the methodology. There was a study in the Klip River on pollution (Wepener et al., 2015), an ecosystem services study in Smit et al. (2017) and the PROBFLO methodology by O'Brien et al. (2018). However, these have not really explicitly looked at a combination of social and ecological endpoints. In Table 17, there is a step-by-step comparison how the RRM methodology compares to the present day Integrated Framework (DWS, 2017). The approaches are inherently different as the RRM makes use of various inputs as a starting point for the environmental water study including social and ecological data sources. However, the integrated framework has the stakeholder engagement as a consistent input running throughout the environmental water study project. The integrated framework was explicitly designed for the implementation within riverine systems with only some integration with groundwater and wetlands included.

The RRM framework has the potential to integrate all aquatic ecosystems from a catchment into one assessment especially as these systems do not function in isolation. This approach to include estuarine, groundwater and wetland systems within one EWR study should be investigated in future, especially in highly utilised catchments in terms of socio-economic importance.

Table 17: Preliminary comparison between the RRM (O'Brien et al., 2018) and the DWS integrated framework (DWS, 2017) used in environmental water studies.

BN-RRM (O'Brien et al., 2018)	Integrated framework (DWS, 2017)
1. Vision exercise	Step 1: Delineate and prioritise RU and select study sites
2. Mapping and data analyses	Step 2: Describe status quo and delineate the study area into IUAs Step 5: Determine Water Resource Classes
3. Risk region selection	Not explicitly in integrated framework but it does refer to the resource classes and IUAs to some degree.
4. Conceptual model	The integrated framework does not describe this but it is incorporated in the modelling of

BN-RRM (O'Brien et al., 2018)	Integrated framework (DWS, 2017)
	scenarios; especially for flow related relationships in the catchment.
5. Ranking scheme	Not present in integrated framework
6. Calculate risks	Step 3: Quantify BHN and EWR Step 4: Identify and evaluate scenarios within IWRM
7. Uncertainty evaluation	Not explicitly incorporated in integrated framework
8. Hypothesis establishment	Step 6: Determine RQOs Step 7: Gazette Water Resource Classes and RQO's
9. Test hypotheses	Not explicitly in the integrated framework but it is assumed it would be a part of implementation and monitoring of the EWRs
10. Communicate outcomes	Step 7: Gazette Water Resource Classes and RQO's Step 8: Gazette the Reserve

7.2 Water resources management – estuarine systems

The Mooi River Catchment was selected due to the various impacts found on the system. However, as it is an inland river system, there was not the opportunity in the present project to investigate how estuaries could form part of the RRM methodology. However, recently Vezi et al. (2020) published an article on the use of the RRM method in various sub-tropical estuaries in KwaZulu-Natal. The study focussed on the uMvoti, Thukela and aMatikulu/Nyoni estuaries and evaluated four socio-ecological endpoints, i.e. biodiversity habitat, safe environment, fisheries and productivity (Vezi et al., 2020). This study provided a foundation to further develop endpoints that are able to evaluate the risks of multiple stressors in these three catchments. The study highlighted that research should be focused on the collection of the necessary data to refine the RRM for estuaries. The outcome of the study provided a framework that will facilitate decision-making in these three catchments for all stakeholders; especially decisions related to restoration and rehabilitation for these estuaries.

7.3 Scale of the RRM methodology

The use of the RRM methodology within the South African landscape has the advantage that it can be implemented at various scales. The method could be applied in one river catchment as implemented in the Mooi River Catchment or it could be implemented at a larger scale such as the Vaal River Catchment. This makes the RRM method applicable to drive and implement a Catchment Management Strategy. The estuarine example (Vezi et al., 2020) as well as the Klip River (Wepener et al., 2015) are examples of smaller scale implementation of the RRM method while the implementation of the RRM in e-flow studies in the Lesotho Highlands project (O'Brien et al., 2018) are an example of a larger scale example. More examples of the different scales can be found in Landis and Wiegers (2007) as well as in O'Brien et al. (2018).

7.4 Non-flow related issues

The RRM is also able to provide information on non-flow related issues that are often difficult to determine in methods specifically designed to assess EWRs in rivers. These issues include non-perennial rivers and their EWRs and EWRs in wetlands that are not dependent on flow such as seeps, depressions and flats. In the Mooi River case study, one of the social endpoints was related to recreational use of the impoundments for sailing and canoeing; although indirectly linked to flow, many of the determinants to maintain this service is not flow related, or at least only partially related to flow. As the RRM method is designed to model the relationships that is responsible for a specific endpoint, it is not dependent on flow within a system and it is able to model any relationship so long as sufficient information and data is available on that relationship.

7.5 Disadvantages of the RRM

As with many other methods there are also some disadvantages of the RRM and its implementation in water resource management. Some of these disadvantages are highlighted here:

- It is not directly linked to the WRYM to evaluate scenarios;
- The Netica software that runs the network models would potentially be needed. However, with strategic implementation, this will be minimal. The initial cost would be to set up the model and afterward it would only be tweaked and optimised as the system is improved through monitoring. There are also inexpensive (and free) alternatives for the Netica software in the R software package.
- In some catchments information to establish the conceptual model might be scarce and as such a low confidence with a high uncertainty will be the starting point until monitoring can refine the model.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusion

This project set out to achieve the increased training and skills development of human resources within the water resources management sector and also to evaluate an integration framework within EWR and its implementation. The 19 masters students that have been involved in the project, are producing various research outputs that will contribute to improved water resources management in specifically the Mooi River catchment. These students have learned valuable skills and will potentially be able to improve decision-making around EWRs and water resources management in general following their masters qualifications.

Furthermore, the research outcomes will also benefit the decision makers involved with water development and allocation, especially in the Mooi River catchment area, which has been a hotbed of controversy around water management. For example, the Wonderfonteinspruit, (a tributary of the Mooi River) is home to some of the largest gold mining companies in the world. Polluted mine water is discharging into this stream and has a direct effect on Potchefstroom's water (Winde, 2010).

The BN-RRM model presented here is a holistic method that are able to integrate various data sources and types while still being able to quantify uncertainty within the process. This uncertainty is then the basis for the adaptive management and feedback loops ensuring the RRM model for the Mooi River catchment is continually adjusted and improved for better function. According to Arthington et al. (2018), innovative integrated methods are required to provide meaningful management recommendations for the sustainable utilisation of complex aquatic ecosystems coupled with changing environmental and societal futures. This study demonstrates that the RRM methodology indeed provides such an innovative approach allowing for the selection of relevant socio-ecological and socio-economical management objectives.

8.2 Recommendations

The following recommendations have emanated from this research project:

- The selection of objectives or endpoints for a catchment is crucial. The RRM method provides a structure to select finer scale objectives that are more socially relevant. This then ensures better buy-in of stakeholders that would potentially lead to improvement in the implementation of EWR in a catchment.

- Furthermore, the conceptual model within the RRM will help to understand the cause and effect relationships within a catchment better. This will lead to an improved understanding of stakeholder needs and ultimately improved determination and implementation of EWRs in a catchment.
- Ensure faster uptake of EWR training in the Department of Human Settlements and Water and Sanitation.
- Continuously update EWR learning material when newer research methods and ideas come along.
- Implement the recommendations that have emanated from the student research projects on the Mooi River catchment.
- Further testing of the RRM is needed within the Mooi River catchment to complete various endpoints identified during the stakeholder engagement process.
- The Mooi River Catchment has a significant rural population that utilise natural aquatic ecosystem resources. This resource value is not captured within the formal economy and it is vital to capture these environmental externalities to improve ecosystem value assessment and the RRM.
- The spatial distributions identified in the Vulnerability Index and social wellbeing scores should be explicitly accounted for when managing resources in the Mooi River Catchment.
- In various research reports (Palmer and Munnik, 2018) and this research the challenges to implementation of EWR were evident. However, the success stories (identified in Palmer and Munnik, 2018) have mostly been as a result of a champion consistently pushing the agenda of ecological water and integrated water resource management. This champion could be in the form of an NGO, a research organization or a unit within a government department.

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10 APPENDICES

Appendix 1: Raw Census Data per Risk Region

Description		RR1	RR2	RR3	RR4	RR5	Grand Total
Area (km²)		1 524.7	1 545.5	677.8	1 286.0	634.1	5 668.1
Population		14 651.1	504 781.0	100 983.9	79 890.8	45 386.7	745 693.4
Household access to piped water	Piped (tap) water inside dwelling/institution	1 537.4	84 799.9	22 954.0	14 477.4	4 242.7	128 011.5
	Piped (tap) water inside yard	1 499.2	48 640.3	8 615.0	11 549.5	7 820.5	78 124.6
	Piped (tap) water on community stand: distance less than 200 m from dwelling/institution	870.7	16 050.6	852.2	1 690.8	911.7	20 376.1
	Piped (tap) water on community stand: distance between 200 m and 500 m from dwelling/institution	124.3	5 800.0	216.3	422.6	377.7	6 940.9
	Piped (tap) water on community stand: distance between 500 m and 1000 m (1 km) from dwelling /institution	51.9	1 821.6	66.7	135.9	293.9	2 370.1
	Piped (tap) water on community stand: distance greater than 1000 m (1 km) from dwelling/institution	11.1	320.5	27.3	76.3	13.3	448.5
	No access to piped (tap) water	232.8	1 339.8	401.9	309.3	262.8	2 546.6
Households Access to internet	From home	207.2	8 062.6	4 766.7	1 773.3	504.9	15 314.7
	From cell phone	527.2	27 852.9	6 434.7	3 820.6	1 978.5	40 613.9
	From work	127.3	5 879.4	2 000.8	1 019.4	384.8	9 411.8
	No access to internet	3 385.3	105 267.6	17 435.9	20 831.8	10 671.6	157 592.2
	From elsewhere	80.6	11 719.3	2 500.0	1 215.5	382.2	15 897.5
Household Dwellings	House or brick/concrete block structure on a separate stand or yard or on a farm	3 133.3	96 185.5	22 038.8	17 802.7	8 000.9	147 161.2
	Traditional dwelling/hut/structure	65.0	276.0	96.7	73.2	39.7	550.5

Description		RR1	RR2	RR3	RR4	RR5	Grand Total
	made of traditional materials						
	Cluster house in complex	16.5	655.1	188.0	653.1	21.6	1 534.3
	Flat or apartment in a block of flats	28.8	3 724.2	4 238.8	3 649.5	149.1	11 790.5
	Townhouse (semi0detached house in a complex)	12.9	512.0	531.2	244.4	58.6	1 359.2
	Semi0detached house	19.4	820.5	307.3	97.2	931.4	2 175.8
	House/flat/room in backyard	59.1	8 862.6	968.5	830.8	314.9	11 035.9
	Informal dwelling (shack; in backyard)	226.1	19 662.8	1 864.9	1 548.8	1 782.2	25 084.8
	Informal dwelling (shack; not in backyard; e.g. in an informal/squatter settlement or on a farm)	579.2	23 677.5	2 419.6	2 426.0	2 378.6	31 480.9
	Room/flatlet on a property or larger dwelling/servants quarters/granny flat	116.5	2 060.6	346.6	177.5	91.2	2 792.4
	Caravan/tent	11.9	104.6	12.5	16.8	18.2	163.9
Education	No schooling	1 249.2	16 709.6	3 499.4	3 865.1	2 867.9	28 191.2
	Some primary	1 793.0	36 848.5	6 871.6	8 249.3	4 725.0	58 487.4
	Completed primary	619.2	16 135.1	2 640.4	3 517.2	1 617.8	24 529.7
	Some secondary	3 136.1	128 614.6	20 322.0	20 769.7	10 540.1	183 382.5
	Completed secondary	1 836.5	99 637.4	22 698.4	13 351.0	6 919.8	144 443.1
	Higher	451.7	23 618.0	10 724.0	3 821.4	1 199.5	39 814.6
Economic Activity	Employed	4 633.7	158 994.5	31 381.1	31 092.7	13 130.4	239 232.5
	Unemployed	1 174.2	74 061.2	9 127.7	9 213.7	4 476.9	98 053.6
	Discouraged work0seeker	313.5	13 803.2	1 788.4	1 871.4	1 053.0	18 829.4
	Other not economically active	3 510.7	111 914.2	28 225.1	16 103.7	11 687.7	171 441.4
Energy Source for Cooking per Household	Electricity	2 744.3	127 442.5	29 291.7	21 768.0	9 754.4	191 001.0
	Gas	212.1	3 217.1	909.4	783.6	356.8	5 479.1
	Paraffin	435.7	25 870.2	2 246.8	5 398.1	3 459.8	37 410.6
	Wood	881.7	1 270.3	403.8	400.5	226.6	3 182.9
	Coal	12.4	249.1	48.5	42.4	38.3	390.7
	Animal dung	26.1	57.6	19.2	25.6	30.4	158.9

Description		RR1	RR2	RR3	RR4	RR5	Grand Total
	Solar	4.7	235.7	40.8	40.2	17.5	339.0
	Other	3.7	132.8	105.8	94.9	4.5	341.7
	None	7.7	288.9	71.0	105.2	32.4	505.3
Energy Source for Heating per Household	Electricity	2 161.7	115 004.4	24 800.2	17 750.7	6 423.6	166 140.5
	Gas	100.6	2 987.1	849.8	648.7	230.1	4 816.3
	Paraffin	171.9	14 119.2	883.0	3 866.7	1 246.6	20 287.3
	Wood	1 214.5	8 384.7	1 422.4	1 488.2	1 472.4	13 982.2
	Coal	17.6	2 406.7	488.5	279.6	537.7	3 730.1
	Animal dung	23.9	131.7	33.2	26.6	34.9	250.3
	Solar	4.9	253.4	77.7	54.1	30.4	420.4
	Other	-	1.4	6.0	2.7	2.0	12.1
	None	632.0	15 479.5	4 571.3	4 541.9	3 946.5	29 171.2
Energy Source for Lighting per Household	Electricity	3 202.2	130 301.6	31 247.0	25 558.4	11 948.0	202 257.3
	Gas	2.8	290.2	37.1	49.7	29.4	409.2
	Paraffin	56.3	7 484.3	133.5	1 012.7	246.9	8 933.7
	Candles (not a valid option)	1 014.7	19 976.1	1 580.5	1 904.7	1 633.0	26 109.0
	Solar	30.0	311.5	58.1	59.4	30.5	489.5
	None	21.3	407.5	77.3	74.8	35.8	616.6
Household Income	No income	540.5	26 378.7	6 741.2	3 951.3	1 981.4	39 593.0
	R10-R4800	166.5	7 772.7	880.7	764.7	552.0	10 136.7
	R4801-R9600	290.8	11 056.1	1 385.5	1 233.6	966.0	14 932.0
	R9601-R19600	1 073.6	21 504.7	4 325.0	3 025.2	2 588.0	32 516.6
	R19 601-R38 200	1 064.1	27 849.5	5 310.5	4 139.7	3 458.0	41 821.9
	R38 201-R76 400	546.4	29 021.7	4 598.0	9 386.8	2 254.3	45 807.4
	R76 401-R153 800	261.7	17 647.1	4 004.3	2 908.6	1 171.7	25 993.4
	R153 801-R307 600	206.0	11 350.7	3 110.1	1 807.4	573.4	17 047.6
	R307 601-R614 400	116.5	4 755.4	1 819.4	1 002.9	270.4	7 964.6
	R614 001-R1 228 800	38.8	982.2	602.1	294.6	68.4	1 986.1
	R1 228 801-R2 457 600	12.8	254.0	168.9	70.1	14.9	520.8
	R2 457 601 or more	10.3	196.1	190.9	73.1	26.2	496.7
Household Language	Afrikaans	2 491.5	50 531.6	33 460.2	13 401.4	4 287.8	104 172.5
	English	666.4	22 118.0	5 427.0	2 950.3	1 150.7	32 312.6
	IsiNdebele	168.4	4 344.6	748.9	346.2	502.9	6 111.0
	IsiXhosa	1 154.5	83 013.0	7 009.9	20 697.6	7 099.3	118 974.3
	IsiZulu	425.2	55 510.9	1 754.8	3 880.6	1 009.2	62 580.7
	Sepedi	144.2	16 290.5	704.2	899.4	263.8	18 302.1
	Sesotho	673.7	56 950.3	7 955.6	17 357.5	8 322.9	91 259.9
	Setswana	7 991.4	149 298.1	40 404.1	12 366.2	20 886.3	230 946.1

Description		RR1	RR2	RR3	RR4	RR5	Grand Total
	Sign language	52.3	2 510.8	342.4	504.3	239.6	3 649.4
	SiSwati	33.2	4 642.9	153.0	1 245.3	74.7	6 149.0
	Tshivenda	42.8	7 191.0	222.5	325.8	94.7	7 876.9
	Xitsonga	202.4	30 446.4	438.9	3 394.7	328.4	34 810.8
Demographic Data	Black Male	6 388.7	229 255.5	31 786.4	37 109.4	20 279.3	324 819.2
	Black Female	5 335.7	213 687.7	33 597.3	28 726.9	20 640.4	301 988.0
	Coloured Male	92.2	7 485.4	4 734.7	650.3	288.9	13 251.4
	Coloured Female	68.9	7 962.0	5 296.7	658.6	321.9	14 308.2
	Indian Male	74.6	3 922.4	620.6	138.3	114.5	4 870.5
	Indian Female	57.3	3 330.6	618.9	89.3	58.7	4 154.8
	White Male	1 319.6	18 415.1	11 145.8	5 898.8	1 746.6	38 525.9
	White Female	1 248.0	18 790.4	12 744.8	6 236.1	1 758.0	40 777.3
	Other Male	48.3	1 300.0	295.2	254.1	118.5	2 016.1
	Other Female	17.2	626.5	148.6	131.7	58.3	982.4
	Total Male	7 924.8	260 381.7	48 578.8	44 049.0	22 547.6	383 481.9
	Total Female	6 726.3	244 405.9	52 403.7	35 842.1	22 839.6	362 217.5
Waste Removal Service per Household	Removed by local authority/private company at least once a week	839.8	129 005.9	27 493.2	21 589.1	3 709.9	182 637.8
	Removed by local authority/private company less often	125.8	3 279.3	368.4	1 611.2	289.4	5 674.0
	Communal refuse dump	156.5	7 316.8	260.3	672.3	1 214.9	9 620.9
	Own refuse dump	2 840.7	14 227.5	3 792.7	3 490.5	6 735.6	31 087.0
	No rubbish disposal	299.4	4 432.4	1 087.1	1 107.9	1 826.9	8 753.7
	Other	65.5	506.1	129.1	192.3	145.5	1 038.5
Employment Sector	In the formal sector	2 525.4	123 932.5	23 427.9	24 804.1	7 234.7	181 924.7
	In the informal sector	1 168.6	15 813.2	3 887.9	3 001.1	3 000.4	26 871.2
	Private household	885.7	17 863.8	4 164.2	3 101.7	2 732.0	28 747.3
	Do not know	185.0	3 197.6	731.7	633.3	351.4	5 098.9
Primary source of domestic water per household	Regional/local water scheme (operated by municipality or other water services provider)	1 046.3	149 369.1	31 257.5	25 114.6	12 046.7	218 834.2
	Borehole	2 688.6	5 119.5	1 330.6	2 148.1	1 319.7	12 606.5
	Spring	44.9	102.2	12.6	17.5	16.8	194.0
	Rain-water tank	31.3	277.5	39.3	144.9	30.6	523.7

Description		RR1	RR2	RR3	RR4	RR5	Grand Total
	Dam/pool/stagnant water	22.6	90.9	26.9	36.7	21.8	198.9
	River/stream	21.9	42.4	5.2	19.2	19.9	108.5
	Water vendor	6.6	594.3	102.4	71.5	142.1	917.0
	Water tanker	406.2	1 643.3	142.2	697.1	257.5	3 146.3
	Other4	59.1	1 523.2	218.7	414.2	68.4	2 283.5
Access to Sanitation Services per Household	Flush toilet (connected to sewerage system)	1 259.1	123 904.8	29 550.5	24 570.2	10 068.8	189 353.5
	Flush toilet (with septic tank)	635.9	5 932.6	568.6	1 152.8	602.8	8 892.7
	Chemical toilet	35.6	935.5	21.6	193.1	27.5	1 213.4
	Pit toilet with ventilation (VIP)	919.9	10 844.6	485.8	513.8	274.0	13 038.0
	Pit toilet without ventilation	1 093.1	13 244.0	833.8	1 456.1	765.6	17 392.5
	Bucket toilet	48.0	1 297.8	138.3	150.2	268.7	1 902.9
	Other	117.9	921.1	252.2	321.4	225.5	1 838.0
	None4	218.5	1 679.8	1 280.9	301.3	1 689.1	5 169.6

Appendix 2: Land cover and crop type data

Area Land Cover (DEA 2013/14) (Ha)	RR1	RR2	RR3	RR4	RR5	Total
Water	221.40	263.08	411.27	510.42	16.12	1 422.29
Natural / Undeveloped Land	94 059.86	95 709.94	50 337.02	85 188.10	40 118.68	365 413.59
Cultivated	56 199.63	39 199.29	12 460.10	38 726.50	18 247.58	164 833.09
Plantation	1 077.88	2 731.74	421.54	685.51	330.74	5 247.41
Mining	373.79	3 982.59	174.65	849.70	105.20	5 485.93
Degraded Land	49.45	262.90	75.93	287.14	57.47	732.88
Urban	400.91	12 360.92	3 833.82	2 380.17	4 521.07	23 496.88
Area Field Type (DAFF 2011) (Ha)	**RR1**	**RR2**	**RR3**	**RR4**	**RR5**	**Total**
Annual Crop Cultivation	51889.09	32721.24	11387.68	33299.28	14188.62	143485.91
Horticulture / Viticulture	6.13	29.67	7.96	8.17	13.44	65.37
Old Fields	1707.46	445.18	261.32	1186.13	592.43	4192.52
Pivot Irrigation	2588.88	1831	529.75	833.43	2857.49	8640.55
Shadenet	0	40.13	0	0	0	40.13
Small Holdings / Subsistence	563.39	2188.37	0	267.08	2546.92	5565.76

Appendix 3: Percentage data utilized for Social Wellbeing Score (SWS)

% Population (As per Census 2011)	RR1	RR2	RR3	RR4	RR5
Access to piped water	70%	84%	95%	91%	87%
No Access to piped water	30%	16%	5%	9%	13%
Formal housing	77%	71%	86%	85%	69%
Informal Housing	23%	29%	14%	15%	31%
Secondary school and above	25%	38%	50%	32%	29%
Below secondary school	75%	62%	50%	68%	71%
Employed	48%	44%	44%	53%	43%
Unemployed	52%	56%	56%	47%	57%
Above Min wage	28%	40%	44%	54%	31%
Below Min Wage (<R38 000 pm)	72%	60%	56%	46%	69%
Water Service	24%	94%	94%	88%	87%
No Water Service	76%	6%	6%	12%	13%
Access to flushing toilet	44%	82%	91%	90%	77%
No Access to Flushing Toilet	56%	18%	9%	10%	23%