DEVELOPING A CITIZEN SCIENCE FRAMEWORK FOR WATER RESOURCES PROTECTION TO FACILITATE OPERATIONALIZATION OF RESOURCE DIRECTED MEASURES AT CATCHMENT LEVEL, SOUTH AFRICA

By

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Declaration

I, the undersigned hereby declare that this thesis entitled: ***'Developing a citizen science framework for water resources protection to facilitate operationalization of resource directed measures at catchment level, South Africa'*** is my own original work which has not been submitted to any other institution for any degree or examination, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Stanley Mvuselelo Nzama

Full name

Signature

05 April 2021

Date

Dedication

This thesis is dedicated to my parents, my father Sales Nzama and my mother Phyllis Nzama including my brothers and the sister but not forgetting my children Andiswa, Bandile, and Phawu.

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Abstract

Maintenance of water resources protection practice for water availability, uninterrupted water utilization, and for ecosystem integrity is critical for sustainable achievement of resource security for all. Therefore, operationalization of water resource protection strategies such as resource directed measures, especially at catchment level where water resources utilization takes place is critical. The main aim of the current study was to develop a citizen science framework for operationalization of resource directed measures at catchment level. Such a framework used a nexus approach, and its development was guided by the principles of socio-ecological model from a systems thinking perspective. This demonstrated importance of resource directed measures which are accepted as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level, where local citizens become part of such practice.

Local operationalization of resource directed measures provides a basis for practical policy implementation at catchment level, thereby informing decisions taken on water resources protection and sustainable water use for several purposes. It provides an understanding of how policies which are formulated for water resources protection purposes influence land use activities and other non-land use activities to ensure water availability for current and future generations. Furthermore, localized operationalization of resource directed measures facilitates ecological ecosystems protection such that goods and services derived from such ecosystems are sustained. The research problem of the current study was a lack of available and feasible plan for resource directed measures practice at catchment level which has a direct influence on the continued water quality deterioration and unsustainable utilization of water resources. This study argued that a citizen science framework needed to be developed and such a plan must be informed by science-policy interface that is practical, reflective and must consider the nexus approach using the concept of citizen science in order to improve the practice of resource directed measures at local level in an acceptable manner by practitioners.

The study followed a descriptive case-research study design and applied a pragmatic approach where mixed methods were used. This study used a combination of desktop and case study analysis. The desktop analysis was applied to assess utilization of science-policy nexus in policy implementation practice for water resource protection. The desktop analysis was applied to investigate role of Water-Energy-Food-Environment (WEFE) nexus in water resources protection practice. The analysis included systematic literature surveys, document surveys, historical water quality data, river flow records, and groundwater levels data. The case study analysis was used to demonstrate the validation and verification of a process based operational plan for catchment orientated resource directed measures. The current study provided evidence-based results from reported citizen science projects to demonstrate practical involvement of local citizens in water resources protection activities from a system analysis perspective.

Furthermore, the case study analysis provided evidence from a case study catchment where historic data were used to assess compliance with established resource directed measures numerical limits. This study revealed that science-policy integration, policy-science integration, and mixed integration are the nexus theoretical models commonly used for facilitating engagements between scientists and policy makers in policy development and implementation practice. When such models were assessed for their consideration in policy implementation in the context of water resources protection practice in South Africa, the study found that mixed integration theoretical model drives policy implementation using scientific studies of resource directed measures. This showed how scientific studies support policy implementation. Such findings showed that South Africa is able i) to translate information in legislation into practice using science and ii) to use science in policy development and implementation. Operation of WEFE nexus approach in water resource protection practices was assessed using Gibbs Reflective Cycle Model of reflective practice. The results indicated that processes followed for undertaking resource directed measures studies incorporate WEFE nexus concept, implying that WEFE nexus plays a key role in water resources protection practice. However, when initiatives such as capacity development through Public-Private Partnership (P-PP) were assessed for their role in sustaining application of WEFE nexus in water resources protection practice, the results indicated that such initiatives are inadequate in their current configuration to sustain the nexus, an insight that provided the basis for further exploration on how such initiatives can be configured to sustain the required nexus.

In addition to the demonstration of science-policy nexus application in policy implementation, and the assessment of WEFE nexus operation in water resources protection practice, the study developed a process-based framework for operationalization of resource directed measures at local level. This framework provides an ordered model which incorporates nexus approach characterised by science, policy, and citizen centrism which tend to facilitate participation of citizens in local water resources protection activities, thus supporting policy implementation for water resources protection using a bottom-up approach. Additionally, the framework directs policy practice at different levels of implementation from national through regional to local level, thus supporting a top-down approach of policy implementation. Therefore, the framework supports concurrent application of top-down and bottom-up approaches of policy implementation for water resources protection.

The study has far-reaching contributions in the field of water resources protection. Firstly, it is the demonstration of science-policy nexus application in relation to evidence-based policy formulation and implementation in water resources management and protection practices to mitigate water resources challenges. The second contribution is the application and integration of the WEFE nexus concept into water resources protection processes to improve its uptake in practice, while enhancing sectorial collaboration for efficient water resources protection and sustainable utilization, thereby contributing towards fast-tracking achievement of sustainable development goals (SDGs).

The third contribution is the provision of insight on the role and importance of appropriate configuration of capacity building programmes directed towards sustainability of water resources protection practice and the implementation of WEFE nexus principles at a catchment level. The fourth contribution is the proposal of a model for acceptance of resource directed measures as policy implementation strategies for water resources protection and their practice at catchment level.

Fifthly, the contribution is in relation to the social value where the study demonstrates the feasibility of the proposed citizen science framework to facilitate involvement of local citizens in water resources protection activities, and indication of how the framework can be used as a proxy for water resources protection practice at other catchments. The sixth contribution is in terms of scientific value where the study practically showed how to use data collected by professional scientists and local citizens for the purpose of assessing compliance with established resource directed measures numerical limits. Lastly, the study contributed to knowledge generation in the subject of water resources protection though sharing of results emanating from this study with scientific community and public made through publications and conference presentations. The four publications or journal articles or papers that were produced from the current study contributed new knowledge to the scholarship community in the field of water resource protection.

Contribution of the study

1. Publication [Journal article]

- **Nzama, S.,** Mpoma, H., & Kanyerere, T. (2020). Using groundwater quality index and concentration duration curves for classification and protection of groundwater resources: Relevance of groundwater quality of reserve determination, South Africa [Submitted to Journal of Sustainable Water Resources Management, Paper published to the Journal of Sustainable Water Resources Management, DOI Number: https://doi.org/10.1007/s40899-021-00503-1].
- **Nzama, S.,** Mkandawire, T., & Kanyerere, T. (2020). Science-policy nexus: using resource directed measures as policy implementation plan for improved water resource protection, South Africa [The paper is ready for submission to the relevant Journals]
- **Nzama, S.,** Levine, A., & Kanyerere, T. (2021). Application of Water-Energy-Food-Environment Nexus in water resources protection practice from a reflective policy and solutions perspective: Case of South Africa [The paper is ready for submission to the relevant Journals]
- **Nzama, S.,** Levine, A., & and Kanyerere, T (2021) A proposed citizen science model for water resources protection at catchment level using strategies of resource directed measures, South Africa [The paper is ready for submission to the relevant Journals]

2. Conference proceedings: (Oral and Poster presentations)

- *Nzama, S., Levine, A., & Kanyerere, T. (2019). Groundwater resources protection: Reflection on relevance of groundwater quality component of reserve for provision of clean water and sanitation*. Oral presentation at the 2nd Southern African Development Communities (SADC) Groundwater Conference titled: Groundwater contribution to achievement of Sustainable Development Goals in the SADC Region: Johannesburg, South Africa, 4-6 September 2019.
- *Nzama S.M., & Kanyerere, T.O.B. (2021). Science-policy nexus: using resource directed measures as policy implementation strategies to promote integrated water resource management, South Africa*. Oral presentation at the International Water Resources Association (IWRA) online conference, 7-9 June 2021.
- *Nzama, S.M., Mapoma, H.W.T., & Kanyerere, T.O.B. (2021). Using groundwater quality index and concentration duration curves for classification and protection of groundwater resources, South Africa*. Poster presentation at the International Water Resources Association (IWRA) online conference, 7-9 June 2021.

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List of Acronyms

AUC	African Union Commission
CBE	Charge Balance Error
CSF	Citizen Science Framework
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
FDC	Flow Duration Curve
GRCM	Gibbs' Reflective Cycle Model
GRDM	Groundwater Resource Directed Measures
HSRC	Human Sciences Research Council
IUA	Integrated Units of Analysis
IWRM	Integrated Water Resource Management
LAC	Latin American Countries
LDC	Load Duration Curve
MAP	Mean Annual Precipitation
MV-WMA	Middle Vaal Water Management Area
NDP	National Development Plan
NGS	National Groundwater Strategy
NWA	National Water Act
NWP	National Water Policy
NWRS	National Water Resource Strategy
NW&SMP	National Water and Sanitation Master Plan
P-PP	Public-Private Partnership
RDMs	Resource Directed Measures
RQOs	Resource Quality Objectives
SA	South Africa
SADC	Southern African Development Communities
SDCs	Source Directed Controls
SDGs	Sustainable Development Goals
SEM	Socio Ecological Model
STATS-SA	Statistics-South Africa
UK	United Kingdom
UN	United Nations
UNECE	United Nations Economic Commission for Europe

UNGC	United Nations Global Compact
UNHRC	United Nations Human Rights Council
UNICEF	United Nations International Children's Emergency Fund
US	United States
USA	United States of America
UWC	University of the Western Cape
WEF	Water-Energy-Food
WEFE	Water-Energy-Food-Ecosystem/Environment
WHO	World Health Organisation
WMA	Water Management Area
WMS	Water Management System
WRC	Water Research Commission
WRCs	Water Resource Classes
WRCS	Water Resource Classification System

List of Units for Measurements used

°c	degree celsius
$kg.day^{-1}$	kilograms per day
mamsl	meters above mean sea level
Mm^3/a	million cubic meters per annum
mm/a	millimeters per annum
mg/l	milligrams per liter
ms/m	millisiemens per meter

Chapter 1: General introduction

1.1 Background of the study

The background of the study presents the study overview, global context in the scholarship on water resource protection, and local context on water resource protection practice. The present study is about developing a citizen science framework for water resource protection that is envisaged to facilitate operationalization of resource directed measures (RDMs) using nexus approach. The study argues that science-policy interface must be practical, reflective and must consider the nexus approach using the concept of citizen science. Such a plan can address some of the reported challenges in addition to improving acceptance of RDMs as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level. The process of developing, validating and verifying such a plan is central to the proposed study so that the developed citizen science framework for water resource protection is applicable to catchments of different physiographic and socio-economic characteristics.

1.1.1 Study overview

The research work described in this thesis is pragmatic and its aim is to help provide a fundamental understanding of practical policy implementation towards water resources protection. Rather than attempting to focus on one particular aspect of policy implementation, the study chose to investigate homogeneous clusters for which policy practice is investigated by applying a nexus approach. Only with this nexus approach does the main theme of the thesis which is policy implementation towards water resource protection, become tractable. Challenges associated with water sources emanate from local level where water resources reside, land use activities take place, and where water users directly interacts with water resources. Therefore, effects of policy interventions directed towards water resource protection and their sustainable use, become evident when such practise is localised. The argument proposed in the present study is that science-policy interface must be practical, reflective and must consider the nexus approach using the concept of citizen science. Such a plan can address some of the reported challenges related to water resource protection in addition to improving acceptance of resource directed measures (RDMs) as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level.

The process of developing, validating, and verifying such a plan is central to the present study so that the developed citizen science framework for water resource protection is applicable at various catchments. The framework is designed by applying nexus approach, where the principles of socio-ecological model (SEM) from systems thinking perspective are followed. The framework is validated with case studies at selected catchments using records sourced from reported studies.

Parameters such as groundwater levels, groundwater quality, surface water quality, and river flows are used for assessing RDMs operationalization. This present study, therefore, is about developing a citizen science framework for water resource protection that will facilitate operationalization of RDMs at catchment level using nexus approach. The framework designed, validated, and verified in the present study has a potential to support local decision making for water resources protection. The framework also has a potential for wider replication, where it can be readily extrapolated for use in other catchments to facilitate policy monitoring and review towards water resource protection practices.

1.1.2 Current debate in the scholarship on water resource protection

This section of the thesis provides an overview of the current debate in the scholarship on water resource protection. The overview is important in understanding trends and key issues and methods used in the field of water resources protection at global level as part of water resource management.

Water represents almost three-quarters of the earth surface with only less than three percent of this water being characterised as freshwater (Adb Allah, 2020). However, despite accumulation of minor portion of the earth's surface, water is arguably, the life blood of existence which is critical for socio-economic development, healthy ecosystems and for human survival. The availability of sufficient, potable water is critical in fostering water supply and vigorous ecosystems services, agricultural production, industrial activities, and for food security (Masindi and Abiye, 2018). Therefore, efficient utilisation of such limited natural resource is critical for water supply and for life sustainability (Ishaku et al., 2013; Luo et al., 2020). However, accessibility to such resource especially potable water for food, health, and sanitation is sometimes limited (Yeleliere et al., 2018). Furthermore, due to unprecedented urbanization, climate change, population, and industrial growth which all together puts enormous pressure on water availability and its security, freshwater pollution, depletion, and its protection is a global striking challenge of our time in the 21st century (Sindik and Araya, 2013; Jabeen et al., 2015; Verbist et al., 2020).

Recent studies show that about 36% of the world's population live in water-scarce regions and it is postulated that growing populations and the ever-increasing demand for food and energy will exacerbate water scarcity problems (WHO/UNICEF, 2017; UNGC, 2018). A study conducted by the World Bank indicated that the world will not be able to meet the great development challenges of the 21st century without improving how countries manage their water resources (World Bank, 2014). Thus, designing practical measures in managing water resources remain essential in the water sector. Achievement of SDGs by 2030 is hinged on water availability. For example, UNECE (2018) noted that water is a cross-cutting indicator for the realisation of SDGs such as those linked to clean water, clean energy, food security, and ecosystem.

This deduction is supported by Mugagga and Nabaasa (2016) who found that sustainable management of water and sanitation is central to the attainment of several SDGs, particularly SDG 1 (no poverty), 2 (no hunger), 3 (good health), 14 (life below water) and 15 (life on land) across Africa. Hence, solutions to current challenges in water resources management are key towards achievement of the set SDGs targets. Over the years, there has been a pressure on policy developers and water resource managers to develop and implement intervention to mitigate impacts on water resources and socio-economic system. This has motivated policy implementers and researchers to identify ways of working together to better implement policies and strategies for effective protection of water resources (Cosgrove and Loucks, 2015; Lezak and Thibodeau, 2016; Manzano-Solís et al., 2019).

Studying water resources protection in the context of their sustainable utilisation using systems thinking approach appears to be a solution-based manner demonstrating how water resources protection policies should be implemented and evaluated for their effectiveness in addressing existing water resources challenges. Appropriate response to policy problems characterised by complexity such as those concerned with environmental management and regulation require use of systems thinking which offers a way of rationalising aspects of existing practice and of suggesting directions for improvement (Stewart and Ayres, 2001). Armah (2020), argue that systems thinking attempts to achieve a balance synthesis in terms of identifying existing challenges within a system and their causes, using the principles of systems analysis. Making informed decisions, as individuals and society, requires an understanding of the complexity of the systems such as economic, environmental, hydrological, and social systems across a range of spatial and temporal dimensions and require a systems-based approach (Mai et al., 2019; Armah, 2020). "Systems thinking" is an important conceptualization for research and policy makers in terms of understanding the interactions between the natural and human systems which is essential to formulate and implement effective sustainable policies (Hynes et al., 2020). To sharpen our understanding, investigations on policy practice towards water resources protection using lenses of systems thinking are critical. The theory of systems thinking has been used for identifying methods as well as an analytical and theoretical framework for the present study.

Literature indicates that there is a continuum of evolutionary forms of science-policy integration towards averting current challenges associated with water resources protection such as interaction between policy makers and university scholars or policy makers and consultancies (Grimm et al., 2018). However, it has been argued that the role of science in policy formulation and implementation should not be merely a matter of societal involvement in setting priorities and defining the agenda for research, instead it should also concern the reciprocal relationship, so that science-based knowledge and advice are adequately used in policy making processes (Mejlgaard et al., 2012). The concept of science-policy nexus is still not clearly understood by many, hence inadequate utilisation of the concept in policy practice.

The evident for this observation is abundant where available data and information exist from scientific research outputs, but policy makers seem not utilising such information when developing policies and strategies for water resource protection. For example, interaction between groundwater and surface water (GW-SW) bodies is well documented (Kotse at al., 2006; Parson, 2008; Owor et al., 2009; Weitz and Demlie, 2014; van Toll and Lorentz, 2018; Madlala et al., 2019), and understanding of such interactions is essential for water resources management in an integrated manner. However, application of GW-SW interaction concept in policy practice especially for water resources protection has been sluggish. The challenge has been exacerbated by poor understanding and collaboration that exist between scientific and political communities (Levy and Xu, 2012). The aspect of science-policy nexus role in policy implementation is addressed in the first objective of the present study.

Practices in the water resources protection are key towards achieving water security, however water is a cross cutting resource required for food, energy, and for ecosystem integrity, thus a comprehensive management approach is critical (Momblanch et al., 2019). This is reflected on the Water-Energy-Food-Environment (WEFE) Nexus which has been adopted as a holistic management approach towards achievement of inter-disciplinary societal goals such as SDGs for clean water, clean energy, hunger eradication, and life on land. This aspect is addressed in the second objective of the current study where assessment on the application of WEFE Nexus approach in water resource protection practice was carried out in order to show contributions of such aspects in the nexus towards achievement of socio-economic development goals.

Improved water policy development and implementation is key in addressing water challenges; however, implementation of policies has been challenging primarily because of lack of capacity, implementation plans, and other related factors associated with costs (Jabeen et al., 2015; Harwood et al., 2018; Tuokuu et al., 2018). This argument has been supported by Barbosa et al. (2016) who noted that research evidence suggests that policy implementation challenges are common in water resources planning and management which is characterised by difficult process of moving from policy to action. Willaarts et al. (2020) reported that in many arid and semi-arid regions, water scarcity is not just a growing environmental challenge but also a structural problem. The concept of citizen science has emerged in the last decade as a new approach for policy implementation especially in low-income countries where data scarcity is predominant and where conventional methods are expensive and logistically challenging (Hyder et al. (2017; Paul and Buytaert, 2018; Njue et al., 2019). Thornhill et al. (2017) argued that while state agencies predominantly monitor water resources at regional scale, citizen science is capable of monitoring resources at local level enabling capturing even small-scale pollution events taking place where water resources reside. Citizen science has a potential to directly inform decision making trough data generation as well as important realisation of involving more informed communities who are directly in connection with their environment (Thornhill et al., 2017).

Considering challenges associated with data scarcity especially in developing countries, lack of using citizen science as an alternative policy implementation plan remains problematic or a concern. For example, Capdevil et al. (2020) pointed out that there is significant capacity within communities which could be explored through utilisation of citizen science. Therefore, non-utilisation of the citizen science concept in policy implementation signifies substantial under-realized opportunity which should not be allowed hence the focus on citizen science in the present study. In other ways, the concept of citizen science is applied in the context of policy practice towards water resources protection at local level in the present study. The concept is entrenched in the novel citizen science framework designed for operationalization of RDMs at catchment level which is presented and discussed in chapter 5 of the current thesis.

1.1.3 Current debate in the practice on water resource protection

In the context of current debate in practice on water resource protection, the South African context is reflected upon. The reflection is important in understanding local situation and issues related to water resources protection. Such understanding is key in developing required and relevant interventions.

South Africa (SA) is a water stressed country with only less than 1 700 mm per person per annum (DWA, 2011b) located in a semi-arid region and has limited water resources. Despite the situation fair provision of adequate water services to all in an ecologically sustainable and economically efficient manner has been a high priority for the country (Weaver et al., 2017). Although provision of clean water supply in the country is comparable to other developed countries, however, water supply in other areas especially those characterized by rural settings remains a challenge (Madigele, 2017; Edopkayi et al., 2018). It is estimated that in SA about 5 million people continue to live without a source of potable water within a reasonable distance from their houses (Wanda et al., 2015). It is also estimated that more than 60% of South Africa's rivers are currently being overexploited (Donnenfeld et al., 2018). Water quality deterioration from water resources have also been reported, which poses a serious threat to potable water industry (van Rensburg et al., 2016). Challenges related to water quality deterioration in the country have been confirmed by du Plessis et al. (2014) who noted that, several water management areas are experiencing water shortages while natural systems are put under enormous pressure which led to the overall deterioration of water quality.

Water is recognised as a strategic resource that is critical for social and economic development in South Africa (SA). The South African National Development Plan (NDP) outlines that "by 2030 the country ought to ensure that all South Africans have access to clean running water in their homes; produce sufficient energy to support industry at competitive prices, ensuring access for poor households, while reducing carbon emissions per unit of power by about one-third; ensure household food and nutrition security; implement interventions to ensure environmental sustainability and resilience to future shocks".

These aspiration of the NDP are in line with the United Nations (UN) set targets for SDGs linked to clean water (SDG 6), affordable and clean energy (SDG 7), hunger eradication (SDG 2), environment (SDG 15).

Accordingly, management of water resources within a WEFE Nexus approach is pivotal towards achievements of the NDP aspirations and the set SDGs targets by 2030. Thus, there is a need for development of a roadmap to achieve the set targets for SDGs by 2030 in SA utilising the WEF Nexus approach (Mabhaudhi et al., 2018). The legislative framework which guides water resource protection in the country, puts efficiency, sustainability, and equity as central guiding principles in dealing with the country's scarce water resources. The National Water Act (NWA) which was promulgated in 1998 requires that water is managed for the benefit of everybody by ensuring its protection, use, development, conservation, management and control of water resources in a manner that takes into account the need, equity, redress, efficiency, safety and growth, amongst other factors (NWA, 1998). The Act has become one of the most progressive legal documents of environmental legislation, globally (Seward, 2010).

The South African legislation mandates the protection of the nation's scarce water resources by prescribing a series of measures to achieve this protection while at the same time acknowledging the important role of water resources in supporting local social and economic development (Seward, 2010). Water resource protection measures prescribed by the NWA include, firstly, classification of significant water resources into water resource classes (WRCs) based on the degree of water resource utilisation or on the level of change from a pre-development state. Class I, Class II, and Class III represents water resources that are minimally, moderately, and heavily modified or used, respectively. Secondly, determination of water resource reserve and conditions (taking into consideration ecological water requirements and basic human needs), and thirdly, setting of resource quality objective limits and narrative statements. RDM studies are undertaken in a progressive mode in order to ensure that policy implementation in a practical way for water resource protection is realised, and positive strides and significant progress have been recognised in this regard (Seago, 2016; Riemann et al., 2017), and such progress is continuously sustained based on the number of RDM studies being undertaken thus far. To date, studies on RDMs have produced many resource quality objectives (RQOs) with numerical limits and narrative statements that are deemed necessary to improve state of water resources in SA, thereby enabling sustainable water resource utilisation when these measures are operationalized (DWA, 2012; DWS, 2018).

Although RDM practice at national and regional level is evident, however RDM uptake and practice as policy implementation strategies towards water resources protection is still limited at catchment level. Such limited practice of RDM is partly due to the absence of a feasible RDM implementation plan at catchment level.

There are existing gaps in knowledge and understanding of water resource protection processes which has led to inadequate implementation of the associated regulations for different water resources such as RDM (Riemann et al., 2017).

Odume et al. (2018) argued that lack of RDMs implementation strategy at catchment level lead to contestation of the gazetted resource quality objectives by water users. Therefore, appropriated implementation plan for RDM which is catchment orientated needs to be developed and such a plan needs to consider Citizen Science and WEFE Nexus approaches which are relevant to users, environment, and policy makers. Such a plan can address some of the exiting challenges in addition to improving acceptance of RDMs as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level. In a nutshell, the present study is about the above stated aspects regarding RDM.

1.2 Problem statement

1.2.1 Research problem

Lack of available and feasible plan for RDMs practice at catchment level has a direct influence on the continued water quality deterioration and unsustainable utilization of water resources. Continued water quality deterioration and unsustainable water resources remains a challenge in SA (Masindi and Abiye, 2018; Dlamini et al., 2019). This complexity presents a serious challenge in support of the country's economic development activities and achievement of SDGs by 2030. These challenges are compounded by lack of available appropriate tools and plans for utilisation towards water resource protection to avert existing challenges. RDMs can be used as water resource protection strategies at local level to ensure sustained water utilisation and to promote local socio-economic development. However, RDM studies undertaken at regional are amalgamated, and downscaling such measures to a local scale (source point) where water resources are utilised and where the citizens dwell that are supposed to be part of the management practice of water resource remains a challenge. For example, unsustainable use and lowering quality of water resources become imminent and felt by water users locally, before such factors become evident at regional level. Yet citizens are not part of monitoring activities such as water quality and quantity or local resource protection activities in general which means that locally relevant water resource protection measures are discounted. Odume et al. (2018) argued that lack of RDMs implementation strategy at catchment level led to contestation of the gazetted resource quality objectives by water users. Hence, it is critical that water resource protection strategies such as RDMs are prioritised for operationalization at catchment level where the citizens become part of such an operationalization practice.

Therefore, an appropriated RDMs implementation plan for RDM which is catchment orientated needs to be developed and such a plan needs to consider Citizen Science and WEFE Nexus approaches which are relevant to users, environment, and policy makers. Such a plan can address some of the exiting challenges in addition to improving acceptance of RDMs as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level. This is the focus of the present study.

1.2.2 Unit of analysis

This section of the thesis describes unit of analysis upon which the study is framed and elaborates on what variables formed the unit of analysis that were investigated. The present study is about policy implementation where a plan is developed to consider Citizen Science and WEFE Nexus approaches which are relevant to users, environment, and policy makers. A policy is a guide which entails broad statement of future goals and actions, and expresses ways and means of attaining them, therefore policy implementation involves translation of goals and objectives of a policy into an action (Khan, 2016). Policy studies traditionally, embrace a scientific approach to the identification of problems and their solution (Browne et al., 2018) and such approach has been adopted in the present study. The variables studied included policies and regulations, strategies for policy implementation, levels of policy implementation, role players on policy implementation, water resources, and water quality and water quantity. Policy implementation levels included national, regional, and local, while policy implementation role plays were limited to government institutions mandated with water resources protection, and local citizens. In terms of water resources, only groundwater and rivers were considered with the exclusion of dams and/or lakes, estuaries, and wetlands. River flows, groundwater levels, groundwater quality, and river quality were the water variables that were studied.

1.2.3 Research question

Based on the systematic reviewed literature, policy implementation on water resource protection displays a positive picture at national and regional level while at local scale where water resources reside the review shows a sluggish progress (Seago, 2016; Riemann et al., 2017). However, it is important to note that challenges associated with water resource protection at local level are evident with continued unsustainable water resource utilisation and water quality deterioration (Masindi and Abiye 2018), making science-policy interventions critical towards water resources protection practice. Therefore, the main research question for the present study is 'how does a citizen science framework ensures implementation of science-policy nexus in the water resource protection field of water resource management?' In other words, to what extent can citizen science frameworks ensure implementation of science-policy nexus in the water resource protection field of water resource management?

1.2.4 Research hypothesis: Central argument of the study

The present study hypothesized that if a citizen science framework is developed and validated for water resource protection, then RDMs will be operationalized at all levels including local level, making science-policy nexus a reality in the water resource management discipline. The study aspired to answer this question and proved the hypothesis. In other words, we assume that if there is no available suitable RDM operational plan at local level, policy implementation towards water resources protection will remain limited, and that there will be no reporting system to evaluate policies for their effectiveness in mitigating existing water resources challenges. Therefore, science-policy interface must be practical, reflective and must consider the nexus approach using the concept of citizen science. Such a plan is envisaged to address some of the reported challenges in addition to improving acceptance of RDMs as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level.

1.3 Study aim and objectives

1.3.1 Study aim

It is important to note that challenges associated with water resource protection at local level are evident with continued unsustainable water resource utilisation and water quality deterioration (DWA, 2011b; Barnard et al., 2016; Chinyama et al., 2016; Masindi and Abiye 2018). These challenges are compounded by lack of available appropriate tools and plans for utilisation towards water resource protection to avert existing challenges locally. RDMs can be used as water resource protection strategies at local level to ensure sustained water utilisation and to promote local socio-economic development.

Therefore, the study aims to demonstrate the feasibility of operationalizing RDMs at catchment level using a citizen science framework and to showcase the appropriateness of RDMs as policy implementation strategies towards water resources protection.

1.3.2 Study objectives

In order to ensure that the study aim is achieved, the following objectives were formulated: 1) assess the application of science-policy nexus in policy formulation and practice towards water resource protection. 2) Establish the application of reflective practice models to assess operation of water-energy-food-environment nexus approach in water resource protection practices. 3) validate a process based operational plan for catchment orientated resource directed measures.

1.4 Study rationale

1.4.1 Importance of the study

Outcomes of the study are envisaged to have different contributions to the discipline of water resource management with a focus on water resource protection in several ways:

For example, the analysis of WEFE Nexus role in water resources protection provides basis for designing a system for fast-tracking progress on the use of WEFE Nexus in policy implementation towards achieving SDGs by 2030. The novelty of the study is seen through the four papers prepared for publications which contribute to scientific knowledge or the scholarship in the field of water resource protection and management as follows: 1) Paper 1 on the application of science-policy nexus in policy formulation and practice towards water resource protection, 2) Paper 2 on the application of reflective policy models to assess operation of water-energy-food-environment nexus approach in water resource protection practices, 3) Paper 3 on the validation and verification of a process based operational plan for catchment orientated resource directed measures. Paper 4 on the capacity building and social learning for local citizens in the water resource protection (education hydrology). Such contribution will be achieved by developing positive attitudes such as the level of awareness and knowledge of water resource protection at local level by water users. The overall intended outcome of the present study is that a suitable citizen science framework for operationalizing RDMs at catchment level becomes available. Such framework will be validated and verified to demonstrate its feasibility of operationalizing RDMs at catchment level, thus showcasing the appropriateness of RDMs as policy implementation strategies towards water resources protection.

The study has far-reaching impacts, namely, a) case study for policy implementation and evaluation, b) achievement associated with several policy frameworks, c) practical skills in institutions during water resources protection activities, d) knowledge contribution through publications, e) resources for teaching and learning on water education in schools, f) a resource for capacity building programmes in water institutions to implement the citizen science framework. In terms of improvement on policy implementation and evaluation, the novel citizen science framework developed will facilitate RDM practice at local level, thus enabling policy implementation and evaluation for its effectiveness towards water resources protection. The study will be a benchmark in testing the developed plan in assessing its contribution in achieving several policy frameworks such as the South African National Development Plan 2030 (NDP 2030), Sustainable Development Goals (UNHRC, 2011), and African Agenda 2063 (AUC, 2015).

1.4.2 Conceptualisation of the study

In general, the idea of developing an operational plan for catchment orientated resource directed measures was conceived by the existing RDM studies. Although the present study is a stand-alone project, but it is directly linked to the RDM studies undertaken by the Department of Water and Sanitation (DWS) in different catchments as water resource protection practice. To date, studies on RDMs have produced many resource quality objectives (RQOs) with numerical limits and narrative statements that are deemed necessary to improve state of water resources in SA thereby enabling sustainable water resource utilisation.

Such numerical limits are useful in testing compliance of water resource managers towards RDMs practice (Pollard et al., 2012). For example, Dlamini et al. (2019) showed that it is possible to use historical water quality data to assess compliance with gazetted RQOs. This example demonstrates the usefulness of using historical data for monitoring RDMs compliance at catchment level. The current study went beyond the use of secondary data by advocating the use of citizen science and nexus approaches in generating information for policy makers and practitioners in water resource management practices and research. Key concepts of science-policy integration, WEFE nexus, and citizen science were considered and described to contextualise water resources protection and integrated water resources management practice. These are the key conceptual frameworks for the present study.

1.5 Study scope and nature

1.5.1 Scope of the study

The present study aimed at developing a citizen science framework for operationalizing resource directed measures at catchment level. Such a framework used nexus approach and followed the principles of SEM from systems thinking perspective. The framework was then validated with case studies at selected catchments using records sourced from reported studies. Parameters such as surface water ecological status, groundwater levels, groundwater quality, surface water quality, and river flows were used for assessing RDMs operationalization. Surface water flows and groundwater levels provide useful information for understanding compliance with established river flows and groundwater volumes. For example, maintaining low flows in a river system ensures that there is sufficient minimal water to sustain ecological ecosystem within a catchment. In terms of groundwater, maintaining established levels of groundwater table ensures that compliance with resource quality objectives established for groundwater use is achieved. For example, maintenance of groundwater table at a certain level ensures groundwater availability and sustainable use within a catchment. The present study did not focus beyond the afore-mentioned scope or coverage in terms of parameters.

1.5.2 Nature of the study

This study focuses on policy implementation towards water resources protection, which is about developing a plan for policy practice at local level, thus development and validation of such a plan is central to the study. This present research study followed a descriptive case-research study design embracing a pragmatic approach where mixed methods were used to investigate water resource protection policy implementation at local level. The case study is based on South Africa, which is a country with availability of water resources, much like the climate, varying significantly across the country. The main concern about water resources in the country of South Africa is that surface water resources in most areas are currently fully developed and the demands exceed the present water resource availability.

Areas such as the Vaal, Umzimvubu-Tsitsikamma and Pongola-UMzimkhulu Water Management Areas (WMA) are stressed catchment areas requiring interventions for water resources protection and sustainable use. Since the use of mixed methodological approach yields different results and interpretations of such results tend to have challenges due to underlying philosophical principles embedded in such methods, a comprehensive rigour analysis (quality control or quality assurances) in such methods were carried out to determine reliability and validity of such results before interpretations of such findings. Primary and secondary data were sourced from historical records and primary sources to achieve the study objectives.

1.6 Outline of thesis report

This thesis is made up of six chapters outlined successively, namely: 1) General introduction, 2) Literature review, 3) Study area description, 4) Research design and methodology, 5) Synthesis of results and discussion on the three research objectives, 6) Conclusion and recommendations. Chapter 1 of the present study provides the study overview, background to the study in terms of scholarship and context debate on water resource protection, problem statement, and study aim and objectives. It further discusses significance of the study, conceptualisation of the study, and lastly presents outline of the thesis. Chapter 2, critically analyse results of other studies that are closely related to the three study objectives in order to contextualise the present study. Main focus is directed towards methodological approach followed, methods that were used, results that were found, and settings where studies were carried out. The review has been presented systematically in relation to the specific objectives of the current study. Chapter 3 provides a description of the study area where the research problem was implemented. The current study used three case study areas to develop a citizen science framework. However, the description provided on these study areas was broader to provide a broader contest to the current study. Chapter 4 describes research design that was followed for this study, research methodology chosen for the study, research methods used for data collection and analysis, quality assurance and control instituted to ensure validity and reliability of the research findings, research integrity measures that were applied which strengthened reliability of findings of a research study. Results from the three study objectives are presented in chapter 5, where description of main data, data analysis, results interpretation, comparative analysis, implications of the results, and study evaluation are discussed. Chapter 6 presents conclusion and recommendations for practical considerations in policy implementation and for further research work emanating from the study findings which was beyond the scope of the present study.

Chapter 2: Literature review

2.1 Introduction

Chapter 1 has presented background of the study; problem statement and study aim with specific objectives. This chapter 2 presents the reviewed literature on the global, regional, and national status concerning water resources protection to contextualise the current study and to identify knowledge gap on water resources protection practices. The review has been presented systematically in relation to the specific objectives of the present study with a focus on what is known and not known on water resources protection. Previous studies conducted on utilisation of science-policy nexus in policy implementation, application of Water-Energy-Food-Environment (WEFE) nexus concept in water resources protection practices, and on the application of Socio-Ecological Model (SEM) in policy practice were reviewed.

Such studies conducted have great relevance to the present study. These studies were reviewed based on their methods applied, results obtained, settings where studies were conducted, and methodological approaches used in line with the specific objectives of the current study. In policy practice, science-policy nexus plays a critical role where policy provides questions to be researched and science provides solutions to challenges faced by policy makers. However, the concept of science-policy nexus is still not clearly understood, hence inadequate utilisation of the concept in policy practice. It is therefore important to understand how science-policy nexus works in reality. Such understanding is critical towards improved utilisation of the concept in policy practice. The review of literature on the aspect of science-policy integration is relevant to address the first objective of the current study.

In terms of WEFE nexus, the application of the concept in policy practice has been adopted as a holistic management approach towards achievement of inter-disciplinary societal goals such as Sustainable Development Goals (SDGs) for clean water, clean energy, hunger eradication, and life on land. Therefore, understanding of how the WEFE nexus concept is applied in policy practice forms bases for use in water resources protection practice to sustainably achieve resource security for all, thus fast-tracking achievement of SDGs by 2030. The literature review presented in this section provides a clear understanding of the WEFE Nexus as a key concept applied in water resources protection and the focus of the second objective in the present study as discussed in chapter 5 and 6. With regards to the SEM, understanding of how its core principles are applied in practice is important. Such understanding guides policy implementation towards water resource protection practice which requires consideration of different levels of policy implementation. Such aspect is addressed in the third objective of the present study where the SEM is used as an analytical framework for designing citizen science framework which facilitate Resource Directed Measures (RDM) practice at localized scale.

The literature review chapter argues that detailed, analytical, and reflective review of existing methods on water resources protection practice is essential. Such review provides the basis for reliability and validity of the results of the present study for present and future researchers.

2.2 Previous studies to contextualize the current study

2.2.1 Global status concerning water resources protection

This section of the thesis provides a literature review on studies undertaken on science-policy nexus, WEFE nexus, and citizen science as they are applied in the subject of water resources protection at global level. The review is important that it provides a foundation for contextualizing the current study and to identify existing knowledge gaps at global level.

Economic development, social securities, and natural resources sustainability are fundamental towards achievement of Sustainable Development Goals (SDGs) which are aimed at protecting the planet, while ensuring that all people still enjoy peace and prosperity, presently and in the future (Morton et al., 2017). However, natural resources are increasingly under great pressure due to factors such as rapid economic growth demand, population increase, urbanization and industrialization, environmental implications of pollution and waste discharges, as well as limited amount of available water due to decreases in rainfall and stored water supplies (Parish et al., 2012; Elmhagen et al., 2015; Carmona-Moreno et al., 2019; Dlamini et al., 2019; Morris, 2019). The reported observations give the impression that food security is threatened. For example, it has been reported that two thirds of the global population are already living in areas facing severe water scarcity which is a threat to food security (Chouchane et al., 2018), and it is postulated that 40% of the global population in 2050 will live in countries without enough land nor water to meet the demands of their population (Ashoori et al., 2017; Ibarrola-Rivas et al., 2017). Such demand on freshwater is evident not only because of the growth by economically developed countries, but also by developing countries (Nishida et al., 2016). Such increase in water demand has financial implication which becomes a challenge for developing countries, especially countries that experience limited financially resources (Anon, 2019).

Water resources availability such as sustained stream flows and groundwater availability are essential for freshwater ecosystem and biodiversity support that provides goods and services for human wellbeing and threat to such resources requires immediate intervention measures. Decline in shallow groundwater levels affect ecological ecosystem such as amphibian species leaving in groundwater-dependent wetlands (Serrano, 2016). Devastating droughts events have been reported in the areas of Western and Central Europe such Poland and Germany which led to diminished spring discharges at a percentage between 4% and 52% (Staśko and Buczyński, 2018), while quantity of river discharge in Arctic regions in the United States have been found to be declining due to various factors including climatic variation (Rawlings et al., 2019).

Killian et al. (2019) made an observation that observed declines in groundwater-level elevations and stream flow, contemporaneous with increases in irrigation in the area, have raised concerns about future groundwater availability and the effects of groundwater withdrawals on stream flow.

In Bangladesh, groundwater depth and groundwater-level deficit (drought) has been reported to be continuously increasing (Mustafa, 2017), and the decline has been linked with impact by urbanization, and as a result groundwater extraction in many locations which has become unsustainable with predicted catastrophic events like earthquake, subsidence and pollution being highly possible (Kutub, 2015). Due to current challenges related to stream low flows, experienced in several countries' recommendations have been made on complementary management for high flows that occur early in the growing season with maintenance of adequate baseflows to maintain ecosystem functioning in the face of hydrologic alterations induced by climate change and human water demand (Diehl et al.,2020). In terms of groundwater availability, intervention measures such as artificial recharge to the aquifers and water-saving technologies have been recommended to prevent groundwater mining (Mojid et al., 2019). Although increased water demand has been linked to population growth at global level (YiTong et al., 2020), however, different views with regards to population density and water demand have been reported. Sanchez et al. (2020) investigated how future scenarios of population densities and climate warming will jointly affect water demand across two rapidly growing U.S. states (North Carolina and South Carolina). The findings of the study indicated that water demand increased because of rising temperatures could be mitigated by applying policies that promote higher density development. Nevertheless, current water resources challenges require appropriate policy interventions and effective implementation plans especially in water-scarce countries. For instance, studies on future socio-economic and climate have revealed that achieving a low-carbon development pathway can potentially reduce global municipal water demands in 2060 by 2-4% (Parkinson et al., 2016; Miller et al, 2021; Wright et al, 2021).

Reported water resources challenges related to water quality deterioration, and sustainable water availability are few of the parameters for environmental boundaries that define human wellbeing and livelihoods (Gurdak et al., 2017). Such challenges are pivotal to the increased global water, energy, food, and environmental water requirements which have resulted in amplified conflicts and trade-offs among the water resources sectors. Ecological ecosystem integrity and water resources protection are key to sustainable achieve resource security for all, (Momblanch et al., 2019), and such understanding is central to Water-Energy-Food-Environment (WEFE) Nexus application in practice. The nexus has been promoted as a holistic management approach towards achievement of inter-disciplinary societal goals such as SDGs for clean water, clean energy, hunger eradication, and life on land.

For instance, Integrated Water Resource Management (IWRM) approach has been used as a multi-purpose management approach to maximize on social and economic benefits through jointly management of water and land (Momblanch et al., 2019). However, Benson et al. (2015) and Momblanch et al. (2019) argued that IWRM has some limitations in terms of representing interactions among different sectorial policies, and therefore, the WEFE Nexus has been considered as an alternative approach.

Although WEFE Nexus is promoted for use in practice (Benson et al., 2015; Momblanch et al., 2019), however limitations associated with the nexus have been reported. For example, Liu, et al. (2017) highlighted that information and knowledge gaps in the understanding of the WEFE inter-linkages are limits the use of the Nexus. Furthermore, the lack of systematic tools that could be used to unravel the WEF nexus and make the approach more operational limits our ability to address all the synergies and trade-offs involved in the nexus, (Liu, et al., 2017). Endo et al. (2020) concurred with Liu, et al. (2017), and pointed out that there are no standalone methods and tools for practicing and implementation of the nexus approach. Nevertheless, progress on the application of WEFE Nexus requires reflection to showcase its applicability to offer integrated solutions for socioeconomic and environmental-related challenges.

Current water resources challenges are complex and multi-sectorial and require evidence-based approach for policy intervention such as science-policy nexus which plays a critical role where policy provides questions to be researched and science provides solutions to challenges faced by policy maker (Hickey et al., 2013). However, science-policy nexus application in policy implementation has not been taken up satisfactory. For instance, McConney et al. (2016) noted that connecting science to policy is a major issue confronting the world today. The researchers pointed out that critical scientific knowledge is not effectively communicated to the public and decision makers (McConney et al., 2016). The problem seems to be rooted with availability of scientific product in a form that is easily accessible and understandable to policy makers. This is highlighted in Nebhöver et al. (2013) who noted that accessibility of science product in policy-relevant formats remains a challenge. Graffy (2008) indicated that there is a critical need to develop better theoretical understanding of the science-policy nexus and practical management strategies to enhance accountability and policy relevance of scientific research while preserving its core of independent enquiry to improve the effectiveness and efficiency of government interventions (Ranchod, 2016).

Ranchod (2016) pointed out that science research should make consideration of an interactive approach to contextualise how research products get used beyond the efficiency and effectiveness of knowledge generation. This agrees with Nebhöver et al. (2013) who as reported earlier, indicated that accessibility of science product in policy-relevant formats remains a challenge.

For instance, it has been pointed out that research product and research results with complex data need to be summarised, translated, and presented in a short, concise, and implementable policy recommendations for decision-makers (Grimm et al., 2018).

Although the need to integrate science and policy for more sustainable environmental policy making is well recognised, however, McFadden et al. (2009) and Driscoll et al. (2011) pointed out that examples or instances of converging theories and analytical frameworks for practical uptake of science-policy nexus remain relatively few in numbers. As a result of this knowledge gap, the key question for policymakers is no longer whether or why science product is needed in policy development and implementation, but how the science product is used to develop socially acceptable and environmentally friendly solutions?

Application of the citizen science concept in policy practice is widely reported especially in the field of water quality (Farnham et al., 2017; Hyder et al., 2017; Jollymore et al., 2017; Rae et al., 2019; Quinlivan et al., 2020; Redmon et al., 2020), water quantity such as rainfall data collection, surface water level and discharge data collection, and ecological status assessment (Njue et al., 2019; Rae et al., 2019; Ferhi et al., 2020). Furthermore, studies on the application of citizen science in groundwater level and quality monitoring have also been reported (Little et al., 2015; Baalbaki et al., 2019; Manda et al., 2020; Plson, 2020), which depicts wide applicability of the citizen science concept. Despite the potential exhibited by citizen science in policy implementation towards water resource protection, some limitations have been reported. For example, Wieser et al. (2020) reported that sites selected by citizens for water resource assessment are not always representative of the sample. The Authors noted that in most cases previous studies on work to account for biased site selection have relied on knowledge of covariates to explain differences between site types, but such knowledge is often unavailable (Wieser et al. (2020). Nevertheless, success stories on the application of citizen science are prevalent in literature (Cele, 2015; Bannatyne et al., 2017).

Feasibility of citizen science as an alternative approach for policy implementation at catchment level towards water resource management has been tested (Fehri et al., 2020). In the study, rainfall data collected by citizens were compared to data from reference stations, where data from both sources showed a significant correlation of between 0.91-0.98 (Fehri et al., 2020). This is an indication of the potential processed by citizen science approach in data collection especially in areas experiencing monitoring data scarcity required for decision making. Despite significant application of citizen science in policy practice to assist in fast-tracking achievement of SDGs by 2030, however, the concept is more widespread in developed regions such has the US, Europe, and Australia (Shulla et al., 2020). Shulla et al. (2020) reported lack of participatory approach in governance and that not all countries have strategies in place at national or local levels to support application of citizen science.

2.2.2 Regional status concerning water resources protection

In the African context, challenges associated with water quality deterioration, river flow regime, and ineffective policy practice towards water utilisation have been reported (Odiyo and Makungo, 2012; du Plesis, 2017; Ramulifho et al., 2019). These challenges together with other many factors contribute to an increasing gap between water availability and demand in Africa (Harding et al., 2020). This observation is apparent in Douagui et al. (2019) who investigated source of groundwater quality impact in the Southern Part of Abidjan District, Côte d'Ivoire. Their study was critical in elucidating sources of groundwater quality deterioration. For instance, when they applied correlation assessment methods between physicochemical parameters, their study indicated that there was a strong correlation between physicochemical parameters (Douagui et al., 2019). The study concluded that source of groundwater quality deterioration in the study area was mainly related to geogenic (rock-water interaction), anthropogenic sources (domestic sewage), and intrusion of marine and lagoon waters (Douagui et al., 2019).

Prior research indicates that watershed basins in Africa are prone to management challenges which may result in conflicts if not properly managed. For examples, a case study undertaken in the Nile River Bain on the roles and challenges faced in managing watersheds revealed that there is a sluggish in the implementation of coordinated, planning and development program which leads to unsustainable utilization of water resources (Mutekanga, 2016). The Author associated the challenge with a lack of coordination and detailed effective collaboration among some of the major players such as the Nile Basin Initiative and other development partners. Calhman and Hora (2016) argued that established agreements within watershed basins should institute clear paths and rules for monitoring, use and surveillance of water, and that the process should be carried out in an integrated manner. The observation connotes those policies developed for protection and management of water resources would not be good enough to curtail existing challenges if there are no existing plans put in place to implement policies, and in cases where there is lack of policy implementation plans, conflict may arise.

While challenges related to water availability seem not to be a problem in the Western region of the African continent, however, challenges related to water supply, water quality deterioration, and water basin management are apparent. This is evident when water resource challenges in Cameroon, Ghana, and Nigeria are explored. Cameroon is ranked as the second country in Africa (after the Democratic Republic of Congo) with the highest water quantity availability in water resources, which is estimated to be three times the world's average of 7,000 m^3 (Ako et al., 2010). However, access to such abundant water from resources has been reported as a major problem due to inadequate management and authorities' inability to understand the pattern of urbanization for effective planning (Fonjong and Fokum, 2017). In Ghana, challenges associated with surface and groundwater quality deterioration have been reported to be worsening (Yeleliere et al., 2018).

For instance, it has been reported that in the Eastern Region, drilling records indicate that 20-30% of rural boreholes have iron and manganese concentrations well more than the World Health Organisation (WHO) water quality guidelines (0.3 mg/L and 0.1 mg/L, respectively) (Kulinkina et al., 2017). Illegal mining, waste and leachate from chemical fertilisers have been noted as sources of pollution (Yeleliere et al., 2018). Although in Nigeria, within the region of the North-Central, there are no apparent reported water challenges, which is due to water availability in water resource systems which is higher than the present use within the spatial location of rivers which also enables enough supply to all sections of the states in the region (Salami et al., 2013). However, Emenike et al. (2017) reported that access to water within the Ado-Odo and Ogun State is mostly limited to the private sources because of the level of water quality and accessibility. Water quality degradation had been found mostly in Lagos Rivers, Kano, and Kaduna where most industries are located, and a need for water resource protection measures such as prosecution of water resources polluters by the Federal Ministry of Environment has been recommended (Idu, 2015). Nwankwoala (2014) gave an indication that despite huge water resources in Nigeria, water resource development activities have not been efficient with the phenomenal population growth, and the researcher recommended policy reform in the country.

In the Southern African Development Community (SADC), issues related to policy implementation and governance have been reported. For instance, in Malawi, water challenges linked with governance issues have been reported with indications that water supply and sanitation services is still confined to urban populations due to governance administrative challenges (Chiluwe and Nkhata, 2014). A study by Adams (2018) indicated inconsistencies in the proportion of households that satisfy Malawi versus the United Nations and World Health Organization minimum water-access standards. Combination of factors including increased water demand, poor communication between stakeholders, and weak regulation and enforcement have been reported as challenges being experienced in Namibia, and as a result development of more robust and resilient strategies has been recommended (Lewis et al., 2019).

Ihemba and Esterhuyse (2020) reported that groundwater use for irrigation has increased above the sustainable safe yield for the aquifers in the GrootfonteinTsumeb-Otavi Subterranean Water Control Area (GTO-WCA). The study proposed specific management solutions such as amendment of the legislation and policies to ensure that the management of Karst aquifers, in the country including the allocation of abstraction quotas is clearly addressed (Ihemba and Esterhuyse, 2020). Such reported challenges call for reinforcement of existing policies and improvement on their implementation. While water scarcity and water quality deterioration seem to be common in many African countries, however, policy related challenges are also apparent. For example, lack of water resource protection practices for sustainable water supply has been identified amongst other factors as a driving factor for the experienced challenges especially in the Sub-Saharan African countries (UNHRC, 2011).

This is an indication that solutions on water resource challenges should not only focus on water quality and availability, but also on other aspects such as water governance and policy implementation (Salami et al., 2013).

Although water resources challenges have been experienced in the SADC Region, however, it is encouraging to note that, policy interventions have been established to curb current challenges for the sub-continent. For instance, water scarcity challenges associated with increased frequency and intensity of droughts and increased water use have been experienced in the SADC Region (Matchaya et al., 2019). Due to the nature of river basins and the uneven distribution of water resources, water resource management strategies were necessary at regional level to promote regional integration and avoid conflict (Matchaya et al., 2019). Subsequently, there are existing legal frameworks which give guidance on water resource management within the region such as SADC Regional Water Policy, SADC protocol on shared watercourses, and SADC Regional Strategy Action Plan on Integrated Water Resources Development and Management (Matchaya et al., 2019). Khan et al. (2017) argued that sustainable watershed management requires water resource managers and policy makers to have clear understanding of their water resources systems, their interconnections, and impact of human actions on the natural systems. Such understanding is critical to efficient regional water resources management.

2.2.3 National status concerning water resources protection

South Africa experiences various challenges related to water scarcity, water supply and deteriorating water resources quality which pose threat to ecological ecosystems, economic development, and human wellbeing. The country is a developing state characterised by semi-arid conditions and climatic changes which has a direct influence on water resources availability with only the southwest region of the country that predominantly receives its total annual rainfall during the austral winter months (April-September) (Kabanda and Nenwiini, 2016; Mahlalela et al., 2019). Water resources availability challenges in the country are evident and widely reported in literature which hinders progress economic development activities, social wellbeing, and food security. For instance, 146 of South Africa's 565 rivers are categorised as having 'very low' flows, while a further 105 are 'low' and another 88 'moderately low which translate to more than 60% of South Africa's rivers currently being overexploited (Donnenfeld et al., 2018). This observation is in agreement with findings by Ndebele et al. (2020) who reported that the country's rainfall trend was positive between the years of 1800-1900, while a negative trend was observed in the period 1900-2016. While rainfall variability has a direct influence on water supply availability, such challenge has also been reported to influence farming activities (Mkuhlani et al., 2020). Therefore, understanding of climate change impact in the country is essential towards sustainable water resources management practice (Nkhonjera, 2017).

Due to water scarcity challenges experienced in some parts of the country with recent crisis brought on by the Cape Town's "Day Zero" drought, studies have documented the need for policy intervention such as strategies to enhance management of water supply and water resources sustainability (Booysen et al., 2019; Scheihing et al., 2020).

Although South Africa faces several challenges with regards to water resources, such as high demand for water supply and water resources availability in some catchments, however, water quality deterioration is predominant among water resources challenges in the country. This is highlighted in several water resources quality assessment studies. For example, eutrophication, emerging water quality concerns such as endocrine disrupting chemicals, salinity, trace metal accumulation, and physicochemical properties exceeding regulatory standards have been reported (Crafford and Avenant-Oldewage, 2011; Jordaan, & Bezuidenhout,2013; Moja et al., 2013; Barnard et al., 2016; Chinyama et al., 2016). Nutrient enrichment such as high levels of Phosphorus, chemical oxygen demand (COD) and Nitrogen have been linked to ecological changes, mostly notably blooms of algae or macrophytes (Griffin et al., 2014; Cullis et al., 2018). Eutrophication may impact ecological systems such as fish migration (Downs et al., 2018), and have aesthetic, recreational, agricultural, and human health impacts (Grant et al., 2014; Griffin et al., 2014). Water quality problems related to microbiological and physicochemical quality within the Klein Jukskei catchment, Johannesburg, have been linked with local conditions influenced by informal settlements and industrial waste discharges (van der Hovena et al., 2017). Such water quality problems influenced by local conditions require policy interventions that consider local conditions. Clasen et al. (2007) argued that choices among water quality interventions must be guided by local conditions.

Water quality problems associated with groundwater resources have also been reported (Masindi and Abiye, 2018). For example, several villages such as Siloam Village, Milaboni, and Tshikombani located within the Nzhelele River in the Limpopo Water Management Area have been reported to be vulnerable to water quality problems such as high levels of calcium, magnesium and nitrate in private boreholes, attributed to the agricultural practices and washing of clothes in the neighbourhood of the boreholes (Odiyo and Makungo, 2012). The reported water quality challenges demonstrate prevalence and challenges faced for water resources protection in the country which requires immediate policy intervention. In response to the reported water resource challenges in the country, positive strides have been undertaken in terms of policies development, strategies formulation, and establishment of regulations. For example, the first Groundwater Strategy was formulated in the year 2010, and the strategy recognized the importance of resource directed measures processes among others as plans towards achieving groundwater resource protection (GS, 2010).

However, much emphasis was put on the aspect of water quality than quantity, and this issue was adressed in the National Groundwater Strategy of 2016 where Theme 4 of the latest strategy puts protection of groundwater resources and aquifer-dependent ecosystems as one of the objectives which requires consideration of both quantity and quality aspects (NGS, 2016).

The National Water Resource Strategy of 2004 is a policy document which provided direction on water resources management in the country, and it recognized an approach adopted as a measure to protect water resources (NWRS, 2004). This approach comprised two complementary strategies, namely, Resource Directed Measures (RDMs) and Source Directed Controls (SDCs). However, the strategy was reviewed in response to the existing water resources challenges, where chapter 5 of the reviewed strategy recognizes the importance of protecting water resources (NWRS, 2013).

Furthermore, in response to water resources challenges a regulation on water resources classification system (Regulation Number 810) for the purpose of water resources protection was legalised in the year 2010 (DWA, 2010). The Regulation consists of the seven-step procedure formulated on the principles of integrated water resource management for classification of all significant water resource, eight step procedure for determination of water resources reserve, and seven step for determination of resources quality objectives. Groundwater resources protection methodologies used for determination of groundwater reserve, classification of groundwater, and determination of groundwater resources quality objectives were developed to harmonize and standardize RDM linked to groundwater resource protection in line with the gazetted Regulation number 810. Due to exacerbated water quality challenges in the country, Integrated Water Quality Management Policies and Strategies were developed from revision, update, and consolidation of water quality related policies (DWS, 2017b). The new water quality policy enables integrated management of all aspects of water quality in the country. Lastly, the amalgamated National Water and Sanitation Master Plan was formulated to ensure coherent management of water resources and efficient water supply and sanitation services for the country (NW&SMP, 2018). Notwithstanding good water quality management structures, strategies, approaches, programmes, instruments, and tools that have been developed and implemented nationally, however, water quality problems in South African water resources remain a challenge (Griffin et al., 2014).

Although the reviewed literature clearly indicates that South Africa experiences various challenges related to water resources, such as availability, supply, and water quality deterioration, however policies, strategies, and regulations seem to be in place to curb existing challenges. However, the profound challenge seems to be linked with implementation and evaluation of such strategies and regulation. For example, Ramulifho et al. (2019) noted that ever since the development of the environmental flow concept and methods in country very few studies have assessed the institutional constraints towards environmental flow implementation.

Their findings revealed absence of institutional establishments with clear roles and responsibilities, and lack of understanding of environmental flow benefits. Therefore, the challenge is how to sustain operationalization of such policy interventions in response to water scarcity, water quality deterioration, water supply, and environmental protection. This thesis argues that novel solutions are obligatory to improve policy practice towards water resources protection, especially at local level.

In literature, much has been published on specialised fields of water resources impact assessment in the country such as water quality, ecology, groundwater management, governance (Nastar and Ramasar, 2012; du Plessis et al., 2014; Wepener et al., 2015), however, not much has been published on the subject matter, especially on RDM implementation. Few studies that investigated feasibility of implementing RDM at catchment level were first reported in 2012 (Pollard et al., 2012), and lately in 2019 (Dlamini et al., 2019). Pollard et al. (2012) assessed the state of compliance with ecological reserve within the Luvuvhu, Letaba, Olifants, Sabie-Sand, Crocodile and Komati Rivers using river flow regime in SA. The study found that there was a lack of planning and integration of the ecological reserve methods with operations and difficulty associated with real-time predictions of ecological reserve requirements. The study further, highlighted that such factors constrain planning, monitoring, and management actions to mitigate non-compliance (Pollard et al., 2012). The results indicated that river flow regime can be used to assess compliance with RDM such as RQOs numerical limits associated with low flow requirement.

Odume et al. (2018) used a systematic literature review to investigate how RQOs are set and in turn establish how effluent discharge limits are informed by RQOs which are introduced into water use license as conditions. The study indicated that there are some contestations from water users in terms of how RQOs are going to be achieved and who is responsible for achieving the established RQOs. In addition, the study highlighted that users and regulator agreed that they need to understand the link between water resource class, RQOs and effluent discharge standards (source directed controls) for responsible and sustainable management of water resources (Odume et al., 2018). The outcome of the study highlights the need for an appropriated RDM implementation plan that should be able to clearly indicate who is responsible for what, and how findings should be reported and by who to effect decision making at catchment level. Dlamini et al. (2019) investigated effects of nutrients loading capacity on the achievement of RQOs within the Elands River catchment. The study used Nitrate and Phosphate nutrients to assess compliance with surface water quality linked RQOs, and river monthly flow data to establish flow regime of the Elands River (Dlamini et al., 2019). The study concluded that management of nutrients load is critical especially during low flows, and recommended that because of a strong correlation between nutrient loading and flow regime which varies per season, water pollution and compliance status should be defined based on the flow regime for each season (Dlamini et al., 2019).

Despite work by Pollard et al. (2012), Odume et al. (2018), and Dlamini et al. (2019), however, these studies did not cover the aspect of groundwater which is part of water resource protection by RDM. For instance, RDM treats groundwater as an important water resource which should be afforded comparable protection measures as surface water, and groundwater has been included in all RDM studies undertaken up to date. Furthermore, the aspect of reporting RDM compliance and non-compliance was not addressed by the studies. Therefore, an appropriate plan that guides how RDM compliance should be monitored, evaluated, and reported is still lacking. Such plan should be able to tell us who is supposed to monitor and report RQOs compliance and non-compliance and tell us what should be done in cases of non-compliance in order to assist in decision making and trigger policy review when necessary. This suggests that a feasible model that considers aspects such as institutional arrangement, roles and responsibilities, monitoring, evaluation, and reporting necessary is required. These aspects are explored in the present study.

2.3 Synthesis of literature review on science-policy integration

In order to appropriately respond and meet the most water resource challenges of the 21st century, use of scientific knowledge in the development and implementation of rationale and evidence-based policies is important (Bednarek et al., 2018). Understanding of science-policy integration, where physical bases of natural science is combined with practice in managing real life challenges becomes critical in translating scientific knowledge into effective sustainability policies (Chiu et al., 2020). In order to learn from the experience of projects and studies that have been undertaken, and to identify existing knowledge gaps in practice, literature is reviewed on the application of science-policy nexus, and methods that have been used to assess such utilization.

Dunn et al. (2018) give an account for practical application of the science-policy nexus concept in policy practice. In their study which was undertaken in Australia provide insight on the application of science-policy nexus in urban water management within the Melbourne area. In their assessment, they identify three science-policy nexus theoretical models, namely a) science-push, b) policy-pull, c) co-production. The study defines science-push theory as a conception where researchers and information providers set the agenda for producing and disseminating science, while policy-pull is conceived as a model which necessitates policy makers to be receptive to science and to access information and expertise. However, the study points out that such model has been criticized for suffering from selective production of knowledge for decision making which can be regarded as manipulation (Dunn et al., 2018).

Co-production is defined by the study as a partnership approach in which the research agenda is an ongoing highly interactive process. Such revelation agrees with Sarkki et al. (2015) who argued that one-way linear knowledge model often fail to influence policy makers. However, when a consideration is made that for nexus to exist two parties must play a role otherwise nexus won't exist.

In the context of such understanding, one could argue that based on the definition provided by Dunn et al. (2018) on the science-push and policy-pull models, the resultant interaction is linearly skewed towards one direction, which is from scientists to policy makers. It has been argued that communication between science and policy domains is most effective when it flows in both directions (Akhtar-Schuster et al., 2016). Such hypothesis has been supported by Hughes et al. (2018) who argue that the nexus two-way interaction enables better communication of policy maker's priorities and science related measures (policy-science integration) and better communication of science research products in advancing policy interventions (science-policy integration).

Although integration of science and policy has widely been recommended for evidence-based policy formulation and implementation, however, formalizing and defining science-policy integration especially in management system has been a challenge and much remains to be done to understand how scientists and policy makers engage each other at science-policy interfaces (McConney et al.,2016; Nyssa, 2019; Cormier et al., 2020). Complexity of scientific products has been cited as one of the reasons leading to limited utilization of scientific results in policy implementation practice (Nebhöver et al., 2013). Therefore, appropriate transformation of scientific products into readily usable information by policy makers is essential for science-policy nexus sustainability (Frost et al., 2017). Moreover, when scientific products are not translated into understandable and readily usable formats, the rationale and instrumental nature of conception for science evidence and its use is subjected to tempering by non-scientists influence of evidence on policy (Ranchod, 2016). Chiu et al. (2020) argue that to improve and sustain science-policy nexus application in policy practice it is critical that science research provides any policy relevant findings clearly and unambiguously.

Nevertheless, improvements on the application of the nexus in policy practice are evident. For example, de Jong (2016) investigated science-policy nexus by analysing eutrophication challenges in the North Sea area within the European countries. The study revealed that scientists working on eutrophication management can deal with complexity and uncertainty at the political through simplification of facts by focusing on nutrients as the main source of the problem, at the same time excluding other possible causes (de Jong, 2016). Such observation is critical in the understanding of the nexus and its uptake in policy implementation practices. However, knowledge gap associated with the study is evident. For instance, the study only focused on one aspect of the nexus which is the science-policy interface (science informing policy) without reflecting on policy-science interface (policy informing science).

Studies that reflect on both aspects of the nexus that provide an indication of how each component of the nexus (science and policy) influence each other are important for improvement in terms of knowledge on how the nexus functions. In China, policy-science nexus was investigated by studying knowledge exchange between environmental scientists and policy makers (Zheng et al., 2020).

The study compared knowledge management research in China to global trends and evaluated knowledge management for environmental policy and management in the country. The study found that none of the papers which considered knowledge management in the environmental sector examined the science-policy-practice interface in the country. Furthermore, the study revealed that most of the papers reviewed reported a one-way interaction between scientists and users, suggesting significantly less awareness and use of two-way knowledge exchange methods by Chinese scientist (Zheng et al., 2020). Tieberghien (2014) investigated role of the media in the science-policy nexus in Belgium. Using a case study of the Belgian drug-policy debates between 1996 and 2003, the study assessed how the misrepresentation of scientific knowledge in the media may, or may not, have an impact on the contribution of scientific knowledge to the drug-policy making process in the country. Findings by the study showed that media discourse strongly influenced the public's and policy makers' understanding as well as the content of the Belgian drug policy debate between 1996 and 2003. The study made a conclusion that the presentation of scientific knowledge in the media was often inaccurate or distorted due to the lack of contextual information or statistical misinformation, and that such inappropriate presentation of information by the media led to selective utilization of scientific knowledge (Tieberghien, 2014)

In terms of methodological approaches that are currently used in studying science-policy nexus, several methods such as, case studies, document review, communities of practice, and 'policy lab' methodology are available (López-Rodríguez et al., 2015; Ojha et al., 2020; Ramirez and Belcher, 2020). A combination of case study and document review methods has been applied to investigate science-policy interface (Ramirez and Belcher, 2020). In their investigation, the researchers used Brazil as a case study to characterize the design and implementation of a research project on the influence of timber harvesting on Brazil nut production. Ramirez and Belcher (2020) used document review methods to collect data from websites, government documents, presentations, and projects outputs, emails, and meetings minutes. One of the stand-out findings by the study is that the research project design and implementation to influence timber harvesting on Brazil nut production had limitations in terms of legitimacy and relevance. An indication was that, despite effectiveness in terms of direct communication with policy makers to provide research input to the management guidelines, however low levels of participation and collaboration with regional stakeholders reduced the overall perceived legitimacy of the research, and unidirectional communication of results undermined perceptions of research relevance (Ramirez and Belcher, 2020). Although the study by Ramirez and Belcher (2020) provided practical case study on the application of science-policy nexus, however, the limitation of the study is that the analysis applied depicts science-policy interface as a liner process, a theory that has been contested by many who argued that the nexus is a bi-directional process of engagement between policy makers and scientists (Young et al., 2014; Sarkki et al., 2015).

Communities of practice methodology was proposed and applied to assess science–policy interface in addressing environmental problems in arid Spain by López-Rodríguez et al. (2015). The methodology is based on brokering approach where workshops are organized to facilitate mutual understanding and trust between scientists and policymakers, thus mutually identifying major environmental concerns requiring policy intervention. The study was able to identify environmental problems requiring priority and agreement on the priorities was reached (López-Rodríguez et al., 2015). The findings of the study revealed the importance of the methodology used in terms of its capabilities in promotion of a culture of shared responsibility for the implementation of management actions based on collaborative work, thus facilitating uptake of the nexus concept. Although the methodological approach followed by the study is prone to limited resources such as time frame, however, the approach adequately addresses the aspect of transparency considering stakeholder engagements ensured through the consultative process. Stakeholder engagement is widely advocated to integrate diverse knowledge and perspectives to deal with potential conflicts of interest and lack of such engagements often negatively impacts the expected performance of projects (Lillebø et al., 2017; Shackleton et al., 2019; Bahadorestani et al., 2020).

2.4 Synthesis of literature review on WEFE Nexus

This section of the study argues that in order to achieve sustainable resource security for all, an integrated, holistic, and multi-sectorial approach is essential, and that the WEFE nexus provides for such an approach. Therefore, there is a need to foster policy practices that adopt WEFE nexus approach in order to stand a better chance of achieving SDGs targets by 2030. This motivates the need to investigate application of WEFE nexus concept in water resource protection practices using RDM strategies. For the WEFE nexus application in water resources protection practices its four sectorial components should be considered in the processes and procedures followed for undertaking RDM studies. Based on the outlined argument, literature is reviewed to identify knowledge gaps in practice related to WEFE nexus application

Recent studies highlighted the need for integrated policy responses that facilitates application of WEF nexus which is seen as a holistic approach to address common threats to WEF security (Olawuyi, 2020). WEF Nexus is the repurposed realization that acting from the perspective of individual sectors results in fragmented decision-making which is not suitable for achieving SDGs. (Shannak et al., 2018; Laspidou et al., 2020). Karabulut et al. (2019) investigated the sectoral policies on the environment-water-food, and energy (EWFE) in the Mediterranean Region for their coherence. Using developed policy scenarios in the context of WEFE Nexus, the study was able to assess potential synergies and conflicts among the sectoral policies (Karabulut et al., 2019). The study found that policies on sustainable use of ecosystem services and biodiversity conservation maybe the key policies towards successful management of the multiple sectors that share the use of natural resources.

Despite significant research and debates on WEF nexus potential and its application in policy practice, (Endo et al., 2017; Terrapon-Pfaff et al., 2018), however practical application of the nexus is still limited. Leck et al. (2015) argue that as much as the WEF nexus is seen as a holistic approach for policy intervention to current challenges, however, its implementation is challenging. For example, decision making processes, and communication and collaboration among others have been identified as barriers in nexus implementation in the United Kingdom (Howarth and Monasterolo, 2016).

In a study conducted in Germany (Franz et al., 2018) on globalization and the water-energy-food nexus, global production networks and global value chains were used to analyse society-environment relations. The results from the study provided insight on the understanding of the intertwined workings of environmental changes with processes of economic globalization. Although the study covered local context to some degree, however, much more emphasis was placed on the influence of globalization on WEFE nexus. Major nexus challenges are experienced at local level (Terrapon-Pfaff et al., 2018).) The study seems to be limited in terms of guiding how policy practice should be spearheaded towards WEFE nexus application to enhance local resources security.

Guo et al. (2020), conducted a study on sustainability assessment of the water-energy-food nexus in China. The main objective of the study was to evaluate the sustainability trends of regional WEF nexus using Jiangsu Province as a case study. A step-by-step methodological approach, where a composite index, combined with single WEF sector indicators and WEF linkage indicators that reflect the characteristics of the nexus was followed. Findings from the study indicated that the Jiangsu Province is following a path of unsustainable development of the WEF nexus. Sub-standard indicators of the water and energy systems, some of which are declining, were linked as a cause of unsustainable development of the WEF nexus in the province (Guo et al., 2020). However, the study only deals with establishment of the WEF nexus sustainability assessment and does not provide any advice on what policy decision makers should do to reverse the unsustainable development of the WEF nexus observe in the province. Therefore, the study lacks integration aspect for WEFE nexus application in policy practice.

Perhaps, a study by Gondhalekar and Ramsauer (2017) provides much more compelling insight on how to fuse WEFE nexus concept with policy practice, especially in urbanized areas. Using WEFE Nexus approach, the study investigated policy adaptation approaches that could be used in response to climatic changes in order to act more effectively in the city of Munich, Germany. The study showed that use of WEFE nexus concept in policy practice for climatic adaptation has beneficial outcomes. For example, the study found that intensive urban agriculture could provide for 66% of local demand for fruit and 246% of local demand for vegetables (Gondhalekar and Ramsauer, 2017). However, the study has some limitations in relation to the practical aspects, as it is highly hypothetical with many assumptions.

Furthermore, the study is confined within an urbanized area, whereas climate change impact cut across urban and non-urban areas. Although locally relevant understanding of climatic changes and their associated impacts has been promoted (Nash et al., 2020), however, climate change impact is not only confined in urbanized areas as it is not a localized phenomenon. In the United States of America (USA), Gurdak et al. (2017) investigated effects of scale in controlling groundwater vulnerability in the water–energy–food nexus within the California Coastal Basin aquifer system. The objective of the study was to understand the controls of on nonpoint source (NPS) nitrate (NO_3^-) contamination in groundwater which is motivated by the widespread detection of NO_3^-, implications for human health and aquatic ecosystems, groundwater sustainability, and a growing realization that such understanding across spatial scales promotes management and policy choices that optimize the Water-Energy-Food (WEF) Nexus (Gurdak et al., 2017). The identified gap from the study is that it only focuses on groundwater as isolated resources whereas practices on integrated management of water resources are promoted for resources security (Claassen, 2013).

Several methods have been used to investigate WEFE nexus application, and review of such methods is critical towards understanding of their limitations and applicability to the present study. Li et al. (2019) proposed the use of interpretive structural modelling (ISM) method to create a hierarchy structure for factor identification and analysis to explain and quantify complex relationships in WEF-nexus. Although factor analysis provided in the study suggests that the portrayed nexus structure could provide valuable references for further quantification and for the purpose of decision making (Li et al., 2019), however, the methodology seem to be complicated for practical application by policy makers in policy practice, who often require a feasible tool which is easy to understand and use in practice.

Mahlknech and González-Bravo (2018) used diagram methods to assess WEF nexus in the Caribbean and the Latin American Countries (LAC). The diagram methods involved developing a WEF nexus Index composed of indicators such as availability, access, and stability of sector's resources, and such methods provided an actual overview of the current state of the WEF nexus in the LAC (Mahlknech and González-Bravo, 2018). Similarly, Nhamo et al. (2020) proposed an analytical model that can be applied to manage WEF resources in an integrated manner using the Analytic Hierarchy Process (AHP). The model presented by the study act as a tool to quantitatively assess the cross-sectorial linkages among resources and indicate performance of resource utilisation and management, and to assess progress towards SDGs, among other uses (Nhamo et al., 2020). Karabulut et al. (2019) used multiple criteria analysis (MCA) approach to investigate the coherence among the sectorial policies, either supporting or conflicting with each other, on cross-cutting strategies and their impacts on ecosystem and their services within the WEFE nexus context. The MCA methodology followed in the study allowed to better distinguish potential synergies or conflicts between sector policies (Karabulut et al., 2019).

However, the MCA methodology requires extensive stakeholder engagement to develop multi criteria to use for assessing to assess sectorial policy impacts on cross-sectorial strategic targets which is a time-consuming process. Qualitative systematic mapping has been used to study WEF nexus application in policy practice. For example, Terrapon-Pfaff et al. (2018) applied a systematic analysis of the linkages between small-scale energy projects in developing countries, and the food and water aspects of the development in such countries. The study provides insights on how to identify interconnections and potential benefits of integrating the nexus concept into local level projects (Terrapon-Pfaff et al. (2018). Methods of systematic mapping allow for visualization of existing synergies and conflicts among the nexus sectorial components, and to assess whether the nexus concept is systematically integrated into project design or project evaluation.

Reflective practice which advocates for critical thinking and integration of theory and practice has been promoted as a method of developing knowledge entrenched within practice (McBrien, 2007; Bass et al., 2017). The use of reflective practice in environmental management practice allows for organizational learning which requires continuous assessment of project performance to identify and learn from success and failures through adaptive management (Bryant and Wilson, 1998). Despite the simplicity of the reflective practice methods which propagated them being widely applied in practice, most notably in the field of health science (Bass et al., 2017; Mantzourani et al., 2019), however, application of such methods has been limited in the field of environmental management especially water resource protection. In the present study reflective practice has a relevance in outlining how the process of reflection leads to developing new insights and understanding on the application of WEFE nexus in water resources protection practices.

Knowledge gaps identified from the reviewed studies are that understanding of synergies and conflicts within the WEFE sectorial components is still limited. Reported practical case studies on WEFE nexus application in policy practice to fast-track SDGs achievement by 2030 are limited. Integration of the WEFE nexus concept in existing policy practice approaches such as integrated water resources management, or any other policy intervention programmes to enhance its utilization is still lacking. In order to advance practical application of the WEFE nexus concept in policy practice, it is important that existing programmes and policy implementation strategies are adapted and enhanced to integrate nexus concept in their implementation. Such practice could be reflected in case studies through reflective practice. Therefore, the current study attempts to fill the identified gaps by answering the following questions: 1) what are the critical synergies and conflicts among the WEFE components and their influence on water resource protection practices? 2) How to improve utilization of the WEFE nexus concept in policy practice to fast-track achievement of SDGs? 3) How to build capacity for policy makers and institutionalization of local and regional knowledge to sustain and share best practices on the WEFE Nexus?

2.5 Synthesis of literature review on citizen science

Continuous monitoring to trace changes in the state of water resources is one of the most essential aspects of policy practice. However, state resources may often be insufficient to comprehensively cover for both temporal and spatial aspects sufficiently. Citizen science approach has been used to supplement and increase scale of monitoring while optimizing use and protection of water resources. Therefore, creation of an enabling environment for local water users and to form part of water resources management practices to promote water resources protection and that reduce water wastage and promote local surface and groundwater resources protection and their sustainable utilization is crucial. In addressing the third objective of the present study, literature review on citizen science studies is undertaken to identify knowledge gaps in practice in terms of what works well and what does not work. Citizen science, where citizens play an active role in the scientific process and policy implementation programs, is increasingly used to expand the reach and scope of scientific research while also achieving engagement and gain an appreciation for the environment (Jollymore et al., 2017; MacPhail and Colla, 2020). Citizen science is considered as a cost-effective way to gather data over a large geographical range while simultaneously raising public awareness on the policy relevant issue (Rambonnet et al., 2019).

The concept of citizen science has since become increasingly applied in various fields such as indigenous and invasive alien species assessments (Johnson et al., 2020; Lehtiniemi et al., 2020), earth sciences related projects (Lee et al., 2020), water quality assessment (Farnham et al., 2017), and integrated water resources management (Paul and Buytaert, 2018). Furthermore, the concept of citizen science has been widely used in several projects globally. For example, in the New York City, United States, citizen science-based water quality monitoring was investigated to ascertain role and benefits of citizen scientist's communities in water resource management programs (Farnham et al. (2017). The study illustrated how to engage with citizen scientists in water quality testing activities working towards mutual beneficial goal of constructing a large database of historical bacterial concentrations in waterways. In a similar study, employees of North Carolina childcare centres in the United States were recruited as citizen scientists to assess Lead (Pb) occurrence in drinking water taps (Redmon et al., 2020). The study demonstrated the feasibility of applying community-based water quality testing using citizen science approach.

In China, citizen science approach has been used in water quality management practice to improve state of water quality within the metropolitan areas. For instance, a study by Thornhill et al. (2017) utilized data from the citizen science project (FreshWater Watch) to identify key indicators, potential drivers, and potential controls to water quality across the metropolitan areas of Shanghai, Guangzhou and Hong Kong (Thornhill et al., 2017). The study provided insight on the importance of data collected by citizens in decision making related to water resource protection.

However, the study was only confined in urbanized areas within the same biosphere. Citizens residing in in urban areas usually have access to basic services such as municipality water supplies, conditions which are different from non-urbanized areas. Citizens living in rural areas are often entirely connected, dependent and directly interact with the environment they live upon.

Role of citizens in water quality data collection in Canada has been reported. For example, water quality assessment was undertaken in the shoreline parks around the Island of Montreal and within the Vancouver, British Columbia region (Lévesque et al., 2017; Shupe (2017). In the two investigations, volunteers were recruited and trained by researchers on water sampling and in recording in situ water quality parameters. The role played by volunteers in data collection activities in terms of the assessment of the quality and utilization of shoreline parks provided additional information to support planning and management activities of municipalities (Lévesque et al., 2017), while in a study by Shupe (2017) trained volunteers made it possible to for the high-resolution sampling in understanding seasonal and spatial dynamics of stream water quality.

Use of citizen science concept and motives for citizen involvement in science and state projects have been explored and reported in the United Kingdom (UK). For example, citizen science has been applied in practice such as biodiversity management (Pescott et al., 2015), where local citizens were recruited to provide volunteer-based plant monitoring in the Britain and Ireland. The study highlighted that involvement of local citizens in the project led to the recognition that knowledge of specie's abundance at finer scales often provides more powerful means of detecting and interpreting plant species changes, and that such revelation has led to the development of a new abundance-based National Plant Monitoring Scheme in the UK (Pescott et al., 2015).

Although much of the reported studies on citizen science application have focused mainly on water quality data collection, however citizens also play key role in collection of hydrological data, especially in low-income countries such as Kenya. For example, Weeser et al. (2018) undertook a study to evaluate the quality and quantity of data generated by citizens in a remote Kenyan basin and assesses whether citizen science is a suitable method to overcome data scarcity. The study installed thirteen water level gauges equipped with signboards explaining the monitoring process to passers-by. The study revealed that water level data collected by citizens were comparable to the data obtained from automatic gauging station in terms of quality, an indication that citizens can provide water level data of sufficient quality and with high temporal resolution (Weeser et al., 2018). A similar study in Tunisia reported a significant correlation between rainfall data collected by citizens when compared with data obtained from reference stations and such results indicates adaptations and local capacity building for data collection in the Tunisian water sector (Fehri et al., 2020).

Successful application of citizen science concept in practice does not only require involvement of local citizens, but furthermore, their motive for getting involved in volunteer-based environmental management practice must be understood. Such understanding is critical in the volunteer recruitment process and for recruitment and for sustaining volunteer-based environmental management practices. A study by Dunkley (2018) reported that early affective bonds formed with ecological spaces endured throughout life courses became one of the motives for citizen science participation which enable local citizens to remain connected to local environments, thus a desire to participate in environmental research and a commitment to protecting local environments. In the Netherland, motivation for local citizens' participation has been linked to the concern of the environment (Carballo-Cárdenas and Tobi, 2016).

Although role of non-scientists in policy implementation activities such as data collection is widely reported, however, the uptake of citizen science has thus far been limited (Paul et al., 2018). One of the challenges for application of citizen science approach in practice is related to the acceptability of data collected by citizens. Quinlivan et al. (2020) noted that professional scientists have negative perceptions about citizen science data, questioning data credibility in terms of quality and reliability. Scott and Frost (2017) concurred with Quinlivan et al. (2020) and pointed out that citizen science data credibility depends on the motivation and engagement of the group volunteers. McGoff et al. (2017) noted biasness in data collected by citizens as compared to data collected by professional scientists with a potential for type II error. Such biasness emerges when the self-selected site approach is used, which is known to be appealing to volunteers who are usually interested in discovering water quality in their own neighbourhood (McGoff et al., 2017). Nevertheless, studies have shown that citizens are capable of good quality data if quality control measures are put in place such as appropriate training and clear data collection protocol. For instance, Rambonnet et al. (2019) recommended that sample protocol, quality control and management of volunteers should be instituted in to ensure successful utilization of citizen science approach. The recommendations are supported by Scott and Frost (2017) who argued that large scale citizen science projects completed in real time use simple, less precise methods than professional science. Such methods should be less sophisticated so that citizens can accurately perform the steps after only training session (Scott and Frost, 2017).

Despite challenges limiting uptake of citizen science approach in practice, exploration of the potential possessed by using citizen science continues, and that is reflected on several studies undertaken using different methods. However, much of the studies that have been undertaken in studying citizen science are based on linear models whereby volunteers' participation is only limited to data collection. Vann-Sander et al. (2016) argue that when such approach is followed understanding of the impact citizen science have in policy and natural resource management maybe overlooked.

The study recommended that for citizen science to be fully utilized in policy and management context, a fundamental shift must occur to systemically encompass the views of all stakeholders and converge on a common understanding of its role and utility beyond the current science-centric discourse, and such fundamental shift could be facilitated by applying systems thinking approach in policy practice (Vann-Sander et al., 2016).

2.6 Frameworks

In presentation of the frameworks that were used as a guide to build and support the present study, and to make findings more meaningful and acceptable, the theoretical, conceptual, analytical, and the interpretation frameworks are discussed.

2.6.1 Theoretical framework

The present study is about developing a citizen science framework for water resource protection that will facilitate operationalization of resource directed measures using nexus approach. The study argues that science-policy interface must be practical, reflective and must consider the nexus approach using the concept of citizen science. Such a plan can address some of the reported challenges in addition to improving acceptance of RDMs as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level. In the process of developing, validating, and verifying citizen science framework, a case study approach is used, which is based on the Middle Vaal Catchment in South Africa. In examining options to improve policy practice towards water resources protection at catchment level, theory of systems thinking provides a useful prototype. The theory allows blending together of different disciplines such as Humanities and Science to address existing social challenges (Mononen, 2017) which is central to the present study.

This conception of systems thinking attempts to achieve a balance synthesis in terms of identifying existing challenges within a system and their causes, using the principles of systems analysis (Armah, 2020). Basically, this cohesive theoretical framework enables a person to view systems from a comprehensive perspective which includes seeing all parts, patterns, and their interconnections in a system rather than seeing only specific parts in the entire system (Jagustović et al., 2019). Theory of systems thinking does not only deal with analysis of systems, but also seeks to describe how systems analysis approach could be utilized to operate within complex and dynamic systems (Church et al., 2020). Moreover, the principles of systems thinking theory have been applied to a wide range of systems analysis such as crop and food production, corporate sustainability, environmental management, human geography, policy practice, and water resource management (Anandhi and Kannan, 2018; Jagustović et al., 2019; Paterson and Holden, 2019; Rehman et al., 2019; Ahlström et al., 2020; Armah, 2020; Church et al., 2020). In the current study the principle of systems analysis assists in the analysis, interpretation, and explanation of the results obtained.

In explaining theory of systems thinking, five fundamental assumptions of systems thinking are identified, namely: 1) interconnections, 2) feedback loops, 3) adaptive capacity, 4) self-organising, and 5) mind-set behaviour. The core concept of interconnections within systems is explained as a relationship between parts and that those parts are connected to make a larger whole (Church et al., 2020). The feedback loops core concept has been defined as "closed sequence of cause-and-effect relationships between elements: when a change in one element leads, after some time, to a change in another element within the same system. Adaptive capacity within systems, refers to the ability of actors to maintain basic structure of the system, and this happens when agents learn from their experience and act accordingly (Williams et al., 2017). Self-organising is known as the autonomous behaviour of the system which arises without an internal or external controller due to the interaction between the components of a system (Jagustović et al., 2019). The mind-set behaviour concept is described as a change in individual's mind set in taking concrete action to drive systemic change (Williams et al., 2017). The highlighted assumptions provide a guide in choosing the appropriate methods for the present study, which takes into consideration that complex human-environment-economic systems occur within dynamic frameworks influenced by numerous actors, factors, processes, and interactions, and thus cannot be simply understood in terms of linear chains of cause and effect.

2.6.2 Conceptual framework

From theoretical orientation of systems thinking, the present study sets out to examine how the three concepts linked to systems thinking, namely, a) science-policy integration, b) water-energy-food-environment [WEFE] nexus, and 3) citizen science fit together to explain systems analysis and its role and influence on policy practice directed towards water resources protection.

The first part of the study focuses on the assessment of the science-policy nexus application in policy formulation and implementation towards water resource protection. In order to showcase that science-policy nexus can be designed and prioritized to support the sustainable agenda, the South African case study is presented where science-policy integration directs water resources protection practices from local, regional, and national level. The second part of the study focuses on the assessment of WEFE nexus approach's operation in water resource protection practices. To provide for such understanding, reflective policy models are applied to reflect and illustrate the significance of RDM in promoting societal benefits in a wider context including achievements of socio-economic development goals such as SDGs through application of WEFE nexus concept.

The third part of the study focuses on development, validation and verification of a process-based citizen science framework which needs piloting for its feasibility as a catchment orientated resource directed measures operational plan.

To validate the novel plan for its practical and broader applications in monitoring, evaluation and reporting the progress about resource directed measures for improved water resource protection practices at various catchments, assessment is based on case studies at selected catchments using records sourced from national databases and reported studies.

The three stages of the study are interlinked, and in this regard three types of interlinks are recognized. The first linkage involves transition from policy formulation and implementation using science-policy nexus and scientific RDM strategies in the first stage of the study to policy practice using scientific RDM studies and the WEFE nexus concept in the second part of the study. The second linkage involves transition from the second to the third stage of the study which is ensured by downscaling RDMs to a local scale (source point) where water resources are utilised and where the citizens dwell. The citizen science framework developed and validated in the third part of the study facilitates the involvement of citizens in the management practice of water resources. Lastly, the third linkage involves transition from the third stage back to the first stage of the study. This is ensured by monitoring, evaluation and reporting the progress about resource directed measures for improved water resource protection practices so that goals of using water resource in an equitably, efficiently, and sustainably manner could be achieved.

2.6.3 Analytical framework

The analytical framework which was structured to guide the analysis in the current study in order to achieve desired outcomes is presented in Figure 2.1. In addressing the first objective of the current study, Science-Policy nexus is identified as a category with Policy, and Science being sub-categories. Policy implementation, Science-policy nexus theoretical models, and RDM studies are identified as variables analysed to achieve the first study objective.

Water resource protection practice, WEFE nexus, and RDM processes are identified as a category, and sub-categories, respectively, linked to the second objective. WEFE nexus application, reflective practice models, and RDM studies were identified variables that were analysed for the second study objective. The third study objective was achieved by identifying citizen science framework development and validation as a category, and citizen science framework development process, and citizen science framework validation process as sub-categories. Socio-ecological Model (SEM) modification, citizen science framework components configuration, and multi-level framework application were analysed as variables for citizen science framework development. In order to validate the citizen science framework, reported citizen science projects, and a case study on use of historic data were identified as variables of analysis.

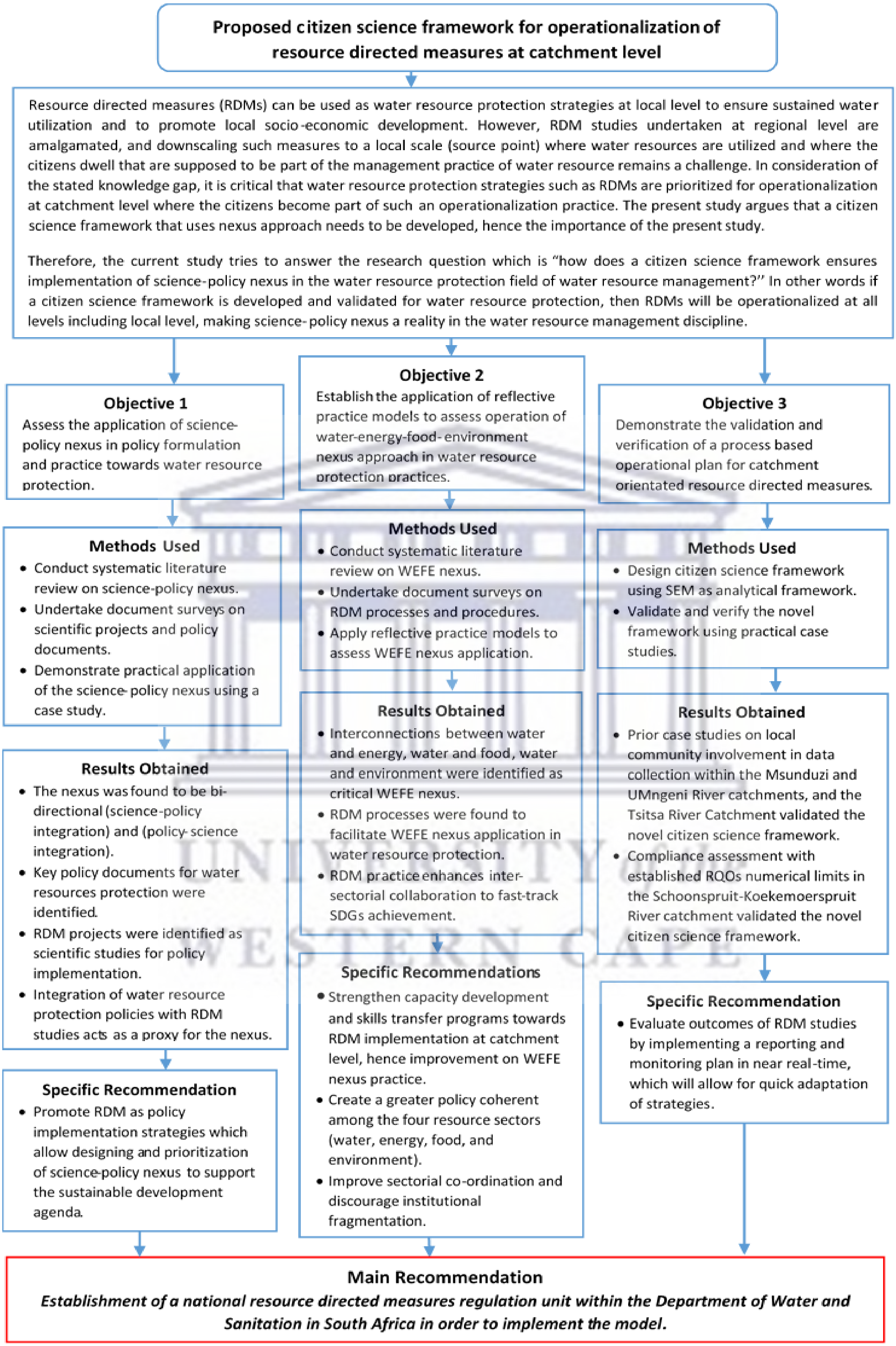

Figure 2.1: Analytical framework of the present study (Author's construct)

2.6.4 Interpretation framework

In terms of the interpretation framework constructed for the present study, discussion on data adequacy, data validity, and data reliability is presented. The interpretation framework aims to provide a plan that was followed to ensure that data collection, and analysis are complete, reliable, consistent, and relevant to the subject of the present study. Adequacy of data collected was ensured by considering aspects of data quantity and data detail (richness). In terms of data quantity, the present study various sources for data collection such as archived data survey, document review, and detailed literature review. In terms of data detail (richness) the study followed a case study approach where more than one case study is provided. For example, three case studies are provided in terms of validating the novel citizen science framework; two case studies for reported citizen science studies, and one for use of historic data.

Reliability is one of the measures of quality assurance in a research study which concerns the extent to which a measurement of a phenomenon provides stable and consist of result, hence it is usually associated with data collection. In ensuring data reliability, data were sourced from legal documents, such as public policies. Scientific reports used were sourced from reported case studies published in scientific journals, thus their reliability. Furthermore, only data from audited national databases were used, which increased their reliability.

Validity determines whether the research truly investigated what was intended to be investigated and to what extent that the findings are accurate and useful, and it comes in the form of internal (credibility), and external (transferability). In order to ensure credibility of the results findings, the investigation followed a concurrent mixed methods design, where different data collection methods (methods triangulation) were used (internal validity). Literature review was based on peer reviewed journal articled through well-known research databases such as science direct, in addition to the use of well-known and utilized reflective practice models, such as the Gibbs reflective cycle model. The afore-mentioned aspects depict internal validity. Piloting of the novel citizen science framework was instituted to ensured real-time replication of the model in various catchments (External validity).

2.7 Summary chapter / overview on gap analysis

The present study argues that science-policy interface must be practical, reflective and must consider the nexus approach using the concepts of citizen science and WEFE nexus which are relevant to users, environment, and policy makers. Such approach provides enhances effective and efficient operationalization of policy implementation strategies for water resources protection and sustainable utilization. In order to contextualize such proposition, literature review presented in this chapter assessed science-policy integration, application of WEFE nexus which is seen as a holistic approach to address common threats to WEFE security and use citizen science concept which enables participation of local citizens in policy implementation activities. The purpose was to identify existing knowledge gaps in research and practice relevant to the present study.

Integration of science and policy requires understanding and continuous interaction between policy makers and scientists to manage water resources effectively. However, such integration is often characterized by one-way linear knowledge transfer model which often fail to influence policy makers. This challenge becomes aggravated when scientific products are not translated into understandable and readily usable formats, which then becomes vulnerably to tempering by non-scientists to influence evidence on policy. Science-policy integration which follows a two-way interaction enables better communication of policy maker's priorities and science related measures (policy-science integration) and better communication of science research products in advancing policy interventions (science-policy integration). Furthermore, appropriate transformation of scientific products into readily usable information by policy makers is essential for science-policy nexus sustainability.

Although WEFE nexus is seen as a holistic approach for policy intervention to current challenges, however, its implementation is challenging, and practical application of the nexus is still limited. Literature indicates that application of WEFE nexus has a potential to fast-track achievement of SDGs by 2030, however, integration aspect for WEFE nexus application in policy practice is sluggish and inadequately explored. Decision making processes, communications and collaborations were cited as barriers in nexus implementation in some countries. In some instances when WEFE nexus studies are undertaken, the focal point is skewed to either surface or groundwater resource as isolated resources while in practice integrated management of water resources is promoted for resources security.

While there is an increasing number of research and case studies on the application of citizen science concept in practice, however, initiatives for integrating citizen science in water resources management programmes in the context of water resources protection remains limited and rarely reported. Development of a more structured water resources management plans that create enabling environment for local citizens to form part of such operation is critical. Such knowledge gap limits effective and efficient implementation of policies directed towards water resources protection at local level where water resources availability and use challenges sprout.

Chapter 3: Study area description

3.1 Introduction

Chapter 2 is about literature review on previous studies to contextualize the present study, where theoretical, conceptual, analytical, and interpretation frameworks have been presented. This chapter 3 describes the case study area including its location, physiographic features, socioeconomic settings, major water tributaries, and assessment sites and their location. The description of the case study area outlined in this chapter provides insight into the conditions and factors that are likely limit or enable practical application of science-policy interface that considers the nexus approach and uses the concept of citizen science for policy implementation towards water resources protection. Understanding of such factors remains fundamental for testing the novel framework. The argument of this chapter is that comprehensive description of the study area is essential for validation and verification of the novel citizen science framework for its feasibility to facilitate operationalization of water resources protection strategies at catchment level.

3.2 Selection of the study area

Although the research interest of the study focused on RDM practice throughout the country, but for the purpose of validating the novel citizen science framework for operationalization of RDM at catchment level, only three case study catchments were prioritized for such purpose. The two-case study area of the uMsunduzi and uMngeni River catchments, and the Tsitsa River Catchment were selected because citizen science projects had been reported in these areas. However, selection for the case study area of the Schoonspruit-Koekemoerspruit River catchments was based on the land use activities taking place in the area, RDM studies undertaken in the area, availability of monitoring sites, and good database. The factors considered for the selection of the Schoonspruit-Koekemoerspruit River catchments case study area were employed to ensure that the main objective of the study is achieved. In this regard, the uMsunduzi and uMngeni River catchments, and the Tsitsa River Catchment case study areas are described briefly, while full description of the Schoonspruit-Koekemoerspruit case study area is provided.

In terms of the uMsunduzi and uMngeni River catchments, the uMsunduzi catchment covers an area of 875 km^2 with 115 km tributary length, and passes through the centre of Pietermaritzburg, the province of KwaZulu-Natal. The uMngeni catchment is about 4 416 km^2 with the river length of 265 km. Both catchments are densely populated with an average of 2 500 people per km^2, and 5 000 to 20 000 people per km^2, respectively, and they are impacted by intense industrial and urban developments (Cele, 2015). The catchment had been identified as a potential study catchment for citizen science project because of reported and experienced water quality challenges such as general illegal waste disposal from residential areas, pollution challenges due to industrial pollutants, and raw sewage flowing directly into the streams (Cele, 2015).

The Tsitsa River catchment is about 4 000 km^2 with a length of 550 km, with many parts of the catchment being rugged and difficult to access, which prompts engagement with local communities to assist in water resource assessment through citizen science initiatives (Bannatyne et al., 2017). The study area had been chosen for the citizen science project to assess suspended solid fluxes and yields to provide insight into the sources, magnitude and dynamics of catchment soil erosion and loss, thus providing important data on catchment management and monitoring which is critical for supporting decision making, planning, and interventions (Bannatyne et al., 2017).

3.3 Regional positioning of the Schoonspruit-Koekemoerspruit River Catchment case study area

The Schoonspruit-Koekemoerspruit River Catchment forms part of the Middle Vaal Water Management Area (MV-WMA) of the greater Vaal River System. The catchment lies entirely south of the equator between latitudes 25˚ 55.33'S and 26˚ 19.11'S and longitudes 26˚ 44.29'E and 26˚ 52.86'E (Figure 3.1) The MV-WMA is found in central South Africa, where it extends across the Free State and North-West Provinces and covers approximately 52 500 km^2 (Figure 3.2). The Water Management Area is located downstream of the confluence of Vaal and Rietspruit Rivers and upstream of Bloemhof Dam, extending north to the headwaters of the Schoonspruit River and south to the headwaters of the Vet River (DWA, 2012b). It occupies a sensitive position within the Vaal River System because of its location downstream of the heavily urbanised and industrialised heartland of South Africa. Although the MV-WMA hosts a mining industry of its own in the form of the Klerksdorp (KOSH area) and Free State (Welkom Virginia area) gold fields, however, mining activity is considerably greater and more varied in the neighbouring Upper Vaal WMA, and it is the impact hereof that is of greatest consequence to the MV-Water Management Area.

The Water Management Area is bordered by the Upper and Lower Vaal WMAs to the east and west, respectively, as well as the Crocodile West/Marico and the Upper Orange WMAs to the north and south, respectively. Major towns in the WMA include Klerksdorp, Welkom, and Kroonstad. Numerous inactive mines are found in the north and west of the WMA, many of which were small diamond claims. The tertiary drainage basins in the Water Management Area comprise C24, C25, C41, C42, C43, C60 and C70 of third order of catchment management. The Vaal River is the main drainage in the Water Management Area flowing in a westerly direction (DWA, 2012b).

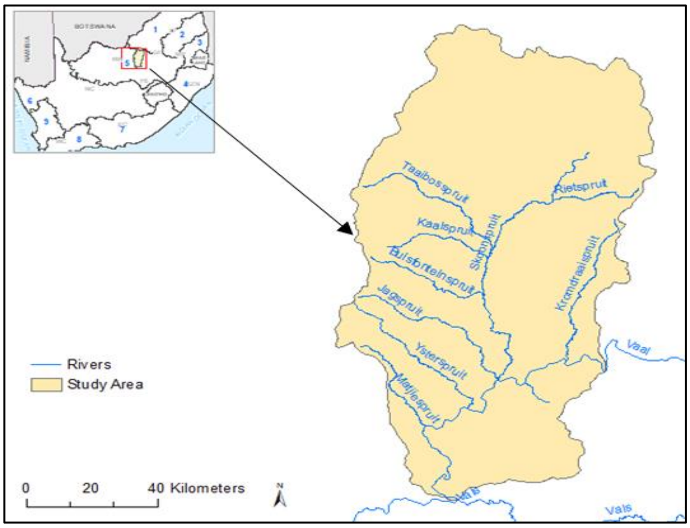

Figure 3.1: Locality map of the Schoonspruit-Koekemoerspruit River Catchment

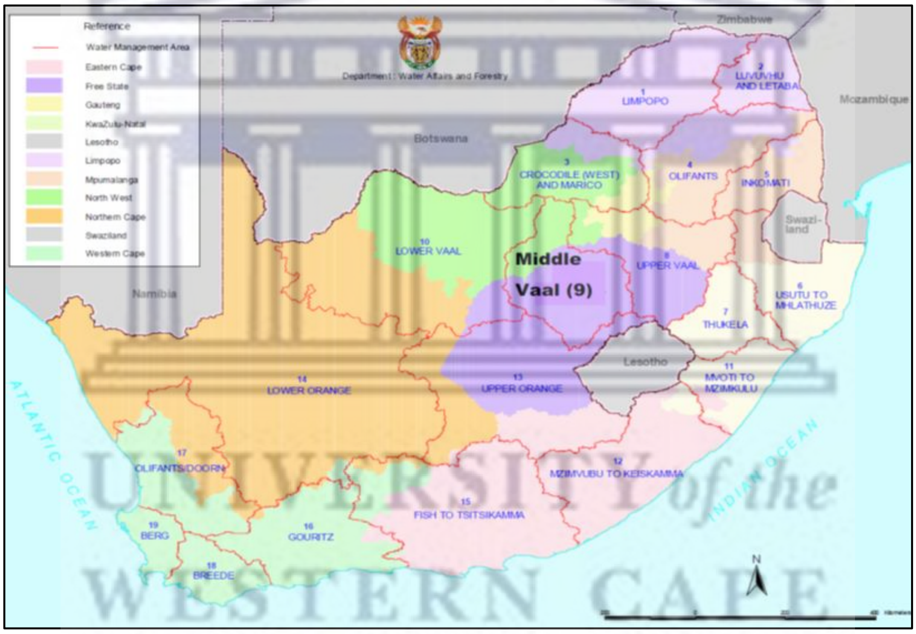

Figure 3.2: Location of the Middle Vaal Water Management Area within the North-West and Free State Provinces (Source: DWAF, 2004).

3.4 Physiographic features of the Schoonspruit-Koekemoerspruit River Catchment

In order to provide detailed physiographic features of the study area, aspects of size and topography, climate, rainfall, major tributaries and dams, and groundwater resources and availability are discussed. Quantity and quality of water depends on the characteristics of physiographic features.

3.4.1 Size and Topography

The Schoonspruit-Koekemoerspruit River Catchment, which is the area of focus is composed of nine quaternary catchments which together make up the study area size of approximately of 9 962 km^2 (Table 3.1). Quantity and quality of water depends on the characteristics of topographic features.

Table 3.1: Quaternary catchments forming up the Schoonspruit-Koekemoerspruit River Catchment

Study Area	Quaternary Catchment	Size of the Quaternary Catchment [km^2]	Size of the Study Area [km^2]
Schoonspruit-Koekemoerspruit River Catchment	C24A	839	9 962
	C24B	530	
	C24C	1 350	
	C24D	364	
	C24E	925	
	C24F	2 020	
	C24G	985	
	C24H	840	
	C24J	2 109	

The catchment extends from the eye of the Schoonspruit River to the confluence of Schoonspruit and Vaal Rivers. It covers five main towns being Ventersdorp, Klerksdorp, Stillfontein, Oarkney and Coligny (Figure 3.3). The upper reached of the Schoonspruit is surrounded by irrigated agriculture and in the lower reaches it flows through Klerksdorp, Kanana and gold mining activities. The Koekemoerspruit runs through intensive gold mining areas (Hartebeesfontein and Stilfontein) and its confluence with the Vaal River is upstream of Klerksdorp and the Midvaal Water Company. These human activities are important for validation and verification of the novel citizen science framework for its feasibility to facilitate operationalization of water resources protection strategies at catchment level. Quantity and quality of water depends on such characteristics of water sources and activities.

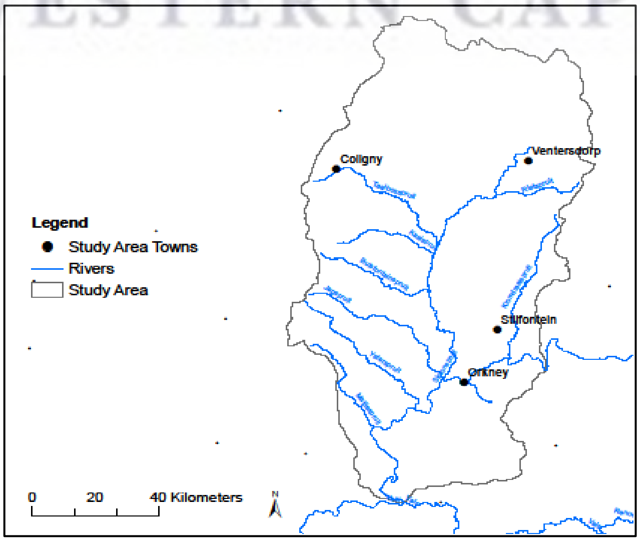

Figure 3.3: Location of towns within the Schoonspruit-Koekemoerspruit River Catchment

The topography of the study area is characterised by a relatively flat landscape exhibiting an elevation ranging from 1500 of meters above mean sea level (mamsl) in the hilly upper reaches and of about 1300 mamsl in the lower reaches of the Schoon Spruit River catchment (Figure 3.4). Such topographic features are fundamental for understanding the factors that control the quantity and quality of water resources for implementing resource directed measures in the catchment.

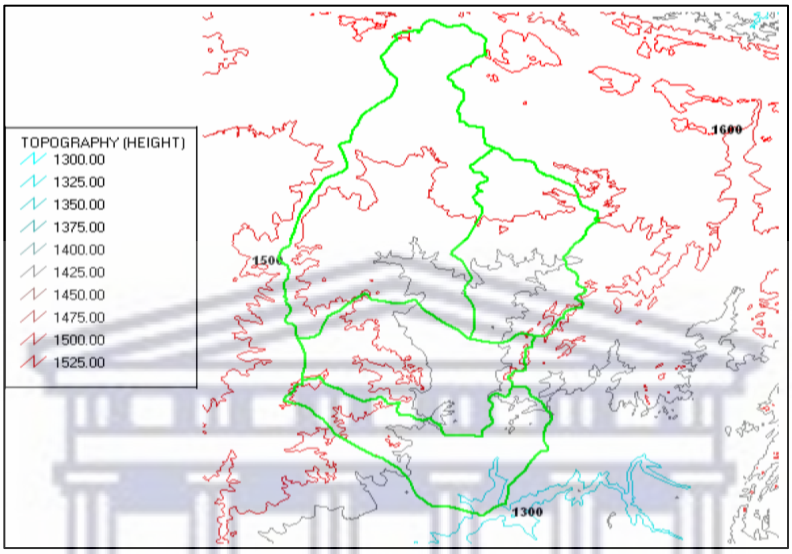

Figure 3.4: Variations of elevations within the Schoonspruit-Koekemoerspruit River Catchment

3.4.2 Climate

The climate characteristics across this study area can vary considerably from West to East. It is a typical South African Highveld, with warm to hot rainy summers and cold, dry, sunny winters and it may be characterised as temperate and generally semi-arid (EHC, 2007; DWA, 2012b). The minimum mean temperature varies from -1 to 15°C and the maximum mean temperature between 19 to 30°C (EHC, 2007). However, the summers are hot with daily maximum ranging between 27 to 30°C with extremes of 35 to 40°C Maximum daily temperatures are experienced in January and minimum temperatures in July, giving an indication of maximum evapotranspiration in January and evaporation in July. Temperature averages about 30°C in summer and 18 °C in winter. Such climate characteristics are critical for understanding the hydrology and hydrogeology of the study catchment.

3.4.3 Rainfall

The Mean Annual Precipitation (MAP) for the study catchment is 577 mm per annum (Figure 3.5). This is an average of data obtained from 22 rainfall stations in the catchment that all have different periods over which data were collected. On average the period with data is 45 years with the longest record of 96 years and the shortest of 4 years (EHC, 2007). Such rainfall characteristics are critical for understanding the availability and quality of water resources in the study catchment.

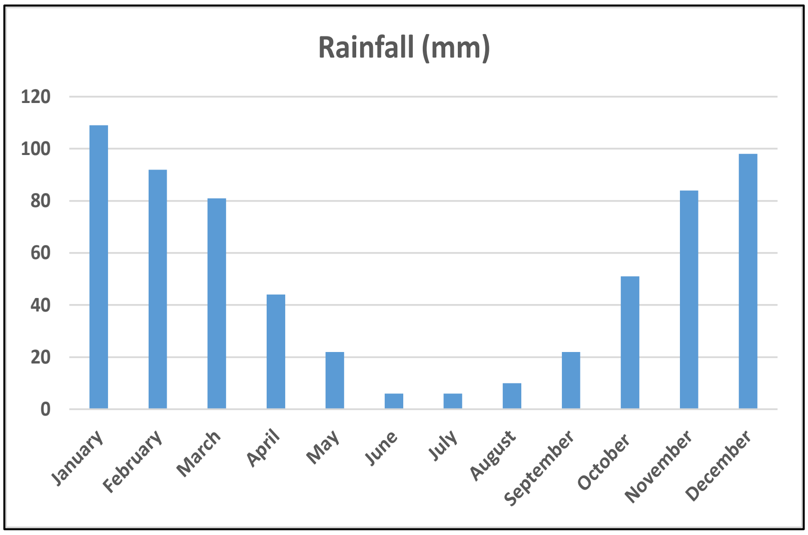

Figure 3.5: Average monthly rainfall distribution (January-December) in the Schoonspruit-Koekemoerspruit River Catchment (EHC, 2007).

3.4.4 Major tributaries and dams

The major tributaries of the Schoonspruit-Koekemoerspruit River Catchment (Figure 3.6) are Rietspruit, Taaibosspruit, Buisfonteinspruit, and the Jagspruit which are linked to the Schoonspruit main tributary. The groundwater recharge point or Ventersdorp eye of the Schoon Spruit ensures that the Schoon Spruit flows all year round. The eye water is mainly used for irrigation and for domestic water supply. The Kromdraaispruit is a main tributary of the Koekemoer Spruit which originates from the north of the Koekemoer Spruit and drains to the east of the Koekemoer Spruit until it joins the latter stream about 3,5km to the north of the point where the Koekemoer Spruit crosses the N12 road. From the confluence with the Kromdraai Spruit no other stream of note joins the Koekemoer Spruit until it flows into the Vaal River about 16,5km further downstream. The Koekemoer Spruit joins the Vaal River in the vicinity of Buffelsfontein Gold Mine about 6km downstream of Vermaasdrift (DWAF, 2006a). Five dams are fond in the catchment, namely, i) Johan Naser Dam, ii) Rietspruit Dam, iii) Elandskuil Dam, iv) Taaibosspruit Dam, and v) Buisfonteinspruit Dam. The dams are used for the purpose of irrigation and for domestic water supply. Such description on water resources is fundamental for improved understanding on the hydrology and geohydrology in the study catchment. In addition, such knowledge guides validation and verification of the novel citizen science framework for its feasibility to facilitate operationalization of water resources protection strategies.

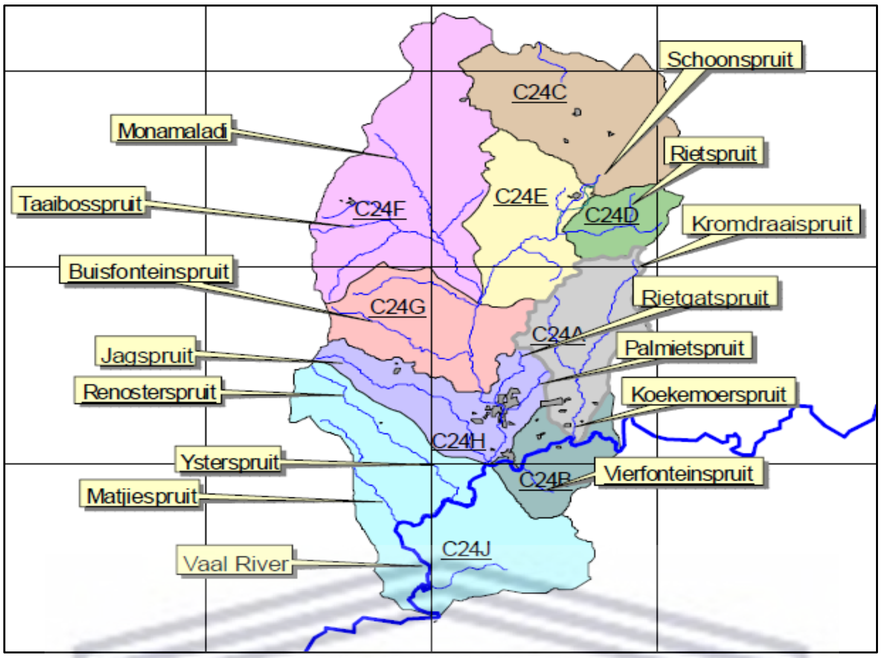

Figure 3.6: Major water tributaries in the Schoonspruit-Koekemoerspruit River Catchment (DWAF, 2006a)

3.4.5 Groundwater resources and availability

Several aquifer types can be identified due to heterogeneity of the geology across the study area. However, the Malmani dolomite forming Karst aquifer system with a potential borehole yield of > 5.0 l/s, which forms part of the Chuniespoort Group of the Transvaal Sequence are most significant (EHC, 2007). Groundwater movement is associated with preferential flow along the North-East trending joints and faults towards the Vaal River and the Stillfontein Gold Mine. Although several minor aquifers of various formations of the Ventersdorp Supergroup have developed throughout the study area (Figure 3.7), such aquifers are limited in terms of their hydraulic characteristics hence borehole yields from these aquifers range between 0.1 to 2.0 l/s. Groundwater dependant ecosystems include: Klerksdorp and Kimberly Thornveld-Woodlands with trees and shrubs with a number of species that may be deep rooted and depended on groundwater and may be sensitive to lowering of water table through groundwater dependant ecosystem processes. High groundwater water table and good quality groundwater are present due to shallow aquifer resources and diffuse and focussed recharge events during high rainfall events.

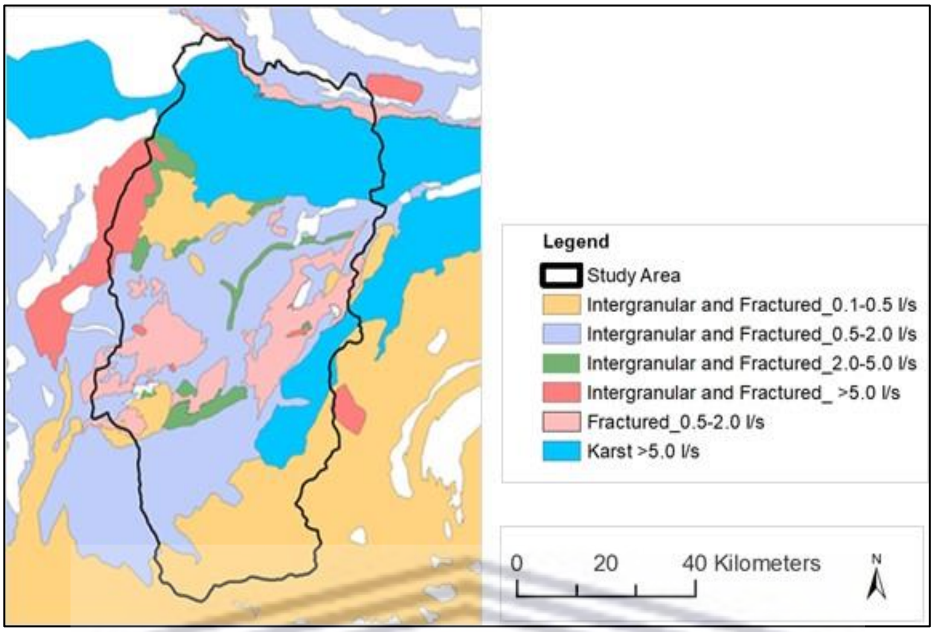

Figure 3.7: Various aquifer types found in the Schoonspruit-Koekemoerspruit River Catchment

3.5 Socioeconomic settings of the Schoonspruit-Koekemoerspruit River Catchment

The socioeconomic settings of the Schoonspruit-Koekemoerspruit River Catchment are presented by describing population characteristics and land use activities reported in the study catchment. These activities are essential for inhibiting or supporting the practical application of science-policy interface that considers the nexus approach and supporting or not supporting the concept of citizen science for policy implementation towards water resources protection.

3.5.1 Population

The total number of people residing within the study area is estimated at 478 525, as per the population census of 2011 (Table 3.2). Increase in the population growth has a direct influence on the allocation of resources such as agricultural water use and water supply. For example, the irrigation sector is by far the largest water user in South Africa. Any percentage reduction or increase in water use in this sector will therefore have a significant effect on the total water availability.

Table 3.2: Estimated population in the study area as per population census of 2011 (STATS-SA, 2012)

Study Area	Quaternary Catchment	Population of the Quaternary Catchment	Population Size of the Study Area (per person)
Schoonspruit-Koekemoerspruit River Catchment	C24A	89 194	478 525
	C24B	22 899	
	C24C	6 088	
	C24D	3 873	
	C24E	36 954	
	C24F	27 367	
	C24G	270	
	C24H	290 233	
	C24J	1 647	

3.5.2 Land use activities

Although the most important user of water in the Schoonspruit catchment is the Schoonspruit Irrigation Scheme that originates at the Ventersdorp Eye, however, domestic water supply from groundwater, and mining are also notable water users (Figure 3.8). Agriculture and mining dominate the lower part of the study area, while intensive agriculture and intensive domestic water use occur in the middle and the upper part of the study area, respectively. There are three existing irrigation schemes in the study area are, Schoonspruit Irrigation Scheme, the Ventersdorp Eye Subterranean GWCA, and the Klerksdorp Irrigation Board. A weir diverts the Eye's water into a canal for use by irrigation and for Ventersdorp Municipality water supply (DWAF, 2006b). The rest of the water from the Eye is released into the Schoonspruit for downstream users (ecological water requirements and irrigation). Land use activities give an idea about the type of water system mostly used in a particular area, and the nature or state of water quality likely to occur. Therefore, land use activities in the present study, provided an important piece of information on the location of the dominant water system, the possibility of unsustainable water resource utilization and their quality impact.

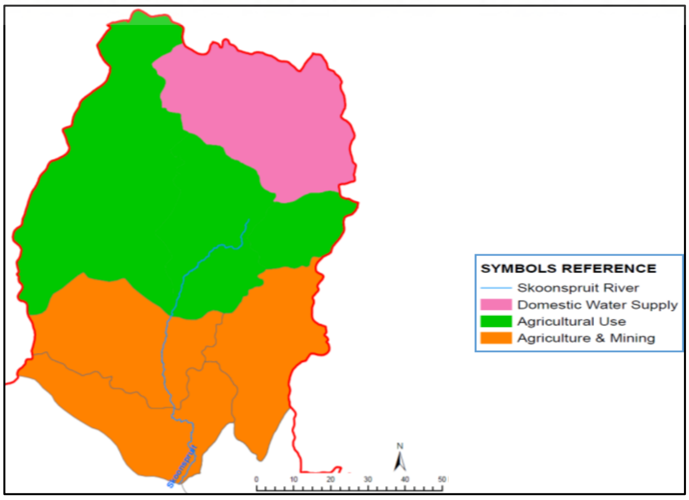

Figure 3.8: Dominant land use activities in the Schoonspruit-Koekemoerspruit River Catchment

3.6 Water resources challenges in the Schoonspruit-Koekemoerspruit River Catchment

The Schoonspruit-Koekemoerspruit River Catchment experiences several challenges for both groundwater and surface water resources mostly associated with water quality deterioration (DWS, 2014). Naturally, the river flows in the Koekemoerspruit sub-catchment are seasonal and there are periods when the river dries up. However, the flow patterns have been changed due to the mine dewatering discharges as well as discharges from the Stilfontein wastewater treatment works into the system. As a result of this flow pattern changes, sections of reeds have developed in the lower reaches of the river which has provided habitats for aquatic life. The water quality in the river is impacted by mine dewatering discharges as well as the seepages from the tailings storage facilities, pollution control dams and storm water management systems. The mine impact on water quality is largely related to salts and toxics such as heavy metals. Cyanide is also present in the water in times of tailings spills or leakages from the slurry pipelines that traverse the river. The wastewater treatment works discharges also impacts on water quality specifically on the nutrient concentrations in the river.

The dolomite aquifer systems in the catchment sustain stream flows in the Schoonspruit sub-catchment. However, these aquifer systems are significantly impacted by extensive irrigations. These extensive abstractions from the dolomitic aquifer for irrigation have resulted in the reduction of flow from the Schoonspruit Eye and falling groundwater levels in the dolomitic groundwater compartment over time, thus directly impacting on downstream users. Fertilizers are also applied to the irrigation areas. This has resulted in local nitrate concentrations in the groundwater exceeding 10 mg/L as nitrogen. Elevated salt concentrations in the groundwater have also been identified in places. The reduction in flow and potential deterioration in the water quality at the Eye will impact on the water users and ecology of the Schoonspruit downstream of the Eye. The interaction between the Eye discharge and the flow and water quality requirements of the Schoonspruit fed by the Eye discharge requires careful management of the water balance of the dolomitic compartment. The current groundwater monitoring protocols and programme need to be reassessed (DWS, 2014).

3.7 Water resources protection practice in the Schoonspruit-Koekemoerspruit River Catchment

Water resources protection practice is ensured by undertaking resource directed measures studies and their implementation thereof at catchment level. Some of the resource directed measures studies undertaken in the study catchment or as part of the MV-WMA includes, Groundwater reserve determination for the Middle Vaal Water Management Area (DWA, 2012b), Classification of significant water resources (River, Wetlands, Groundwater and Lakes) in the Upper, Middle and Lower Vaal Water Management Areas (DWA, 2012a), Determination of resource quality objectives in the Middle Vaal Water Management Area (DWS, 2014), and the Gazetting of the reserve for the water resources of the Vaal Catchment Area (DWS, 2019).

Such studies provided information for validation and verification of the novel citizen science framework for its feasibility to facilitate operationalization of water resources protection strategies at catchment level.

The water resource classification study (DWA, 2012a) proposed a water resource class III for the Schoonspruit-Koekemoerspruit River Catchment. Class III is a configuration which indicates a catchment that is highly utilised or modified from its pre-developmental state. Actions to address water quality challenges as well as improvement in agricultural practices were recommended for the catchment management (DWA, 2012a). The resource quality objectives study established several indicators linked to surface water quality and flows, as well as groundwater quantity and quality with associated numerical limits (DWS, 2014). It is important to note that in areas where resource directed measures studies have been gazetted, such measures are legally binding to authorities responsible for managing water resources especially at catchment level. In this context there needs to be implementation plans put in place to operationalize such measures, hence the importance of resource directed measures practice in the Schoonspruit-Koekemoerspruit River Catchment.

3.8 Assessment sites and their location

In order to verify and validate the novel citizen science framework using the Schoonspruit-Koekemoerspruit River Catchment, a surface water site, and four groundwater sites were selected for such purpose (Table 3.3). The validation protocol was to temporally analyse the historical stream flow regime to assess compliance with established resource quality objectives linked to surface water flows for environmental water requirements. The protocol was also applied to temporally analyse groundwater and surface water quality data to assess compliance with established resource quality objectives linked to both groundwater and surface water quality. Lastly, the design was applied to temporally analyse changes in groundwater levels to assess compliance with established monthly critical recession rate linked to resource quality objectives for groundwater quantity in the catchment. The process of citizen science verification and validation was undertaken at catchment scale.

Table 3.3: Assessment sites used for citizen science verification and validation in the Schoonspruit-Koekemoerspruit River Catchment

Assessment site	Site type	Component	Latitude	Longitude
C2H139Q01	Surface water	Water quality and quantity	26˚ 54.964’ S	26˚ 49.032’ E
C2N1143	Groundwater	Water quantity	26˚ 2.387’ S	26˚ 27.759’ E
C2N1150	Groundwater	Water quantity	26˚ 39.384’ S	26˚ 52.346’ E
2626DB00350	Groundwater	Water quality	26˚ 35.115’ S	26˚ 54.917’ E
2626DB00386	Groundwater	Water quality	26˚ 39.783’ S	26˚ 52.333’ E

3.8.1 Surface water sites

The surface water site chosen was C2H139Q01, and its selection was based on the availability of a long-term data for stream flow and for water quality. It has been previously reported that mine dewatering discharges as well as discharges from the Stilfontein wastewater treatment works into the Koekemoerspruit influence the stream flow pattern changes which has provided habitats for aquatic life. (DWS, 2014). While the flow regime was recorded at the C2H139Q01 site, water quality assessment was also undertaken at the same monitoring site. Therefore, historical data obtained from the selected site provided information on surface water compliance for both quality and quantity.

3.8.2 Groundwater sites

Two groundwater sites were selected for the purpose of analysing fluctuations in the groundwater table because of prevailing local conditions (Table 3.3). The C2N1143 groundwater site was selected to analyse fluctuations in the groundwater table as a results of groundwater abstractions for irrigation purposes in the catchment. The C2N1150 groundwater site was chosen to asses' impact of mining activities on the groundwater table. Information generated from the two groundwater sites was important in assessing compliance with critical recession rates established for resource quality objectives linked to groundwater quantity. Additional two groundwater sites (2626DB00350 and 2626DB00386) were selected for the purpose of analysing changes in groundwater quality in the study area. Information produced from the two sites was important in assessing compliance with chemical concentrations established for resource quality objectives linked to groundwater quality.

3.9 Chapter summary

In this chapter, the current study argues that comprehensive understanding of physiographic aspects, socioeconomic activities, and conditions of water resources within the Schoonspruit-Koekemoerspruit River Catchment as a case study area gives essential information on local factors and prevailing conditions that are likely to enhance or hinder water resources protection practice at catchment level. This chapter has presented the physiographic factors which have been described by outlining the climate, rainfall, major tributaries, and groundwater resources and availability. This chapter also presents socioeconomic aspects by outlining population size, and land use practices in the catchment. It has also described prevailing water resources challenges in the study area. Lastly, surface and groundwater sites used for data collection have been described and their candidature for use in such data collection process. The description of the study area in this chapter 3, provides insight into the conditions and factors that are likely limit or enable practical application of science-policy interface that considers the nexus approach, and uses the concept of citizen science for policy implementation towards water resources protection. The argument of this chapter is that comprehensive description of the study area is essential for validation and verification of the novel citizen science framework for its feasibility to facilitate operationalization of water resources protection strategies at catchment level.

Chapter 4: Research design and methodology

4.1 Introduction

Chapter 2 has presented literature review on previous studies to contextualize the present study, while the description of the study area chosen for the present study has been presented in chapter 3. The present chapter 4 presents research deign and explains the methodology that was followed. The current chapter 4 contains the following aspects: 1) research design, 2) methodological approach, 3) research methods, 4) quality assurance, 5) research integrity, and 6) study limitations. This current chapter explains research methods that were used to collect and analyse data to answer the research questions so that the set objectives of the study are achieved. Strengths and weaknesses of the methods used for this study are described to justify their appropriateness for the current study. The argument of the current chapter is that comprehensive description of research design adopted, methodological approach followed, 3) research methods used for data collection and analysis, quality assurance measures instituted, research integrity applied, and study limitations provides credibility on how the study was conducted. Such credibility is essential for the validity and reliability of the study outcomes, and usability of the results by other researchers including practitioners.

4.2 Research design

4.2.1 Study design

The intention of the study design is to integrate the different components of the study such as collection, measurement, and analysis of data in a rational and analytical manner to ensure that the identified research problem is adequately addressed. The current study followed a descriptive case-research study design and was informed by i) dual learning pathways of science and policy, ii) limited use of science product in policy practice, iii) limited application of water-energy-food-environment (WEFE) Nexus in water resource protection practice to fast-track achievement of SDGs by 2030, iv) limited RDM uptake and practice at catchment level as implementation strategies towards water resources protection, and v) limited resources to follow other forms of study designs which are labour, resource, and time consuming.

In policy practice, 'evidence-based' approach such as science-policy nexus plays a critical role where policy provides questions to be researched and science provides solutions to challenges faced by policy makers. Such approach is informed by readily available information emanating from scientific research outputs, which further assists in translating developed policies into actions (Cashman, 2012; Grimm et al., 2018). However, the concept of science-policy nexus is still not clearly understood, hence inadequate utilisation of the concept in policy practice. The evidence for this observation is abundant where available data and information exist from scientific research outputs, but policy makers seem not utilising such information when developing policies and strategies for water resource protection.

Descriptive-case study research allows a researcher who has identified a problem to explore and understand the context in which the identified problem exists, to come up with an effective strategy (Meerah and Osman, 2013). The present study aspired to develop and validate a model for effective RDM uptake and practice at catchment level to protect water resources. From the study aspiration, the researcher pursued to collect and analyse data using descriptive approaches to provide knowledge for developing the model which had to be validated and verified for its feasibility using case research approach. Therefore, it was deemed suitable to conduct the study by following a descriptive-case study research design in finding appropriate answers to the main research question of the present study.

4.2.2 Methods for sampling design

Several commonly used sampling techniques include simple random, clustering, and systematic (probability) sampling, while judgment or purposive or theory-based, and convenience sampling are grouped together as non-probability sampling. Omona (2013) argue that in choosing a sample size and sampling design within a particular qualitative study, a researcher must acknowledge that sampling often may represent an iterative process of reflection that is based on many factors, including the context, method of collecting data, and type of generalisation required. The author indicated that sampling techniques used in qualitative research such as purposive (theory-based) sampling are most relevant when individuals, groups, or settings are selected because they help the qualitative researcher to develop or expand a theory (Omona, 2013). Van Rensburg et al. (2013) commented that judgment / purposive sampling is made based on available information or researcher's information about the population where such knowledge is used to pick elements for the sample and is shaped by the available time the researcher has. Although Omona (2013) and van Rensburg et al. (2013) argue that this type of sampling is mostly subjective as it depends on the researcher's consideration rather than scientific criteria, however, they pointed out that when this type of sampling is used by a researcher who knows the population being studies, then it has some value. Purposive sampling design is suitable for studies which investigate characteristics or circumstances of a population, and in the present study, it was considered as a necessary sampling design to investigate policy implementation and to test feasibility of the novel citizen science framework.

The sampling design and its components that were considered when the design was established indicated in Table 4.1, and they consist of i) target population, ii) data collection method, iii) sampling frame, iv) sampling method, v) sample size, and vi) sampling approach. Target population is described as the collection of elements that possess relevant information pursued by a researcher for interpretations to be made, and it is defined in terms of sampling units, elements, extent, and time (Kabir, 2016). Sampling frame is a comprehensive list of all the units or elements in a target population, while sample size represents number of elements in a population sample (van Rensburg et al., 2013).

Table 4.1: Components of the sampling design with its associated variables

Sampling Design Component	Variables of choice
Target Population	Policy documents; Scientific reports; Government reports; Government institutions; National databases
Data Collection Methods	Archival data surveys/ Desktop record reviews
Sampling Frame	Legislative documents; Water resources strategies, RDM Regulation documents; RDM strategies; Reports on RDM studies; Water quality databases; Hydrology databases; Catchment Management Agencies business plan documents; Research reports on Citizen Science studies. stream flow data; Groundwater levels data; physicochemical concentrations (PO_4; NO_3+NO_2; SO_4; Mg; Electrical Conductivity; Na; Ca; Cl; pH);
Sampling Method	Judgment / Purposive sampling
Sample Size	Groundwater samples; surface water samples; water chemistry; groundwater levels; surface water flows; policy documents; RDM studies; subject related studies from literature
Sampling Approach	Non-probability Sampling

4.2.3 Data type and their sources

Table 4.2 presents type of data, classification of data, and sources of data used to answer specific research questions linked to each objective of the study outlined in section 1.3.2. Research data is defined as any information that has been generated or created, observed, collected, and collated to validate original research findings (Goundar, 2013). Research data can be obtained as primary, secondary, or tertiary data (van Rensburg et al., 2013). Primary data can be obtained by the researcher through field experiments (van Rensburg et al., 2013). Advantages associated with use of primary data is that results derived from such data have low level of uncertainty caused by lack of knowledge of the product being investigated (Jiang e al., 2020), while disadvantages such as costly, and time consuming have been reported (Goundar, 2013).

Secondary data is acquired through government publications or from internal reports (Ajayi, 2017). Although disadvantages such as non-real-tie data and not original are associated with the use of secondary data, however, use of such data comes with an advantage of using readily available source of data emanating from primary data which makes secondary data collection rapid and easy (Ajayi, 2017), hence suitable for studies with limited financial and resources. Tertiary data is usually derived from secondary sources, but such data should be used with cautious as it has been further removed from the original source (van Rensburg et al., 2013). Primary, secondary, and tertiary data can be classified as either quantitative or qualitative (Ajayi, 2017). The class of research data collected defines type of analysis associated with data that has been collected.

For example, qualitative data is analysed using qualitative data analysis methods, while quantitative data is analysed using quantitative data analysis methods. Research data can be acquired in different ways such as observation (observational data), experiments (experimental data), simulations (simulated data), and derivative (derived data) (Igwenagu, 2016). Sources of research data may include open access sources, published sources, and archived data), however, choice on the type, class, and source of data depends on the main research question being investigated and research design followed (Creswell, 2014).

Table 4.2: Description of research data types and their sources

Research Objective	Type of Data	Classification of Data	Source of Data
1. Assess the application of science-policy nexus in policy formulation and practice towards water resource protection.	Secondary	Qualitative	Open access and published sources
2. Establish the application of reflective policy models to assess operation of water-energy-food-environment nexus approach in water resource protection practices	Secondary	Qualitative	Open access and published sources
3. Demonstrate the validation and verification of a process based operational plan for catchment orientated resource directed measures	Secondary	Quantitative and Qualitative	Archived data on databases and research journals

In the current study, both quantitative and qualitative secondary data acquired from archived records, open access, and published sources were deemed appropriate to answer the afore-mentioned specific questions linked to the main research question. In order to answer the research question linked to the first objective, secondary data on water resource protection strategies were obtained from the DWS. Data on RDM studies undertaken, in progress, and those that are yet to be undertaken were sourced from the DWS and other relevant open sources such as Internet in a form of reports. These data were obtained per WMA. Qualitative secondary data on the application of science-policy nexus were sourced from reported case studies in literature, through internet and science databases, and they were in a form of peer reviewed research articles. Scientific reports on the application of WEFE nexus, and reports on reflective practice were sourced from literature. Data on water resource classification procedure, reserve determination procedure, and RQOs determination procedure, in addition to water requirements for energy production, agricultural production, basic human needs, and environmental ecosystem protection per WMA were obtained DWS in reports. The data collected were used to answer the research question linked to the second research objective.

In answering research question linked to the third research objective where the study aspired to development of citizen science framework, data on reported case studies where the Socio-Ecological Model (SEM) and citizen science concept have been applied in practice were sourced from scientific reports in literature and internet sources. As previously indicated, data on RDM studies where numerical limits for RQOs indicators linked to groundwater and surface water had been established were sourced from the DWS in reports. Data on groundwater levels, stream flows, were obtained from the DWS Hydrological Services, after identifying river gauging station and groundwater monitoring sites on the basis of data availability and operational status. Data for surface water quality, and groundwater quality were obtained water management system (WMS) database of the department of water and sanitation [DWS] in as a comma-delimited text file. These were secondary data sets.

4.3 Research methodology

In describing the characteristics of the present study that were considered in selecting the appropriate methodology, the three research methodologies namely: 1) quantitative methodology, 2) qualitative methodology, and 3) mixed methodology are acknowledged and discussed.

4.3.1 Quantitative methodology

Quantitative methodology is used to investigate general trends across population and focuses on quantifying and analysing numerical data using specific statistical methods (Goundar, 2013; Apuke, 2017). The methodology incorporates surveys and statistical analysis in addition to other methods to answer words such as "how much? Have students pass rate improved over time? (Muijs, 2004). For example, Muijs (2004) points out that four main types of research question are suitable for using quantitative research methodology, namely: 1) when a research tries to investigate and provide a quantitative answer, 2) when numerical changes will form part of the study, 3) when wanting to find out about the state of something such as unemployment rates, 4) when quantitative research is suited in the testing of hypothesis. Quantitative methodology can be used for collection of data from both experimental and non-experimental studies (Muijs, 2004). Quantitative research offers some advantages, for instance it can provide estimates of a larger population, allows use of statistical comparisons between various groups, and it can effectively translate data into easily quantifiable charts and graphs (Sukamolson, 2007). Furthermore, advantages associated with savings on cost and time, access to quantity data that has been tested, and availability of longitudinal data have also been reported (Goundar, 2013). However, quantitative research has some limitations. For example, large samples are required, which tend to be more expensive. Quantitative research usually has a rigid structure, which makes it less flexible method of research and, when handled improperly, is vulnerable to statistical errors which sometimes come from sampling errors (Goundar, 2013).

4.3.2 Qualitative methodology

Qualitative research studies describe a situation in its natural state rather than attempting to quantifiably measure variables. For instance, Goundar (2013) pointed out that the goal of understanding a situation from its natural context is largely lost when textual data are quantified. Van Rensburg et al. (2013) indicated that techniques applied in qualitative research involves studying concepts that capture the meaning of the experience (situation), action or interaction of the element. It also involves analysis of collected data by means of no quantitative frameworks and category systems. Units that were studied were selected in a purposeful, manner using a purposeful selection of a wide variety of subjects, which were then observed (van Rensburg et al., 2013). Data were collected, analysed to understand the situation, and then deductions were made. Although qualitative research is usually designed to be completed quickly, however, it looks deeper than analysing ranks and counts (Goundar, 2013). Qualitative research is known for its flexibility to conduct. For example, Yeung (1995) applied qualitative personal interview to explore Hong Kong transnational corporations. The study indicated that qualitative research methods provide much flexibility to both data collection and analysis. Disadvantage associated with qualitative research is that findings from such studies cannot be tested to discover whether they are statistically significant or due to chance and furthermore the results cannot provide definitive conclusions (Atieno, 2009).

4.3.3 Mixed methodology

Mixed research methodology study can be described as a methodology whereby a researcher uses multiple methods of data collection and analysis (van Rensburg et al., 2013). This statement agrees with what has been reported in literature. For example, Sukamolson (2007) pointed out that mixed methodology approach is generally considered when quantitative and qualitative methods are combined and used. Mixed methodology is also known as multiple methods or triangulation whereby multiple methods are used to study a single topic, for example combining quantitative and qualitative methods in a single study (methodological triangulation), or whereby two or more analytical techniques to analyse the same set of data are used (analysis triangulation) (O'Leary, 2019; Egerod et al., 2020). The advantage of a mixed research methodology is its ability to complement one set of results with another, to expand a set of results, or to discover something that would have been missed if only a quantitative or a qualitative methodology had been used (Halcomb and Hickman, 2015). It has been argued that mixed methodology is the most appropriate in conducting a good research study (Sukamolson (2007). Granikov et al (2020) argued that combining quantitative and qualitative methods enhances the breadth and depth of understanding of a phenomenon and the corroboration of knowledge.

4.3.4 Justified study methodology

Although the current study largely uses a qualitative methodology, to a smaller extent, quantitative methods were used.

For example, the study by DWS, (2014) reported on the parameters of analysis on water quality and observed that maintenance stream low flows were established as indicators for RQOS linked to surface water, while groundwater levels were selected as indicators for RQOs linked to groundwater. This means that when science aspects of science-policy nexus are considered, quantitative methods have to be used. Furthermore, physical (river flows, groundwater level) and chemical parameters (Nitrate, Phosphate, Magnesium, Fluoride, Sulphate, Chloride) were also selected as indicators for surface and groundwater resources linked RQOs (DWS, 2014). The current study put emphasis on science-policy interface which needs requires mixed methodological approach where qualitative and quantitative methods and data are used for analysis. In this way the policy makers have numerical data and accurate descriptive picture of the matter being addressed. For example, du Plessis et al. (2014) quantified and predicted the water quality associated with land cover change within the Blesbokspruit catchment using quantitative methods where they identified temporal trends of water quality over short periods of time and possible sources of pollution and areas of concern. Masindi and Abiye (2018) used quantitative methods to assess influence of geology and anthropogenic activities on groundwater chemistry. The proposed study used quantitative methods to establish compliance with established RQOs numerical limits.

4.4 Research methods

4.4.1 Data collection and analysis methods for science-policy nexus

Odume et al. (2018) indicated that contestation by stakeholders within the upper part of the Vaal River catchment arises because of lack of conceptual understanding on the scientific bases of RQOs. In the present study, this aspect is addressed in the first objective, namely: to demonstrate application of science-policy nexus in policy formulation and practice towards water resource protection to showcase how policy feeds science, and how science feeds policy in reality. Literature review sources on peer-reviewed literature were carried out to unveil the gap on the science-policy nexus application in policy practice. Archived record review methods were used where relevant policies within the identified relevant institutions with were reviewed and abstracts of relevant sections from the identified policy documents were documented. Collated data were categorized into three water resources protection themes, namely a) policy implementation, b) policy implementation strategies, and c) policy practices. Archived record review methods were also used to collect data on RDM studies undertaken in the country. Such data gave an indication of the catchment where such studies have been completed, in progress, and in areas where they are not yet commissioned. Reflection on the use of RDM studies which are scientific in nature was presented through a practical case-study of South Africa to demonstrate how science-policy integration can directly impacts water resource protection practices from a local, regional, and national perspective.

Seward (2010) reported that there is a misunderstanding about RDM, where many people view these measures as putting people against the environment. Therefore, in terms of data analysis methods, case study analysis method was used to analyse collected data and to showcase how RDM strategies are used to enhance science-policy integration in a practical way towards water resource protection. Qualitative case study enables capturing of information in a more explanatory mode (Crowe, et al. 2011; Hvalič-Touzery et al., 2017). Crowe, et al. (2011) in their paper argued that case study method is useful to employ when there is a need to obtain an in-depth appreciation of an issue of interest in its natural context. Case study method is well suited for studies exploring policy implementation strategies. For example, Ameyaw and Chan (2013)'s study on the increased awareness of risks that could erode or reduce potential benefits of existing public-private partnerships (P-PPs) in the water supply sector in Ghana used a combination of literature survey and case study. Vandecasteele et al. (2015) used case study method to investigate potential impacts of shale gas development on regional water resources within the Baltic Basin in Poland, both in terms of quantity and quality.

4.4.2 Data collection and analysis methods for WEFE nexus

Sustainably achievement of resource security for all, the integrity of ecosystem services and the associated resource base must be maintained while access to resources is expanded and consolidated (Momblanch et al., 2019). This is reflected on the Water-Energy-Food-Environment (WEFE) Nexus which has been adopted as a holistic management approach towards achievement of inter-disciplinary societal goals such as SDGs for clean water, clean energy, hunger eradication, and life on land. This aspect is addressed in the second objective of the present study where assessment on the application of WEFE Nexus approach in water resource protection practice was carried out to show contributions of such aspects in the nexus towards achievement of socio-economic development goals.

Literature survey and document review methods were used in combination for the purpose of collecting data. Use of literature survey methods enabled data collection from reported studies on the application of water-energy-food-environment (WEFE) nexus in practice. Such data were necessary to identify knowledge gap on the use of the nexus in fast-tracking achievement of SDGs linked to SDGs 2, 6, 7, and 15. Document review methods were applied to collect data on existing processes and procedures that are followed when RDM studies are undertaken. Such data formed bases for scrutinizing RDM procedures for consideration of the WEFE nexus when RDM studies are undertaken. Document analysis ensured that such data become available for scrutiny in the present study.

Descriptive analysis and methods of reflective practice were used for data analysis. Descriptive analysis provided insight about synergies and trade-off between nexus components. Such knowledge is critical towards understanding how the synergies can be enhanced and trade-offs minimalized to improve application of the nexus concept in policy practice. Methods of reflective practice such as the Gibbs Reflective Cycle Model are widely used (Bass et al., 2017; McBrien, 2007).

Gibbs Reflective Cycle Model were used in the present study to reflect and illustrate the significance of RDM in promoting societal benefits in a wider context including achievements of socio-economic development goals such as SDGs through application of WEFE nexus concept.

4.4.3 Data collection and analysis methods for citizen science

The process of validation and verification is fundamental in the development of the citizen science framework to ensure that the developed operational plan for catchment orientated resource directed measures facilitates the improvement of RDM practice at catchment level. This approach addresses the reviewed and reported challenges regarding the RDMs. For example, Pollard et al. (2012) pointed out that there is a lack of integration of the ecological reserve methods with operations at catchment level. In agreeing with Pollard et al. (2012), Odume et al. (2018) reported that lack of clarity between RDM and sources directed controls (SDC) has brewed contestation among water users in the upper Vaal catchment. These observations justified the need to develop RDM operational plan that would at least include aspects such as, roles and responsibilities, monitoring, auditing, reporting and review. Based on this need, the present study developed and validated a process based and catchment orientated resource directed measures operational plan to improve RDM practice at catchment level.

Data on Socio-Ecological Model (SEM) application, numerical limits, and indicators for RQOs linked to surface and groundwater, reported citizen science projects, surface water quality, stream flows, groundwater levels, and groundwater quality were collected using different data collection methods. Collected data were sorted into a feasible format, analyzed, and interpreted to give guidance on the development, validation, and verification of the citizen science framework. Literature surveys, descriptive record surveys, and desktop archived data reviews were used as data collection methods. In terms of literature survey, systematic and purposive literature review was undertaken on the SEM background to understand its nature and the history behind the model. Since the citizen science framework addresses aspects of people (roles and responsibilities) and environment, the Socio-Ecological Model (SEM) which was developed by Bronfenbrenner in 1974 to draw attention to individuals and to consider the entire ecological system in which growth occurs was deemed appropriate theoretical frame in guiding citizen science framework development. Socio-ecological model by Bronfenbrenner remains one of the most widely known theoretical frameworks in many disciplines when human-environmental interactions studies are carried out (Vélez-Agosto et al., 2017).

Literature surveys have been widely used in studies investigating policy practice (Aldieri et al., 2019; Sinharoy, et al., 2019; Shittu, 2020). For examples, Sinharoy, et al. (2019) investigated drivers and barriers of water, sanitation, and hygiene (WASH) policies in urban informal settlements in low and middle-income countries using literature surveys of peer-reviewed and grey literature. Peer-reviewed literature on the on the application of the SEM model in various fields of practice provided insight into versatility of the model.

Furthermore, literature on the adaptation of the SEM's core principles in policy practice was essential to establish its candidature as analytical framework for designing citizen science framework. Literature review methods were also used to gather data on reported citizen science case studies where local communities have been involved in data collection projects. Such reported case studies were critical in validating the citizen science framework. In terms of data collection using descriptive surveys, document review on RQOs studies that have been conducted in the country was undertaken. Descriptive survey methods are most suitable for studies investigating present phenomena in terms of prevailing conditions, practices beliefs, processes, relationships or invariably trends, and may include applications such as document analysis (Salaria, 2012; Khedher et al., 2020). For example, Saini et al. (2019) used a document analysis technique such as multi-objective optimization (MOO) framework to design an extractive single document text summarization (ESDS) system. In the present study, the review of documents and reports was deemed as an appropriate data collection method, and it enabled data collection on the established RQOs numerical limits and indicators linked to surface water and groundwater resources.

Desktop archived data review methods were used to collect data on parameters such as groundwater levels, groundwater quality, surface water quality, and river flows. Such data were used for assessing RDMs operationalization at catchment level and compliance with the established RQOs. Surface water flows and groundwater levels provide useful information for understanding compliance with established river flows and groundwater volumes. For example, maintaining low flows in a reviver system ensures that there is sufficient minimal water to sustain ecological ecosystem within a catchment. In terms of groundwater, maintaining established levels of groundwater table ensures that compliance with RQOs established for groundwater use is achieved. For example, maintenance of groundwater table at a certain level will ensure groundwater availability and sustainable use within a catchment. Collected data on river flows were sourced from the Directorate: Hydrological Services of National Office of department of water and sanitation (DWS), and such data were used to establish stream flow regime and compliance with established RQOs numerical limits linked to surface water quantity. Data on groundwater levels were obtained from the DWS Free for compliance with the established RQOs critical groundwater recession rate. Data on groundwater and surface water quality were sourced from the WMS which is a national water quality database of the DWS, and the data were used to assess compliance with established RQOs for water quality linked to groundwater and surface water. Data were collected according to guidelines prescribed by Weaver et al. (2007).

Collected data were analyzed using four data analysis methods, namely, i) case study analysis, ii) descriptive statistics, iii) flow duration curve analysis, and iv) load duration curve analysis. i) Case study analysis was undertaken for practical demonstration of the feasibility of the citizen science framework as RDM operational plan at catchment level.

Case study areas were the Msunduzi and uMngeni River catchments located within the Pongola to Mtamvuna WMA, the Tsitsa River Catchment within the Mzimvubu-Tsitsikamma WMA, and the Schoonspruit-Koekemoerspruit, River Catchment located in the Middle Vaal WMA. The case study catchments were used to analyzed feasibility of the framework for citizen science participation in water quality data collection (the Msunduzi and uMngeni River catchments, and the Tsitsa River Catchment), and to demonstrate use of historic data for compliance assessment with established RQOs (the Schoonspruit-Koekemoerspruit, River Catchment). The rationale for this selection was that citizen science based research activities were carried out in these catchments and outcomes of such studies formed the bases for validating the citizen science framework and that water resource challenges have been experienced in these catchments, thus requiring policy interventions.

ii) Descriptive statistical analysis was used to summarize quantitative data sets into simpler and more understandable forms, such as mean, median, 5th percentile and 95th percentile, and standard deviation. Time series trends for each groundwater quality variable were established and compared with the water quality classes for domestic water use (WRC, 1998) as per recommendation for RQOs. The results from the analysis were computed in Microsoft Excel. The data were first checked for quality control in terms of analytical precision as per the principle of electro-neutrality (Younger, 2007) before use to ensured reliability of the analysis. This was achieved by calculating the percentage of charge balance error (% CBE) using the following formula in equation 4.1.

$$\%CBE = \frac{(\sum cations - \sum anions)}{(\sum cations + \sum anions)} \tag{4.1}$$

Although the rule requires that all water samples comply with the principle of electro-neutrality, however, some exceptions exist which state that if %CBE is less than 5%, then the analysis can be regarded as accurate for all uses, and that if %CBE lies in the range of 5-15%, then the analysis should be used with caution. In the present study all water samples that had %CBE of >5% were excluded from the analysis. For qualitative analysis data were translated to quantitative data by ranking according to different water quality classes for domestic water use (WRC, 1998). Descriptive statistical analysis was also used determine groundwater recession rate from groundwater level records which were reported on monthly basis. Groundwater level recession rates were calculated based on groundwater level recession rate per month using the equation 4.2.

$$dh = (h_0 - h_n) / t \tag{4.2}$$

Where, dh = groundwater level recession rate (metres below ground level/day) h_0 = groundwater level on day 1; h_n = groundwater level on day 30; t = number of days. The calculated recession rate was then compared to the established groundwater RQO critical recession rate, and the results were recorded on the Microsoft Excel 2013 spreadsheet in graphical form.

iii) Flow duration curve (FDC) analysis was employed on the collected river flow data which was used to establish the flow regime along the Schoonspruit-Koekemoerspruit, River Catchment. Data were then analysed based on temporal variation by considering dry and wet seasons. FDC is known as a graphical illustration of the percentage of time (duration) a particular stream flow equals or exceeds a given value over a historical period for a particular river basin and such illustration uses time series data recorded at selected gauged site (Chouaib et al., 2018; Requena et al., 2018). A method by CDFW (2013) was followed to create FDCs to establish percentage of time and the level at which the ecological water requirements flows are met and sustained in the Schoonspruit-Koekemoerspruit. The FDCs were generated using the average yearly and monthly river flow data, which was ranked in a descending order for the total of n values in Microsoft Excel. Each discharge value was given a rank (M) starting with 1 for the largest value of discharge. The equal or exceedance probability for each daily flow was determined using the formula in equation 4.3.

$$P = [M / (n+1)]\ 100 \qquad (4.3)$$

Where, P = the probability that a given flow will be equalled or exceeded (% of time);

M = assigned rank number.

n = the total number of days for period of record.

The FDC was plotted with calculated P values on the X-axis (% equalled or exceeded) and corresponding flow values on the Y-axis ($m^3.s^{-1}$).

iv) Load duration curve (LDC) analysis assisted in establishing surface water quality compliance at different flow regimes with established RQO. LDCs were developed using the Probability values calculated from the FDC corresponding to numerical limits established for RQOs linked to surface water quality and were plotted in $kg.day^{-1}$. The loads of the LDC were calculated using the formula in equation 4.4.

$$\text{Load} = Q \times \text{water quality limit} \times \text{conversion factor} \qquad (4.4).$$

Where, Q = daily flows ($m^3{\cdot}s^{-1}$).

Water quality limit = RQO numerical limit for quality ($mg.\ l^{-1}$).

Conversion factor = the conversion between the concentration, volume, and time units to derive the load in $kg.day^{-1}$. For Q in ($m^3{\cdot}s^{-1}$) and RQO numerical limit for quality in $mg.\ l^{-1}$, the conversion factor would typically be 60 sec × 60 min × 24 h × 1000 l/1000,000mg.

The LDC was constructed by plotting the P values (%) derived from (4.1) on the X-axis and load values derived from (4.2) on the Y-axis as per method by Dlamini et al. (2019).

4.5 Quality assurance / Quality control

4.5.1 Evidence on adequacy of the collected data

In addressing adequacy of the collected data in the present study, aspects related to quantity of data collected and the degree of detail (richness) provided by the collected data to support findings for each of the three-study objective is outlined. Nebhöver et al. (2013) made a remark that science-policy interaction facilitates the direct flow from emerging knowledge into policy and practice, and vice versa by direct inclusion of policy perspectives into research processes. In simple terms, science-policy integration takes place in two forms, namely, i) when policy provides questions to be researched, and ii) when science provides answers to the researched policy questions. Therefore, in undertaking science-policy nexus studies, the two forms of science-policy interactions must be considered as integrated. In terms of the first study objective, consideration was made on data collection that reported studies on both forms of interactions are included in literature review to get a full insight on the knowledge gap of the nexus application in policy practice. Furthermore, the practical case study which is presented in chapter 4 of the thesis emerged from collected data, and it illustrates how policy-science and science-policy interfaces can be operationalized efficiently and effectively, by following and integrated processes. Therefore, collected data was adequate to address the first objective of the present study.

In consideration of data adequacy for addressing the second study objective, the degree of detail provided by collected data is reflected upon. Reflective practice which advocates for critical thinking and integration of theory and practice has been promoted as a method of developing knowledge entrenched within practice (McBrien, 2007; Bass et al., 2017). In establishing the application of reflective policy models to assess operation of WEFE nexus approach in water resource protection practices, detailed data not only on processes followed for undertaking RDM studies, but also on activities performed on each step when such processes are followed were essential. Data collected through document and report analysis on activities associated with each step of the water resources classification, water resource reserve determination, and resource quality objectives determination were necessary and adequate in the use of the Gibbs' Reflective Cycle Model (GRCM) which led to developing new insights and understanding on the application of WEFE nexus in water resources protection practices.

Glenton et al. (2018) pointed out that while one in-depth interview could yield a rich and valid account of one's person's experiences and is sufficient to document, however, three such interviews could be sufficient to prove that people may experience the same phenomenon differently. Similarly, in terms of ensuring that adequate data were collected to validate and verify the citizen science developed in the present study, three case studies have been presented. Two case studies were presented to dress the aspect of local citizens contributing to data collection for water resources protection practice (uMsunduzi and uMngeni River Catchments, and Tsitsa River catchment) in different settings.

One case study was presented on the use of historic data for assessing compliance with established RQOs for water resources protection practice (Schoonspruit-Koekemoerspruit River Catchment). Dlamini et al. (2019) used a case study of the Elands River to assess compliance with the established RQOs, however the study was limited only to surface water resources. Groundwater is excluded in RDM studies as a result data collection in the present study to validated citizen science framework went beyond surface water and included groundwater level, and groundwater quality data. Thus, data collected in addressing the third study objective were deemed adequate.

4.5.2 Evidence on reliability of the collected data

Reliability is one of the measures of quality assurance in a research study which concerns the extent to which a measurement of a phenomenon provides stable and consist of result, hence it is usually associated with data collection (van Rensburg et al., 2013; Taherdoost, 2016). However, such explanation is relevant for reporting findings animating from quantitative research studies. In qualitative studies, reliability could be understood as a measure of the researcher's approach being consistent across different researchers and different projects (Haradhan, 2017). In the context of the current study, reliability is described in terms of data collected which was based on the same approach (case study) used to answer specific research questions, and such description is presented objective by objective.

Objective 1: The model of science-policy nexus was investigated and presented in the first objective of the current study. It was formulated on data extracted from legal documents. In addition, data from literature and reports emanating from scientifically driven RDM studies undertaken by specialists was also used. Therefore, all data used are reliable and were obtained from reliable sources such as published reports by state organs, hence reliability of the investigation's findings.

Objective 2: Investigation for the second study objective made use of data obtained from public policies which had undergone rigorous validation processes including public scrutiny and legal review. For example, RDM processes that formed bases for reflecting on WEFE nexus application in water resources protection practice are legal documents that had been legally vetted through legal processes before they became an accepted regulation by the public.

Objective 3: In order to ensure reliability of the research findings on the third objective, archived historic data from secondary data sources were obtained from audited national databases, and such use of archived data increased reliability. Van Rensburg et al. (2013) argued that use of secondary data increases reliability as data to be analyzed concerns confirmed past events. Furthermore, the two case studies used for the purpose of validation the citizen science framework were sourced from reported case studies on citizen science projects, and such case studies had already undergone scientific review and approval for publication, thus their reliability.

4.5.3 Evidence on validity of the collected data

Haradhan (2017) argued that a research study can be reliable but invalid, and this is an indication of the importance of validity consideration in a research study when findings are reported. This section gives an account of how research validity was assessed, and furthermore, describes evidence that is relevant to assessment of validity for each study objective in the present study. Validity determines whether the research truly investigated what was intended to be investigated and to what extent that the findings are accurate and useful (Golafshani, 2003). A similar definition is given by Haradhan (2017) as "validity of research is an extent at which requirements of scientific research methods have been followed during the process of generating research findings". Creswell (2014) argued that validity is one of the strengths of qualitative research and is based on determining whether the findings are accurate from the standpoint of the researcher or the reader. Research validity comes into two forms (Creswell, 2014), namely: 1) Internal (credibility) which is attributed to the way in which data collection or analysis was performed (Johnson et al., 2019; Handa et al., 2020), 2) External (transferability) which indicates whether the study findings could be transferrable to other settings. To ensure internal validity, a researcher applies appropriate approaches such as peer review and triangulation (Creswell, 2014). External validity can be assured by using a detailed account to support replication of the study to different settings (Haradhan, 2017).

Objective 1: In order to ensure credibility of the results findings, the investigation followed a concurrent mixed methods design, where different data collection methods (methods triangulation) were used (internal validity). Triangulation strengthens a research study and is an important approach to establish valid propositions and to control bias (Golafshani, 2003). Interpretation and reporting of the investigation's findings were based on the convergence of the results from different methods (qualitative and quantitative) which led to greater validity. For example, quantitative methods were used to analyses data on the number of RDM studies undertaken per catchment. The outcomes of the analysis were converted and presented in percentage terms. Qualitative methods were used to establish whether there are any RDM studies undertaken in the country and to ascertain location where such studies have been undertaken. Data analyzed were presented in graphical forms where maps were created to indicate catchment where FRDM studies have been completed, in progress, and those that were yet to be undertaken.

Objective 2: Credibility of research findings obtained by reflecting on the aspect of WEFE Nexus in water resource protection was informed by sources of data utilized and methodology applied for undertaking reflection. Data were collected by undertaking literature review on WEFE Nexus from peer reviewed journal articled through well-known research databases such as science direct.

Furthermore, the investigation made use of well-known and utilized reflective practice models such has Gibbs Reflective Cycle Model to reflect on the role of WEFE Nexus in water resource protection practice. The afore-mentioned examples depict internal validity.

Objective 3: One of the important aspects of model development is piloting and optimization before full deployment. In the present study the citizen science framework was validated and verified using three case studies in three different water management areas such as Msunduzi and uMngeni River Catchments in the Pongola to Mtamvuna, Tsitsa River catchment in the Mzimvubu to Tsitsikamma, and the Schoonspruit-Koekemoerspruit River Catchment in the Vaal. Such validation established whether the novel framework could be replicated in real-time at catchment level and be used as a tool for full implantation of RDM practice at localized scale (External validity).

4.6 Research integrity

Research integrity strengthens reliability and trust on the methods used and research findings of a research study, and such reliability and trust could be achieved by meeting professional standards expected out of researchers such as acting with sincerity and striving for consistency of thought and action (Gajjar, 2013; Satalkar and Shaw, 2019). This section reflects on the integrity of the present study by describing theoretical requirements on research integrity, application of the principles of the research integrity, and operationalization of responsibilities on ethical conduct of research as they relate to the current study.

4.6.1 Theoretical requirements on research integrity

Aspects of research integrity can be understood as that which is morally justifiable and represents certain standards according to which research community regulates its behaviour (van Rensburg et al., 2013). For example, the South African Human Sciences Research Council (HSRC) Code of Research Ethics of 2020 stipulates four ethical principles as bases for undertaking a research study, namely: 1) respect and protection, 2) transparency, 3) scientific and academic professionalism, and 4) accountability. The principle of scientific and academic professionalism read with the University of the Western Cape (Academic Institution where the current study is registered) approved Policy on Research Integrity (UWC, 2014) was applied. In pursued to achieve the highest possible level of scientific quality in research in accordance with the professional code of the UWC (2014), the present study discusses integrity maintenance as it relates to different stages of the research process and is discussed y reflecting on operationalizing responsibilities on ethical conduct of research.

4.6.2 Application of the principles of the research integrity

In reflecting on the principles of research integrity that were applied in the present study, technical and legal aspects of the research are considered.

In terms of technical aspects of the present research study, research integrity was ensured by consideration of validity and reliability of the research findings as discussed in section 4.5. The terminology used in all three study objectives is clear, simple, and unambiguous as per expected standard academic practice (Godsal, 2006). It was ensured that sources of data from which the information used, was acknowledged accordingly to avoid plagiarism. Furthermore, it was ensured that reported findings are accurate, realistic, and supported by the collected data. This was applied throughout for the three study objectives. Legal aspect of a research study may relate to the administrative consequences that could result from a breach of an ethical responsibility in research (Loue, 2002). In order to ensure integrity maintenance for the present study, the reported research findings were not fabricated, forged, trimmed, or changed to avoid fraudulent findings. Lastly, the study used publicly accessible data from open sources and in cases where unpublished data was use, contributors to such data were acknowledged to respect for intellectual property.

4.6.3 Operationalizing responsibilities on ethical conduct of research

In terms of the first objective of the study, the investigation intends to uncover the most practically and efficient way of using science-policy nexus in policy practice towards water resource protection which is fundamental to human wellbeing. It is believed that the choice of the research objective is applicable, it was formulated in an unbiased manner, data was accessible, and the research objective does merit the scientific research. The methods selected for data collection and analysis as discussed in section 4.4 were appropriate for the intended purpose. This was ensured by using more than one method (triangulation). For example, literature review and case study were used as two methods for data collection.

The study intended to establish the application of reflective policy models to assess operation of water-energy-food-environment nexus approach in water resource protection practices. The choice of the objective was appropriate as it relates to water resources protection linked with the achievement of the SDGs by 2030. The investigation aspired uncover how the concept of WEFE nexus is applied when studies on resource directed measures towards water resource protection are undertaken. Although the second objective was important and formulated in an unbiased manner, however, it was susceptible to organisational constrains in terms of data content. Therefore, to ensure that such constrains do not prevail, research data on the procedures followed for undertaking resource directed measures studies were abstracted from publicly accessible Regulation on water resource classification system (Regulation 810 of 2010). In terms of data treatment, a widely used model of reflective practice (Gibb's Reflective Cycle Model) was applied on data collected to avoid subjective data analysis and biased interpretation.

In terms of the third objective, the study sought to demonstrate the validation and verification of a process based operational plan for catchment orientated resource directed measures. This objective completed the overall research study where it linked the first and second objectives. The study objective was formulated in an unbiased manner after consideration of data accessibility. The choice of using the principles of socio-ecological model in guiding the development of the citizen science framework as RDM operationalization plan was appropriate suitable for the purpose of the investigation.

4.7 Study limitations

Firstly, resource directed measures studies treats groundwater as surface water resources in terms of protection. Furthermore, RDMs such as RQOs requires that four components of water resources (quantity; quality; vegetation; biota) must be considered for water resources protection. However, very limited studies have been reported and published on the subject theme. Such situation poses limitation in terms of providing detailed baseline knowledge gap and appropriate policy interventions. However, the approach followed in the present study facilitated consideration of both groundwater and surface water in terms of quantity and quality components in addition to the biota component which was provided by the reported two citizen science case studies.

Secondly, to evaluate RDM practice at catchment level, compliance assessment with established RQOs requires data collected over a longer period, at least over a period of five years. For example, RQOs linked to groundwater involves maintaining established levels of groundwater table at certain level to ensure groundwater availability and sustainable use within a catchment. However, changes in groundwater levels and quality takes time to manifest, and therefore data which spans over a long period of time were required to validate and verify feasibility of the citizen science framework as RDM operationalization plan at localized scale. Limited availability of time and financial resources for the study had limitations on the framework validation aspects. Nonetheless, the approach followed in the present study enabled use of historic data that provided similar outcomes as when real-time data had been used.

Thirdly, the present study followed a qualitative case study approach which enabled capturing of information in a more explanatory mode. However, such explanation and results emanating from the study may not be the same should the same approach be applied elsewhere in catchments that differ in settings and conditions. However, the research design followed in the study enabled use of multiple case studies from different catchments with varying conditions, which provided broad perspective and insight about the feasibility of the citizen science framework.

Chapter 5: Results and discussion

5.1 Introduction

Chapter 4 has explained the research design and research methods that were used to collect and analyse data for the present study. The current chapter 5, presents and discusses results on: objective 1 which assessed the application of science-policy nexus in policy formulation and practice towards water resource protection; objective 2 which established the application of reflective practice models in assessing operation of water-energy-food-environment nexus approach in water resource protection practices; and objective 3 which demonstrated the validation and verification of a process based operational plan for catchment orientated resource directed measures. The chapter pronounces the feasibility of the developed citizen science framework as a plan for improving operationalization of RDM at catchment level using case studies. This chapter 5 contends that i) improved knowledge of science-policy nexus forms a basis for understanding the concept of nexus and its application in the field of water resources protection, thus enhancing its utilization in policy implementation practice. ii) better understanding of the critical synergies and conflicts among the WEFE components and their influence on water resource protection practices improves utilization of the WEFE nexus concept in policy practice in order to fast-track achievement of SDGs. Such practice requires capacity building for policy implementers and institutionalization of local and regional knowledge to sustain and share best practices on the WEFE Nexus. iii) The process of validation and verification is fundamental in the development of the citizen science framework to ensure that the developed operational plan for catchment orientated resource directed measures facilitates the improvement of RDM practice at catchment level.

5.2 Description of main data

To present the main data generated and findings of the present study, key results obtained for each of the study objectives are considered for description.

5.2.1 Results on application of science-policy nexus in policy formulation and practice

In description of the data obtained from objective 1, science-policy nexus theoretical models existing in practice are presented. Furthermore, existing policies and scientific studies undertaken for water resources protection within South Africa are presented as a case study for demonstrating practical application of the nexus in practice. The three types of science-policy nexus theoretical models existing in practice are presented in Table 5.1., namely, i) Science-Policy Integration, ii) Policy-Science Integration, and iii) Mixed Integration. Each of the nexus models has both advantages and limitations. The three nexus models are applicable in practice where scientists engage policy makers. However, their choice of application depends on the type of anticipated engagements between policy makers and scientists, and desired outcomes of such engagements.

Table 5.1: Three existing types of science-policy nexus identified in literature

Policy / Regulation	Nature of Engagement
Science-Policy Integration (SPI)	• Provides rationale and evidence-based solutions • Independence from political influence
Policy-Science Integration (PSI)	• May provide policy relevant solutions • Allows incorporation of public opinions
Mixed Integration (MI)	• Policy relevant problems are investigated • Scientific research products are translated into readily and understandable formats by public and policy makers • Science research products are easily taken up for implementation thus improving effectiveness and efficiency of government interventions

The analysis from the collected data indicates that required policies and legislations for water resources protection are available in South Africa. Table 5.2 provides key policy documents identified through document review processes as drivers of water resources protection practice in the country. Such policy documents, strategies, and plans facilitate policy implementation towards protection of the country's scarce natural water resources as per the legislative requirements.

Table 5.2: Illustration of key policy documents on water resources protection in South Africa

Policy / Regulation	Document Type	Year of Promulgation
White paper on water policy of 1997 (NWP, 1997)	Policy	1997
National Water Act (Act 36 of 1998), (NWA, 1998)	Legislation	1998
National Water Resource Strategy of 2004 (NWRS, 2004)	Strategy	2004
National Water Resource Strategy of 2013 (NWRS, 2013)	Strategy	2013
National Groundwater Strategy, 1st Edition (NGS, 2010)	Strategy	2010
National Groundwater Strategy, 2nd Edition (NGS, 2016)	Strategy	2016
National Regulation Number 810 of 2010	Regulation	2010
National Water and Sanitation Master Plan (NW&SMP, 2018)	Plan	2018

In order to ensure that policy implementation for water resources protection is practically realised, several RDM studies have been undertaken in the country and some are currently underway at least at the time when data collection for writing this thesis was undertaken in September 2019, as indicated in Table 5.3.

Table 5.3: Summary of RDM studies undertaken at national level presented in percentage terms (September 2019)

Status	Water Resource Classification	Reserve Determination	Resource Quality Objectives	RDM Studies (National Level)
Completed	58% (11 of 19)	36% (7 of 19)	58% (11 of 19)	51%
In progress	26% (5 of 19)	32% (6 of 19)	26% (5 of 19)	28%
Not yet done	16% (3 of 19)	32% (6 of 19)	16% (3 of 19)	21%

To demonstrate practical application of Science-Policy Nexus in policy implementation towards water resources protection, the case of South Africa where RDMs are used as scientific studies to implement policies is presented and illustrated in Figure 5.1. The illustrations on Figure 5.1 depict processes followed when abstracts from legal documents are translated into science, and science outcomes converted back to legal abstracts. Such illustration is key towards understanding how South Africa uses science to develop evidence-based abstracts of policies and how policy drives undertaking of science studies for water resources protection.

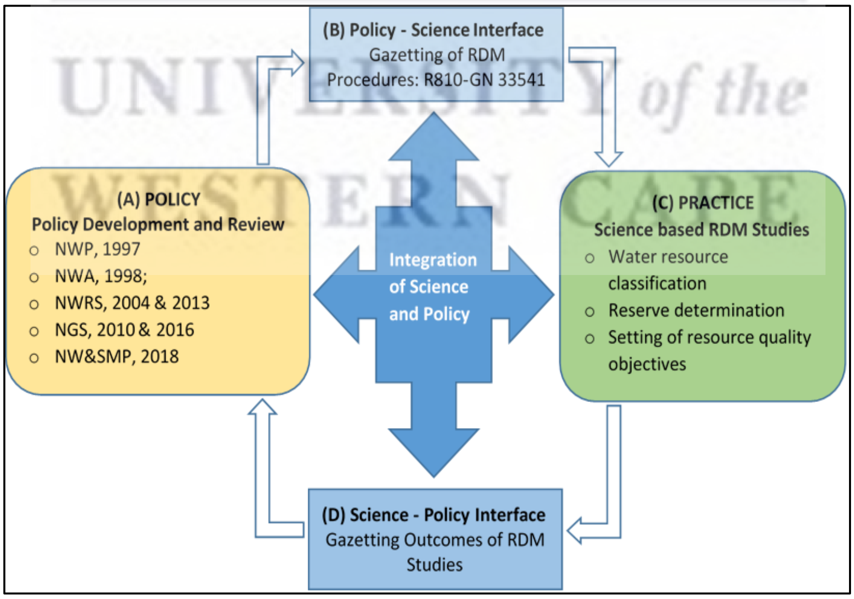

Figure 5.1: Illustration of practical application of Science-Policy Nexus in water resources protection in South Africa (Author's construct)

5.2.2 Results on application of reflective practice models

This section describes data generated from the second objective of the present study. Data obtained on existing WEFE nexus synergies and conflicts, application of the WEFE nexus in RDM processes, and role of capacity development in sustaining WEFE nexus application in water resources protection practices are presented. Six different types of WEFE nexus synergies and conflicts were identified by the study (Table 5.4). Three types of nexuses are recognized from such synergies and conflicts, namely, 1) nexus between water and energy sectors, 2) nexus between water and food sectors, and 3) nexus between water and ecosystems/environment sectors. In the context of the present study, six types of WEFE nexus integrations are most relevant for water resources protection as indicated in Table 5.4. These are: 1) water-energy interaction, 2) water-food interaction, 3) water-environment interaction, 4) energy-water interaction, 5) food-water interaction, 6) environment-water interaction. These interactions are also known as nexus.

Table 5.4: WEFE Nexus interactions relevant to water resources protection

WEFE Integration Number	Type of Interaction	Nature of Interaction
[1]	Water-Energy Interaction	Water influences energy security
[2]	Water-Food Interaction	Water influences food security
[3]	Water-Environment Interaction	Water influences environmental security
[4]	Energy-Water Interaction	Energy influences water security
[5]	Food-Water Interaction	Food influences water security
[6]	Environment-Water Interaction	Environment influences water security

When the aspect of WEFE Nexus was assessed for consideration in water resources protection practices, it was found that the nexus is well incorporated in RDM processes. Such consideration is evident when water resource classification, water resource reserve determination, and resource quality objectives procedures are examined (Table 5.5). The WEFE Nexus aspects are considered in steps 2 and 3 of the water resource classification procedure, step 4 of the water resource reserve determination procedure, and step 3 of the resource quality objectives determination procedure.

Table 5.5: Aspects of WEFE Nexus in resource directed measures processes

WEFE COMPONENTS	RDM CONTEXT		
	Water Resource Classification	**Reserve Determination**	**Resource Quality Objectives**
Water	Step 2 of the water resource classification procedure	Step 4 of the reserve procedure	Step 3 of the resource quality objectives procedure
Energy	Step 2 of the water resource classification procedure	-	Step 3 of the resource quality objectives procedure
Food	Step 2 and 3 of the water resource classification procedure	-	Step 3 of the resource quality objectives procedure
Environment	Step 2 and 3 of the water resource classification procedure	Step 4 of the reserve procedure	Step 3 of the resource quality objectives procedure

5.2.3 Results on validation and verification of a process based operational plan

This section describes results obtained when the Citizen Science Framework (CSF) which facilitates participation of citizens in local water resource protection activities and its suitability for catchment orientated resource directed measures (RDMs) was investigated and validated using case studies. The framework is presented in Figure 5.2.

The findings of the study revealed that the CSF incorporates nexus approach characterised by science, policy, and citizen centrism which tend to facilitate participation of citizens in local water resources protection activities. Furthermore, the results indicate that in cases where policy implementation follows a top-down approach, local citizens can be empowered to act collectively in implementing water resources protection policies from the bottom-up approach. The CSF was found to be supportive of concurrent operation for both top-down and bottom-up approaches in policy implementation, which necessitates improvement on RDMs up-take at catchment level. The suitability and flexibility of the CSF for guiding operationalization of RDMs at catchment level enabled use of the framework for compliance assessment with established RDM numerical limits.

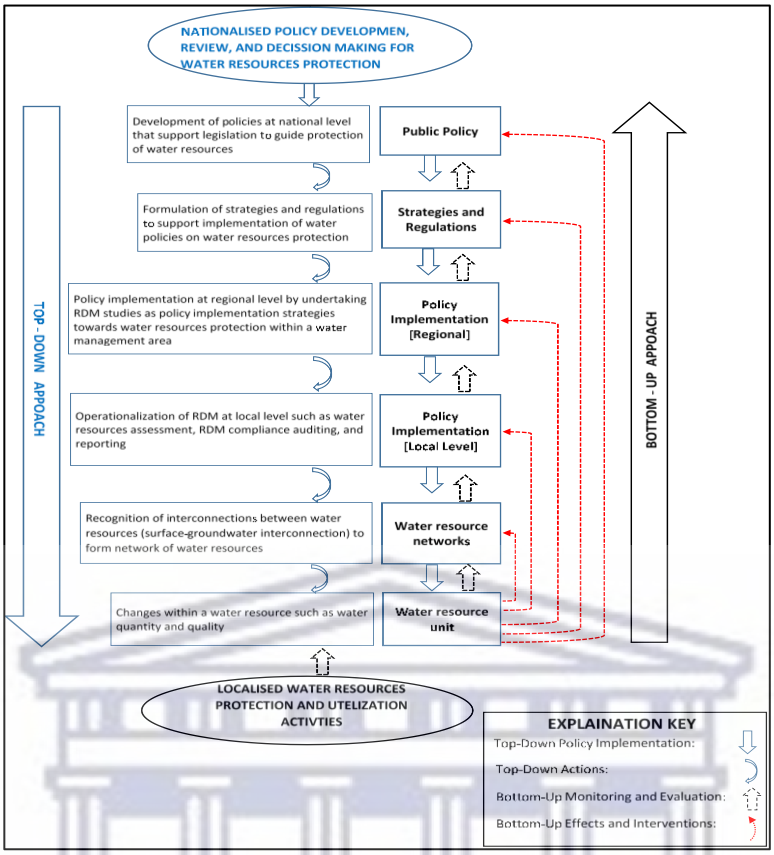

Figure 5.2: Citizen Science Framework for implementation of resource directed measures at catchment level.

5.3 Computational analysis [Data analysis/statistical analysis]

This section provides analyses that were applied in assessing data obtained for studying the three study objectives. Therefore, data analysis is presented systematically per study objective.

5.3.1 Descriptive and analytical analysis on science-policy nexus in policy formulation and practice

To ensure that the first objective is achieved, a combination of three approaches was used. The first approach involves literature review on science-policy nexus theoretical models that exist in practice (Table 5.1), and the second approach was an in-depth analysis of policies and strategies devoted to water resources protection practices in South Africa (Table 5.2), including number of RDMs studies undertaken in the country. The Microsoft Excel spread sheet (Microsoft Excel 2013) was utilized for descriptive statistical analysis of water resource classification, reserve determination, and resource quality objectives to produce a table which contain number of studies completed, in progress, and studies that are yet to be commissioned (Table 5.3), and descriptive statistics were applied to spatially show areas (using maps) where such studies have been undertaken (Figure 5.4a-c). The third approach involved presentation of the case study based on the South Africa context to demonstrate practical application of science-policy nexus in policy implementation towards water resources protection.

The case study involved analysis of the processes followed where abstracts of legislation and related national policies are converted to science (policy-science integration), and outcomes of science studies are converted back to legal abstracts (science-policy integration) (Figure 5.1).

5.3.2 Descriptive and analytical analysis on application of reflective practice models

An inductive approach to describe and understand WEFE nexus application in water resources protection practice was adopted in the present study. Although synergies and conflicts among the WEFE nexus components were not quantified, however, the approach followed by the current study, qualitatively provided insight on the interactions between nexus components. In this section, methods of literature surveys, content analysis, and reflective practice were used. Literature surveys were used to identify types of interaction among WEFE nexus components which are deemed crucial in water resources protection practice. Content analysis allowed the study to scrutinize processes and procedures followed when RDM studies are undertaken. Applying content analysis on unstructured data collected on RDM processes and procedures provided insight on the consideration of WEFE nexus in RDM studies towards water resources protection. The Gibbs reflective practice model was applied to assess and describe role played by Public-Private Partnership in capacity development activities to sustain WEFE nexus application in water resources protection practice.

5.3.3 Descriptive and analytical analysis on validation and verification of a process based operational plan

To fulfil the third objective of the study, various methods for the purpose of data analysis were applied. Document records review and framework analysis (Dixon-Woods, 2011) methods were applied to publicly available information, scientific papers, books, and reports on water resources protection policy implementation activities. Framework analysis methods enabled identification and configuration of framework themes for CSF development. The framework analysis method is an excellent tool for supporting thematic analysis because of its ability to explicitly apply the principle of undertaking qualitative analysis to a series of interconnected stages (Pietersen et al., 2016). Data were categorized into six themes, namely 1) public policy level, 2) strategies and regulation level, 3) regional policy implementation level, 4) local policy implementation level, 5) water resources network level, and 6) single water resource, which were then configured into different levels of SEM core systems. The aspect of citizen science was then in-cooperated into the configuration of the identified themes to complete the CSF design. Content analysis methods were applied to the two selected case studies of reported citizen science projects to validate the CSF. Furthermore, descriptive statistics were applied to the collected quantitative data to validate the framework on compliance assessment with established RDM numerical limits. Flow Duration Curve (FDC) (Dlamini et al., 2019) and time series analysis techniques were applied on the collected stream flow, and water quality data to assess compliance with established RQOs numerical limits linked to surface water quantity and quality, respectively.

Recession rate for groundwater level, and time series analysis were used to assess compliance with established RQOs numerical limits linked to groundwater quantity and quality.

5.4 Interpretation of results/Discussion of results

This section discusses results presented in section 5.2. The results are discussed in detail per study objective to establish and interpret their meaning.

5.4.1 Interpretation of results on science-policy nexus in policy formulation and practice

This section addresses the first objective of the present study which was to assess the application of science-policy nexus in policy formulation and practice towards water resource protection. The study assumed that improved knowledge and understanding of how the nexus work, would facilitate collaborations between researchers (private sector) and policy makers (public sector) to ensure that researchers are answering policy-relevant questions and results from scientific work are readily available for policy development and implementation towards water resources protection. To fulfil the first objective of the current study, three questions were answered: i) what is understood by science-policy nexus, and how is the concept contextualized in practice? ii) What is the role of science-policy nexus in water resources protection? iii) Using an example of a practical case study, how policy-science and science-policy interfaces can be operationalized efficiently and effectively, particularly in developing countries? The types of science-policy nexus theoretical models, South African policies and scientific studies for water resources protection, and evidence of practical science-policy nexus application in policy practice in the South African context are considered for description of the main data generated for the first study objective. From data generated, Science-Policy Integration (SPI), Policy-Science Integration (PSI), and Mixed Integration (MI) are recognised as three types of science-policy nexus integration models applied in practice (Table 5.1).

Science-Policy Integration (SPI):

Science-Policy interactions are characterised by science driven interaction where science become dominant in the engagement with policy. In this type of interaction, researchers and information providers set the agenda for producing information which is independent of political influence, and it provides rationale evidence-based solutions. However, limitation associated with this kind of engagement is that solutions obtained may not necessarily address policy relevant problems. Furthermore, such model of engagement has been criticized for suffering from selective production of knowledge for decision making which can be regarded as manipulation (Dunn et al., 2018).

Policy-Science Integration (PSI):

In Policy-Science interactions, engagements are primarily driven by policy, where policy becomes issues takes centre stage.

Such engagements are critical in discussing policy issues requiring relevant policy resolutions from science. However, the problem with this king of engagement is its vulnerability to political manipulation to drive a specific agenda and pre-existing interests which may not necessarily be about addressing social problems (Tieberghien, 2014).

Mixed Integration (MI):

Mixed Integration is characterised by partnerships in which the research agenda is an ongoing highly interactive process with equally, and mutually shared engagements between science and policy. In such engagements, policy relevant problems are presented, and science allowed to investigate evidence-based solutions relevant to the problem. In this king of interaction, no party becomes dominant, as the engagements are only about finding best solution to existing policy relevant problems. It has been argued that communication between science and policy domains is most effective when it flows in both directions (Akhtar-Schuster et al., 2016). Such hypothesis has been supported by Hughes et al. (2018) who argue that the nexus two-way interaction enables better communication of policy maker's priorities and science related measures (policy-science integration) and better communication of science research products in advancing policy interventions (science-policy integration). The discussion provided on the three types of science-policy nexus theoretical models, answers the first question linked to the understanding and contextualization of the science-policy nexus in practice. In answering the second question linked to the understanding of science-policy nexus role in water resources protection, the context of South African water resources protection practices is discussed.

A comprehensive list of key legislations, policies, strategies, regulations, and plans for different sectors essentially linked and used in water resources protection practices as per legislative requirements are presented in Annexure 5.1. However, policies, strategies, and regulations relevant to the context of the current study are presented in Table 5.2. The White paper on water policy was developed in 1997, and it outlines the direction to be given to the development of water law and water management systems (NWP, 1997). The White Paper forms a foundation for development of other water resource protection policies and legislation. The White Paper outlines the direction to be given to the development of water law and water management systems. Its objective is to set out the policy of the government for the management of both quality and quantity of the country's scarce water resources. Principles of equity, efficiency, and sustainability are laid in the White paper (1997) upon which the NWA (1998) is founded. The purpose of the NWA (1998) is to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways which take into account amongst other factors: promoting equitable access to water; redressing the results of past racial and gender discrimination; promoting the efficient, sustainable and beneficial use of water in the public interest; facilitating social and economic development; protecting aquatic and associated ecosystems and their biological diversity and ; meeting international obligations (NWA, 1998).

Chapter 3 of the NWA prescribes resource directed measures such as water resource classification, reserve determination, and setting of resource quality objectives as water resource protection strategies all water resources, which includes a water course, estuary, surface water and groundwater (NWA, 1998).

The National Water Resource Strategies (NWRS) set out how water is protected, used, developed, conserved, managed, and controlled sustainably and equitably. The first NWRS (NWRS, 2004) recognizes resource directed measures as the approach adopted to protect water resources as per the NWA (1998), while the aspect of water resources protection is also outlined in chapter 5 of the second NWRS (NWRS, 2013).The National Groundwater Strategies (NGS, 2010 and NGS, 2016) were developed to ensure that legislation such as the NWA is implemented successfully, especially when the aspect of groundwater is considered in terms of resource protection and sustainable utilisation. The objective of the National Water and Sanitation Master Plan (NW&SMP) is to provide an overall perspective of the situation in the water and sanitation sector and a consolidated plan of actions, to improve the current situation to meet the desired future state of the sector, defined by Government's vision, goals and targets until 2030 such as the NDP and SDG's targets (NW&SMP, 2018). The National Regulation Number 810 was promulgated in 2010, and it provides for a national water resource classification system (NWRCS), as laid down by the NWA. The Regulation is intended to ensure the ecological sustainability of all the significant water resources by taking into consideration the social and economic needs of competing interests by all who rely on the water resources (DWA, 2010). The Regulation, outlines definitions, procedure for determining different classes of water resources, procedure for determining the reserve, and procedure for determining resource quality objectives. In terms of classification of significant water resource, the Regulation is used to classify water resources into Class I, Class II, Class III, depending on the extent of use of the water resource, by following the 7-step procedure outlined in the Regulation 810. In terms of water resource reserve determination, the reserve is determined for each water resource class by following the 8-step procedure outlined in the Regulation 810. Resource quality objectives are determined for each water resource class by following the 7-step procedure also outlined in the Regulation 810.

The outcomes derived by undertaking water resource reserve studies are ecological conditions, estimates of ecological water required to sustain ecological ecosystems, and minimum water requirements to satisfy for basic human needs Outcomes of resource quality objectives studies are numerical limits and narrative statements used for the management and assessment of water resources to ensure that desired states of such water resources are achieved. Figure. 5.3 illustrates how water resources protection policies and RDM studies are fused together for policy implementation towards water resources protection.

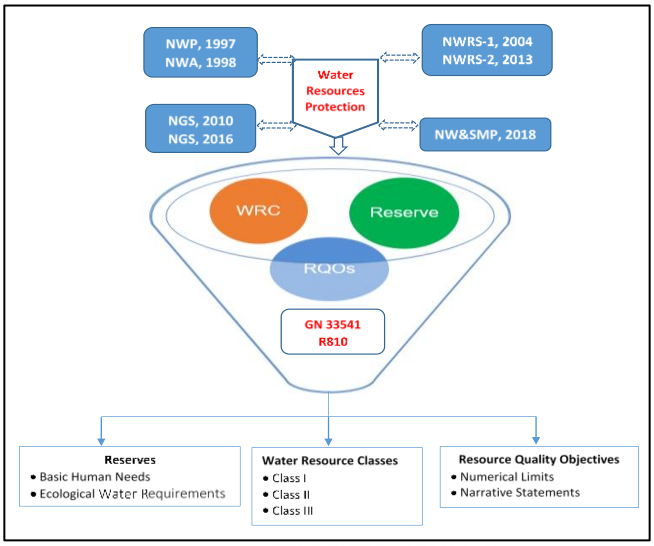

Figure 5.3: Merging of water resources protection policies and RDM studies in water resources protection practice (Author's construct)

In order to showcase how policy-science and science-policy interfaces can be operationalized efficiently and effectively, particularly in developing countries, a practical case study of South Africa is discussed. The discussion is linked to the third question linked to the first study objective.

As shown in Table 5.3, the results indicates that 58% of the water management areas have water resources classification studies completed, 26% in progress, and only 16% of the water management areas have water resources classification studies that are not yet commissioned (Figure 5.4a). In terms of water resource reserve studies, such studies have been completed in 36% of the areas, while 32% of the areas have the reserve studies in progress, and 32% of the areas have studies not yet undertaken (Figure 5.4b). Resource quality objectives studies have been completed in 58% of the catchment areas, with 26% for studies in progress, and the studies have not yet been undertaken in 16% of the catchments (Figure 5.4c). At national level, 51% of the country have RDM studies completed, 28% in progress, and 21% still required RDM studies to be commissioned. The analysis indicates that RDM studies as policy implementation strategies for water resources protection cannot at the same time in all catchment areas, but instead are undertaken in a progressive mode. The indications are that only about 20% of the areas where RDM studies are not yet commissioned.

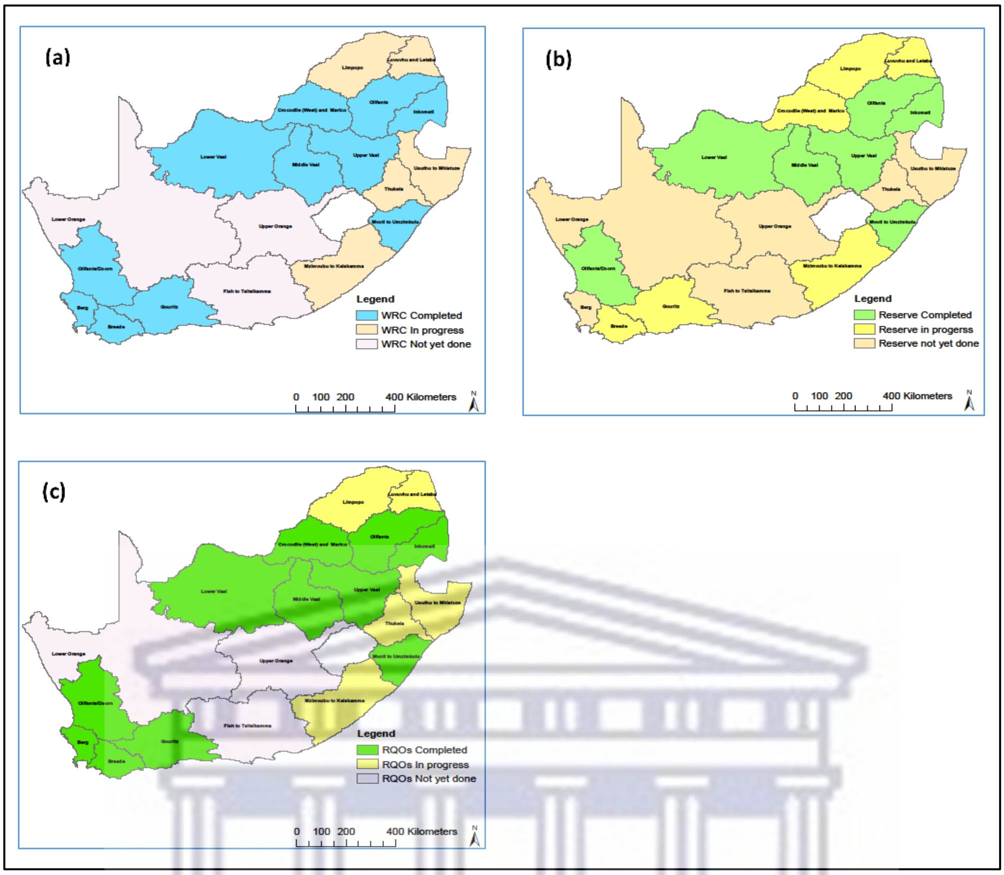

Figure 5.4a-c: Maps showing areas where RDM studies have been completed, in progress, and not yet undertaken (a) water resource classification, (b) resource quality objectives, and (c) water resource reserve.

In order to examine the science-policy nexus theoretical model depicted in RDM studies, a conceptual model is provided in Figure 5.1. The model gives an explanation and illustration of how policy is converted to science, and science converted back to policy using outcomes of RDM studies as scientific products. The consortium of policy documents (Table 5.2) is fundamentally linked to water resources protection practice in the country. They form part of the public policy development and review phase, indicated as *"A"*. These legal documents consider RDMs as tool for policy implementing (practice) for water resources protection. Policy practice is ensured by undertaking RDM studies (as per policy requirement) which are scientific in nature indicated as *"C"*. These studies include determination of water resource classes, determination of the reserve and setting of resource quality objectives. However, there is a phase of transition from policy development to policy implementation (practice), referred to as "*Policy - Science Interface*" indicated as *"B"*. The Policy - Science Interface transpired when procedures for undertaking RDM studies were legalized in Regulation 810 in the Government notice number 33541 in the year 2010. The outcomes of RDM studies are water resource classes, reserve limits and conditions, and resource quality objectives limits and narrative statements. These outcomes are scientific in nature and are converted back to policy abstracts through a process of gazetting (legalizing) referred to as "*Science-Policy Interface"* indicated as *"D"*.

Therefore, in the South African context application of science-policy nexus in water resources protection practice consists of four phases, namely, 1) policy development and review phase, 2) conversion of legal abstracts into science phase, 3) science studies and research phase, and 4) conversion of science products back into legal abstracts phase. The mode of science-policy interaction observed in the presented case study is mixed integration of science and policy which is bi-directional in nature, where science feeds policy development to curb issues at hand, and policy feeds science for policy implementation.

5.4.2 Interpretation of results on application of reflective practice models

Application of the Water-Energy-Food-Environment (WEFE) Nexus in RDM processes provides sound evidence for the role played by WEFE nexus in water resources protection practices. Highlighting such evidence encourages multi-sectorial policy implementation practice to fast-track achievements of SDGs by 2030. This section of the thesis discusses evidence that application of WEFE nexus approach in RDM studies facilitates multi-sectorial water resources protection practices which offer integrated solutions for socioeconomic and environmental-related challenges. Such evidence is provided and discussed by answering the three questions, i) which WEFE nexus integrations are the most relevant to water resources protection practice? ii) what is the role of WEFE nexus in RDM studies? and iii) what is the role of Public-Private Partnership (P-PP) in WEFE nexus sustainability towards water resources protection?

In answering the first question, twelve existing types of interactions within the four components of WEFE nexus sectors are provided in Annexure 5.2. However, only six are most relevant to water resources protection in the context of the current study (Table 5.3). The four WEFE components are defined differently, depending on the context in which they are investigated. In the context of the current study, the water component is defined in terms of its water uses, energy component is defined in terms of energy sources, food is defined in terms of food production, and environment is defined in terms of life on land, life in water and atmosphere (Annexure 5.3). The identified interactions linked to water resources protection were consolidated, mapped, and presented in a simplified form for easy of understanding and explanations (Figure 5.5).

Nexus between water and energy sectors:

Water and energy are fundamentally interlinked, and therefore, understanding of how water and energy sectors interact with each other is vital for economic development and life sustainability. For example, large volumes of water are needed for electricity generation through hydro-power and for cooling purposes in coal fired power generation, while water abstraction, water treatment, and distribution use electricity (Hamiche et al., 2016). Globally, energy demands are expected to have grown by 40% from 2010 towards 2035, globally (Dai et al., 2018).

In South Africa, the total energy demand forecast is expected to increase in the fold of 2.0% by 2030 and 1.66% by 2050 as predicted from the year 2018 (DE, 2019). While energy security is important for economic development and life sustainability, however its production may have undesirable consequences on the receiving environment, such water pollution. This suggests that any approach that pursues to develop and manage either water or energy sector independent of the other is not appropriate and is likely to fail. Dai et al. (2018) argued resource management approaches such as water conservation tend to reduce the amount of energy spent on water treatment and distribution, while energy serving practices to transport, heat and treat water can lower pressure on water resources, as the water required to produce the energy can either be saved or re-allocated for other uses. Therefore, understanding of the links between water and energy has a potential to assist policy makers and resource managers in water and energy conservation and sustainability, thereby contributing towards sustainable development and meeting the set targets linked to sustainable development goal 6 and 7.

Nexus between water and food sectors:

Availability of water for domestic water use and other water uses sustains life and other essential uses such as crop irrigation, food processing and distribution. On the other hand, type of food production determines the amount of water required for crop irrigation. Energy consumption is estimated at about 30 percent of total global energy used for various purposes such as food production, transport, and distribution (FAO, 2014). However, such figures could change to the worst due to high demand for food production because of industrialization and eve increasing global population. For example, the world's population is expected to reach 9.7 billion in 2050 which may result in the shortage of resources (Amorim et al., 2018). On the other hand, demand on energy availability would require alternative sources of energy production to sustain energy sustainability. Alternative sources of energy production such as biofuels have been used as alternative sources of energy (Benites-Lazaro et al., 2020). However, Benites-Lazaro et al, 2020 argue that utilization of agricultural products for energy production, may put more pressure and risk on food security due to limited water that maybe available for crop production. Therefore, understanding of water-food nexus and its application in policy implementation practices is important for energy and food security.

Nexus between water and ecosystems/environment sectors:

Interactions between water and environment may not always be clearly understood unless it is adequately articulated in terms of the context in which it is explored. For example, one can argue that water forms part of the environment and cannot be treated as a separate resource. In the context of the present investigation, water and the environment are discussed in terms of their sub-components and their respective variables (Annexure 5.3). Availability of sufficient water of required quality is important to sustain terrestrial and aquatic ecosystem, while weather conditions such as rainfall patterns influence availability of water.

Furthermore, geological structures form different types of aquifers systems which influences the nature of water in terms of quantity and quality. Furthermore, poor water quality may negatively affect aquatic life which provides ecosystem services such as food. All the factors described give an account of nature of interaction which occurs between water and the environment/ecosystems.Therefore, analysis of nexus between water, energy, food, and environment to understand their interconnections is important for current and future generations (Amorim et al., 2018; Momblanch et al., 2019).

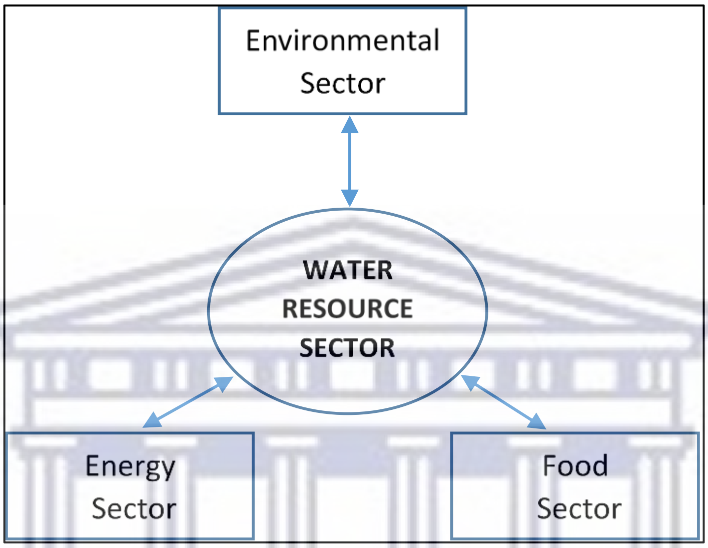

Figure 5.5: Illustration of the WEFE Nexus interactions relevant to water resources protection practice (Adapted and modified from Momblanch et al., 2019)

In answering the second question linked to objective 2 of the present study, the 7-step procedure followed for determining water resource classification (Annexure 5.4), the 8-step procedure for determining water resource reserve (Annexure 5.5), and the 7-step procedure for determining resource quality objectives (Annexure 5.6) are considered for discussion. Key steps of the water resources classification, water resource reserve determination, and resource quality objectives determination procedures (Table 5.4) are discussed for facilitating application of the WEFE nexus in RDM studies. The analysis of data collected shows that the aspect of WEFE Nexus well considered in RDM studies.

Step 2 of the water resource classification: Linking the socio-economic and ecological value and condition of the water resources

The main objective of this second step of the water resource classification procedure is to establish a set of qualitative relationships that specify how different levels of water resource use, ecosystem condition, and ecosystem goods and services affect economic value and social wellbeing (Dollar et al., 2010; DWA, 2012d). A water resource classification study undertaken by the then Department of Water Affairs (DWA, 2011a) within the Olifants Water Management Area, established that from a total of eleven (11) ESKOM's coal-fired power stations, eight of these stations are found in the Olifants.

These stations produce approximately, 70% of South Africa's electricity (DWA, 2011a). Therefore, an integrated units of analysis 1 (IUA-1) for water resource management within the Olifants catchment was identified as a home to many thermal power generators which provide a large proportion of South Africa's energy requirements, and such area was considered as a priority area for strategic water use linked to energy production. The area required management such that water availability for strategic energy production is sustained while ensuring that water resources in the area are minimally impacted by ash waste from energy production processes *(water-energy nexus).*

Step 3 of the water resource classification: Quantifying the ecological water requirements and changes in non-water quality ecosystem goods, services, and attributes

This step pursues to quantify the volume, distribution, and timing of a variety of ecological water requirements alternatives at each of the identified nodes (Dollar *et al*., 2010). This is further followed by describing resultant changes in non-water quality ecological goods and services attributes. The outcome of step 3 is a table of environmental water requirements for each node quantified for at least four levels of ecological integrity. This step is linked to step 4 of water resource reserve determination procedure (King and Brown, 2006; Dollar et al., 2010). The evidence becomes apparent when a study undertaken for water resources classification in the Berg Catchment (DWS, 2017a) is analysed. The study identified eighteen (18) estuary sites, where the volume, distribution, and timing of a variety of ecological water requirements alternatives were quantified, in addition to other sites identified for rivers, groundwater, and wetlands (DWS, 2017a). In this case example, the *water-environment nexus* is portrayed.

Step 3 of the resource quality objectives determination: Prioritization and selection of preliminary resource units for resource quality objectives

Furthermore, step 3 of the RQOs provides for the identification and prioritisation of the ecological ecosystems requiring protection in terms of ecological water requirements and maintenance for low flows in river systems (*water-environment nexus*). For example, a study undertaken by the DWS in the Berg WMA (DWS, 2018) groundwater resources contributing to the maintenance of ecological water requirements for low flows were prioritised for protection. The WEFE Nexus depicted in this case is water for environment interaction linked with sustainable development goal 14 and 15 and 6.6. Furthermore, in another study within the same WMA, the urban and domestic household water use was identified as one of the main water users in the catchment and were prioritised for water management operational scenarios (DWS 2016).

Step 4 water resource reserve determination: Determination of the basic human needs and ecological water requirements for each of the selected sites and, where appropriate, align with step 3 of the water resource classification procedure

As aforementioned earlier, this step is linked with step 3 of the water resource classification procedure where *water-environment nexus* was explained. Therefore, in this paragraph only water-food nexus is explained, and this is evident when water for basic human needs and food production is considered. For example, irrigation, lagoon, and marine inshore fisheries were considered in the water resource classification study undertaken in the Berg WMA as the main water use sectors in the catchment requiring prioritization for water use *(water-food nexus)*. The rationale was that increasing the available irrigation water would allow an increase in irrigation area which would lead to a proportional increase in the scale of production (DWS 2016). Furthermore, step 4 of the water resource reserve determination requires that water for basic human needs be quantified *(water-food nexus)*. This is apparent in the study that was conducted in the Mvoti to uMzimkhulu WMA, where basic human needs reserve assessment was conducted to determine the prescribed minimum quantity and quality of water to remain in the water resource to enable the supply of water, according to Schedule 1 of the National Water Act (NWA), to support households, such as informal households, to support life, personal hygiene and other subsistence use (DWA, 2012c). Hence, it is evident that RDM strategies play a pivotal role in the practice of energy-food nexus linked with sustainable development goal for food security.

The review on RDM strategies indicated that RDM studies completed and those being undertaken appear to offer some advances on WEFE Nexus practice. RDM studies are considered multispectral in nature and require variety of skills specialty ranging from the field of ecology, analytical and numerical modelling, economic sciences, geographic information system, geohydrology, hydrology, and social science. However, sometimes skills in such specialised fields may not be immediately available to public institution, as a result Public-private partnerships (P-PP), has been used to facilitate policy implementation (Arimoro, 2018; Brynard, 2009; Walwyn and Nkolele, 2018). For example, Osei-Kyei and Chan (2016), argued that P-PP is considered as an innovative procurement approach which offers good prospects for policy implementation in global construction industry. P-PP as a result, been used to facilitate undertaking of RDM studies and transfer of skills.

Reflective practice which advocates for critical thinking and integration of theory and practice has been promoted as a method of developing knowledge entrenched within practice (McBrien, 2007; Bass et al., 2017). The Gibbs' Reflective Cycle Model (GRCM) is widely used in reflective practice as an important approach for professional practice (Paterson and Chapman, 2013; Mantzourani et al., 2019). GRCM is structured in a cyclical process consisting of six (6) phases of reflection and action which can be used to identify strong points, areas of development, and required actions to improve on policy implementation and practice (Figure 5.6).

In the present study the GRCM was applied to assess its contribution to capacity development towards WEFE Nexus using structure questions formulated in the context of RDM studies linked to water resources protection (Annexure 5.7).

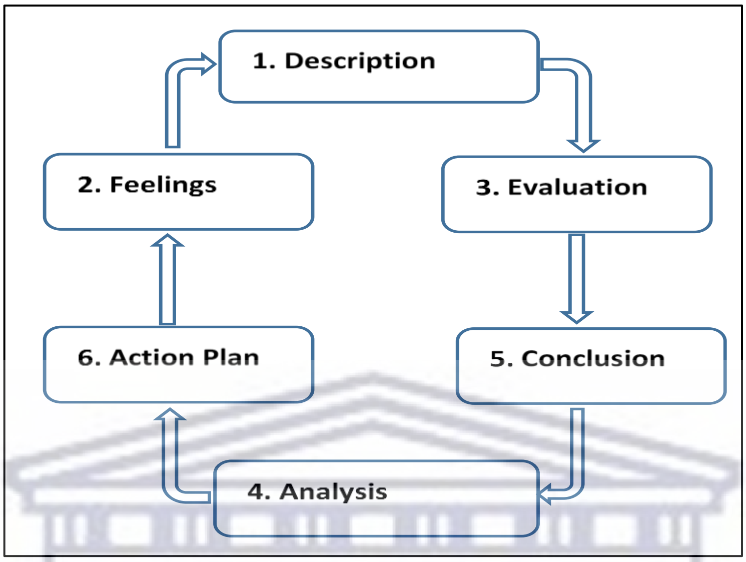

Figure 5.6: Gibbs' (1998) reflective cycle model (Adapted and modified from Paterson and Chapman, 2013)

The reflective model analysis showed that limited knowledge and skills exist between practical policy implementation towards water resources protection and policy implementation process thereby hindering the positive practical intention of WEFE Nexus towards achieving sustainable development and environmental integrity in the water resource protection space. Furthermore, the results from the analysis found that capacity development activities for WEFE nexus sustainability are skewed towards monetary gains rather skills transfer. Lastly, the results indicated that capacity building activities are highly skewed towards water resource and environment sectors only, with limited consideration of the energy, and food sectors the aspect of water only.

5.4.3 Interpretation of results on validation and verification of a process based operational plan

Sustainable water resource availability and utilization call for appropriate policy intervention strategies to be instituted at local scale where water resources are located. However, state resources may often be insufficient to comprehensively cover for both temporal and spatial aspects sufficiently. Therefore, success in policy implementation for water resources protection at local level using RDM strategies requires effective operational plans that seek to integrate policy, science, and citizen centrism where local citizens become part of such water resources protection activities. In this section, a Citizen Science Framework (CSF) which facilitates participation of citizens in local water resource protection activities was investigated, and its suitability for catchment orientated resource directed measures (RDMs) was validated using case studies.

In presenting the findings of the investigation, the aspects of socio-ecological model (SEM) modification for development of CSF, configuration and presentation of CSF, and validation of CSF using reported citizen science projects and historic data are discussed.

Modification of Socio-Ecological Model (SEM)

Pretlow (2018) highlighted that numerous articles have suggested modifications of the social-ecological systems framework (SESF) variables given new empirical analysis of more diverse cases. However, the author pointed out that when such modifications are suggested, key question needs to be asked in relation to epistemological congruence such as "what theory is supporting the modification or inclusion of variables, and does it align with how variables were included historically?" (Pretlow, 2018). Similarly, when such understanding was applied in the present study, similar question was posed in relation to the modification of the SEM model as it becomes useful for different purposes. In answering the posed question, it was established that systems thinking, which is the process of understanding how things influence one another within a whole, is central to ecological models, and accordingly the SEM model. The present study was guided by theories of systems thinking and therefore modification of the SEM model for the purpose of answering the research question conforms to the epistemological congruence of the SEM model.

Previous SEM models were adapted and used as analytical frameworks to develop the citizen science framework. Several SEM models such as Bogardus et al. (2020) who applied the SEM model to determine factors inhibiting application of anterior cruciate ligament (ACL) injury prevention programmes, Baral et al. (2013) who used the model to assess risks associated with HIV epidemics, and Caperon et al. (2019) who determined factors of food dietary behaviour from socio-ecological perspective were among studies reviewed. However, the novel citizen science framework is largely based on Stanger (2011) and Lee et al. (2017) variation of Bronfenbrenner (1977) and Bronfenbrenner (1979) ecological model that consisted of five levels of influence. Reworked ecologically based version of the socio-ecological model to guide CSF development is presented in Figure. 5.7a-b.

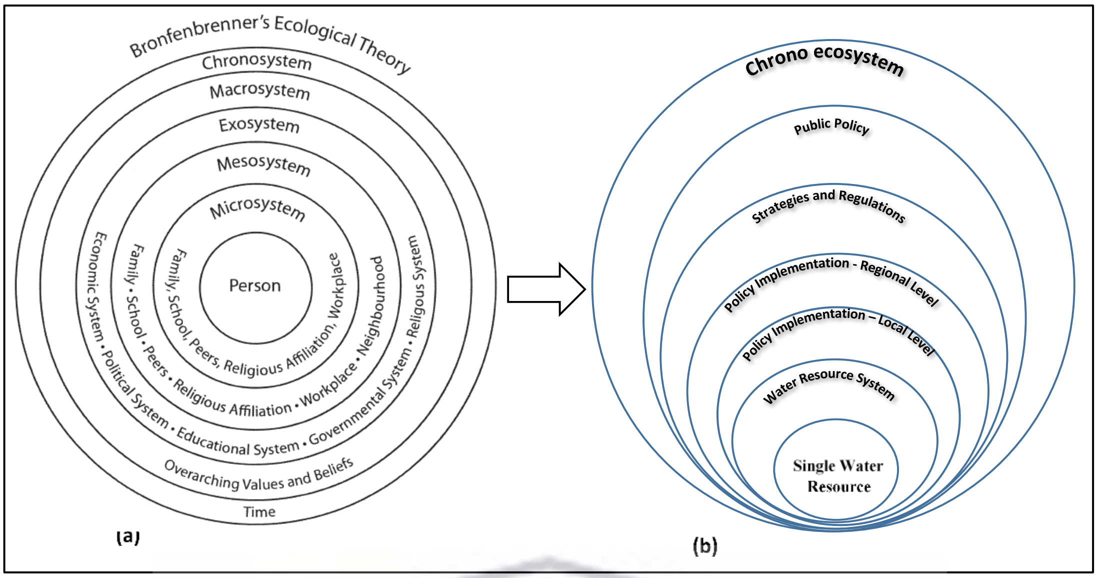

Figure 5.7a-b: Modification of Socio-Ecological Model (SEM) (a) An ecologically based version of the socio-ecological model (adapted from Stanger, 2011), and (b) five core-levels of Citizen Science Framework

Identification and configuration of novel framework themes

Using framework analysis and ecosystem domain identification, five core-levels of the CSF chrono-system were identified within an ecosystem-based approach (Figure. 5.7b). Such core-levels are described and linked to the Bronfenbrenner's SEM. The five levels of influence namely, 1) public policy, 2) strategies and regulations, 3) policy implementation at regional level, 4) policy implementation at local level, 5) water resources networks. The identified levels of influence were linked to form a proto-CSF (Annexure 5.8). In terms of the CSF's perspective the relative contribution of individual levels of policy implementation processes and also their cross-level interactions provide insight into various spheres of influence contributing to the same desired outcome and is critical towards effective and efficient operationalization of RDMs at local level.

The highest level of influence on water resources protection is public policy which is linked with the *macro-system* of the SEM. Public policies are used by the state for the purpose of water resources protection, and such documents outline where, when, how, and what strategies should be used to implement policies for the protection of water resources. The public policy level has a flowing influence on other lower levels. Strategies and Regulations level of influence is linked with the *exo-system* of the SEM, and it specifies rules and regulations for implementation of strategies formulated for policy implementation on water resources protection. RDMs are considered as policy implementation strategies for water resources protection. Formulation of strategies and regulations to support implementation of public policies on water resources protection forms part of activities for water resources protection at this level.

Regional policy implementation concerns policy implementation at regional scale based on the scale of a Water Management Area larger composed of several catchments. The Undertaking of RDMs studies is considered as activities directed towards policy implementation at regional level. This level is linked with the *meso-system* of the SEM. The Local policy implementation level of influence is linked with the *micro-system* of the SEM, and it enables policy implementation at localised scale where water resources reside. Water resources system level of influence is characterised by interconnections between different water resource types such streams, wetlands, aquifers, estuaries, and lakes. At the level of water resource networks undertaking of water resource protection activities such as water resources assessment, management of water use activities is ensured. Such activities have a direct influence not only on water resources networks such as groundwater-surface water interaction, but also on individual water resources that form a core of the CSF for water resources protection. This level of influence is additional to the original levels of SEM, and is named *nano-system* (Stanger, 2011), which is the lowest level of influence on water resources protection.

The proto-citizen science framework (Annexure 5.8) was improved into a complete CSF by incorporating the concept of citizen science which is aimed at integrating civil society into water resources policy implementation and practice. The proposed CSF for RDMs implementation to improve water resources protection at catchment level is presented in Figure 5.2. Top-down approach for policy implementation driven by policy implementers as depicted in the CSF is indicated by arrows facing downwards, while bottom-up approach driven by involvement of citizens in water resources protection activities is indicated by black arrows facing upwards. Bottom-up effects and interventions are induced by changes in water resources status, and such interventions could be affected at any level of influence as indicated by red dotted arrows facing upwards.

Presentation of the novel citizen science framework

In order to demonstrate how scientists, policy makers, and local citizens take part in water resources protection activities as depicted in the CSF, systems diagrams of influence in water resources protection are presented in Annexure 5.9a-d. The CSF supports concurrent operationalization of both top-down and bottom-up approaches for localized water resources protection using RDM strategies, as indicted with a red dotted circle (Annexure 5.9a). The framework is multi-centric, as it is composed of policy, science, and citizen centrism. In terms of science centrism indicted with a red dotted circle (Annexure 5.9b), science studies of RDMs are undertaken to devise better ways of managing water resources such as application of the Integrated Water Resources Management approach. RDM studies apply the concept of science-policy nexus which ensures that RDM studies are undertaken to provide evidence-based policy relevant solutions to water resources protection. The processes of undertaking RDM requires that public form part of such RDM studies through stakeholder engagements and during the process of gazetting (legalizing) RDM outcomes.

In terms of policy centrism as indicted with a red dotted circle (Annexure 5.9c), water resources protection policies are formulated and implemented to improve state of water resources. Formulation and implementation of such policies involves engagement between policy makers and scientists to ensure that policy solutions are based on evidence provided by science.

Policy implementation for water resources protection follows a top-down approach. Annexure 5.9d illustrates the citizen centrism of the framework as highlighted in red dotted circle. Local citizens derive goods and services from water resources such as water abstraction, recreation, cultural activities, and fishing. However, such activities may have detrimental impact on water resources such as unsustainable water abstraction, and water quality deterioration. The CSF, therefore, facilitates involvement of local citizens into policy implementation activities which in turn positively influence policy practice at localised scale and results in sustainable water resources utilisation, which is critical towards SDGs by 2030 and beyond.

Validation of the citizen science framework using reported citizen science projects

To demonstrate the suitability of the CSF in enhancing participation of citizens in water resources protection activities, two case studies are discussed. These cases illustrate how use of the citizen science concept, which is the core of the CSF, may help to improve policy practice at catchment level by involving local communities. The first case study is based on the reported citizen science project for water quality monitoring in the uMngeni and Msunduzi River Catchments (Cele, 2015). The uMngeni and Msunduzi River Catchments are found in the Province of KwaZulu-Natal, where water quality challenges such as general illegal waste disposal from residential areas, pollution challenges due to industrial pollutants, and raw sewage flowing directly into the streams have been experienced (Cele, 2015). However, Cele (2015) noted that despite such challenges, citizen science has played a role in keeping the rivers, streams, dams, and estuaries pollution-free in these catchments. In this case study, perceptions, and experiences of using miniSASS, a citizen science tool that has widely been used in KwaZulu-Natal to monitor water quality of rivers and streams, was investigated.

The study followed an exploratory and descriptive qualitative enquiry where community members residing in the nearby informal settlements, along the banks of the UMngeni River, were trained in sampling and testing techniques using simplified clarifier tubes, and in the keeping records of data for water quality monitoring. Through this approach local communities became actively involved in water quality data collection (Annexure 5.10a) and capturing on the database (http://www.minisass.org/en/) (Annexure 5.10b). The study argued that the science knowledge acquired by local citizens stays with them for a very long time and such knowledge could be transferred to the next generation who will be using and benefiting from goods and services provided by the same water resource (Cele, 2015).

Liu and Ravenscroft (2017) concurred with the aforementioned statement highlighting that empowering local citizen to participate in the policy process enhances chances to achieve a broad consensus on the best approach to addressing existing social challenges.

Findings from the case study indicated that in the uMngeni and Msunduzi River catchments various interventions that employ the concept of citizen science are well in advance. For example, the Researcher noted that citizen science interventions have led to tangible action taken by municipalities where budgets are now being allocated to address river health problems identified in some cases that were based on poor water quality evidence from miniSASS experiments (Cele, 2015). The second case study is based on the reported citizen science project for investigation the design and implementation of a citizen-technician based suspended sediment monitoring network which was undertaken in Tsitsa River catchment within the Eastern Cape Province of South Africa. The study enrolled local citizens as technicians to use basic equipment and Open Data Kit-enabled smartphones to collect flood-focused suspended sediments samples from 11 identified sites along the Tsitsa River and its tributaries in the Eastern Cape Province of South Africa (Bannatyne et al., 2017).

The goal of the project was to assess suspended solid fluxes and yields to provide insight into the sources, magnitude and dynamics of catchment soil erosion and loss, thus providing important data on catchment management and monitoring which is critical for supporting decision making, planning, and interventions (Bannatyne et al., 2017). The study indicated that one of the factors considered for recruitment of local citizen technicians was their location in the proximity of the monitoring sites and those working in farms and in privately owned land. Local citizens received training on suspended solid sample collection and on safety measures which included wearing of a lifejacket, and not sampling at night (Bannatyne et al., 2017). Annexure 5.10c shows how local citizens were trained on the use of equipment for suspended sediment analysis and measurement, while Annexure 5.10d illustrates suspended solids sample collection by local citizens while wearing lifejacket which was one of the key aspects of local citizen technicians training. Although some challenges were reported in the study such as management of local citizen's teams and low confidence on data collected by citizens, however, benefits associated with citizen science were reported as well. For example, the researchers pointed out that use citizen science financially benefitted the project in a sense that there was no need to pay for accommodation as data was collected by local residence (Bannatyne et al., 2017).

Validation of the citizen science framework using historic data

To demonstrate the suitability of the CSF for RDM compliance assessment, a case study of the Schoonspruit and Koekermoerspruit River Catchments is discussed to demonstrate the use of the CSF in improving compliance assessment with established RQOs numerical limits (DWS, 2014) for water resources protection linked to surface and groundwater resources.

In terms surface water quantity, established RQOs numerical for ecological water requirements were estimated at 4.691 million cubic metres per annum (Mm3/a) (Annexure 5.11) which is equivalent to an average flow of 0.149 cubic metres per (m^3/s). Annexure 5.12a-b illustrates average daily and annual flow variability as recorded from 1996 to 2017 at C2H139Q01 monitoring site located between 26˚ 54.964' S and 26˚ 49.032' E. The stream flow data as indicated in Annexure 5.12a shows that flows for ecological water requirement of 0.149 m^3/s established as legalized RQOs numerical limit was sustained 46% of the time. Furthermore, the analysis indicates that such sustainability was only achieved from 1996/1997 to 2011/2012-year cycle (Annexure 5.12b). The implication is that 54% of the time the stream flow was unable to sustain the gazetted RQO for ecological water requirement during the period from 1996/1997 to 2016/2017. When stream flows variability was assessed for maintenance low flows in the months of January during wet seasons (Annexure 5.12), the analysis indicates that the gazetted RQO for maintenance low flows in January (0.1038m^3/s) was met 64% of the time (Annexure 5.13). Maintenance low flows in the months of July during dry season (0.0179) (Annexure 5.14) was met 95% of the time (Annexure 5.15).

In terms of compliance assessment with established RQOs numerical limits linked to surface water quality, concentrations of Magnesium (Mg), Electrical Conductivity (EC), Sulphate (SO_4), Nitrate (NO_3), and Phosphate (PO_4) were considered (Table 5.5). Median values were considered for Nitrate and Phosphate, while 95th percentile was considered for Electrical Conductivity, Magnesium, and Sulphate for the purpose of compliance assessment as per the RQOs study (DWS, 2014).

Table 5.6: Summary of descriptive statistics for studied surface water quality at C2H139Q01

Assessment Site	C2H139Q01				
Water Quality Variables	EC (ms/m)	Mg ($mg.l^{-1}$)	NO_3-NO_2 ($mg.l^{-1}$)	PO_4 ($mg.l^{-1}$)	SO_4 ($mg.l^{-1}$)
Number of samples	135	134	126	136	135
Median	144.70	64.24	*3.21*	*0.69*	428.11
95th Percentile	*194.95*	*90.04*	9.93	3.002	*687.30*
River RQO Numerical Limits	85	100	2.5	0.125	250

The results from the analysis together with the gazetted Middle Vaal RQOs are presented in Annexure 5.16a-e. The results from the analysis indicated that Mg concentration did not comply with established limits only in March 2011 and October 2011 and was within the stipulated limit most of the time. (Annexure 5.16a). The results indicate that Electrical Conductivity concentration of 194.95 ms/m is above the gazetted river RQO numerical limit of 85 ms/m (Annexure 5.16b). The 2010 water quality results indicate that EC concentrations averaged 140.5 ms/m with a highest value of 196 ms/m in the month of February and 80.5 ms/m in the month of December (Annexure 6.6).

In the year 2011, EC concentrations were highest with 219.8 ms/m in March, and lowest with 24.23 ms/m in February indicating an aggressive fluctuation within a period of a month. A similar condition is observation in the year 2012 between October and November. Concentration of EC only complied with established limits in January 2011, March 201, and October 2012, with evidence of increasing concentration trend. Sulphate, Nitrate, and Phosphate concentrations exceeded their respective gazetted river RQO numerical limits between 2010 and 2012, with Sulphate exceeding the limit excessively (Annexure 5.16c-e). Concentration trends for Sulphate and Nitrate have been increasing, while concentration trend for Phosphate has been decreasing.

The feasibility of the framework was also validated by assessing compliance with established numerical limits for groundwater RQOs. In terms of quantity, compliance with the established monthly critical recession rate was assessed at the two groundwater sites C2N1143 located at 26˚ 2.387' S and 26˚ 27.759' E, and C2N1150 located at 26˚ 39.384' S and 26˚ 52.346' E which belongs to the DWS. The results from the analysis are indicated on Annexure 5.17, and Annexure 5.18, respectively. The analysis indicated that at groundwater site C2N1143 recession rate was the highest in June 2016 (2.3 metres/month) and the lowest in January 2018 (-0.48 metres/month). The reception rate has been within the legalized critical rate (0.25 metres/month) from January 2016 to May 2016, and from July 2016 to November 2018. Linear trend at this site shows that recession rate is continuously decreasing thus critical rate is sustained. At the groundwater site C2N1150, recession rate has been fluctuating significantly, where it was the highest in October 2017 (1.0 metres/month) and the lowest in August 2018 (-0.7 metres/month). Although the recession rate at the C2N1150 has been occasionally above the legalized critical rate of 0.25 metres/month (June 2016; October 2017; January 2018; September 2018), however, for a prolonged period of time (July 2016 to September 2016 and February 2018 to September 2018, the recession rate has been within the critical recession rate limits, and this observation is confirmed by determined the linear trend.

In terms of groundwater quality compliance assessment, water quality parameters of Chloride (Cl), Sulphate (SO_4), Nitrate (NO_3), and Fluoride (F) were considered based on their health effects they may have in domestic water use as indicated in the water quality guidelines (WRC, 1998). Concentration levels of the four water quality parameters measured at groundwater sites 2626DB00350 located at 26˚ 35.115' S and 26˚ 54.917' E), and 2626DB00386 located at 26˚ 39.783' S and 26˚ 52.333' E were compared with national standards for drinking water quality (SANS 241, 2015); WRC, 1998), as 300 mg/l for Cl, 250 mg/l for SO_4, 11 mg/l for NO_3, and 1.5 mg/l for F. The results from the analysis are shown in Annexure 5.19a-h, where it is indicated that concentration levels of Cl complied with national standard at groundwater site 2626DB00350 from November 1995 to July 2017 (Annexure 5.19a).

Although Cl concentrations at groundwater site 2626DB00386 did not comply with standard limits from April 2002 to July 2003, however, from August 2003 up January 2006 there was compliance (Annexure 5.19b). The trend indicates a continuous decline in concentration levels for Cl at this monitoring site. In terms of SO_4 concentration levels, there was compliance with standard limits at 2626DB00350 (Annexure 5.19c), and contrary is evident at 2626DB00386 (Annexure 5.19d) where there was no compliance. However, the trend seems to be decreasing but still far off the required limits. Concentration levels for NO_3 did not comply with standard limits at 2626DB00350 from November 2008 and fluctuated significantly up to June 2017 (Annexure 5.19e). The trend shows that concentration levels have been increasing steeply. NO_3 concentrations have been within the limits throughout the period from April 2002 to December 2005 at monitoring site 2626DB00386 (Annexure 5.19f). Concentrations for F have been within the standard limits at both monitoring sites 2626DB00350 and 2626DB00386 (Annexure 5.19g; Annexure 5.19h).

5.5 Comparative analysis of the findings from the current study and previous studies

This section of the thesis provides an explanation and interpretation of the results or findings of the current study by comparing them with the results of previous studies. Such explanations put the results of the current study in context by comparing them with the literature that have been covered in chapter 2 (literature review) of the thesis. This comparative analysis is provided systematically per findings obtained for each of the study objective.

5.5.1 Comparative assessment of results on science-policy nexus in policy formulation and practice

Comparison of the present study findings to earlier studies reveals a consistent approach of science-policy nexus application in water resource protection field, simplification of scientific products into understandable information for use in practice, and stakeholder engagement in policy formulation and implementation initiatives (de Jong, 2016; López-Rodríguez et al., 2015). However, when the comparison was undertaken in relation to use of science-policy nexus theoretical models in other studies, varying outcomes became evident (de Jong, 2016; Dunn et al., 2018; Frost et al., 2017).

Application of science-policy nexus in water resources protection practice facilitates formulation of decisions based on objective scientific evidence (evidence-based approach), and support implementation of such decisions (de Jong, 2016). This corresponds well with the findings of the current study that in the South African context, scientific RDM studies enables appropriate decision making on policy implementation practice towards water resources protection. The outcomes of de Jong (2016) are based on the assessment of eeutrophication management linked to water quality, while the outcomes of the current study are based on RDM studies undertaken linked to both water quality and quantity management (Figure 5.4a-c).

Simplification of science products into more understandable formats leads to a situation with more incremental decision making (de Jong, 2016). For example, de Jong (2016) noted that scientists working on eutrophication management can deal with complexity and uncertainty at the political through simplification of facts by focusing only on nutrients as the main source of the problem. Similarly, the results from the current study indicate that translation of complex science research outputs into more readily usable information enhances application of science-policy nexus concept in water resources protection practice. For instance, outcomes of complex RDM studies are translated into more understandable information such as water resources classes, narrative statements, and numerical limits which are legalized for decision making in water resources protection practice (Figure 5.3).

Communities of practice in science-policy nexus initiatives form part of policy implementation activities towards water resources protection. López-Rodríguez et al. (2015) found that brokering approach where workshops are organized to facilitate mutual understanding and trust between scientists, communities, and policymakers is critical in identifying major environmental concerns requiring policy intervention. This corresponds quite well with the findings of the present study that stakeholder engagement is critical in policy implementation using scientific RDM studies. For example, 6 of the water resource classification, and water resource reserve determination processes, respectively, require evaluation of scenarios with stakeholders (Annexure 5.4; Annexure 5.5). Furthermore, step 6 of the resource quality objectives determination processes requires that consultation with stakeholders to agree on resource units, RQOs, and numerical limits should be undertaken (Annexure 5.6).

Three types of science-policy nexus theoretical models are recognized in practice, namely i) science-policy integration, ii) policy-science integration, iii) mixed integration (Table 5.1). However, much of the findings from several studies are related mostly to either science-policy integration or policy-science integration (Frost et al., 2017; Dunn et al., 2018) with limited practical case examples on mixed integration. The findings of the current study demonstrate how the science-policy nexus mixed integration model can be operationalized practically, where policy is converted to science, and converted back to policy (Figure 5.1). Therefore, the results obtained from the investigation in the current study provide more comparable outcomes among other studies undertaken in different countries.

5.5.2 Comparative assessment of results on application of reflective practice models

The findings of the study indicated that 12 different types of synergies and conflicts among the four WEFE nexus sectors exist in practice (Annexure 5.2). Similar synergies and conflicts have been reported in literature (Rasul, 2016; Momblanch et al., 2019). However, the study went further and recognised 6 synergies and conflicts that are deemed exclusive to water resources protection practices (Table 5.3).

The study also found that RDM strategies facilitate application of WEFE nexus in water resources protection practices where such synergies and conflicts are considered in RDM processes (Table 5.4), as discussed in section 5.4.2 in this thesis. Such findings suggest that it is possible to apply WEFE nexus in policy practice by infusing the concept to existing policy implementation strategies and plans. The results of the current study support reported findings by several authors who suggested that there are no stand-alone methods and tools for WEFE nexus practice (Gondhalekar and Ramsauer, 2017; Karabulut et al., 2019; Endo et al., 2020).

Furthermore, the current study found that Public-Private Partnership (P-PP) plays a critical role in undertaking RDM studies. Such partnership enables the state department (Department of Water and Sanitation) to leverage skills, expertise, and resources of the private sector, and in return private sector gets business opportunities resulting in mutual advantage to both parties. The findings support earlier arguments reported in literature that P-PP is one of the key aspects influencing public policy implementation (Brynard, 2009; Arimoro, 2018; Walwyn and Nkolele, 2018). However, when reflective practice models were applied to assess influence of P-PP for the sustainability of WEFE nexus in water resources protection practices through capacity building activities undertaken as part of RDM studies, the present study found that the P-PP is skewed to towards monetary value with much emphasize centred around water sector only.

5.5.3 Comparative assessment of results on validation and verification of a process based operational plan

In terms of the third objective, the present study found that data collected by citizens are comparable to data collected by professional scientists, and useful in water resources protection practices. The comparability and usability of such data are improved by providing adequate and relevant trainings to non-professional scientists before they embark on data collection activities. The current findings are comparable to earlier findings by Rambonnet et al. (2019) who reported that introduction of sample protocol, quality control and management of volunteers ensures successful utilization of citizen science approach. Contrary to the current study findings, McGoff et al. (2017) noted biasness in data collected by citizens as compared to data collected by professional scientists with a potential for type II error. Such biasness emerges when the self-selected site approach is used, which is known to be appealing to volunteers who are usually interested in discovering water quality in their own neighborhood (McGoff et al., 2017). However, findings by McGoff et al. (2017) can be contested that such observation could be as bases for recruiting volunteers in the proximity of monitoring sites and closer to their areas of residence. For example, in the study conducted in the case study of the Tsitsa River catchment, one of the factors considered for recruitment of local citizen technicians was their location in the proximity of the monitoring sites and those working in farms and in privately owned land, who were then given training on suspended solid sample collection and on safety measures which included wearing of a lifejacket, and not sampling at night (Bannatyne et al., 2017). Such case study serves as an example for practical involvement of local citizens in water resources protection activities.

The current study also found that secondary data can be used as a tool for localised operationalization of RDMs to improve policy implementation for water resources protection at catchment level, and such observation agrees with earlier findings reported in literature. For example, Dlamini et al. (2019) showed that it is possible to use historical water quality data to assess compliance with gazetted RQOs. This example demonstrates the usefulness of using historical data for monitoring RDMs compliance at catchment level. The present study however went beyond the use of secondary data by proposing the use of citizen science and nexus approaches in generating information for policy makers and practitioners in water resource management practices and research.

5.6 Implications of the results

5.6.1 Implication of results on science-policy nexus in policy formulation and practice

The outcomes derived from the first objective of the current study both nexus, and operational relevance which would benefit general stakeholders in the subject water resources protection. In terms of the nexus uptake in policy implementation, the study objective practically demonstrated how to improve collaboration between policy makers and water scientists to ensure that researchers investigate policy relevant solutions, and that research products are presented in a readily, usable, and understandable formats to policy makers and public for easy of policy implementation. Such improvement on the collaboration between scientists and policy makers is likely to enhance science-policy nexus uptake in practice which is essential for evidence-based policy formulation and implementation.

In terms of the operational relevance, it is likely that the analytical approach developed and demonstrated in this investigation can be readily extrapolated to other settings, particularly in developing countries where science-policy integration remains a challenge for meeting water availability and water quality requirements reliably and sustainably. Furthermore, the outcome of the study contributes immensely to the academic spheres by adding to the quantity of literature available that articulates on the use of science in policy development, implementation and evaluation and also to drive science research on relevant questions and knowledge required by policy developers. On the international arena, the study has also contributed to the debate and demonstrates that African countries are also actively engaged in research activities and utilisation of research products that are contributing to water resource protection for sustainable water utilisation.

5.6.2 Implication of results on application of reflective practice models

The implications of the results on the second objective have economic value and social development relevance in addition to operational aspects. In terms of economic value and social development, the outcomes of the investigation projects that when water-energy-food and environment [WEFE] are considered as harmonisers rather than competitors, goals for sustainable development and environmental integrity can be achieved sooner than 2030, especially when operations and uptake of the concept is downscaled and practiced at local scale.

In terms of the operational aspects, the investigation provided practical evidence of how to integrate the concept of WEFE nexus in water resources protection processes to improve its uptake in practice. Such practice improves sectorial collaboration especial water, energy, food, and environmental sectors which are critical in water resources management. Although such evidence is provided using RDM processes in water resource protection to assess application of WEFE nexus in South African context, such findings are useful and applicable in various developing countries where WEFE nexus is being implemented to offer integrated solutions for socioeconomic and environmental-related challenges. Therefore, this study provides a basis for reporting the progress on the application of WEFE nexus.

5.6.3 Implication of results on validation and verification of a process based operational plan

The outcomes of the third objective have an operational relevance which would benefit variety of stakeholders ranging from policy makers, water resource managers, water users such as industries and the public at large. The results highlight the importance of ccapacity building and social learning by citizens on the aspects data collection which improves local citizen participation in water resources protection activities. Participation of local citizens enhances collaboration between policy makers, water resources managers, water scientists, and water users making it possible to increase capacity for policy implementation using implementation plans such as the citizen science framework. The outcome of the investigation shows that application of the citizen science framework allows for participation of local citizens in RDM operationalization at local level, making it possible to assess compliance with established standards in near real-time, thus enabling water resource managers to identify hot-spots for immediate policy interventions at the time when it is required, which is critical for effective and efficient policy practice. The outcomes of the investigation also contribute to the uptake and utilization of citizen science concept in water resources protection practices, thus acting as a proxy for other similar projects and in terms of raising public awareness on the existing water resources challenges linked to quality and availability.

5.7 Evaluation of the study

The purpose of undertaking an investigation on the first objective of the current study was to shed some light on the role of science-policy nexus in policy implementation practice towards water resources protection, and to establish how the nexus can be operationalized effectively and efficiently, especially in developing countries. In undertaking the investigation, the study hypothesized that science-policy interfaces must be practical, reflective, and must consider the nexus approach. The results from the investigation provided insight on how the concept of science-policy nexus is is conceived, by reflecting on theoretical models commonly used in practice.

Furthermore, the study provided practical examples where science-policy nexus is used in practice to inform policy development and implementation for water resources protection, where South Africa was used as a case country.

The argument of the second study objective is that the achievement of national policies through resource directed measures (RDMs) requires consideration of nexus approach such as Water-Energy-Food-Environment (WEFE) nexus. The question linked to such argument is "what is the role of WEFE nexus in water resources protection practices?" To answer such a question, synergies and conflicts of WEFE nexus that exist in practice had to be identified and assessed for their consideration in RDM processes, with further reflection on role of P-PP in sustaining the nexus in such practices. The outcome of the investigation provided practical evidence on how to incorporate WEFE nexus concept in water resources protection processes such as RDM procedures, to improve its application in policy practice. The study further highlighted important aspects that need to be addressed to improve sustainability of WEFE nexus application in water resources protection practices.

The third objective of the current study was undertaken to develop a citizen science framework that facilitates operationalization of resource directed measures at catchment level. The design of such framework was guided by the principles of socio-ecological model (SEM) from systems thinking perspective and made use of a nexus approach. The argument for this study objective is that water resource protection strategies such as RDMs should be prioritised for operationalization at catchment level where local communities become part of such an operationalization practice. The study demonstrated that it is possible to downscale RDMs operationalization to a local scale (source point) where water resources reside and utilised, and where the citizens dwell who are supposed to part of the management practice of water resources. Outcomes of the study offered a new way of understanding collective action between policy makers, scientists, and local communities, through which citizen science framework works. The study also demonstrated that in cases where policy implementation practice follows a top-down approach, local citizens can be empowered to act collectively in implementing water resources protection policies from the bottom-up approach, thus improving state of RDM uptake at localised level.

The importance of embracing theories of systems thinking to influence operationalization of national policies for environmental and human welfare is fundamental for sustainable resource utilization. The importance of integration such as science-policy nexus to enrich engagement between scientists and policy makers in quest for sustainable solutions to environmental and social challenges cannot be overlooked. In the current study integration aspects such as WEFE nexus has been shown to be critical in water resources protection practices for promoting sectorial collaboration between water, energy, food, and environmental sectors. Such collaborations are seen as key drivers of sustainable economic development and social securities, and for fast-tracking achievement of SDGs by 2030.

The concept of citizen science which promotes involvement of citizens in water resources protection activities has been the core of the current study. Therefore, the three specific study objectives of the current study were achieved, and the overall objective (main aim) was accomplished.

5.8 Summary chapter on results and discussion

In policy practice, science-policy nexus plays a critical role where policy provides questions to be researched and science provides solutions to challenges faced by policy makers. Furthermore, the achievement of national policies using resource directed measures (RDMs) strategies requires consideration of nexus approach such as Water-Energy-Food-Environment (WEFE) nexus.

Such consideration contributes achieving goals of the National Development Plan (NDP) of South Africa and the set SDGs targets by 2030. However, efficient policy practice towards water resources protection, especially at localised scale requires proper understanding of how RDM strategies are operationalized at catchment level. Such understanding forms bases for policy monitoring and evaluation. Therefore, as outlined in section 1.3.2, the objectives of the current study were (i) to assess the application of science-policy nexus in policy formulation and practice towards water resource protection, (ii) to establish the application of reflective practice models to assess operation of water-energy-food-environment nexus approach in water resource protection practices, and (iii) to Demonstrate the validation and verification of a process based operational plan for catchment orientated resource directed measures.

In terms of the first objective, the investigation revealed that science-policy integration, policy-science integration, and mixed integration are the three types of theoretical models commonly used in practice when scientists engage with policy makers. When the concept of science-policy nexus was assessed for its application in the South African context, it was found that such concept plays a critical in policy implementation, especially in the field of water resources protection. The study also established that such practice employs the mixed integration theoretical model of science-policy nexus.

When the concept of WEFE nexus was assessed for its role in water resources protection practice, the study found that from the twelve synergies and conflicts that exists among WEFE nexus sectorial components, six are most relevant to water resources protection as discussed in section 5.4.2. Furthermore, the study found that Public-Private Partnership plays key role in water resources protection, where it facilitates undertaking of RDM studies. However, when reflective policy models were used to assess such partnership for its role in WEFE nexus sustainability, the study found that the partnership is skewed towards monetary value and focuses mainly on water sector only.

In terms of the third objective, the study investigated and proposed a citizen science framework (CSF) for operationalization of RDMs at catchment level. The formulation of the framework was based on the principles of Socio-Ecological Model (SEM).

The findings of the study revealed that the CSF incorporates nexus approach characterised by science, policy, and citizen centrism which tend to facilitate participation of citizens in local water resources protection activities. Additionally, the study found that the CSF directs policy practice at different levels of implementation, thus supporting a top-down approach. When the suitability of the CSF was validated using reported citizen science projects, the study found that CSF facilitates participation of local citizens in water resources protection activities to improve implementation of water resources protection policies from a bottom-up approach. Therefore, the framework supports concurrent operation of both top-down and bottom-up approaches of policy implantations. When the CSF was validated for compliance assessment, the study found that the framework is a suitable plan for assessing compliance with established RDM standard limits using historic data.

Chapter 6: Conclusion and recommendations

6.1 Introduction

Chapter 5 of the thesis presents summary of the major findings and discusses results on the first, second, and the third objective of the current study. This chapter 6 presents conclusions derived from the analysis of the results obtained for each study objectives, contributions of the study to scientific research, and it further proposes recommendations from the findings including related future research relative to the subject investigated. The main objective of this study was to demonstrate the feasibility of operationalizing RDMs at catchment level using a citizen science framework, and to showcase the appropriateness of RDMs as policy implementation strategies towards water resources protection. Therefore, the study was about developing a citizen science framework for water resource protection that will facilitate operationalization of resource directed measures using nexus approach. The study argued that science-policy interface must be practical, reflective and must consider the nexus approach using the concept of citizen science. Such a plan can address some of the reported challenges in addition to improving acceptance of RDMs as relevant policy implementation strategies towards improved and integrated water resources management practice at catchment level. The process of developing, validating, and verifying such a plan was central to the present study so that the developed citizen science framework for water resource protection becomes applicable to catchments.

6.2 Conclusion and recommendations on science-policy nexus in policy formulation and practice

In water resources protection practice, evidence-based policy relevant solutions play a critical role in policy implementation appropriately respond to environmental and social challenges, and in such practice, science-policy nexus is fundamental. However, the concept of science-policy nexus is still not clearly understood, hence inadequate utilisation of the concept in policy practice. The evident for this observation is abundant where available data and information exist from scientific research outputs, but policy makers seem not utilising such information when developing policies and strategies for water resource protection. Therefore, the purpose of the investigation was in three folds: Firstly, to investigate existing theoretical models for science-policy nexus used in practice. Secondly, to examine briefly and qualitatively, existing policies and strategies formulated for sustainable water resource utilisation and protection, locally. Thirdly, to practically demonstrate integration of policy and science in policy implementation practice towards water resources protection in South Africa.

The study found that science-policy integration, policy-science integration, and mixed integration are used by scientists and policy makers as mode of engagement with each other in search for policy relevant solutions. In the context of South Africa, the study found that there are existing policies and strategies devoted to water resources protection, and implementation processes for such policies are facilitated by application of science-policy nexus characterised by mixed integration theoretical model which is bi-directional in nature.

Using a case investigation of South Africa, the study demonstrated how the country can translate abstracts of legislation into practice using science, and how science is used in policy development and implementation, practically. Therefore, the objective of the study on assessing the application of science-policy nexus in policy formulation and practice towards water resource protection was achieved.

The study demonstrated, practically how science-policy integration can directly impact water resource protection practices from a local, regional, and national perspective. Therefore, a conclusion was made based on the results of the study that it is possible for researchers and/or scientists and policy makers to collaborate when trying to solve social and policy relevant problems for evidence-based solutions. The study therefore recommends that the findings animating from the investigation are considered for extrapolation to other settings, particularly in developing countries where science-policy integration remains a challenge for meeting water availability and water quality requirements reliably and sustainably. Such promotion for practical application of the nexus is likely to build strong relationships between scientists, policymakers, and public which is key in facilitating mutual understanding on the shared responsibility for water resource protection, management, and sustainable utilization.

It is evident from the findings of the study that when policy makers and scientists engage each other on a common course such as addressing social and environmental challenges such as water resources quality, availability, and ecosystem sustainability, and when appropriate models of engagements such as mixed science-policy and policy-science nexus models are used, the outcomes derived from such engagements are likely to benefit policy makers, scientists, and the public at large. The findings and conclusion derived from the study are consistence with the reviewed literature which was reviewed to affirm findings of the investigation. For instance, the study provided practical evidence where science is used to implement water resources protection policies. The reviewed literature indicated that science-policy nexus supports formulation and implementation of evidence-based policies, and such information support findings of the current study.

6.3 Conclusion and recommendations on application of reflective practice models

In order to sustainably achieve resource security for all, the integrity of ecosystem services and the associated resource base must be maintained while access to resources is expanded and consolidated. Such standpoint is reflected on the Water-Energy-Food-Environment (WEFE) Nexus which has been adopted as a holistic management approach towards achievement of inter-disciplinary societal goals such as SDGs for clean water, clean energy, hunger eradication, and life on land. However, the WEFE sectors have been viewed by many as competing sectors rather than as harmonizers, and such a view has limited the application of the nexus in practice, compounded by lack of stand-alone tools and methods for its practice.

The current study intended to reflect and illustrate the significance of water resources protection strategies such as RDMs in promoting societal benefits in a wider context including achievements of socio-economic development goals such as SDGs through application of WEFE nexus concept.

The analysis showed that RDM processes incorporate WEFE nexus concept in undertaking of RDM studies, suggesting that WEFE nexus plays a key role in water resources protection practice. Such fusion of WEFE nexus with RDM processes enables water resources managers to institute equitable allocation plan of water resources in relation to the four WEFE sectors by striking a balance between water resources use and protection in their operations. However, quantifying the effects of WEFE nexus role in water resources protection practice was not addressed in the present study. Sadly, the study found sustainability of the nexus in water resources protection being questionable as some of the initiatives such as capacity development through Public-Private Partnership (P-PP) were found to be inadequate in their current configuration to sustain the nexus. Nevertheless, qualitative evidence provided for WEFE nexus consideration in water resources protection practice is critical for decision making in water resources management and protection. The second study objective on assessing role of WEFE nexus in water resources protection practices was therefore achieved. Although, the study focused on scientific aspect to larger extent, however, economic, and social aspects were also considered to a limited extent.

In order to ensure that integrity of ecosystem services is sustained while water resources are utilized to stimulate socio-economic developments, the following recommendations are put forward for consideration to improve WEFE Nexus practice: (i) strengthen capacity development and skills transfer programs towards RDM implementation at catchment level, hence improvement on WEFE Nexus practice, (ii) create greater policy coherent among the four resource sectors (water, energy, food, and environment) especially at localized level of practice, and (iii) improve sectorial co-ordination which reinforces synergies among the WEFE nexus components, while at the same time trying to discourage institutional fragmentation which creates conflicts between WEFE nexus components. Such practical application of the results from the study are likely to enhance improvement on the application of WEFE nexus in water resources protection practice which does not only enhance fair allocation of water resources, but also contributes to improvement on socio-economic development and environmental sustainability, thus fast-tracking achievement of SDGs by 2030. The reviewed literature n WEFE nexus affirmed the findings of the current study. For example, the study found that it is possible to implement the WEFE nexus in practice by infusing the concept to operational plans already in place. Such revelation agrees with literature that there are no stand-alone methods and tools for WEFE nexus practice. Furthermore, findings of the study support earlier findings reported in literature that P-PP facilitates policy implementation activities. However, the current study also provided an additional perspective on P-PP in terms of its role in capacity development activities linked to water resources protection practice.

6.4 Conclusion and recommendations on validation and verification of a process based operational plan

Despite a significant progress that has been made with regards to policy implementation towards water resources protection in the country using RDMs, however, most of RDMs studies that have been gazetted (legalised) were undertaken at regional level within specific water management areas, which is the largest scale of water resource management in the South African context. However, downscaling such measures to a local scale (source point) where water resources are utilised and where the citizens dwell that are supposed to part of the management practice of water resource remains a challenge. Therefore, it is critical that water resource protection strategies such as RDMs are prioritised for operationalization at catchment level where the citizens become part of such an operationalization practice. In order to do that, a citizen science framework that uses nexus approach needed to be developed and validated hence the undertaking of the study.

A Citizen Science Framework (CSF) which facilitates participation of citizens in local water resource protection activities was investigated, and its suitability for catchment orientated resource directed measures (RDMs) was validated using case studies. The study demonstrated that involvement of local citizens in data collection and use of archived records of collected data are key factors enabling implementation of the CSF which facilitates operationalization of RDMs at catchment level. Therefore, the third objective of the study on the development, validation, and verification of the citizen science framework for its suitability as a catchment orientated RDMs operational plan was fulfilled. Since the study addressed the aspects of people (roles and responsibilities of citizens) and science (data collection), it can further be concluded that the study is both social and scientific in nature.

To implement the proposed citizen science framework, a national directorate of RDMs compliance in South Africa within the DWS is necessary. Such structure would be able to coordinate all operational activities from national, regional, and local level relevant to RDM practice. Therefore, the study recommends further research on the development of an appropriate model to monitor, evaluate, and report RDM practice for water resources protection at catchment level. The recommended monitoring, evaluation, and reporting (MER) model would at least consider recruitment of local citizens, training and capacity building, definition of roles and responsibilities, data collection and management, and reporting and evaluation, as critical aspects of RDM operationalization using the citizen science framework. It is evident that an improvement in the understanding of how the concept of citizen science works in practice, especially in the field of water resources protection, informs the basis for identifying appropriate response to water resources challenges to improve water quality, availability, ecosystem sustainability and its sustainable use.

The findings and conclusion of the study affirm and contest some of the earlier findings reported in literature. For instance, findings reported in literature that historic data can be used to assess compliance with established standards have been affirmed by the current study. However, the current study contests the reported findings in literature that data collected by citizens (non-professional scientists) lack credibility and are not comparable to data collected by professional scientists. It has been proven in the study that when citizens are provided with appropriate training and data collection protocols, they can collect credible data.

6.5 Unanswered questions/surprising results

Based on the outcomes and due to limitations of the study, the following questions remain unanswered: 1) What is the effect of data scarcity/unavailability on the application of science-policy nexus in practice? 2) How can the application WEFE nexus concept be improved at catchment level? 3) How can the WEFE nexus application be sustained in water resources protection practice? 4) How to keep local citizens motivated to be part of water resources protection activities, and sustain application of citizen science concept in practice? 5) What is the most appropriate plan for monitoring, reporting, and evaluation of RDM practice at catchment level? 6) How to respond and manage land use impact of RDM compliance in cases of non-compliance? The study, therefore, recommends further research on the following aspects linked to the current study within the subject of water resources protection:

(i) Assessing application of science-policy nexus for addressing water resources challenges in data scarce catchments would generate knowledge and practical skills in future research studies. The objective of undertaking such investigation would be to provide insight on how the absence or availability of data affects application of science-policy nexus in water resources protection practice.

(ii) Assessing localised operationalization of WEFE Nexus in the context of a catchment management for water resources protection needs to be carried out in future research work. The research would shed some light on how to incorporate WEFE nexus catchment operationalization in terms of water resources protection activities, and equitable water allocation practice. Such localized implementation of WEFE nexus is likely to have immediate impact and influence on the achievement of SDGs.

(iii) Assessing approaches on capacity development to recommend capacity development programmes suitable for sustainability of WEFE nexus practice in water resources protection and management would be a good study in future research. The investigation would seek to recommend a capacity development plan suitable for sustainable implementation of WEFE nexus concept in water resources protection for national, regional, and local level application.

(iv) Assessing effects of local community participation in RDM activities for water resources protection need further investigation. The research would promote and expand existing knowledge linked to citizen science application in policy practice. This can inform support initiatives for involvement of local citizens in water resources protection activities.

(v) Development of a model for monitoring, evaluation, and reporting of localised RDM practice as a decision support system would be a good study in future. The research would at least consider aspects such as recruitment of local citizens, training and capacity building, definition of roles and responsibilities, data collection and management, and reporting and evaluation. This could inform identification and training of potential citizens to partake in data collection for water resources protection. Training of recruited citizen scientists is critical ensure that each personnel is aware of what is expected from each one of them and the expected outcomes of the intervention, and to understands the implications thereof. Furthermore, training programmes would capacitate local, regional, and national personnel on the gazetted RQOs for their effective monitoring. Roles and responsibilities would be regarding monitoring of the habitat, biota, quality and quantity for rivers and wetlands, and groundwater (water level and water quality sampling) are specified for accountability. The investigation would need to specify the type of data to be collected, frequency of data collection, seasonality, sampling method, the form on which data is collected, data capturing, data storage, and information dissemination. Furthermore, the research would recommend frequency of reporting, distribution of the reports, the format and level of detail, and adaptive management actions in cases of non-compliance.

(vi) Assessing effects of land use activities on compliance with established RDM limits for estuaries, groundwater, surface water, and wetlands would be a good study to assess anthropogenic impacts on compliance with established RDM limits and recommend how to mitigate such impacts.

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ANNEXURES

Annexure 5. 1: Legislation, Policies, Strategies, and Regulations for WEFE Sectors in South Africa

Document Name	Document Type
Water Sector	
Constitution of South Africa (RSA, 1996)	Legislation
White paper on water policy of 1997 (NWP, 1997)	Policy
National Water Act (Act 36 of 1998), (NWA, 1998)	Legislation
National Water Resource Strategy of 2004 (NWRS, 2004)	Strategy
National Water Resource Strategy of 2013 (NWRS, 2013)	Strategy
National Groundwater Strategy, 1st Edition (NGS, 2010)	Strategy
National Groundwater Strategy, 2nd Edition (NGS, 2016)	Strategy
National Regulation on water resource classification system Number 810 of 2010	Regulation
National Water and Sanitation Master Plan (NW&SMP, 2018)	Plan
Energy Sector	
National Energy Act 34 of 2008	Legislation
National Energy Regulation Act 40 of 2004	Legislation
National Environmental Management Act 107 of 1998	Legislation
Energy Efficiency Strategy	Strategy
White Paper on the Energy Policy of South Africa (1998)	Policy
White Paper on Renewable Energy (2003)	Policy
National Climate Change Response Policy	Policy
Integrated Resource Plan (2016)	Plan
Integrated Energy Plan	Plan
National Development Plan	Plan
Department of Energy Strategic Plan 2011/12-2015/16	Plan
Food Sector	
Livelihoods Development Support Programme	Strategy
White Paper on Agriculture 1995	Policy
National climate change policy	Policy
Integrated growth and development plan (IGDP) for agriculture, forestry, and fisheries	Plan
Conservation of Agricultural Resources Act 1983	Legislation
Draft Preservation and Development of Agricultural Land Bill 2016	Legislation
Environment Sector	
National Environmental Management Act 107 of 1998	Legislation
National Environmental Management: Biodiversity Act 10 of 2004	Legislation
National Environmental Management: Protected Areas Act 57 of 2004	Legislation
National Environmental Management: Integrated Coastal Management Act 24 of 2008	Legislation
National Waste Management Strategy	Strategy
National Environmental Management Act: Regulations to phase-out the use of Polychlorinated Biphenyls (PCBs) materials and Polychlorinated Biphenyls (PCB) contaminated materials	Regulation
National Guideline for the discharges of effluent discharge from land-based sources into coastal environment	Plan

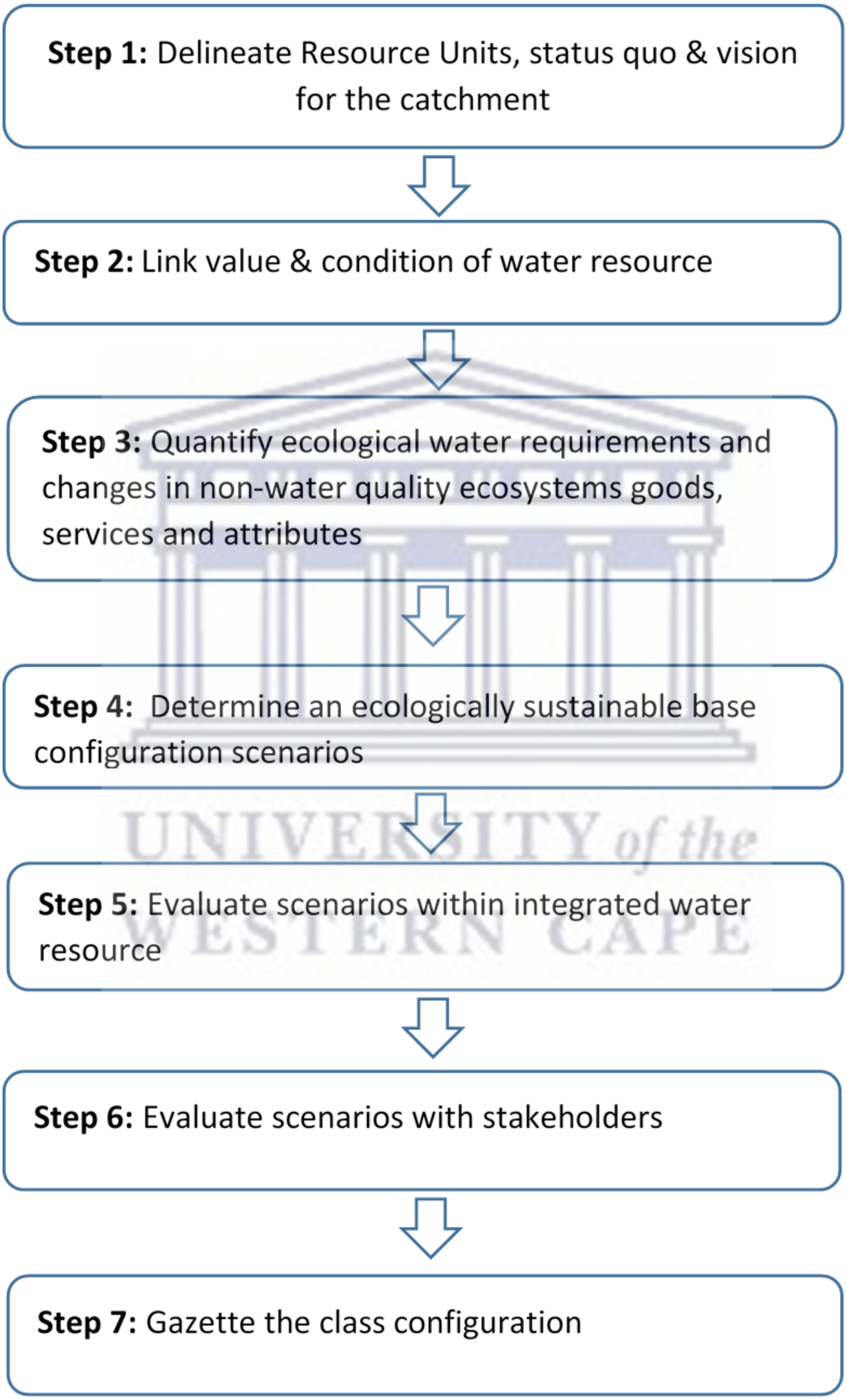
Annexure 5.2: Existing types and nature of interactions among the four components of the WEFE Nexus

WEFE Integration Number	Type of Interaction	Nature of Interaction
[1]	Water-Energy Interaction	Water influences energy security
[2]	Water-Food Interaction	Water influences food security
[3]	Water-Environment Interaction	Water influences environmental security
[4]	Energy-Water Interaction	Energy influences water security
[5]	Energy-Food Interaction	Energy influences food security
[6]	Energy-Environment Interaction	Energy influences environmental security
[7]	Food-Water Interaction	Food influences water security
[8]	Food-Energy Interaction	Food influences energy security
[9]	Food-Environment Interaction	Food influences environmental security
[10]	Environment-Water Interaction	Environment influences water security
[11]	Environment-Energy Interaction	Environment influences energy security
[12]	Environment-Food Interaction	Environment influences food security

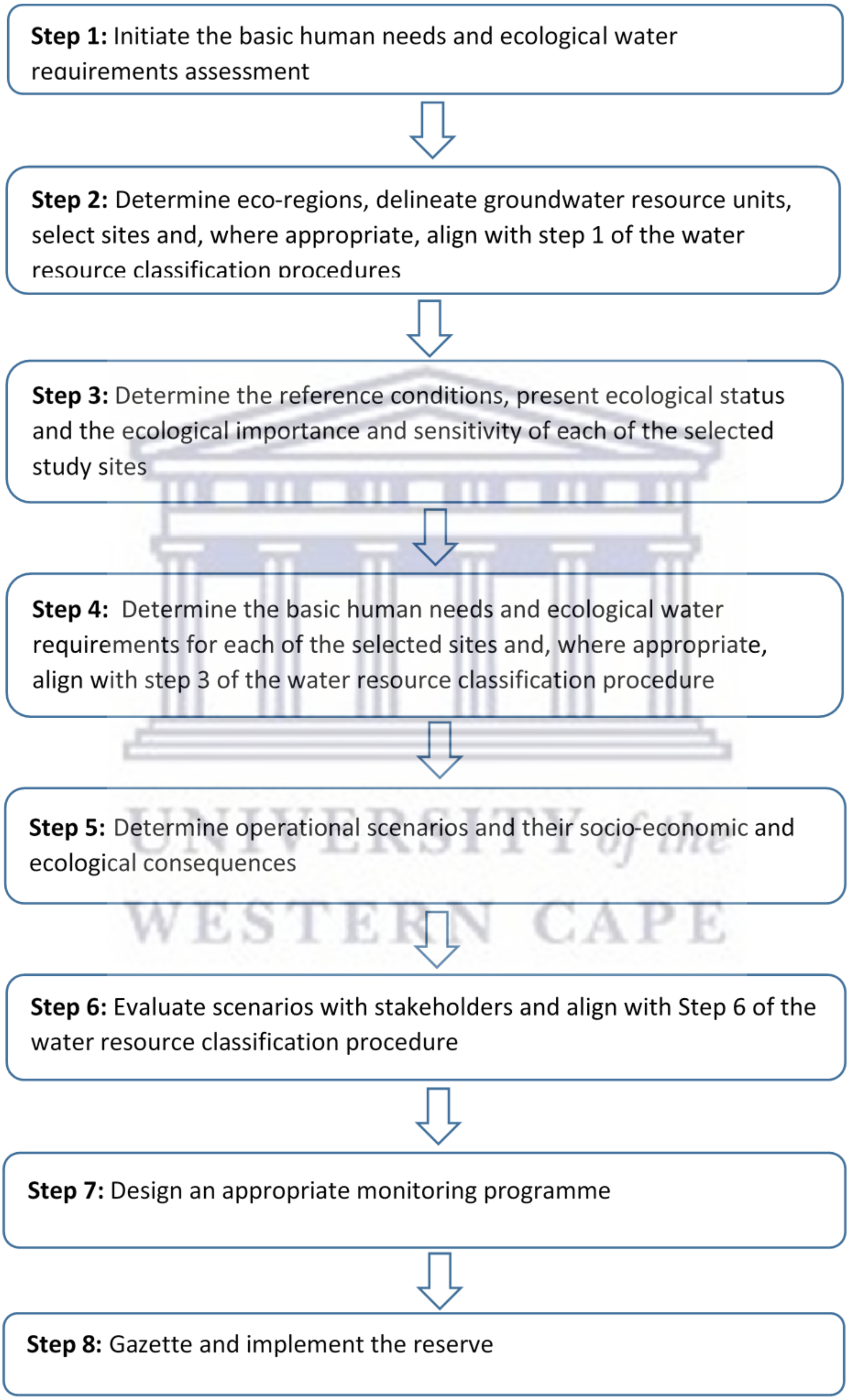
Annexure 5.3: Selected variables forming each of the four WEFE Nexus components

WEFE Components	Sub- Components	Variables for Sub- component
WATER	Water Users	Agricultural Use Aquatic Ecosystem Use Domestic use Industrial Use Recreational Use
ENERGY	Energy Source	Biofuel-Powered Energy Production Coal-Powered Energy Production Hydro- Powered Energy Production Underground Gas Exploration
FOOD	Food Production	Animal Production Crop Production Food Processing
ENVIRONMENT	Life on Land	Protected Areas of National Importance
	Life in Water	Aquifers Dams / Lakes Estuaries Rivers Wetlands
	Atmosphere	Weather Conditions

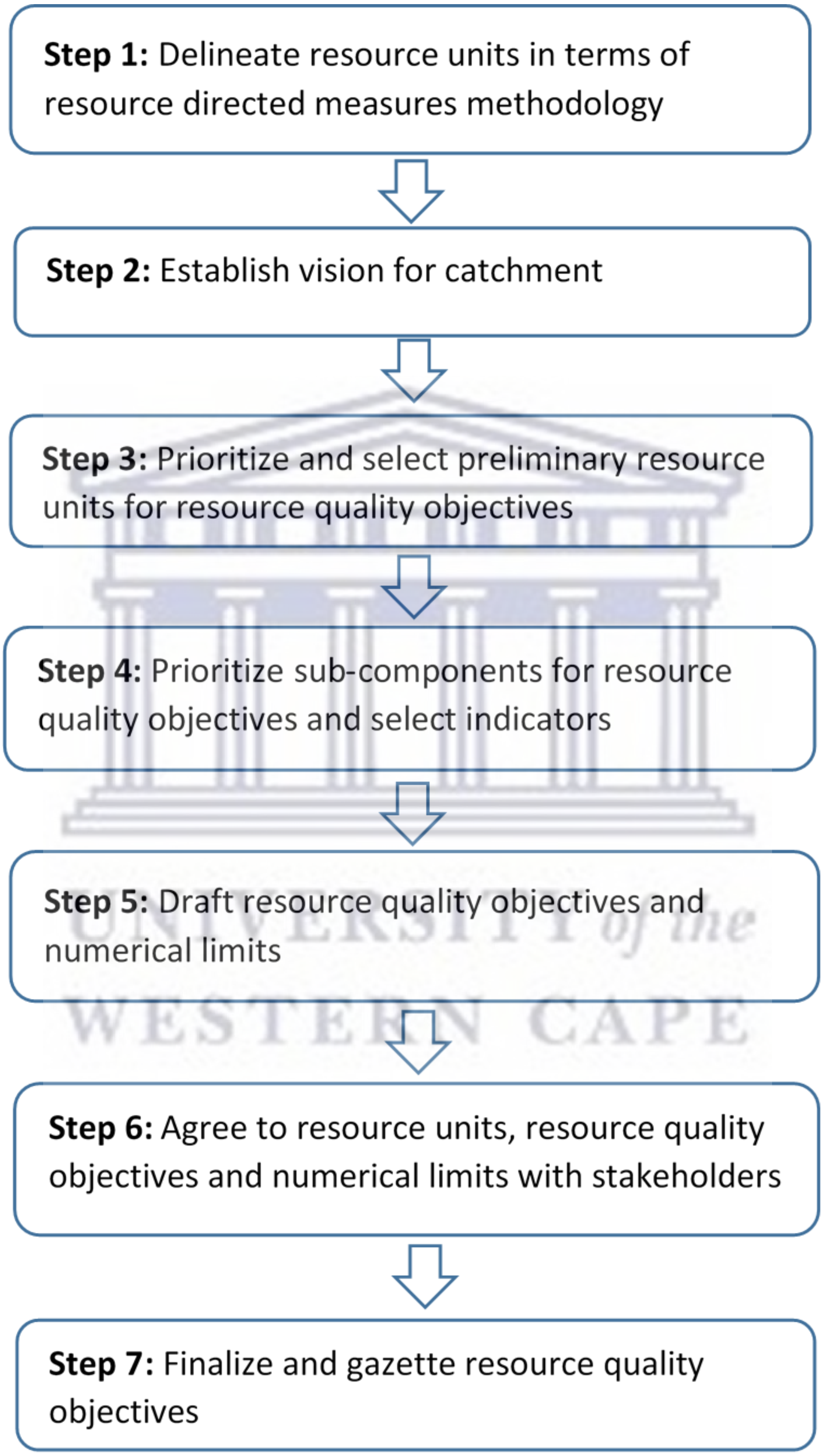
Annexure 5.4: The 7-step procedure to determine water resource classes



Annexure 5.5: The 8-step procedure to determine the water resource reserve



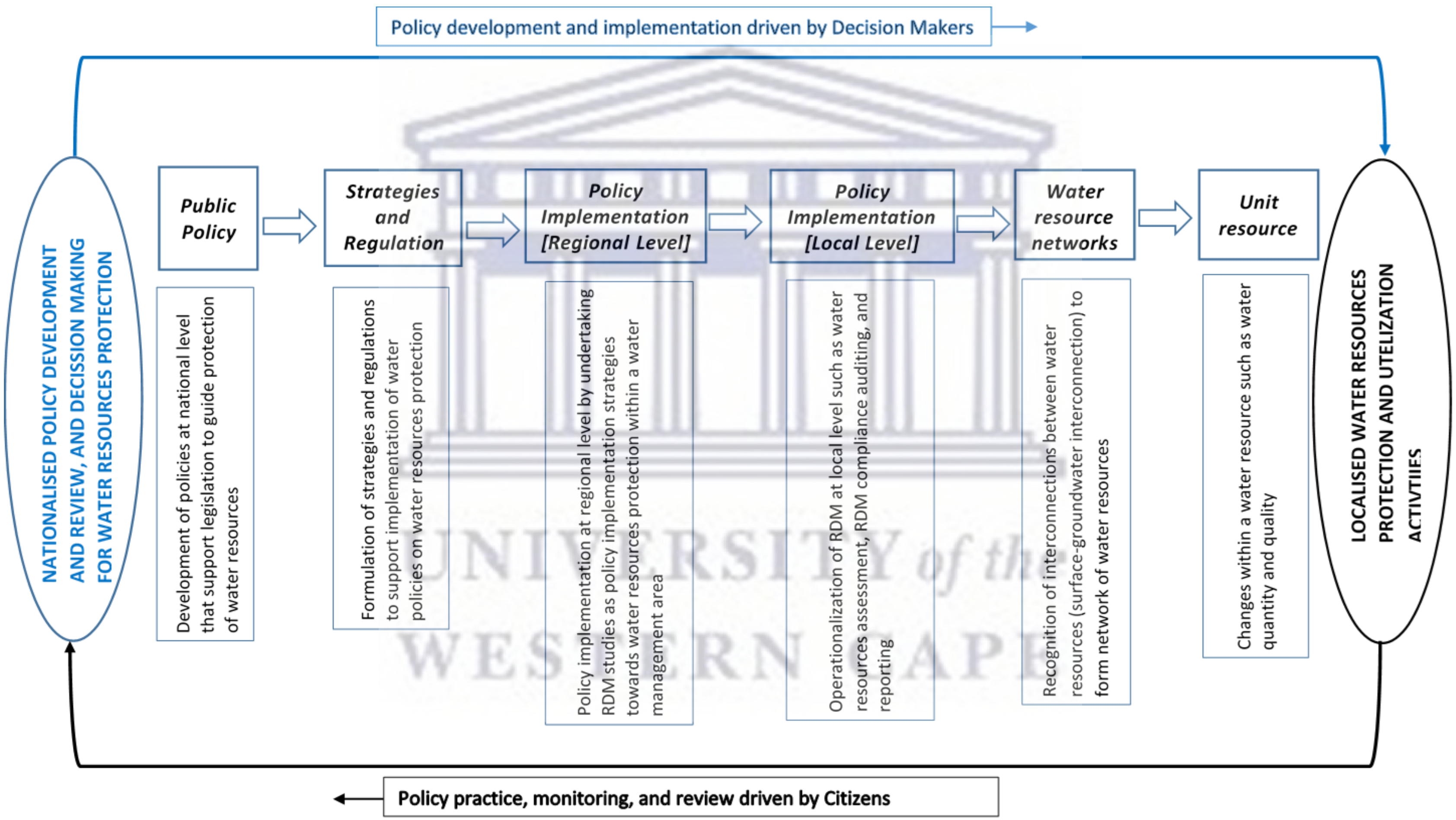
Annexure 5.6: The 7-step procedure to determine resource quality objectives



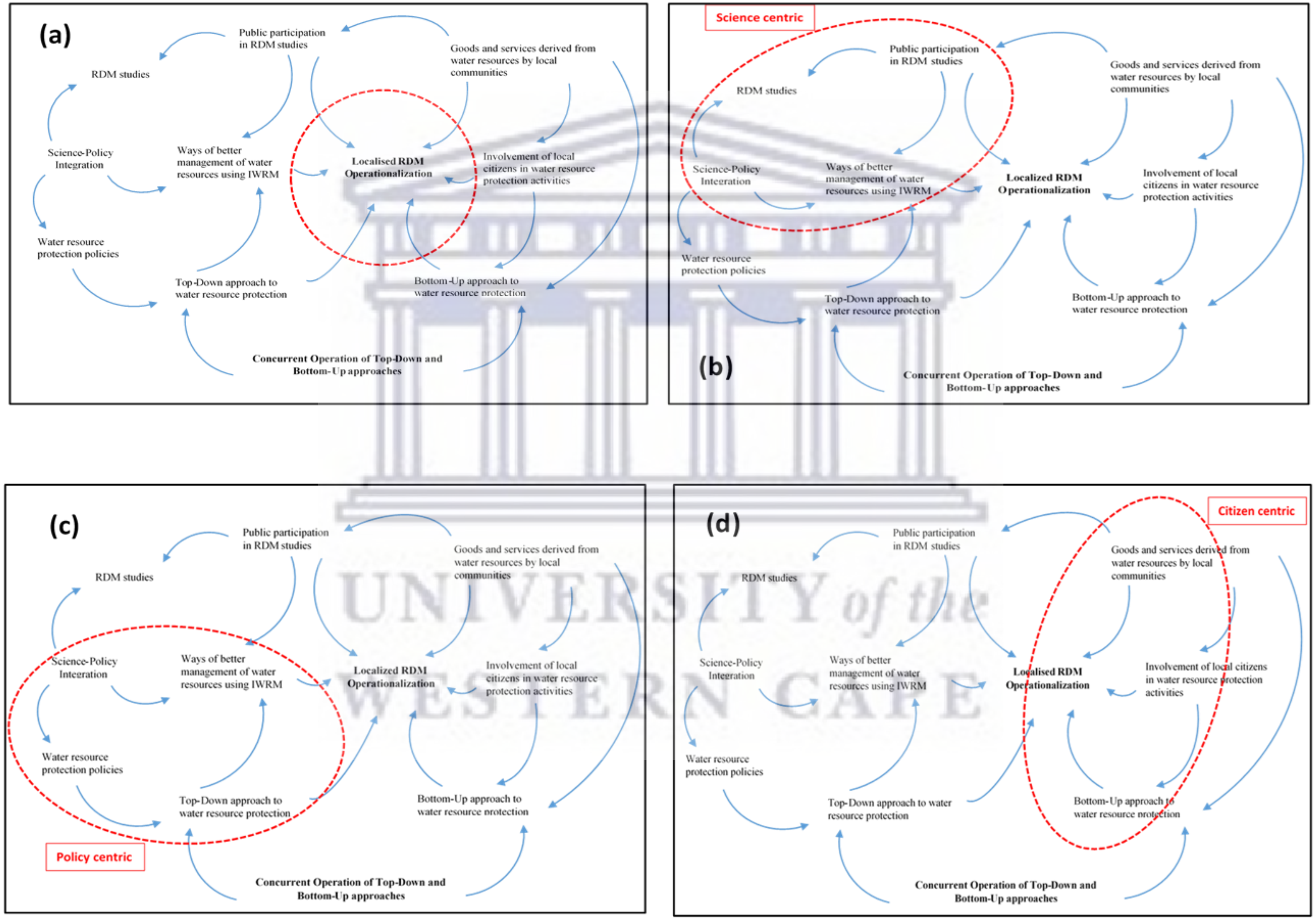
Annexure 5.7: Application of the Gibbs Reflective Cycle Model (GRCM) in the context of WEFE nexus towards water resources protection

Stage	Related Question	Context
1. Description	What happened?	A brief description of how capacity building activities are undertaken using private-public partnership to ensure that water resource protection practices are sustained
2. Feelings	What were the feelings and thoughts?	Brief explanation on the feelings and experiences before, during, and after capacity building activities had been undertaken
3. Evaluation	What was good and bad about the experience?	An objective retrospection about negative and positive aspects of undertaking capacity building activities through a private-public partnership
4. Analysis	What sense can be made of the situation?	An analysis of key factors that led to negative or positive experience about undertaking capacity building activities using private-public partnership
5. Conclusion	What else could have been done?	Conclusion about observations, lessons learned, challenges experienced, and accomplishments about what have been learned about undertaking capacity building activities using private-public partnership
6. Action Plan	What actions could be taken in the future?	Outline of action plans that could be applied in future to build on knowledge and skills acquired for better improvement on water resource protection practices sustainability

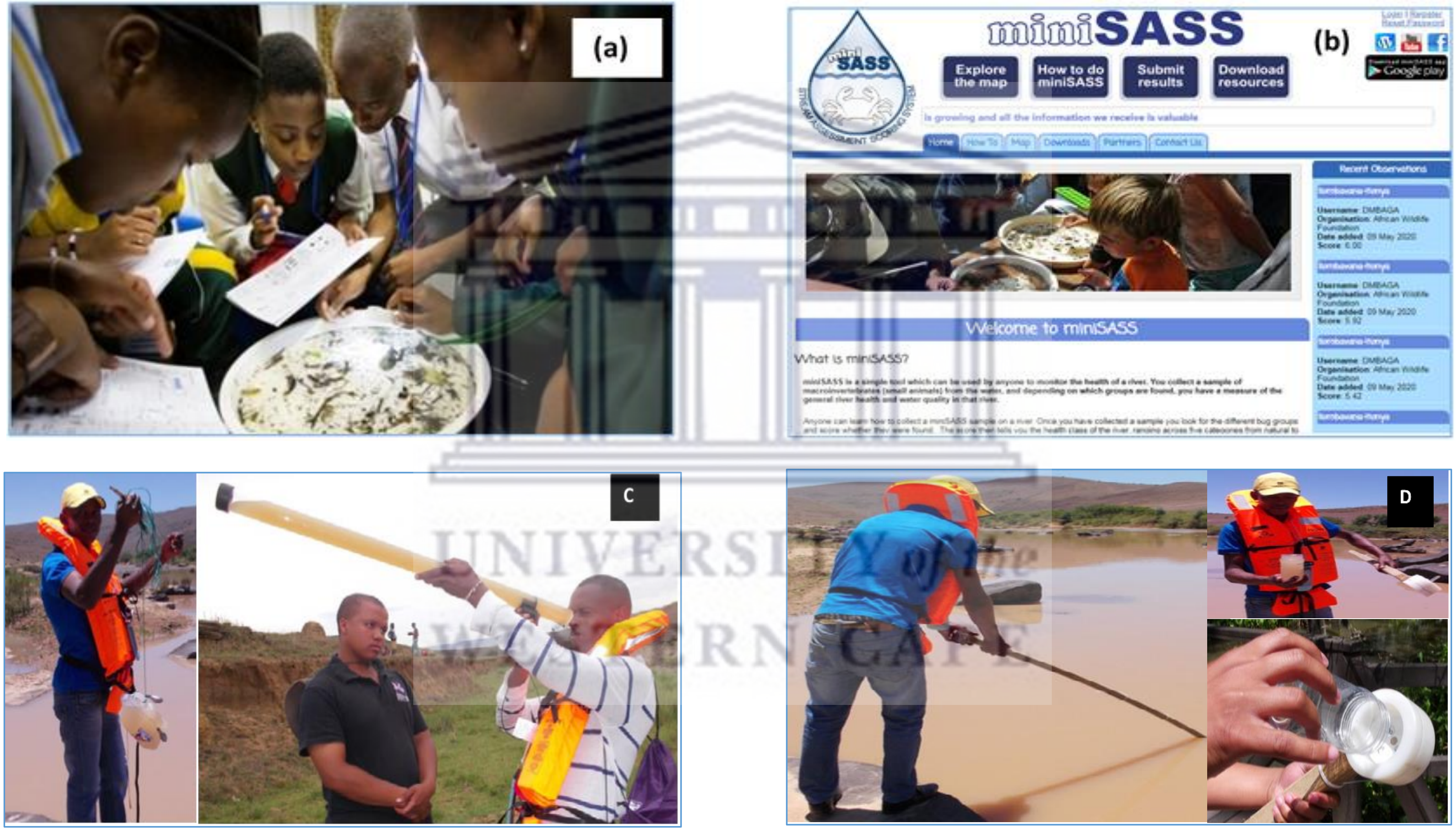
Annexure 5.8: Identified framework themes and levels of influence forming a proto-Citizen Science Framework (CSF)



Annexure 5.9: Influence diagrams showing policy, science, and citizen centrism of the Citizen Science Framework



Annexure 5.10a-d: Water quality data collection and capturing by trained local citizens (Cele, 2015; Bannatyne et al., 2017)

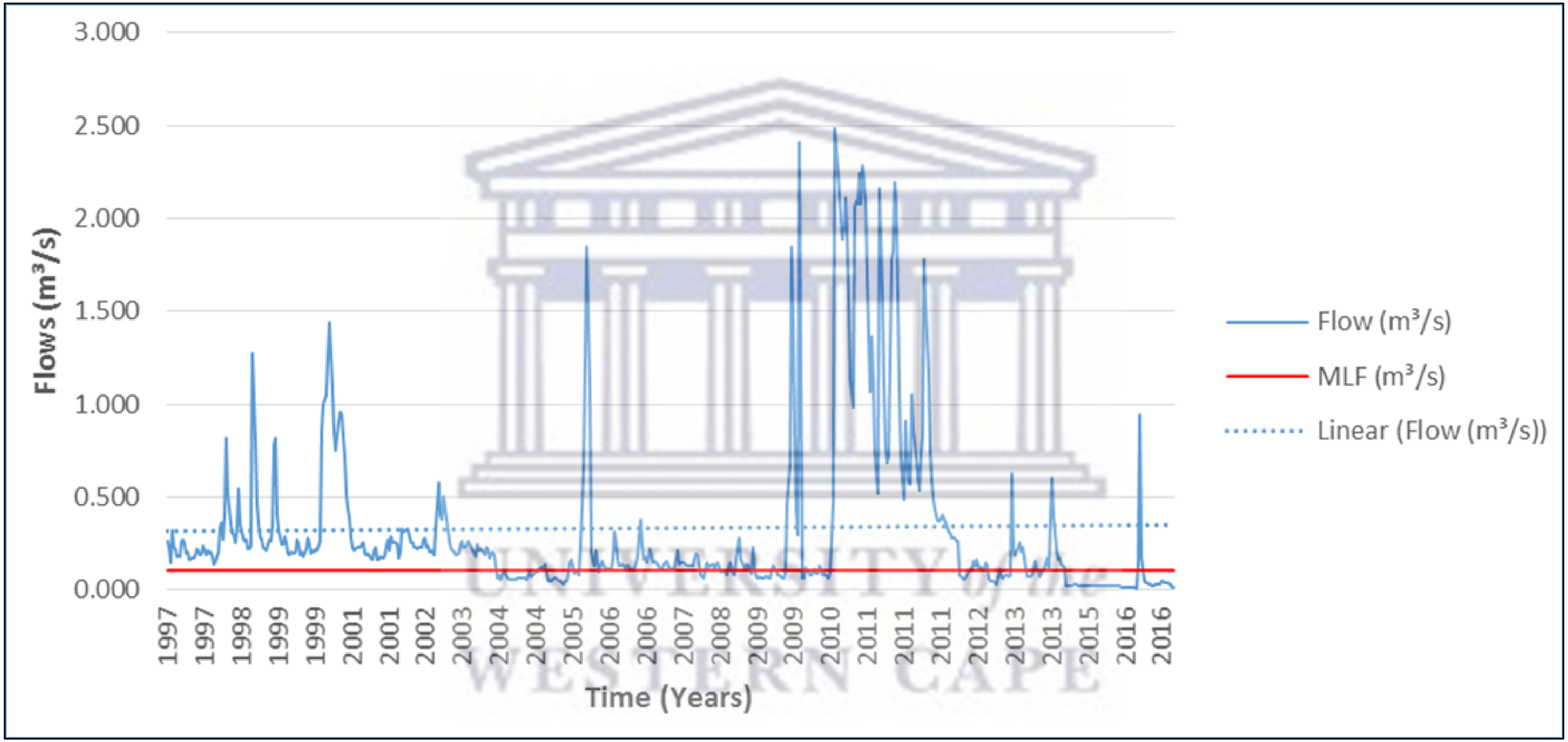


Annexure 5.11: Numerical limits for RQOs linked to Ecological Water Requirements in the study area

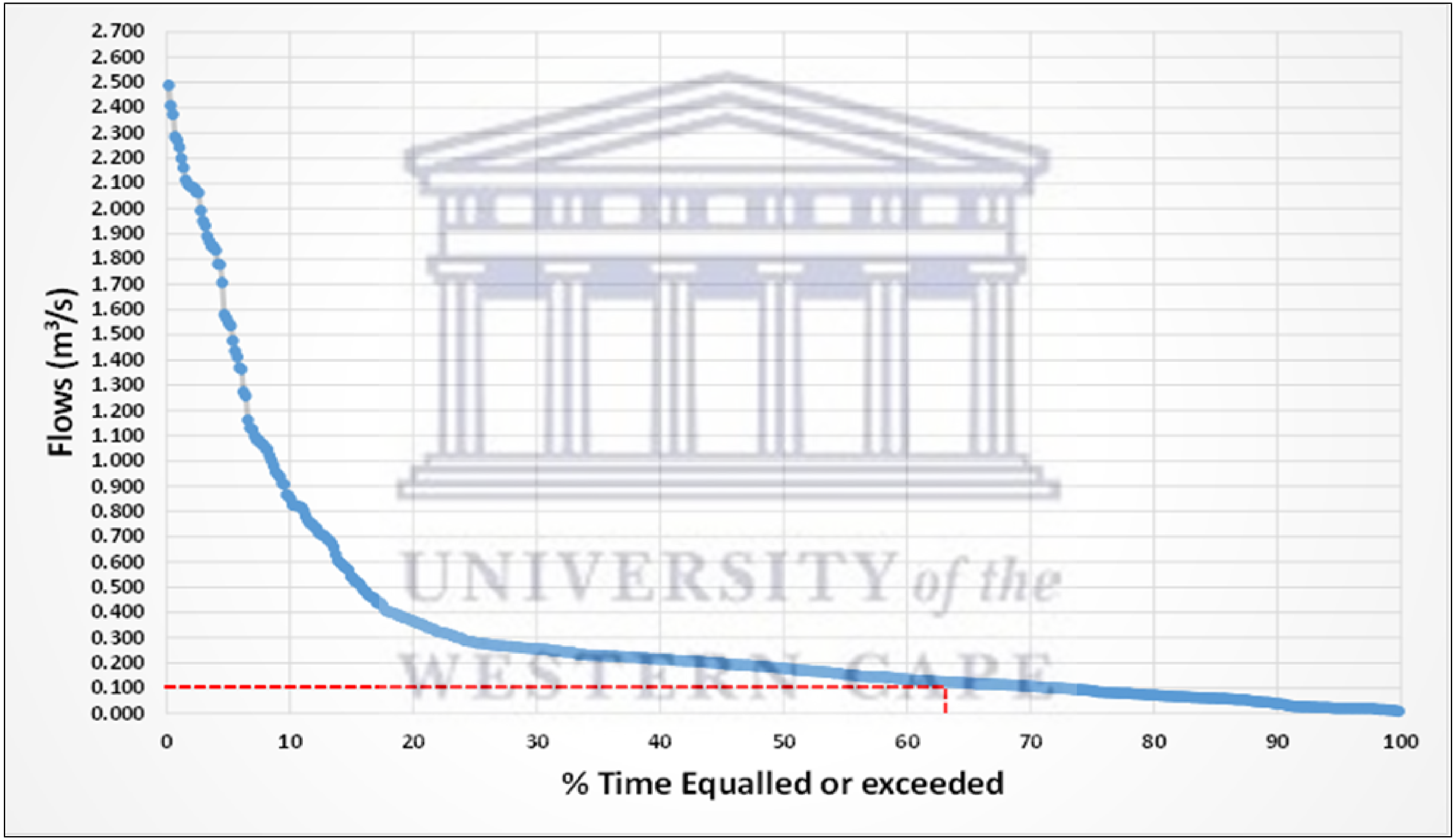
Table 6-3: Resource Quality Objectives for RIVERS AND DAMS in priority Resource Units in the Integrated Unit of Analysis MC SCHOONSPRUIT

River/Dam	RU	Component	Sub-component	Resource Quality Objective	Indicator/measure	Numerical limit					Context of the RQO/ Numerical limit
						Month	*Maintenance Low Flows*		*Drought Flows*		
							m^3/ *second*	*Per-cen-tile*	m^3/ *second*	*Per-cen-tile*	
		Quantity	Low flows	The maintenance low flows and drought flows must be attained to support a healthy condition for the ecosystem and users.	Total EWR (node MC5) = 4.691 million cubic metres/annum (Mm^3/a) (17.91% of the Virgin Mean Annual Runoff) (VMAR) Maintenance flows (percentage value of naturalised flow distribution) Drought flows (percentage value of naturalised flow distribution) The mine water and wastewater treatment works discharges in relation to the required instream flows will have to be managed in future to ensure the maintenance low in the river.	Oct	0.0202	70	0.0037	99	Implementation of the rule and tab tables (Appendix B) as specified in terms of the Water Resource classification study (DWA, 2012). Flows specified are to maintain ecological categories of the water resource in prescribed ecological state and meet the Management Class set. Percentiles (of required flow rate) determined through EWR determination process as per application of appropriate Reserve models and methodology (rule curves).
						Nov	0.0409	80	0.0039	99	
						Dec	0.0571	40	0.0112	99	
						Jan	0.1038	40	0.0112	99	
						Feb	0.1682	40	0.0165	99	
						Mar	0.2012	70	0.0149	99	
						Apr	0.1246	60	0.0000	99	
						May	0.0504	50	0.0037	99	
						Jun	0.0243	70	0.0039	99	
						Jul	0.0179	70	0.0000	99	
						Aug	0.0138	80	0.0000	99	
						Sep	0.0104	70	0.0000	99	

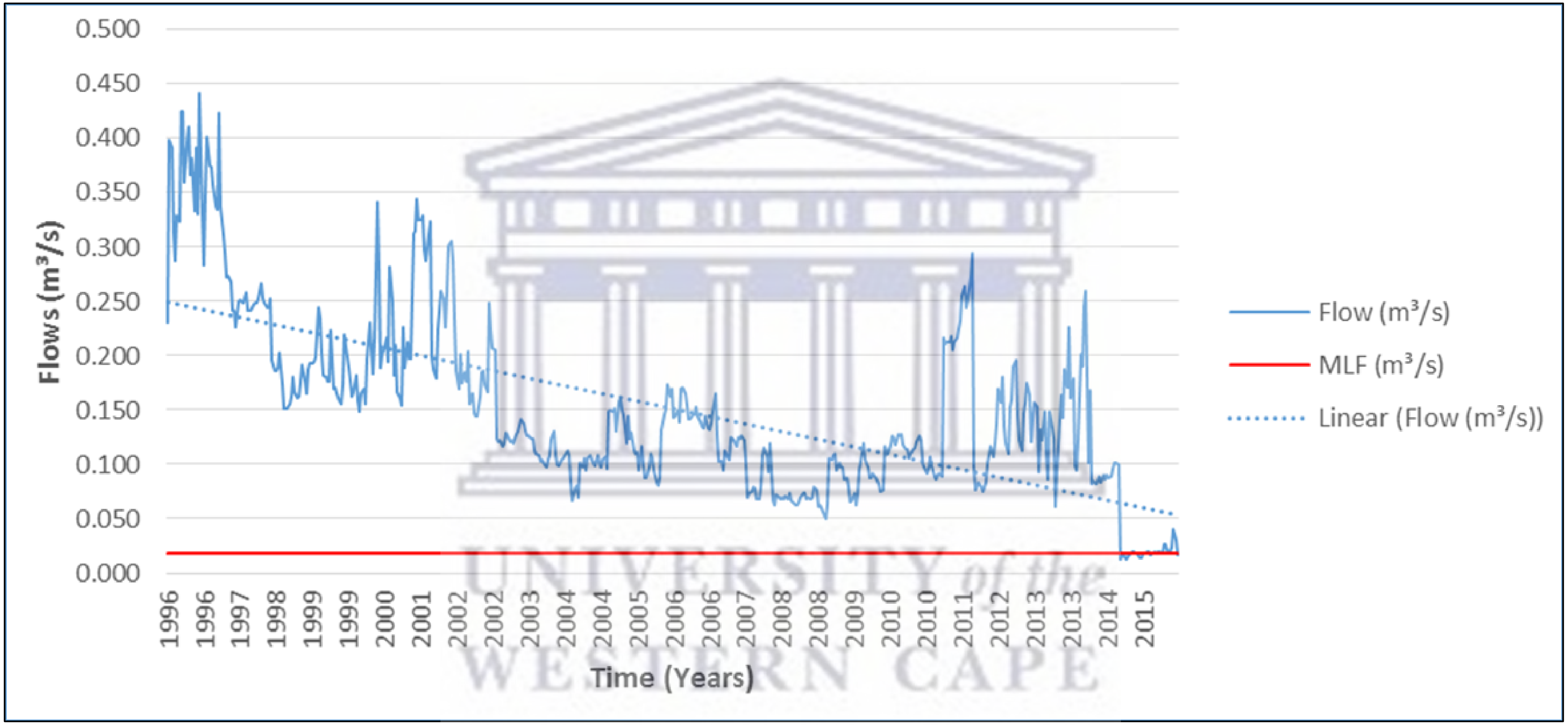
Annexure 5.12: January flow variability from 1997 to 2016 at C2H139Q01 monitoring site



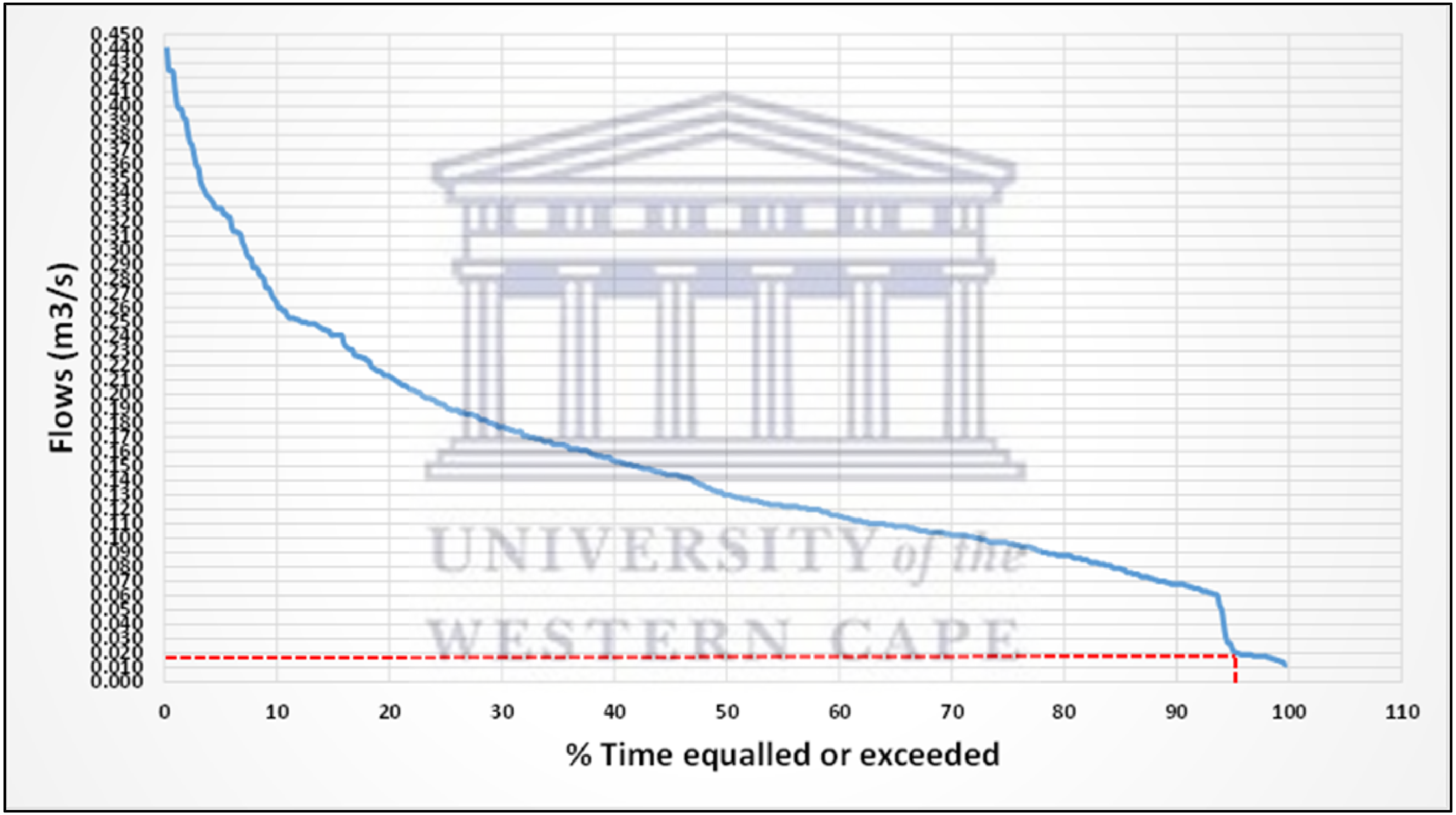
Annexure 5.13: Flow duration curve showing percentage time equalled or exceeded for January from 1997 to 2016 at C2H139Q01 site



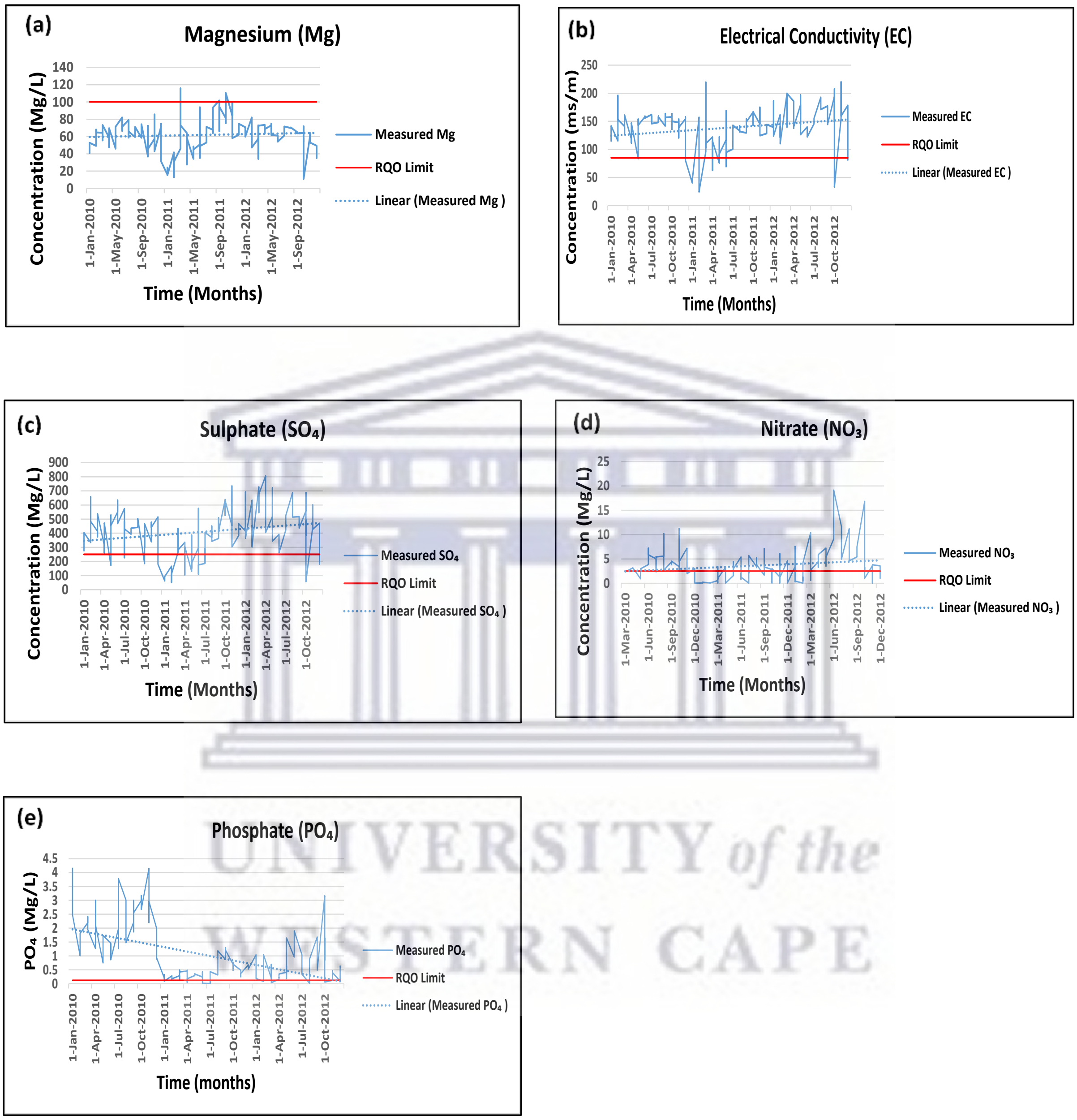
Annexure 5.14: July flow variability from 1997 to 2016 at C2H139Q01 monitoring site



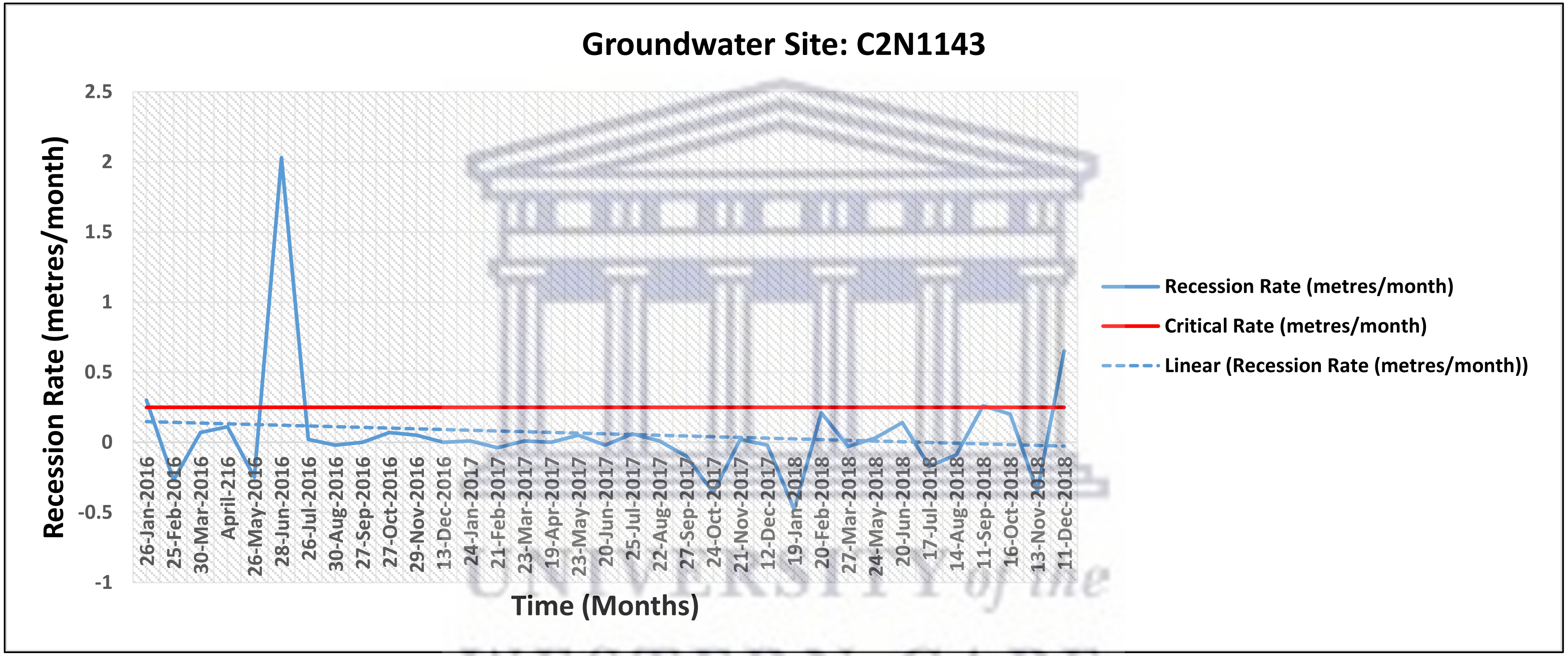
Annexure 5.15: Flow duration curve showing percentage time equalled or exceeded for July from 1997 to 2016 at C2H139Q01 site



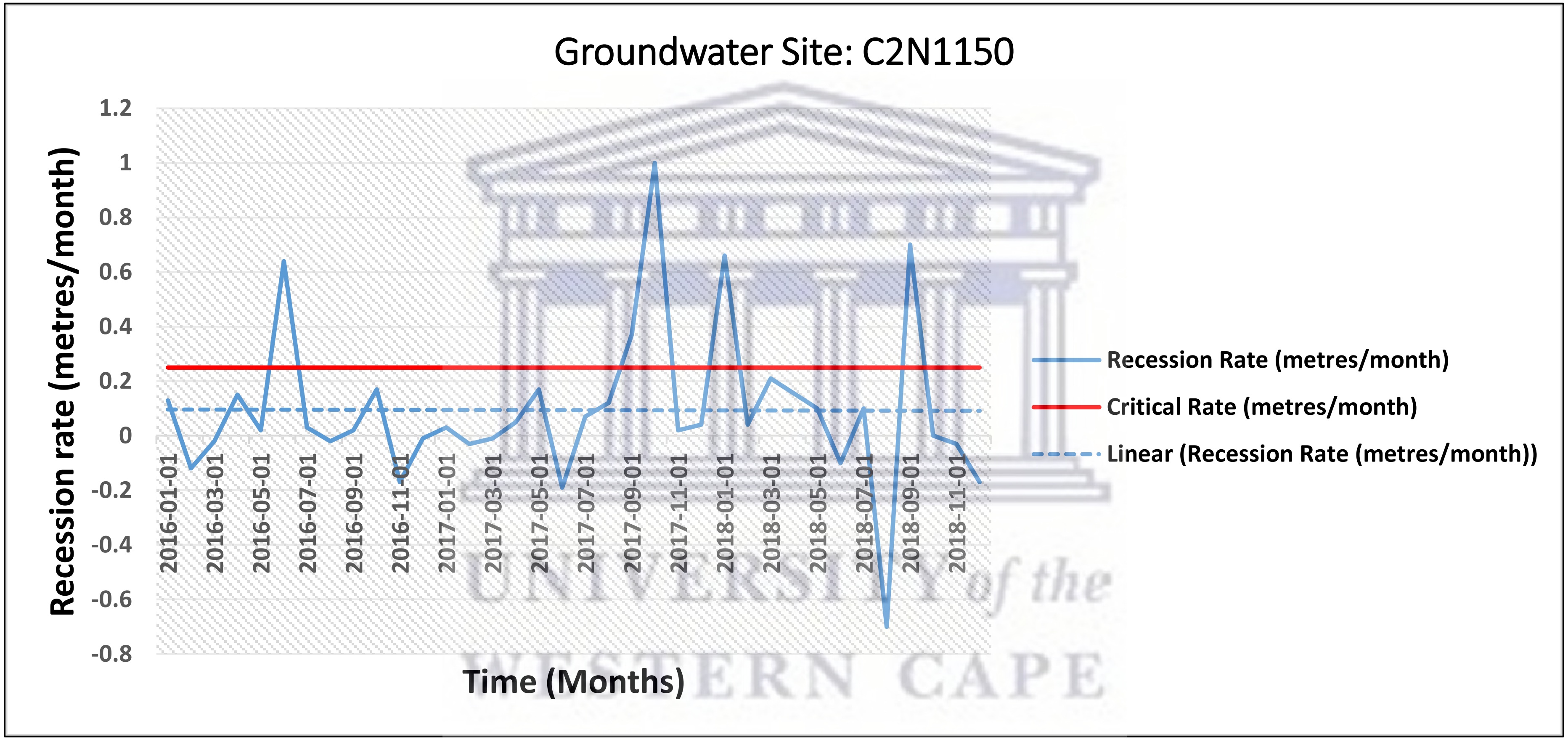
Annexure 5.16a-e: (a) Concentration levels for Magnesium (Mg), (b) Electrical Conductivity (EC), (c) Sulphate (SO_4), (d) Nitrate (NO_3), and (e) Phosphate (PO_4) measured at C2H139Q01 monitoring site



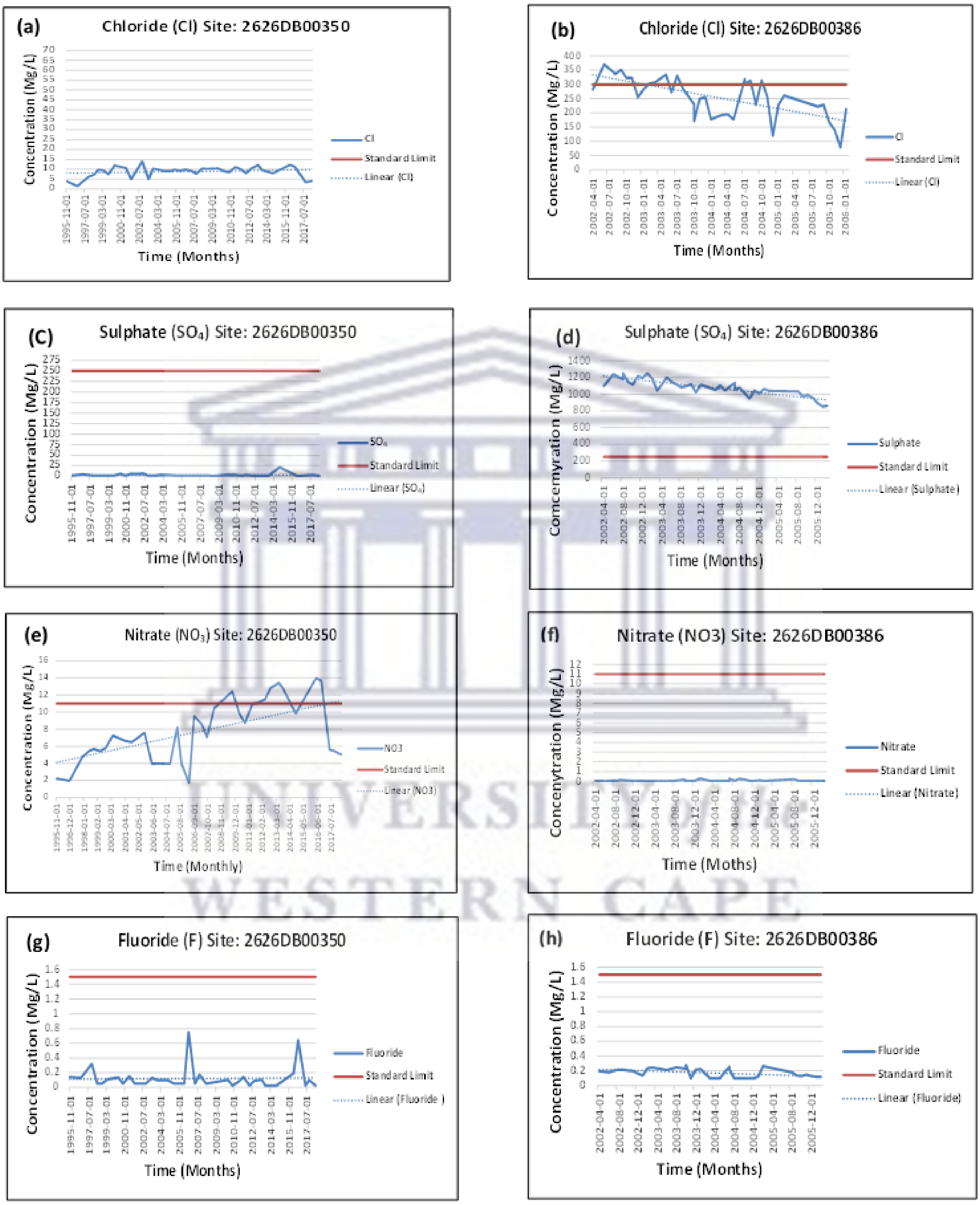
Annexure 5.17: Groundwater recession rate as compared to resource quality objective critical rate at groundwater site C2N1143



Annexure 5.18: Groundwater recession rate as compared to resource quality objective critical rate at groundwater site C2N1150



Annexure 5.19a-h: Concentration levels of groundwater quality assessed at 2626DB00350, and 2626DB00386 groundwater sites

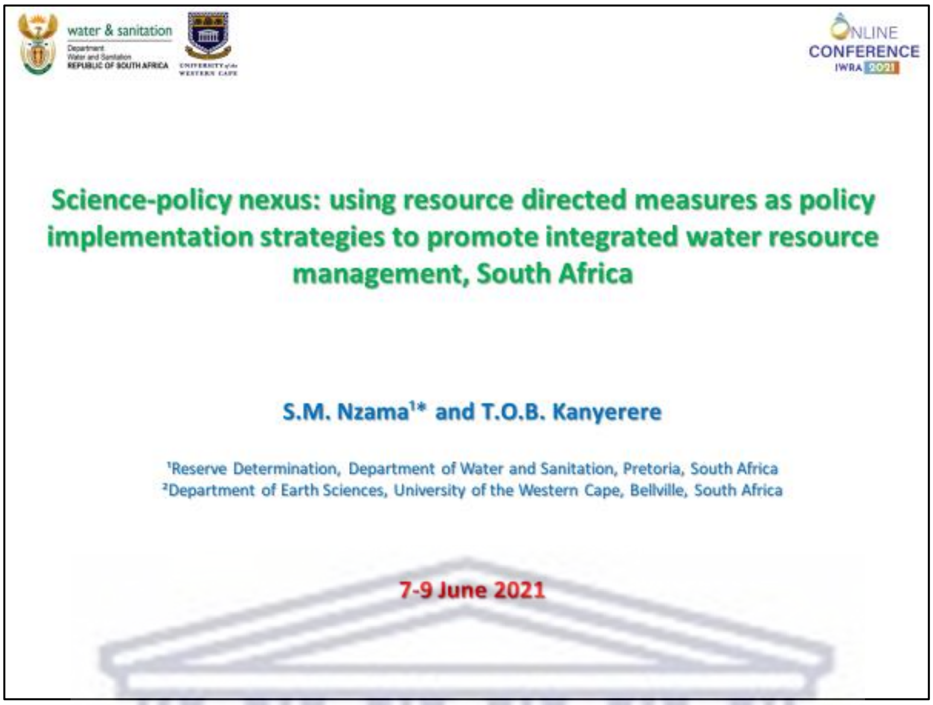


APPENDICES

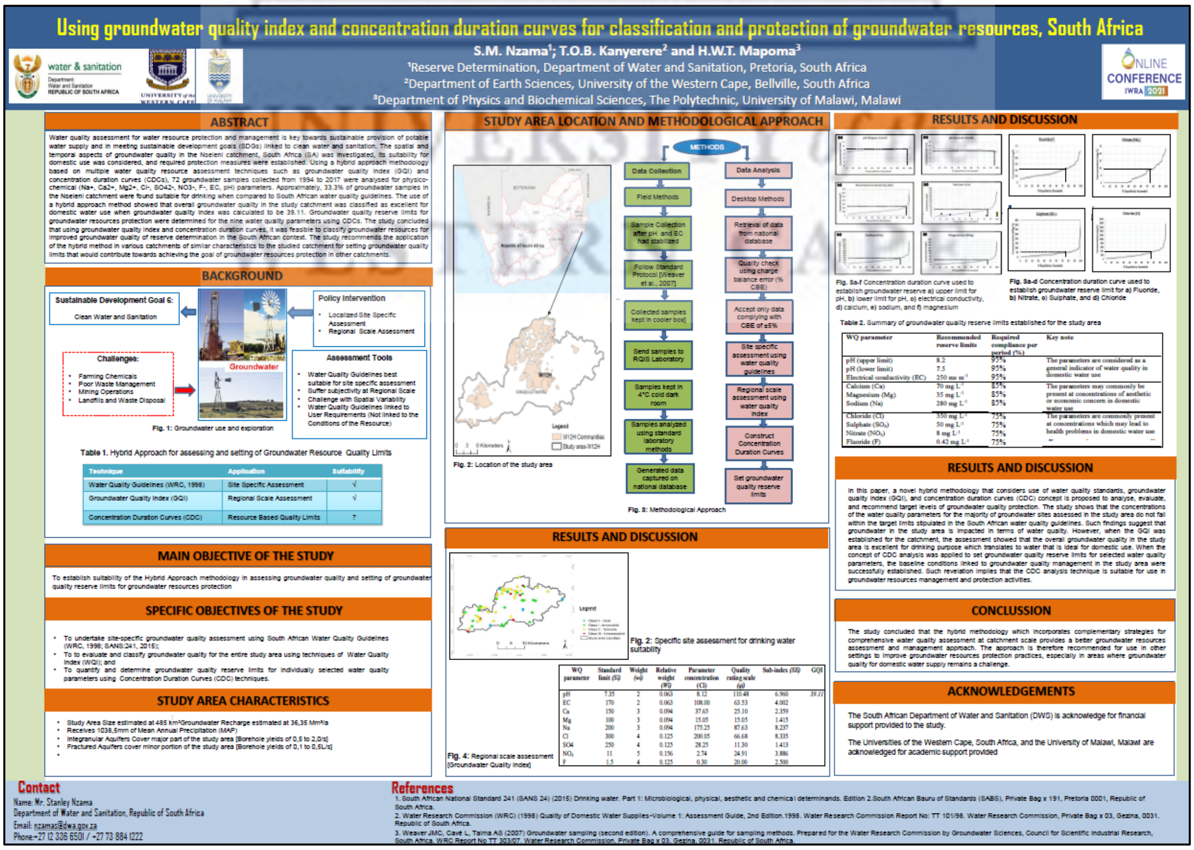
Appendix 1: Presentation at Conferences (Oral Presentation)

Nzamas, S., Levine, A., & Kanyerere, T. (2019). Groundwater resources protection: Reflection on relevance of groundwater quality component of reserve for provision of clean water and sanitation. The paper was presented at the 2nd Southern African Development Communities (SADC) Groundwater Conference titled: Groundwater contribution to achievement of Sustainable Development Goals in the SADC Region: Johannesburg, South Africa, 4-6 September 2019.

- *Nzama S.M., & Kanyerere, T.O.B. (2021). Science-policy nexus: using resource directed measures as policy implementation strategies to promote integrated water resource management, South Africa.* Oral presentation at the International Water Resources Association (IWRA) online conference, 7-9 June 2021.



- *Nzama, S.M., Mapoma, H.W.T., & Kanyerere, T.O.B. (2021). Using groundwater quality index and concentration duration curves for classification and protection of groundwater resources, South Africa.* Poster presentation at the International Water Resources Association (IWRA) online conference, 7-9 June 2021.



Appendix 2: Journal Article Publication

Nzamas, S.M., Mapoma, H.W.T., & Kanyerere, T.O.B. (2020). Using groundwater quality index and concentration duration curves for classification and protection of groundwater resources: Relevance of groundwater quality of reserve determination, South Africa. Paper published to the Journal of Sustainable Water Resources Management, DOI Number: https://doi.org/10.1007/s40899-021-00503-1