SUSTAINABLE GROUNDWATER MANAGEMENT THROUGH MODELLING OF SELECTED HYDROLOGICAL PARAMETERS: A CASE STUDY OF THE MODDER RIVER CATCHMENT OF SOUTH AFRICA

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DECLARATION OF INDEPENDENT WORK

I, Rebecca Alowo, identity number and student number , hereby declare that this research project submitted to the Central University of Technology Free State, for the doctorate: Engineering in Civil Engineering, is my own independent work; complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology Free State and has not been submitted previously to any institution by myself of any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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Signature of student **Date**

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Thank you.

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EXTENDED ABSTRACT

Farmers and water users in arid and semi-arid zones of South Africa have a limited number of water resources. With 98% of South African surface water already allocated and committed, there is an increasing demand for use of groundwater through the use of wells and boreholes.

This study was carried out in the Modder River catchment, which is a sub-catchment under the larger Orange River system. increased population growth and increasing urbanisation have negatively affected water resources in the Modder River catchment since 2000. The population of the Modder River catchment increased from 618 566 in 2001 to an estimated 1 083 886 in 2016. This resulted in increasing water demand and excessive pumping of groundwater, particularly for agriculture and drinking water. At 351 million litres, the Bloemfontein area and Modder River catchment has the highest demand for water in the Upper Orange River Catchment.

Other negative effects are increased degradation of the environment, high levels of human-induced climate changes, and high variability of the natural climate. The net effects have been depletion of aquifers and prolonged periods of drought, which points to a lack of effective groundwater resources management tools and laxity in monitoring groundwater as a resource. Globally, the general trend is to adapt models and artificial intelligence to manage water resources sustainably. Groundwater sustainability models that incorporate artificial intelligence, may be used to enhance the governance of aquifers. Lack of such models is what motivated this research. This was achieved through the development of groundwater sustainability models/indices and information communications technology-based framework for groundwater monitoring that makes use of artificial intelligence to reach informed decisions for improved groundwater management.

The research was guided by a theoretical framework design, which included sustainability modelling of the interactions of the elements and physical processes linking the hydrological cycle with human instigated factors in connection with groundwater. These interactions were climate and utilisation of groundwater, surface water-groundwater water linkages and climate-groundwater interaction connections in hydrological parameters. The parameters were weighted and scored and included precipitation, slope, vegetation cover, evapotranspiration, climatic zones, water quality, aquifer yields, soil composition, aquifer sustainability, population, water use categories, the permit framework and groundwater rights. These parameters were grouped into the following; Factor A: climate, Factor B: rights and equity versus resources,

Factor C: socio-economic matters and Factor D: aquifer sustainability. Delphi techniques of scoring and rating were applied. Scores were assigned with the lowest scores of one relating to poor practices and the highest score of five relating to adequate practices. Climate (Factor A) and aquifer sustainability (Factor D) were summed up to an aggregate score of 30 each, while rights (Factor B) and socio-economic aspects (Factor C) had separate scores of 20 each. The groundwater sustainability range had 19 (slightly reasonable) and 100 (profoundly feasible) scores.

The developed sustainability indices were applied to 51 boreholes in the Modder River catchment of South Africa, for which consent was obtained for the study. These boreholes were both government and private boreholes. ArcView GIS was used to demonstrate the results for each factor for the 51 boreholes towards the groundwater sustainability concept. The sustainability class in the Modder River Basin ranged from low to moderate sustainability. The results showed that only 11 boreholes were sustainable, implying that they were reasonably maintainable. The other 40 boreholes had low sustainability scores, which indicated that they were not sustainable. The moderate sustainability class was typical of areas with extensive dolerite, low slopes, and low recharge.

In order to validate the results, plots of over 70 years of rainfall data and evapotranspiration data of the Modder River Basin catchment were generated. This was to indirectly account for a mini-water balance and how much was available for groundwater recharge. It was found that rainfall was significantly lower than evapotranspiration, which meant there was more evapotranspiration than recharge for long periods of time. The Modder River catchment received its highest bout of rain in 1971/1972. The sustainability maps showed areas with low sustainability scores correlating with areas with a low aquifer sustainability factor since low recharge related to the low sustainability scores.

A further validation analysis was carried out on the final sustainability map, the river network map and recharge map of the study area, as extracted from the countrywide recharge map of South Africa. High groundwater recharge areas (over 34 mm) were found in the eastern and south-eastern parts of the study area. These areas corresponded with high river network presence. The central and western parts of the study area were marked by lower groundwater recharge values (below 12 mm). This was consistent with the derived sustainability final index maps. There was a high correlation between the sustainability index map, the drainage basin map and the recharge map. The final sustainability map value was plotted against measurable parameters (pumping rate, aquifer yield). In this thesis, a calculation of the correlation coefficient values was low at 1.04%, indicating no positive correlation or reinforcement. In addition, the plots of the comparison of the calculated indices with the measured physical values on one hand, and an analysis of the actual end users' validation done to assess the ability of the sustainability index on the other hand, were presented as the final sustainability map value against a measurable parameter storativity (aquifer yield). For this, significant similarity between the storativity plot and the sustainability index map was observed.

Furthermore, the results showed that the ideal pumping rate should be 138 080 cubic metres per year per borehole. This means that only this amount may be pumped, without disturbing the dynamic equilibrium of the aquifer. This pumping rate would support the capture principle approach for the C52 catchment. Currently, the average pumping rates is higher than the aquifer yield. The majority of the points on the major plotted graphs were below the best fit line. This meant that the boreholes were abstracted at a rate that was higher than the aquifer yield. With this finding, the researcher calculated and recommended pumping rates/volume of water for each borehole. This meant that only that amount may be pumped without disturbing the dynamic equilibrium of the aquifer. This pumping rate would support the capture principle approach for the C52 catchment. The recommended pumping rates were based on applying the corrected formula: Pumping rate = 157 397x + 138 080, which was derived after the pumping rate analysis. The recommended pumping rates were proposed because the moderate to low classes represented areas that were the opposite of a favourable scenario: overly high abstraction activity, unfavourable climatic conditions, and slow to little groundwater processes and interactions (high or steep slopes and low rainfall).

From the graph of storativity versus licensed volume that was plotted, this research revealed that higher volumes were licensed, compared to the storage volume of the aquifer. The findings on the final sustainability map provided in this thesis further correlated to this. There was no correlation between the pumping rate/licensed volume and the storativity of C52.

The findings above confirmed the widely documented challenges of groundwater monitoring in the southern African region that most of the water administrative authorities continue to face. One of the reasons is that many water clients do not submit the required compulsory critical data for effective monitoring of water use. This, combined with the absence of limits by water authorities regarding boreholes dug by permit holders, has led to difficulties in decision-making and groundwater conservation. To address this, the potential of artificial intelligence in groundwater management is explored in this research. A framework that makes use of artificial intelligence in groundwater management is proposed. The aim of this framework is to increase the success chances of groundwater management, conservation, and sustainability by means of a monitoring system through real-time updates and early warning signals to water management, and to, thus, reinforce positive behavioural practices on water abstraction and effective water usage. With this, groundwater consumers will have the means to gauge when they are using too much water and municipalities will have the means to gauge if a catchment is over-abstracted. The net gain or impact will be water savings, cost savings and preferable performance of provinces, municipalities and departments that manage water. Besides, once implemented, this framework would ensure automation of the sustainability modelling of groundwater system discussed in the thesis. This would result in an efficient catchment monitoring, allocation, licensing, and characterisation for an effective groundwater management system.

Keywords: Hydrology models; Sustainability of groundwater; Sustainability index; Upper Orange River, C52 catchment; Modder River catchment; Artificial intelligence.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
ANNs	Artificial Neural Networks
BIWSI	Blue Water Sustainability Index
BPN	Back Propagation Network
CALVIN	California Value Integrated Network
C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
GIS	Geographical Information Systems
GPS	Global Positioning System
GRI	Global Reporting Initiative
ICT	Information Communications Technology
IoT	Internet of Things
ISDR	International Strategy for Disaster Reduction
SADC	Southern African Development Community
SMS	Short Message Services
SWAP	Soil-Water-Atmosphere-Plant
SWAT	Soil and Water Assessment Tool
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USSD	Unstructured Supplementary Service Data
WCED	World Commission on Environment and Development
WMA	Water Management Area
WMO	World Meteorological Organization

LIST OF SYMBOLS AND CHEMICAL ELEMENTS

Ca	Calcium
ha	hectare (10 000 square metres)
ℓ/s	litre per second
ℓ/c/d	litre/capita/day
m	metre
m^3	cubic metre
Ma	million years ago
masl	above sea level
Mg	Magnesium
mg/ℓ	milligram/litre
mm	millimetre
m^3/d	cubic metres per day
Na	sodium

Chapter 1

INTRODUCTION

1.1 Background

Tomer and Wheaton (1996) defined a model as “the symbolic form in which a physical principle is expressed. It is a series of equations or formulae with extremely important distinctions, which are that they were built by considering the pertinent physical principles, operated on by logic, and modified by experimental judgment and plain intuition.” Hydrological models remain a basic layout of the hydrologic cycle. They assist in the interpretation of hydrological processes at catchment level and other spatial scales (Dingman, 2015). Research has contributed to groundwater models currently being used to provide predictions and estimations of aquifer properties. These groundwater models have many uses and are also used at other spatial scales, which are all components of water resource management (Gayathri et al., 2015). Outputs from such models have been applied to a wide range of work, from regulation to research. One common characteristic of models is that they should be tenable, sound, and robust (Chow et al., 1988; Teng et al., 2017).

A model is physically based and it aims to represent conversations of mass and energy equations for the hydrological processes. In many hydrological processes, which cannot be solved analytically, models such as nonlinear partial differential equations (Beven, 2001) and the Soil and Water Assessment Tool (SWAT), are used as examples of a physical hydrological model (Brunner & Simmons, 2012). The shortcomings of models lie in the identification of hydrogeological conditions, changes in groundwater recharge, errors in output flows, and modifications of water mining schedules (Buck, 2016).

There are concerns regarding surface and groundwater abstractions. Boreholes generally have an effect close to the point where groundwater abstraction takes place. It ought be guaranteed that the groundwater demands do not contravene the value supply requirements from aquifers. While surface water accessibility, on the other hand, is constantly configured at catchment scale for various levels of catchment, groundwater should be assessed at the scale or level of the autonomous aquifer. In this way, for instance, considering whether Hermanus in the Western Cape has a permit for the deliberation of 1.6 million litres of water from the nearby aquifer, means that it is anything more but a borehole that has been authorised. For the use of an aquifer that has been assessed to be economically viable, with an adequate volume for this assignment, it could take 5, 10 or 20 boreholes to convey this volume of water from the aquifer to Hermanus, with the borehole diameter reliant on the fundamental geohydrology (MacDonald et al., 2012). This can be considered a valuable case because when the yield of an aquifer has been resolved, it would be sensible to accept that water use licenses for those boreholes could be issued up to the largest quantity that can be provided by that aquifer. If catchment scale and supply issues are considered, it should be investigated whether there are hydrological motivations why such licenses ought be issued to candidates or not. Undoubtedly, if the groundwater capacity of South Africa is to be acknowledged at that point, permit experts should review this approach (MacDonald et al., 2012).

According to Roberts (2017), water use in South Africa is closely aligned with economic and population-related activities and as well as to climate change. At 450 mm, the average annual rainfall of South Africa is low and below the world average of about 860 mm per year (Department of Water Affairs [DWA], 2013a). In global terms, the classification of South Africa as “water short”, moving towards “water stressed”, is echoed (Roberts, 2017). Therefore, there is a need to contribute to ongoing studies on the groundwater sustainability of South Africa’s water resources, particularly those in the Modder River catchment, as part of the broad Upper Orange River water management system.

The Modder River catchment was chosen because it is a critical water resource for the Free State province. The Department of Water and Sanitation (DWS), previously the Department of Water Affairs (DWA), has stopped the issuing of new water use licences to a section of the catchment (at Bainsvlei near Bloemfontein) because of over-abstraction. The over-abstraction has been unsettling the groundwater equilibrium balance of the catchment. This was necessary to prevent water insecurity to the inhabitants of Bainsvlei who are predominantly commercial farmers.

At global level, there is a change in moving away from vulnerability appraisal to water security planning. Water security designs involve the advancement of the idea of vulnerability appraisals, which should be followed by focusing on water safety planning, evaluation, and basic control. Flexible water security designs involve managing water safety dangers related to environmental unpredictability and change as a commitment to sustainability systems and adaptable water supply (Karamouz et al., 2020). In the case of South Africa, the National Planning Commission (2013), together with the DWS, noted gaps in the actions regarding the layout in the South African National Water Act, Act 36 of 1998, article 16, such as the lack of appropriate models for dealing with water quantity parameters. The water quantity parameters referred to include both surface and groundwater parameters. This research, therefore, set out to design a means of investigating groundwater sustainability through modelling of geohydrological parameters using the Modder River catchment of South Africa as study area.

1.2 Importance of groundwater in the Southern African Development Community

Water security is important for economic and sustainable development as well as poverty reduction in the Southern African Development Community (SADC). Increasing drought conditions and decreasing surface water supplies are creating opportunities for groundwater sustainability development. Drivers worth mentioning are groundwater development and management in the SADC, incorporating groundwater, unlimited water use, poverty and food security reduction in the region. These apply across the board as they have been found critical throughout the SADC region. Preceding this is the requirement for essential local water supply in both rural and urban places. Increasing urbanisation and the need to mitigate the effects of drought, have become major aspects to consider in water planning in this sub-region (Braune & Adams, 2013).

Macy (2010) provided a record of the SADC geography, in the light of the diverse topography, geology, geohydrology and climate as outlined by the Council of Geoscience (CGS). The geological and geohydrological diversity, being extremely complex in management, was the reason for the development of the SADC Hydrogeological Guide and Maps (Pietersen et al., 2010). The hydrogeological guide and maps were developed to enhance the comprehension of groundwater occurrence in the SADC region; enhance collaboration between member states; and strengthen the comprehension of groundwater asset management. The SADC hydrogeological map is a general hydrogeology outline scale (1:500 000), which provides data on the degree and geometry of provincial aquifer frameworks.

The grouping framework for transboundary aquifers, proposed by the International Groundwater Resources Assessment Centre (IGRAC, 2013), as indicated in Figure 1.1, is internationally accepted, and is adopted in the thesis. The transboundary aquifers that require support in management intervention by member states, were specified in both Davies et al. (2012), and Riedel and Döll (2016). Currently, activities have only been carried out to comprehend the Kalahari Artesian Aquifer Framework and the Ramotswa Aquifer (H) with its boundary between South Africa and Botswana (United Nations Educational, Scientific and Cultural Organisation [UNESCO], 2016). Further work is required on the Karoo sedimentary aquifer (I) which shares a boundary between Lesotho and the Upper Orange River groundwater catchment of South Africa.

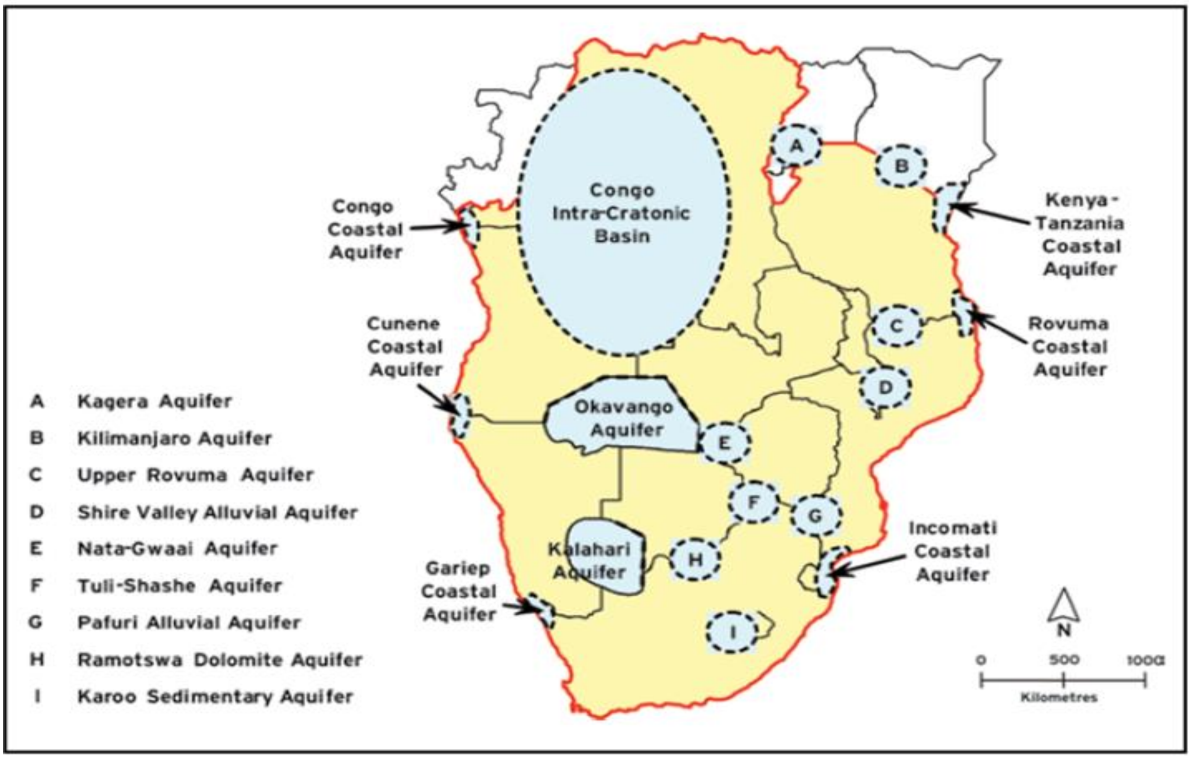


Figure 1.1: Transboundary aquifer map of the SADC
Source: Modified from IGRAC (2013)

1.3 Study rationale

Groundwater sustainability is defined in terms of the nature of the resource, the management requirements and actions of abstraction related to groundwater withdrawal. It is a renewable resource if not over-abstracted. It largely depends on rainfall for continual recharging. The rate of recharge is important for groundwater sustainability. It takes several years for the water table to be renewed in some aquifers and a few hours in others. This understanding must be at the forefront with regard to development purposes that depend on the supply of groundwater (Alley et al., 1999). The wide variations and great lengths of time it takes for groundwater to recharge, makes it imperative to prevent over-pumping of groundwater, as the net effects of groundwater pumping are only realised over time and would take a significant amount of time to manifest. Proven concepts in groundwater sustainability call for an approach that considers the performance of the aquifer system through time, a long-term view on groundwater management and balancing groundwater abstraction (Alley et al., 1999).

Groundwater is one of the world's most extracted raw materials. Its abstraction is estimated globally at 600−700 Km^3/year (Foster et al., 2006; Jarvis, 2008). In some cases, the occurrence and recharge the groundwater are complex. These complexities are in addition to other factors at play in the water cycle, due to human and natural factors that alter the water cycle balance. Furthermore, it was found that groundwater development in most places took place without understanding this balance (put reference/s here). Besides, how groundwater is recharged, its impact on the environment and its complexity is not well understood (Pandey et al., 2011). As a result, groundwater is excessively pumped, leading to depletion and decline in water levels in aquifers, and subsequently a decrease in the yield of water wells, increased salinity intrusion and land subsidence in coastal aquifers. This has raised concerns across the globe (Reddy, 2006).

In the arid and semi-arid areas of South Africa, farmers and communities have a limited number of water provision points. This increases pressure on groundwater resources and has increased the number of wells and boreholes drilled to access groundwater needed for multiple purposes, particularly for agriculture and drinking water. The limited resources of water provision has put undue pressure on aquifers, such as those in the C52 Modder River catchment. The Modder River is a constituent of the broader Orange River system. The undue pressures in this catchment has led to excessive pumping and increased abstraction. The ability to supply water directly from groundwater aquifers to the farmers and other water users depends fundamentally on rainfall, which is a major source of groundwater recharge. With low rainfall in South Africa, groundwater recharge is definitely low (DWS, 2016).

The high rate of groundwater abstraction, also known as excessive pumping, has a number of negative effects. One of these effects is groundwater depletion, a result of fast-rate groundwater extraction from an aquifer. Fast-rate extraction does not allow for adequate recharge of the aquifer (Ponce, 2006). Other secondary effects of depletion are related to climate change. These are surface albedo distortions, increased groundwater salinity, high cost associated with pumping and constant well maintenance, and increased damage of built-up wells (Ponce, 2006).

There have been changes, trends and threats that negatively affect water resources in the Modder River catchment (DWA, 2013b). These include increased population growth (Figure 1.2) and increasing urbanisation (Table 1.1). The population of the Modder River catchment increased from 618 566 in 2001 to an estimated 1 083 886 in 2016 (DWA, 2013b). This resulted in increasing water demand and excessive pumping of groundwater for various uses.

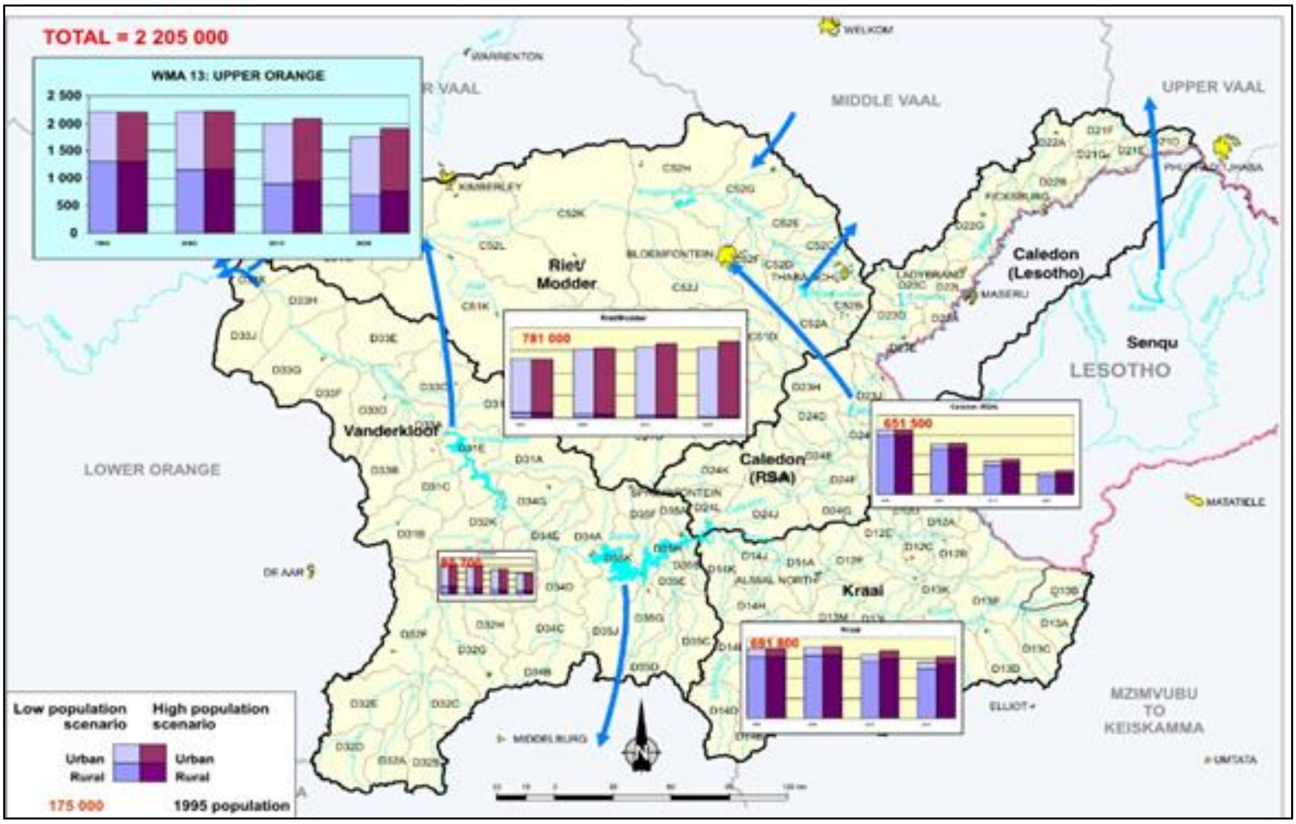


Figure 1.2: Population growth in the Upper Orange River
Source: DWA (2013a)

Table 1.1: Urbanisation and rates of water use (surface and groundwater) in Upper Orange River Catchment

Sub-area	Irrigation	Urban	Rural	Mining and Industry	Power generation	Afforest-ation	Total local require-ments	Transfers out	Grand total
Modder	252	87	10	2	0	0	351	29	380
Senqu	8	2	13	0	0	0	23	491	518
Caledon	12	22	6	0	0	0	40	0	40
Vanderkloof	336	5	5	0	0	0	346	2 809	3 155

Note: Values are in million litres Source: DWA (2013a)

The Modder River catchment, particularly the Bloemfontein area, has the highest demand for water in the Upper Orange River catchment (Figure 1.2), at 351 million litres of the total local requirement (Table 1.1). Other negative effects are increased degradation of the environment, high levels of human-induced climate changes and high variability of the natural climate. The net effects have been the depletion of aquifers and prolonged periods of drought (DWA, 2013b). This indicates a lack of effective water resource management tools and laxity in monitoring groundwater as a resource. Globally, the general trend is to adapt models and artificial intelligence (AI) to manage water resources sustainably. Groundwater sustainability models may be used to govern aquifers through AI. It is therefore necessary to develop groundwater sustainability models or indices and AI (an ICT) tool for groundwater monitoring in order to make informed decisions for improved groundwater management (Knoll et al., 2020; Babbar-Sabens and Minsker, 2010, 2012; Rahman et al., 2019; Yoon et al., 2016; Kim et al., 2016).

1.4 Research aims and objectives

The research aim was to design and model a framework of the important hydrological parameters that govern the sustainability of groundwater in the C52 sub-catchment of the Modder River in South Africa. This framework would address the adverse impact of climate change as well as the increased dependence on groundwater systems. Furthermore, the aim was to model hydrological and human-induced factors affecting the sustainability of a typical groundwater system. To achieve this overall aim, the following objectives were pursued:

- Objective 1: To set up, calibrate and validate a model to predict groundwater sustainability at catchment scale.
- Objective 2: To apply the developed model to predict the sustainability of the groundwater of the Modder River C52 catchment of the Upper Orange River system, using observed data from the Department of Water and Sanitation.
- Objective 3: To test and correlate the results from the model with observed geohydrological parameters of recharge, borehole yield and pumping rate data.

Research QuestionsThe research questions were the following:

- Can groundwater be sustainably predicted on a catchment scale?
- Is the groundwater of the Modder River catchment sustainable?
- Do human-induced factors such as over pumping affect the sustainability of the Modder River groundwater system?

1.5 Methodology and research design

The research objectives and the methodology applied in addressing each of the three research objective, are presented in Figure 1.3, which highlights the tasks carried out under each objective, so that the aims of the research could be achieved.

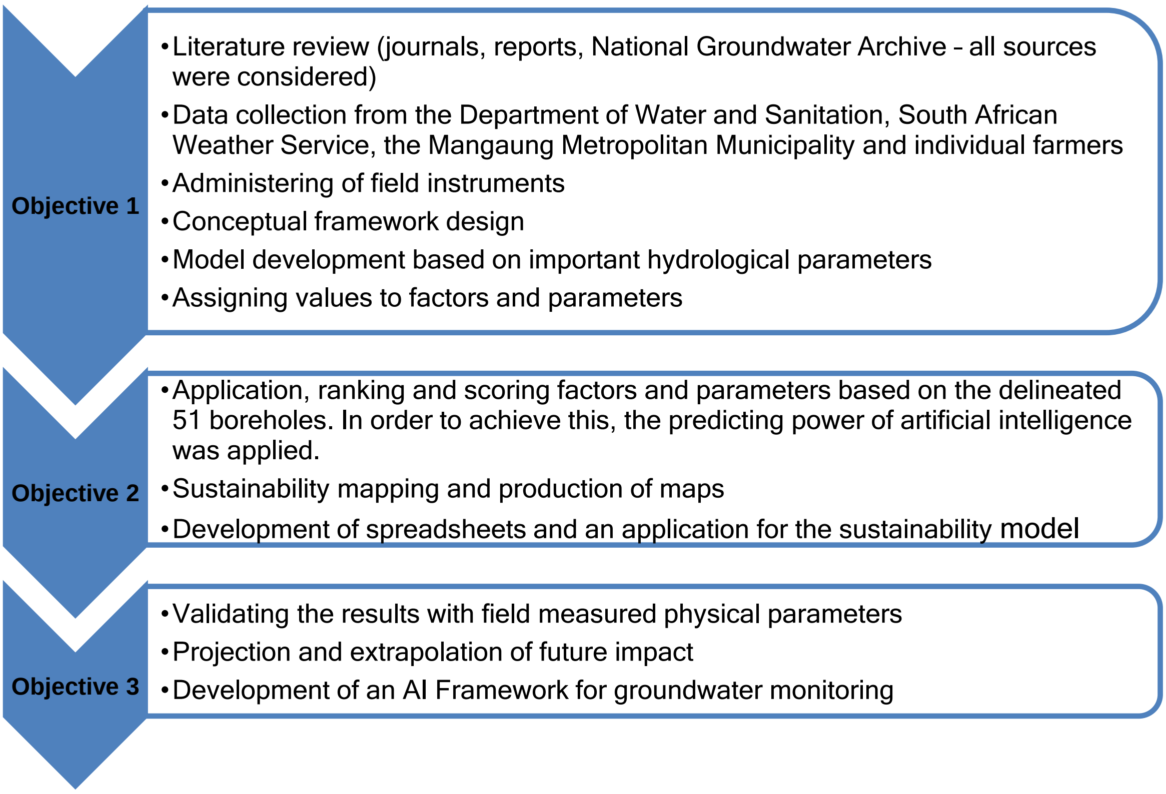


Figure 1.3: The summarised methodology by objective
Source: Author

Objective 1 was supported by a literature review of scientific publications relevant in supporting the setting up of the sustainability model. It further required tasks, such as the development of a conceptual framework and, thereafter, modelling of the hydrogeological parameters within the designed framework.

Objective 2 included tasks such as the application of the designed model to the Modder River catchment, using 51 permitted boreholes as a representative sample from the available 92 boreholes in the catchment.

Objective 3 required the process of validating the resultant maps with field-measured physical parameters. Projections and extrapolations of future impacts were further carried out as part of Objective 3.

The methodology is further explained in detail in the following paragraphs. A detailed literature review was conducted to understand the historical evolution of frameworks available on groundwater sustainability. Data and information relating to groundwater abstraction in the Modder River catchment were collected from the DWS, various databases, semi-structured interviews, case studies and a literature review. The literature review focussed on the groundwater situation globally, in South Africa and in the catchment on which the study was based.

The following hydrological parameters were collected for the catchment:

- Climate data (monthly rainfall amounts, evapotranspiration potential,
- Aquifer parameters (borehole yield, recharge of aquifer, storativity (volume or area),
- Water management information (number of water licences issued, duration of licences, number of serviced boreholes, people and livestock served, average water use)
- lithology,
- topography,
- population,
- spatial analysis of boreholes using Global Positioning System (GPS) coordinates,
- and land area used for mining and irrigation (registered boreholes in the catchment were predominantly for mining and agriculture).

Serviced boreholes referred to the number of boreholes licensed at the time of the study. Licensed boreholes were those that were in operation at the time of the study.

Physical inspection of the boreholes was undertaken to support the interviews. The interviews and discussions were conducted with key people in the DWS in Bloemfontein, using a guiding set of questions (Appendix A). The guiding questions were refined through pre-tests, until the answers presented permitted an appropriate level of analysis. The interviews were used to acquire key quantitative information. The results were used in developing the model.

A conceptual framework was developed based on the physical processes relating to groundwater flows. The focus was on processes that govern the hydrological cycle in relation to groundwater sustainability in the Modder River catchment. Some of the processes identified were land use to groundwater, land use to climate and climate to groundwater interactions. These processes were grouped as factors and included aquifer sustainability, climate, and socio-economic factors, including land use and right or equity of resources. The conceptual framework did not cover the whole hydrological cycle.

As part of the methodology, an in-depth review of the parameters and ranking of the physical processes affecting the groundwater system of the Modder River catchment was conducted. The parameters included the climatic factors (rainfall, evapotranspiration, sunshine, slope, topography, and climatic zones) and the aquifer system (recharge, yields, storativity, aquifer types, and lithology or rock types). Other important catchment factors and parameter rankings analysed were human-induced rights and equity (number of permits issued per year in the catchment, duration of the permits, number of boreholes in the sub-catchment, pumping rate per year) and socio-economic factors, including land use (use per capita, population in the catchment, water uses and tariffs).

The developed sustainability model was applied to the C52 catchment of the Modder River system of South Africa. The hydrologic components were mapped using Geographical Information Systems (GIS) technology in consideration of the Modder River basin's modelling system. The ArcView GIS platform has been widely used and applied globally to address issues of water quality and quantity (Mutenyo et al., 2013). ArcView GIS has further been applied in South Africa as an input to allow for the modelling of the impact of land use change on the hydrology of the Modder River catchment (Welderufael et al., 2013). An Artificial Neural Network model was proposed, based on the findings and outcomes from the scoring and ranking of the factors affecting the groundwater sustainability of the Modder River catchment. The outcome addressed Objective 2 of this research by delivering a model for predicting the sustainability of the groundwater of the Modder River C52 catchment.

Validation of groundwater sustainability maps as a process, was conducted. A basic validation was carried out to test and correlate the maps and results of the model with observed geohydrological parameters of recharge, borehole yield and pumping rate data. A further step involved the comparison of calculated indices with the measured physical variables, such as evapotranspiration and rainfall, with the analysis of the designed questionnaires of the actual end users. Validation was carried out to assess the capacity of the sustainability index to establish values that reflected the physical system.

1.6 Research design limitations

The limitations of the research were that some of the data like well depths were not readily available as people were not in a position to divulge information. Sustainability analysis and AI were covered entirely by modelling; however, this was minimised by setting realistic boundaries, defining the parameter scores and appropriate examination of the factors and their hydrological relationships. Some issues like climate change modelling were beyond the research objectives and were therefore not covered. It was not always possible to get disaggregated groundwater data from aggregated surface and groundwater flows. No land use change maps in relation to groundwater-surface water interactions were available. Groundwater recharge information from previous studies carried out on the C52 sub catchment was also not readily attainable. Application of the proposed groundwater reporting indicators was not conducted as it was not part of the study.

1.7 Groundwater sustainability terms

The United States of America (US) Water Resources Council (1980) stated three terms that resonate with groundwater sustainability. These are: safe yield, groundwater mining and overdraft. Safe yield is important for groundwater sustainability because measuring it frequently prevents over-abstraction of the aquifer system. Furthermore, groundwater mining is another key term in groundwater sustainability. In heavily pumped aquifers, it indicates an extended and increasing decline in the volume of groundwater stored. This effect is typical of semi-arid and arid climate zones. Overdraft is the last key groundwater sustainability term. According to Alley et al. (1999), overdraft is severe, in that it describes situations where abstraction of groundwater from an aquifer system for a development activity is considerably higher than the rate at which the aquifer is recharged. This is an undesirable situation.

1.8 Contribution and achievements of the thesis

The contribution of this thesis to new knowledge was the development of a groundwater sustainability index. The sustainability index makes use of both subjective and physically based techniques. The sustainability index variables for evaluation are simplified to collate and calculate; therefore, the proposed sustainability tool may be used to evaluate the sustainability of groundwater in various catchments.

The developed sustainability method was applied to C52 sub-catchment of the Modder River system of South Africa. The hydrology components were mapped as part of the basin's modelling system, with a user interface and an ArcView GIS platform. The climatic conditions, rights or equity (as related to groundwater resources), socio-economic factors and the aquifer system sustainability maps were produced, and a final sustainability map was generated. The sustainability class in the Modder River basin ranged from low sustainability to moderate sustainability. The moderate sustainability class was typical of areas with extensive dolerite, low slopes, and low recharge.

The groundwater sustainability methodological evaluation is a practical and applicable tool for land-use planning and risk assessment (Nguyet & Goldscheider, 2006). This method maybe used to investigate aquifer sustainability in a similar basin with limited data. Borehole information, such as water levels, is critical to regulators. MacDonald et al. (2012) suggested that a permit for the abstraction of 1.6 million cubic metres of water per year, by a water consumer from a nearby aquifer, could take 5, 10 or 20 boreholes. It should be noted that it is possible to convey this volume of water from an aquifer that has been assessed to reasonably yield an adequate volume for this allotment. It is the volume that has been authorised, not the numbers of boreholes. There are challenges in investigating the amount of groundwater withdrawn; however, not much non-hydrological methodologies are available for investigating this volume. Furthermore, a question can be asked: How do regulators ascertain that groundwater use does not exceed the approved water license? (MacDonald et al. 2012).

Research on the development of an application on a Microsoft Excel© monitoring spreadsheet, using the scores and ranking of the factors, was necessary. This was done with the aim of creating an analysis application for sustainability. An application for the monitoring and evaluation of groundwater levels was considered so that the sustainable yield could be routinely adjusted. This was what this study sought to achieve, and was the achievement of the study. The study had proposed a sustainability index or tool that is supported by AI.

The proposed sustainability tool maybe used to evaluate the sustainability of groundwater in various catchments throughout South Africa and the SADC using the Modder River catchment as a case study. This, in turn, supports behavioural changes and practices among water consumers and municipalities and water managers such as the DWS in South Africa. AI maybe a descriptive logical basis behind the groundwater catchment technology, showcased as an innovative technology solution contributing to achieving the objectives of water sector programmes.

The thesis explored the potential of AI in groundwater management. The purpose of AI in groundwater management is to increase groundwater conservation and sustainability through a monitoring system through real-time updates and early warning signals to water management and reinforces positive behavioural practices on water abstraction and effective water usage. Groundwater consumers will have the means to gauge when they are using too much water and regulatory authorities will have the means to gauge if a catchment is over-abstracted. The net gain or impact will be water savings, cost savings and preferable performance of provinces, municipalities and departments that manage water.

1.9 Layout of the thesis

Chapter 1 provides an introduction to the research, its rationale, its objectives and important definitions used in the thesis.

Chapter 2 contains a detailed literature review on groundwater sustainability. This chapter includes the concept of groundwater sustainability, a review of the various models and factors affecting groundwater sustainability and ensuing challenges. Furthermore, it is a narrative of the application of AI in modelling hydrological factors. This chapter explains how AI extensively supports hydrologic predictions and hydrologic system analyses.

Chapter 3 is a review of the C52 Modder River Upper Orange River catchment. It focuses specifically on the C52 geology, hydrology, hydrogeological conditions, topography, formations and soil types. This chapter characterises the catchment study area. This is important in understanding the catchment's water-bearing capacity.

Chapter 4 captures the elements underpinning the development of the groundwater sustainability index method. The specific methodology and data acquisition are described. Weighting and rating of parameters are explained.

Chapter 5 gives an account of the application of the sustainability index concept to 51 boreholes in the C52 catchment in the Modder River Upper Orange River Basin. This chapter further details the production of maps for all the factors under study in this thesis. A final sustainability map is plotted from the climate, aquifer sustainability, socio-economic factors and rights maps.

Validation of the Modder River catchment sustainability index map is set out in Chapter 6. An explanation of the scores is given according to the classes presented. In addition, the correlation graphs shed some light on the strengths and weaknesses of the sustainability index map. Validation of the C52 catchment is carried out and is specific for this catchment.

Chapter 7 describes the significance of the study and its contribution to new knowledge.

Chapter 8 outlines the conclusions and recommendations based on the findings of this research.

Chapter 2

LITERATURE REVIEW AND OVERVIEW OF GROUNDWATER SUSTAINABILITY

2.1 Concept of groundwater sustainability

The World Commission on Environment and Development (WCED, 1987) defined sustainability as a process of development in which depletion of resources, course of speculations, introduction of technological development or advancement and changes in institutions are all in agreement to integrate both the present and the future potential to address human goals and issues, adjusting environmental effects, population, resources and innovation. Based on this sustainability concept, the quantity of groundwater resources varies between areas and over time (Liu et al., 2020) due to important hydrological factors, such as low yields of groundwater, poor water quality, lack of hydrogeological understanding and increasing threats to water supply and use.

Groundwater sustainability, as a concept, is multifaceted and complex (Senent-Aparicio et al., 2015; Elshall et al., 2020). The same applies to its application in real-life situations and setup (Velis et al., 2017). It is important to clearly understand and harness the multiple impacts and effects of various human-induced activities on groundwater assets and the broader environment (Girmay et al., 2009). According to the WCED (1987), this has led to the concept of groundwater sustainability currently being widely debated. Most debates are on the negative effects of human activity.

In terms of definition, 'groundwater sustainability' may refer to the use and development of groundwater assets, in a way that covers all development concerns and may foresee anticipated changes (Alley et al., 1999; Sahoo et al., 2006; Mays, 2013). In an optimal state, groundwater is said to be sustainable, hence the term 'groundwater sustainability'. This state is neither constant nor static and it is dependent on time and space (Pandey et al., 2011). These conditions necessitate a study or number of studies so that progress in achieving sustainability over the course of time and space is known. In addition, it indicates inadequate attempts to assess performance metrics to quantify groundwater sustainability. This is despite the various discussions in the academic, scientific and water management arenas, the reason being that sustainability is a multidimensional concept (Teodorescu, 2015) and not pure science, even though it may often support scientific appraisal and analysis (Alley & Leake, 2004).

Groundwater sustainability is defined in terms of the nature of the resource, the management requirements and actions of abstraction related to groundwater withdrawal (Velis et al., 2017). Groundwater is a renewable resource if not over-abstracted. In terms of hydrology, groundwater is dependent on rainfall and other processes such as base flow for continual recharge. Currently, artificial recharge (e.g. storm water diverted into boreholes) is widely applied in places like Cape Town to recharge groundwater. The rate of recharge is important for groundwater sustainability. It takes a number of years for the water table to be renewed. This knowledge has to be readily available with regard to development activities that depend on groundwater provision (Alley et al., 1999). The wide variations and great lengths of time it takes for groundwater to recharge makes it imperative to prevent over-pumping of groundwater as the net effects are realised over time and could take a significant amount of time to manifest. Proven concepts in groundwater sustainability call for approaches that consider the aquifer system performance over time, a long-term view on groundwater management and balancing groundwater abstraction (Alley et al., 1999; Wada et al., 2014; Wada, 2016).

For emphasis, Chapter 1 (1.8) stated that groundwater sustainability is often discussed using key hydrologic terms. These terms, as a result of advancement in sustainability science, are expanding and not limited to safe yield, groundwater mining and overdraft (US Water Resources Council, 1980). Safe yield refers to specific effects of pumping. Safe yield considers water quality changes, water level decrease and low stream flow (Van der Gun and Lipponen, 2010). Safe yield is important for groundwater sustainability as measuring it frequently prevents over-abstraction of the aquifer system. Another key term in groundwater sustainability is groundwater mining, which indicates an increasing decline in the amount of groundwater stored. Lastly, overdraft of groundwater is a term that means a rate of higher abstraction as compared to the rate of aquifer recharged.

With regard to the increase in the body of knowledge of groundwater sustainability, articles reviewed were extracted from Web of Science by running the following query using Advanced Search on 'Title' field of "All Databases".

TS=(("Groundwater") OR ("Ground Water")) AND ("Sustainability")

The popularity of the topic was confirmed by the over 4,100 publications returned from this search. The review of these articles revealed a few obstacles towards ensuring groundwater sustainability that ranged from limited funding to an ever-increasing climate change variation (Pandey et al., 2011; Scheiber et al., 2020; Liu et al., 2020). The review also revealed that there was a need to increase the policy and practice and the understanding of groundwater sustainability. Modelling may increase the improvement in groundwater resource understanding, sustainable groundwater management and conservation.

2.2 Importance of groundwater sustainability

This subsection reiterates the importance of groundwater sustainability as part of the relevance of the study. Groundwater, as a global asset, is one of the world's most consumed natural resources. Globally, groundwater withdrawal is estimated at 600−700 Km^3/year (Kresic et al., 2009). This extraction affects the balance between space and time in its natural occurrence (Sikdar, 2019). Groundwater development is increasingly taking place in most places without understanding this balance (Saha et al., 2019). There is still a knowledge gap among groundwater users on fully comprehending how groundwater is recharged and its impact on the environment (Pandey et al., 2011; Senent-Aparicio et al., 2015; Elshall et al., 2020). As a result, groundwater is excessively pumped leading to depletion. Low water levels in aquifers are responsible for salinity intrusion in coastal aquifers, land subsidence and decline in the yield of water wells. This is still a major global challenge (Reddy, 2006; Mays, 2013).

2.3 Sustainability analysis

System dynamics is a method of analysis for complex interdisciplinary systems (Hill and Camacho, 2017; Recio et al., 2018). Sustainability is one of such systems (Karnopp et al., 1990; Sterman, 2000; Ghasemi et al., 2017). System dynamics grounding is part of the dynamics of a non-linear theory and controlled feedback developed in physics, mathematics, and engineering. This may be presented simply as indices and matrices. These theories and tools usually apply to human behaviour; however, the same application is carried out on technical and physical systems (Alcala et al., 2015). System dynamics draws on economics, cognitive and social psychology, as well as social sciences. System dynamics models are designed to solve problems (Sterman, 2000; Mashaly and Fernald, 2020).

Figure 2.1 shows the simulation of the catchment water balance (Bossel, 2007b; Alifujiang et al., 2017). It is a Vensim system dynamic representation of the sinks and holes of groundwater in a catchment. The arrows indicate the flows of water in the water balance system. There are many positive and negative reinforcing loops that represent groundwater sinks. Developments that rely on climate, ecosystems (for example, the water cycle as shown in Figure 2.1) and natural resources, are governed by system laws, physical laws, and behavioural patterns and are based on challenges in the environment (Bossel, 2007a; Karnopp et al., 1990; Liu et al., 2020). Through ecosystems, development paths, processes and humans systems thrive (Bossel, 2007b; Karnopp et al., 1990). In this regard, development is defined as the introduction of technical management practices over particular resources, to attain a sustainable yield over a long period of continued harvesting and replenishment of the resources (Correia de Araujo et al., 2019). Development is constrained by physical limits of resources, energy and dependence on the environment, space, and ecosystems viability (Baalousha et al., 2015). For this reason, safe yield, groundwater mining and overdraft alone are not sufficient in addressing groundwater sustainability (see Figure 2.1).

In real-life, systems are based on deliberate human actions (Bossel, 2007a; Karnopp et al., 1990) (see Figure 2.1). These human actions are augmented by technology, complex reasoning and organisation. The evolutionary process is much longer than the time scale of change imposed by humans. Ecosystem principles alone, within the groundwater models (Figure 2.1), are not sufficient for dealing with human systems and sustainability. For this reason, all aspects under the study of a sustainability system are given equal weighting. Complexity is embraced as opposed to a reductionist approach.

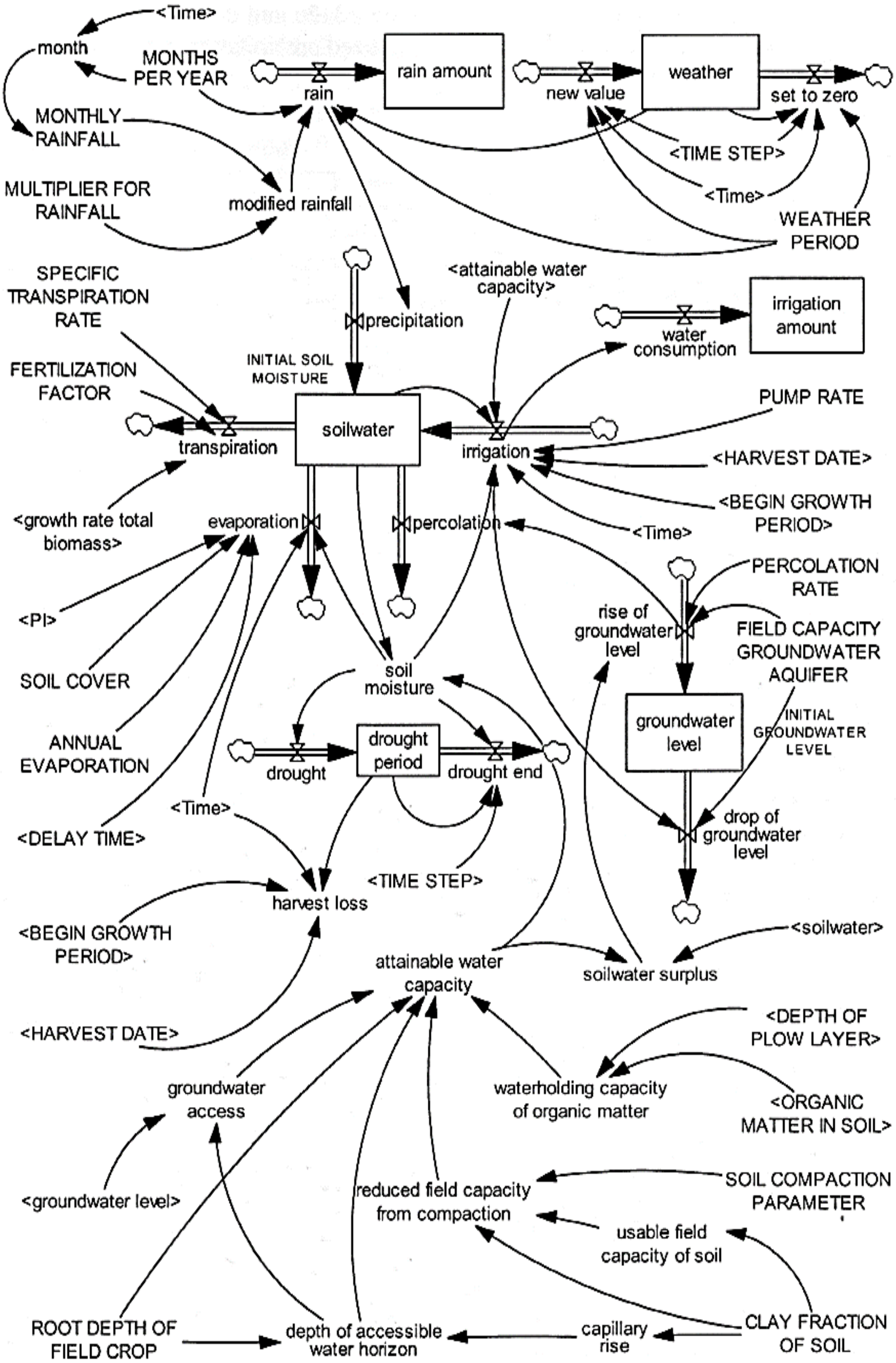


Figure 2.1: Simulation showcasing catchment water balance

Source: (Bossel, 2007b; Alifujiang et al., 2017)

2.4 Global standards of reporting sustainability frameworks

In 1987, the World Commission on Environment and Development embarked on an optimistic objective of sustainable development, depicting it as "advancement, which addresses the issues of the present without compromising the capacity of future generations to address their own issues". The data, made accessible through sustainability reporting, enables internal and external issues to frame opinions and sentiments and to make educated choices around groundwater development in an objective and sustainable manner (Rossi and Luque-Vilchez, 2020).

The models and measures of the Global Reporting Initiative (GRI) (see an example in Figure 2.2) are intended to be used to report on water resource asset use impacts on the economy, the earth and/or potentially the society (GRI, 2012). The GRI guidelines make a typical translation for organisations and partners with which the monetary, ecological and social effects of groundwater abstractions may be impacted and understood. The gauges are intended to improve the global occurrence and nature of data on these effects, consequently empowering further decision-making and responsibility regarding, for instance, groundwater asset use.

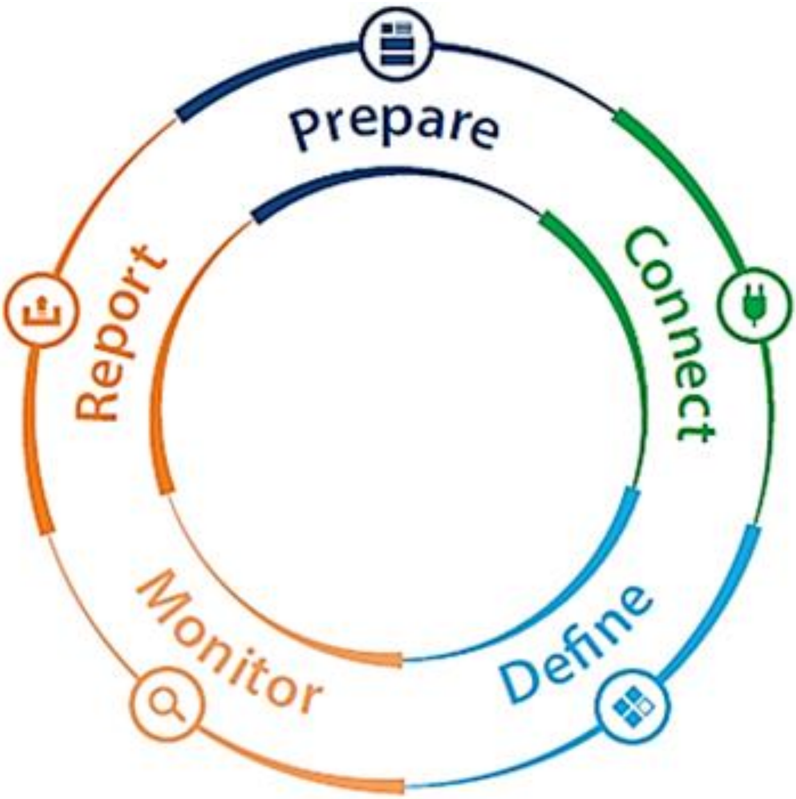


Figure 2.2: Reporting wheel of the Global Reporting Initiative
Source: GRI (2012)

As a best practice, it is recommended that sustainability reporting be supported using frameworks, tools, guidelines, and indices. Figure 2.3 creates the foundation to sustainability reporting, combining economic performance with social responsibility and environmental care for resources such as groundwater. It aims to help businesses set goals. It further measures performance and manages change towards sustainability. Chapter 4 reviews the sustainability standards as applied to this thesis. Table 2.3 (see 2.9.8) summarises the evaluation of various approaches to reporting of typical groundwater assessments. Chapter 5 further reviews the advantages of indices and various tools.

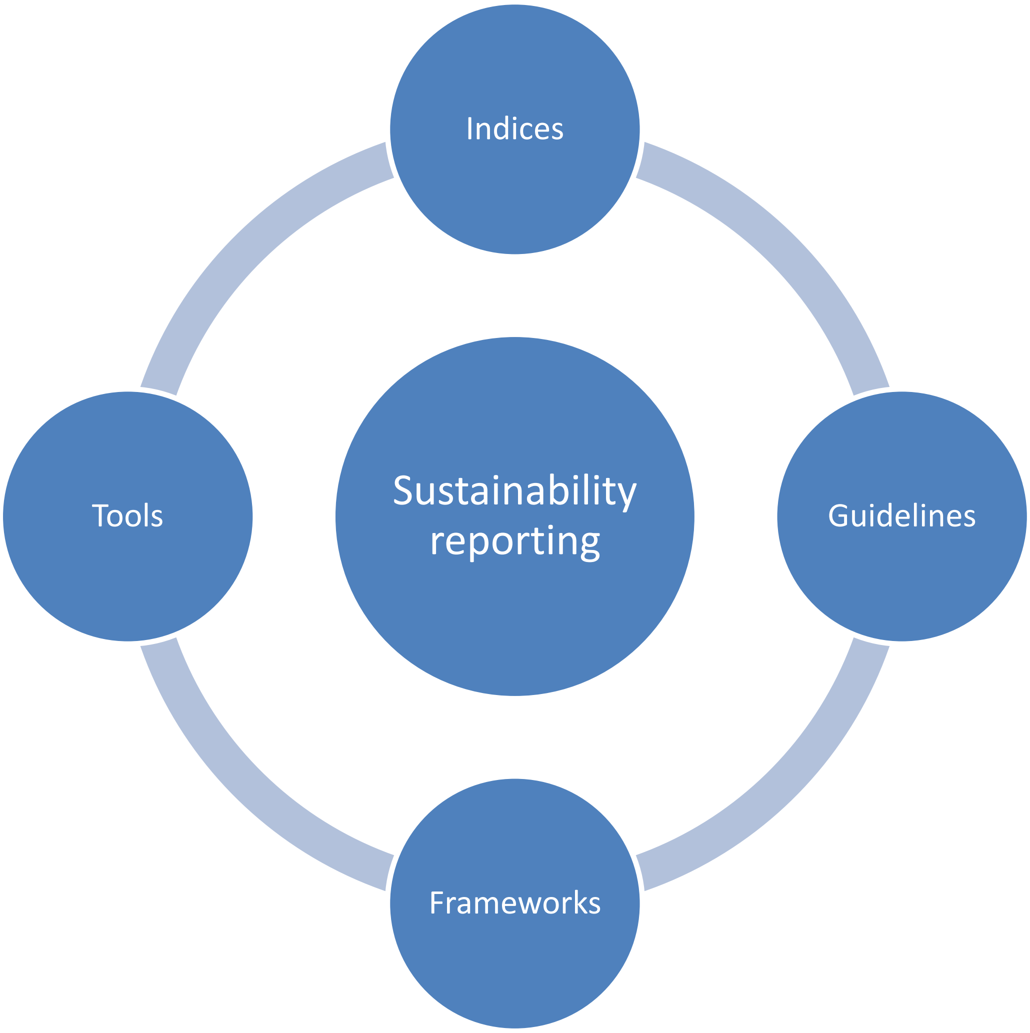


Figure 2.3: Sustainability reporting
Source: Author

2.5 Sustainability reporting for water abstraction

The results and findings are intended to promote a better understanding and correspondence of significant water-related effects and how to oversee them. Through an extensive comprehension of its water use, an industry, country or organisation may evaluate the effects on water assets on which ecological systems, other water users and the reporting organisation itself rely (GRI, 2012). A water-focused industry may need information to further the viability of water management. Because of the solid connection between water withdrawal, use and release, the reported data would be reliable. Since water is a common asset and water-related effects are confined, companies are progressively being urged to (GRI, 2012):

- prioritise activity in zones with high water pressure;
- understand and react to economic, social, and ecological effects;
- aim to profit regarding the requirements and needs of all water users in a water zone; and
- align their methodologies and aggregate activities with alternative water uses, with a viable, open approach.

2.5.1 Groundwater sustainability reporting codes

Sustainability reporting is accomplished by using codes that assist in determining the economic, environmental and social impacts caused by a water user's everyday water activities. The reporting water user will provide a portrayal of how it associates with water, including how and where water is abstracted, how it is used and its effluent released and the water-related effects it causes or adds to, or that are directly connected to its activity, items or management through a business endeavour, for example impacts caused by overflow (Roca & Searcy, 2012):

- A portrayal of its approach for recognising water-related effects, including the extent of appraisals, their time span and any equipment or procedures used.
- A portrayal of water-related effects, incorporating how it works with partners to steward water as a mutual asset and how it connects with providers or users causing significant water-related effects.
- A clarification of the procedure for defining any water-related objectives and focuses that are a part of its management approach.
- A portrayal of any base gauges it has set for the nature of huge effluent releases and how these base norms were resolved, including:

- how gauges for offices working in areas with no neighbourhood release necessities were resolved;
- any internally created water quality gauges or rules;
- any division particular models considered; and
- whether the profile of the abstracted water body was considered.

2.5.2 Broad indicators for groundwater sustainability

When reporting groundwater sustainability, Das and Datta (2001) proposed that the reporting organisation will provide the following accompanying data:

- Totalling up of groundwater use from all zones.
- Totalling up of groundwater use from zones with high water demand and pressure.
- Change in groundwater storage, if distinguished as a critical water-related effect.
- Any relevant data important in determining how the information has been accumulated, for example any gauges, systems and approximations used.

This incorporates whether the data on groundwater use was ascertained, assessed, displayed, or sourced from GIS estimations and the approach taken for this, including the use of any segmented or particular variables.

2.6 Groundwater catchment management

The underpinnings of groundwater catchment management is that adequate planning is achieved on the premise of the current and projected situation in the water management area. This means that the following are to be taken into consideration (De Vries & Simmers, 2002):

- Requirements (reconciliation).
- The vision for the water management area.
- Water availability.

These three tenants above provide an oversight for current and future directions with regard to exploitation of groundwater sustainably.

2.6.1 Techniques for groundwater management

Strong techniques require researchers to investigate the following three areas (Das & Datta, 2001):

- The use of groundwater models.
- The approximation of uncertainty in groundwater models (quantification of groundwater recharge).
- The incorporation of socio-economic aspects of groundwater sustainability.

It is necessary to define the use of the resource in a sustainable way. This was carried out after the analysis of the state of the groundwater in the catchment. The defined working modality should avoid irreversible damage to groundwater and the ecosystem as a resource. This permits the availability of resource water to be extended over a longer period.

In the abstraction of groundwater from a reservoir aquifer, the extraction should not be larger than the recharge. The storage capacity of the aquifer accommodates temporary over-pumping. As the quantities abstracted and loss include evapotranspiration from surface water in agriculture and losses due to run-off, acceptable practices or optimal practices call for limited abstraction to a fraction of the recharge, ensuring that water is available downstream.

2.6.2 Use of groundwater models

Modelling is particularly useful in groundwater assessment and as a management tool because groundwater is slow moving with slow reactions to changes external to an aquifer system. As a tool for prediction and planning, modelling is a necessity (Keese et al., 2005; Liu et al., 2020). On a quantitative basis, groundwater models enable the combination of all available hydrological data with other fuzzy logical aspects into a logical holistic picture (Das and Pal, 2020). The initial steps require the collection of all the system's dominant processes that are understood. In this phase, solely calibrated observed data is integrated and identified. Keese et al. (2005) emphasised that only calibrated models should be used for carrying out predictions. In carrying out a prognosis, the benefit of modelling lies in the straightforward comparison of scenarios across each other and across the board (Liu et al., 2020).

The use of models in groundwater studies are currently widespread. However, they are uncertain, not always reliable and at times underestimate and/or overestimate the resources. Not enough information on the initial input parameters is known; spatial information, such as the use of GIS mapping, is therefore of better value. Parameters are required to avail and initially establish calibration, not a once-off solution, as would have been desired. Groundwater models are generally over-parameterised. Acceptable groundwater models are feasible and the fact that they yield different results with various sets of parameters should be kept in mind. Responsible modelling acknowledges this in analysing parameters.

2.6.3 Approximation of uncertainty in groundwater models – quantification of groundwater recharge

A key measure of groundwater management and measurement is recharge. Recharge is a key parameter for sustainability, particularly in arid to semi-arid areas. Most studies indicate that it is not yet possible to accurately measure the hydrological quantity of recharge (Claassen & Halm, 1996; Otto, 2001). An accurate direct measure of recharge is not yet known or established. Indirect measures exist and will be discussed in this thesis (Table 6.1; Section 6.3), however, they too introduce errors and uncertainties. The methods vary as a result of the variations in rain and recharge events. Most quantification techniques require understanding the concepts of safe/sustainable yields, borehole capacity evaluation through Jacob's extrapolation method, pump testing, specifically recovery, and extended and constant discharge steps. It is usually necessary to be comfortable with the requirement in managing data on wells (depths, screens, casings, pipe sizes, water levels, motor specifications, materials, drawdowns and drilling logs) in aquifer assessments and management (Claassen & Halm, 1996).

The first method of estimating groundwater recharge is the integral approach. The Wundt method (Wundt, 1953) is an example of the integral approach to estimating recharge (Otto, 2001) using base flow analysis of rivers. It is mostly used in humid climates but can be adopted for use in arid and semi-arid zones, such as the C52 catchment that has a low flow.

The second method of quantifying groundwater recharge is using the hydrological water balance. Although this method is inaccurate, it however, provides a working value of recharge. In this method, when surface run-off is removed, groundwater recharge is taken as the difference between evapotranspiration and precipitation. The gaps or limitations of this method are a result of the need to extend the period of recorded rainfall and evapotranspiration data, so that the averages are populated.

The chloride mass balance method, applied to the C52 catchment, represents the third method of measuring groundwater recharge. This method uses chloride routing, as shown in Figure 2.4. This routing is the basis of the estimate of the net recharge of the catchment. For C52, this is a collection from the slopes and channels without the losses through base flow discharged from the catchment.

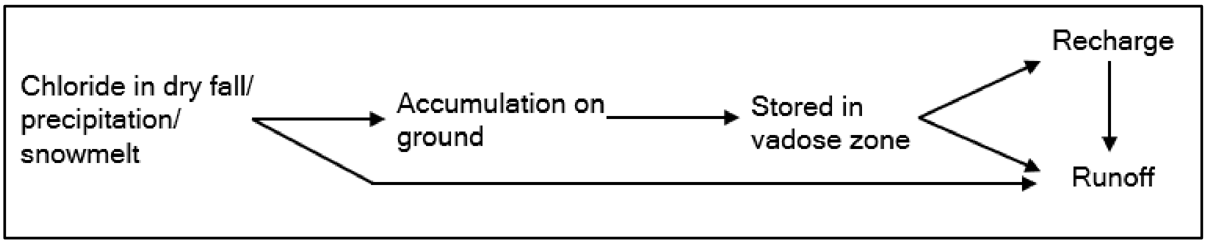


Figure 2.4: Chloride routing model for assessment of groundwater recharge
Source: Aishlin (2006)

When applying the chloride model, Equation 1 is used. It follows that the input chloride mass is equal to the output chloride mass. This equation calculates net groundwater recharge volume denoted as R. This calculation assumes a given number of years of rainfall in the catchment for which discharge takes place. According to Aishlin (2006), it takes more than two years to measure the variability of recharge.

$$R = \frac{(P)(Cl_p) - (Q)(Cl_q)}{Cl_r} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 1$$

In this equation:

P is rainfall (mm/year);

Cl_p is the catchment's chloride concentration of rainfall (mg/l);

Cl_r is the measured groundwater chloride concentration of the catchment (mg/l);

Q is total discharge from the catchment (mm/year); and

Cl_q is average chloride concentration in stream discharge (mg/l), i.e., the Modder River.

The application of this equation requires that the catchment's chloride concentrations for groundwater account for the evapotranspiration effects. This accounts for chloride in the environment. The limitation of this method is that it does not account for human-induced chloride, except for natural conservative chloride, which originates from the sea and moves landward through precipitation.

2.6.4 Incorporation of socio-economic aspects of groundwater sustainability

Incorporation of socio-economic and fuzzy logic aspects of sustainability in groundwater models alludes to decision-making. Decision-making regarding groundwater sustainability takes place in the economic, social and political spheres. These aspects have equal importance and therefore equal weighting as hydrological weighting. Models are useful if they manage to integrate socio-economic aspects. However, most of the models do not do this. The aquifer system's exploitation scenario is a typical problem and it reoccurs when political and socio-economic parameters or factors are at play. The fuzzy social, political, and economic logic is critical as groundwater is an asset enhanced through effective partnerships across knowledge spheres. Negative impacts result from ignorance of these aspects (Negri, 1989).

2.7 Artificial intelligence – overview

Masinde (2013) alludes to AI as the mapping out of systems that copy human discernment, learning and thinking to tackle complex issues. Two AI strategies stand apart with regard to displaying ecological frameworks such as climate and groundwater, namely Intelligent Agents and Artificial Neural Networks. The comprehensive indigenous information on climate change can be displayed using Fuzzy Logic (Berkes & Berkes, 2009; Krupnik & Carleton, 2007; Lauer & Aswani, 2008; Mackinson, 2000). Hamilton et al. (2008) described and compared the performance of AI techniques in modelling environmental systems as summarised in Table 2.1.

Table 2.1: Characteristics of AI techniques as applied in environmental modelling applications

Technique	Description	Advantages	Disadvantages
Case-based reasoning	Solves problems by recalling similar past problems with similar solutions it applies four steps: retrieve, use, revise and retain.	It supports continuous improvement in reasoning, capability, and accuracy and by extension, performance.	Though not for complex systems, Case-based reasoning is based on the 'black-box' approach that offers minimal insight into the system and processes involved.
Rule-based systems	Uses an expert knowledge to derive rules and applies them in solving problems. The rules follow the *'if-then'* syntax to reach decisions.	They are easy to understand, implement and maintain.	Not suitable for ecological systems because they have complex interactions and processes often not well understood.
Artificial Neural Networks (ANNs)	These are highly interconnected systems that operate by mimicking the operations of the human brain. ANNs perform seven categories of tasks: pattern classification, clustering, function approximation, prediction, optimisation, retrieval by content and process control.	Excellent in solving data-intensive and multivariable problems with unclear mapping rules.	Also based on the 'black-box' concept and therefore not good for problems that need explanation of the process used to solve them.
Genetic Algorithms	Mimics the rule of natural selection and solves problems by iterating until a satisfactory solution is found.	They have a simple and robust, computation approach with efficient load balance. They support high levels of implicit parallelism.	It takes large computation time and sometimes premature convergence and a local optimal may occur.
Cellular Automata	Made up of dynamic models, discrete in space, time, and state. They consist of regular lattice of cells which interact with their neighbours. Cellular Automata supports four types of patterns (I-IV); homogenous, simple separated periodic structures, chaotic aperiodic patterns, or a complex patterns of local structures.	They are made up of simple mathematical models that can stimulate complex physical systems. They can incorporate interactions and spatial variations, and also spatial expansion with time.	The main problems emanate from the reflection and absorption boundary conditions. Boundary conditions are also unlikely to reflect real life and have limited capacity to make precise predictions.
Fuzzy Systems	They make use of fuzzy sets to deal with imprecise and incomplete data. Data sets here have values between 0 and 1 and therefore can be used to describe vague statements as in natural language. Fuzzy systems apply techniques such as maximum, mean-of-maxima and centroid defuzzification.	The strength comes from the ability to handle imprecise and incomplete information similar to what human beings have to deal with. They are also easier to understand and apply.	They have no learning capability or memory.
Multi-Agent Systems	An agent is an autonomous piece of software component containing code and data**;** Multi-Agent Systems is a network of agents interacting to achieve goals. Suitable for problems needing fast, concurrent processing to arrive at a solution without conflict resolution.	Their ability to represent complex systems with several stakeholders and allow exploration of alternative management approaches.	They are, however, more suited to social learning among interest groups than prediction of system behaviour.
Swarm Intelligence	It is a form of agent-based modelling inspired by colonies of social animals such as ants and bees; they utilise the 'more are better than one' policy Two commonly used algorithms are Particle Swarm Optimisation and Ant Colony Optimisation.	Swarm Intelligence strength is its two algorithms; they are versatile yet simple enough to be readily accessible for practical applications and easy to implement. The ability to mask out failures and self-organisations gives Swarm Intelligence the ability to solve dynamic problems.	They are less efficient in performing non-linear optimisation with population of potential solutions.
Reinforcement Learning	Involves learning through interaction between a learning agent and its environment; the agent learns to achieve a goal by trial and error. Three types of Reinforcement Learning are pure delayed reward, minimum time to goal and games.	Useful when there is need to create new behaviour rather than modelling existing behaviour.	Limited students have applied Reinforcement Learning alone to solve environmental problems. On its own, it is difficult to formulate a policy that works successfully in real life.

Source: Masinde (2012)

2.8 Water models and artificial intelligence

Groundwater models are examples of hydrological models. A hydrologic model is a mathematical representation of one or more hydrologic processes as a result of precipitation and catchment run-off. Hydrologic models can be used in defining the impact and effects of land management practices on quantity and quality of run-off (Hundecha & Bárdossy, 2004; Linard et al., 2009; Moriasi et al., 2012; Saleh & Du, 2004). The models are unique in that each model is designed with an end in mind, given certain underlying assumptions (State of Minnesota Storm-Water Advisory Group, 1997). Some models are supported by AI (Dutta & Basu, 1984). Table 2.2 depicts the history of AI. AI extensively supports hydrologic predictions and hydrologic system analysis (Chow et al., 1988).

Table 2.2: History of artificial intelligence

Era	Year	Activities/description of events
Birth of AI (1943–1956)	1943	McCulloch and Pitts develop the Boolean circuit model of the brain
	1950	Alan Turing introduces the Turing Test for the evaluation of intelligence and published *'Computing Machinery and Intelligence'.*
	1956	John McCarthy organised the Dartmouth conference where the name AI was formally used. This event is considered the birth of AL.
Golden Years (1956–1974)	1958	John McCarthy invents the Locator/Identifier Separation Protocol (LISP) programming language of AL.
	1969–1973	Many successful programs were written and a new direction was set in the fields of natural language and neural networks.
	1969	A scientist at the Stanford Research Institute develops an intelligent agent equipped with locomotion, perception and problem solving capabilities.
	1973	A robot capable of using vision to locate and assemble models is built.
First AI winter	1974–1980	AI falls into disuse owing to a lack of funding because of high expectations and the failure of AI to produce the promised results. Criticism of the idea shut down the neural network fields for the next ten years.
Boom	1980–1987	The concept of "expert systems" is adopted by many corporations around the world and knowledge becomes the focus of mainstream AI research. The Japanese government funds the 5th generation computer. Rebirth of the neural network by John Hopfield with the introduction of the Hopfield Net. Redevelopment and popularisation of the back-propagation learning algorithm.
Second AI winter	1987–1993	AI suffers another series of financial setbacks, but still continues to make progress. The focus of AI shifts to intelligent agents (robots) to show the world the power of intelligence. This leads to the development of fields such as cybernetics and control theory.
Success	1993–2001	The field finally achieves most of its goals. Successfully used throughout the technology industry owing to improved computing power.
	1997	Deep Blue becomes the first chess computer to beat a (human) world chess champion in 1997.

Era	Year	Activities/description of events
		Adverse development of the intelligent agent (robots). An increase in collaborative research with fields such as mathematics, economics, operation research and programming. Uses of AI now include data mining, industrial robots, logistics, speech recognition, banking, medical diagnosis, and Web search engines.
Deep learning, big data, artificial general intelligence	2000 to present	Owing to access to large datasets, faster computing power and advanced machine learning, AI is now being used in virtually all spheres of life. The deep learning algorithm is developed to overcome the shortcomings of the conventional neural networks such as overfitting. Towards the development of machines capable of general intelligent action such as the AlphaGo program that beats the human world champion in the ancient Chinese game *'GO'* in 2016. Development of smart computing aimed at automating many human functions such as self-driving cars.

Source: Sakala et al. (2018)

A particular groundwater sustainability model covering all aspects, from social, economic, legal, political, technological, and environmental, to hydrological, may not exist; however, there are models that track a few aspects stated earlier, such as changes in the groundwater table and water levels. These models, over time, are influenced by a variety of factors, such as recharge, hydrology, extraction, and surface and base flows in the basins or catchments. Sustainability models may be used to govern aquifers through AI. AI has been used to provide predictions that assist in decision support in the estimation of sustainability regarding aquifer properties, which are one of the components of resource management models. AI extensively supports hydrologic predictions and hydrologic system analysis (Chow et al., 1988).

Many hydrological models are used globally and they cannot all be discussed in this study. There are no groundwater models at catchment level comparable to surface water only models. Nevertheless, many general water management models, including groundwater management models, have been developed such as MODFLOW. Currently, the interest lies in sustainability. The researcher aimed to find a groundwater sustainability model. The following are selected models that focus on water management. They were also selected based on how widely known they are and their adaptation for use in catchments that have high water demand. The gaps in the selected models, with regard to the groundwater sustainability situation, are briefly reviewed. This justifies the need to develop a groundwater sustainability index model.

2.8.1 California Value Integrated Network model

The California Value Integrated Network (CALVIN), depicted in Figure 2.5, is defined as an economic model that looks at the water system and any hydro requirements. It is based on the water supply system of California (Buck, 2016). CALVIN covers economic and management objectives that include operations, policy, and planning solutions. Though not specific on groundwater sustainability, CALVIN covers water supply of both groundwater and surface water. The CALVIN model has been used to allocate portions of water through a series of monthly hydrological data for 82 years. Both Draper et al. (2003) and Lund et al. (2009) stated that CALVIN models agricultural and urban water requirements until 2050, as development levels rise. The model does not cover aquifer system sustainability aspects.

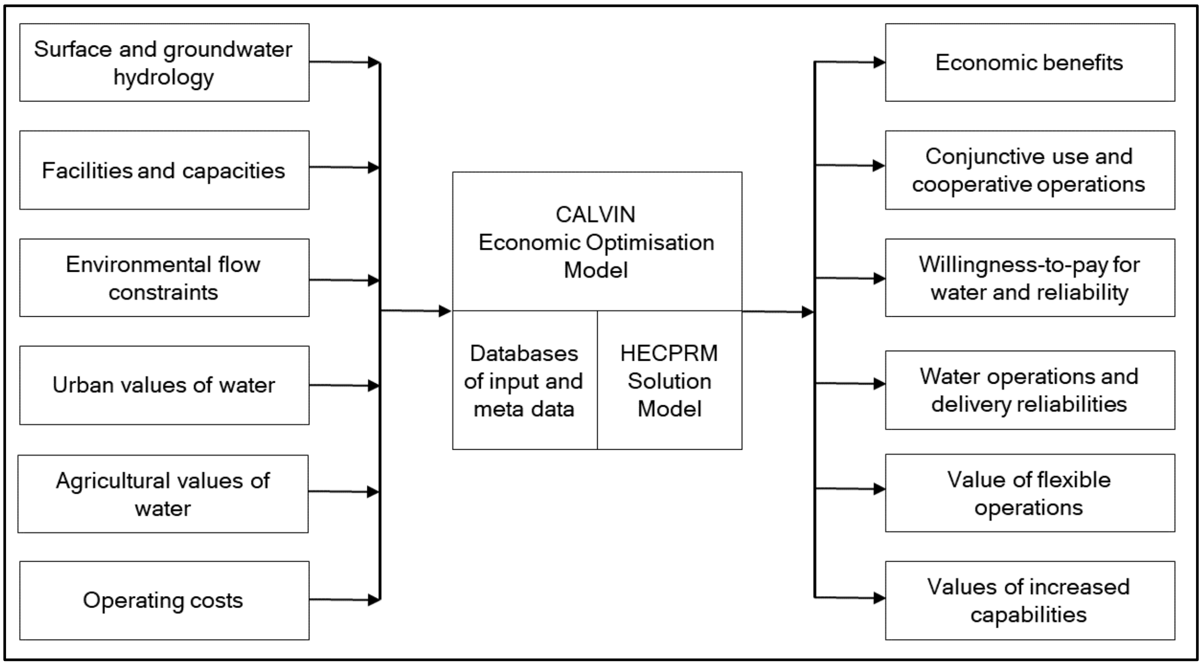


Figure 2.5: California Value Integrated Network
Source: Buck (2016)

2.8.2 California Central Valley Groundwater-Surface Water Simulation Model

The California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) is a surface and groundwater component model that monthly measures the historical crop averages, land use, surface water diversions, stream inflows and precipitation (Brush et al., 2013a). C2VSim appropriates demands for crop water, soil moisture contribution, precipitation, and surface water diversions and establishes the groundwater extraction required to meet the future demand. The model mimics the historical response of surface water and groundwater of the California Central Valley (Figure 2.6).

A flow system, linked to past stresses, allows this model to simulate the impact of projected future stresses. Even though its characteristics bear many important water management aspects, its focus is not on all aspects of groundwater sustainability, such as the rights to water permits, regulation, and social economics. The C2VSim model, according to Brush et al. (2013a; 2013b), allows assessment of complex interactions limited to elevations, water quality and groundwater flows within the California region and adjacent basins.

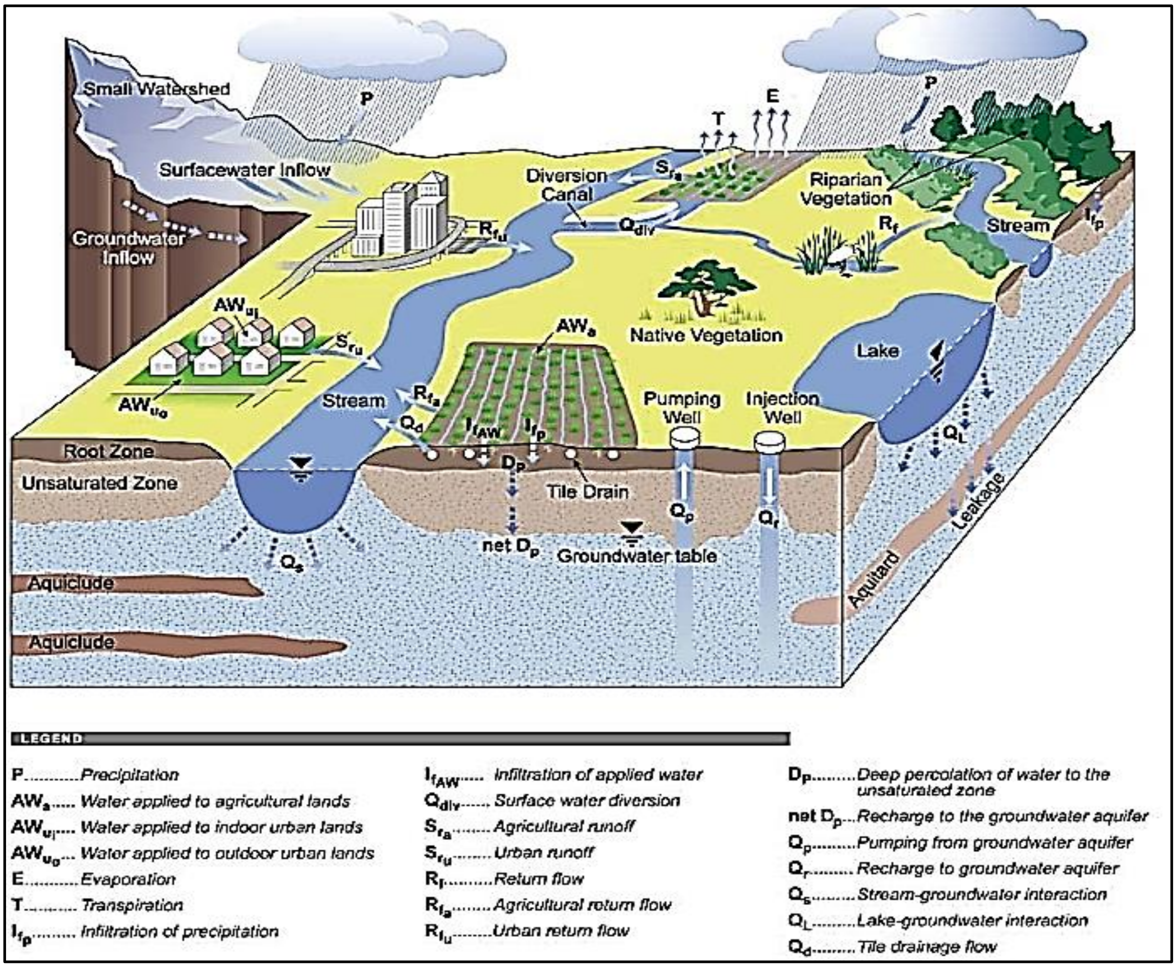


Figure 2.6: Components of the California Central Valley Groundwater–Surface Water Simulation Model

Source: Brush et al. (2013a)

2.8.3 Soil-Water-Atmosphere-Plant model

The Soil-Water-Atmosphere-Plant (SWAP) model is an advancement of a progression and generation model of Californian agriculture created by scientists at the University of California. The SWAP model is an agrarian generation and monetary advancement model. It demonstrates the re-enact land use choices of farmers across 93% of the farming area in California. The final outlay of the model displays documentation and presents consecutive alignment checks that may be found in agricultural production (Howitt et al. 2012). Because the land use and groundwater interaction are currently of interest in discussions on sustainability, the SWAP model was chosen for review.

The SWAP model is a one-dimensional, physically based, agro-hydrological model. The model is expected to emulate water streams, solute transport and plant improvement in a soil-water-atmosphere-plant condition. SWAP imitates vertical soil water streams in a drenched and unsaturated zone by applying the Richard's condition:

$$\partial\theta/\partial t = \partial\, \partial z\, [K(h)\, (\partial h/\partial z + 1)] - S(h) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation } 2$$

Where:

∂t means time;

∂z is the vertical derivative taken as positive upwards (cm);

K(h) is the pressure-driven conductivity indicated by Van Genuchten; Mualem shows (cm/d).

S(h) speaks to the water extraction by plant roots (1/d).

S(h) is typically characterised for a uniform root conveyance as:

$$S(h) = \alpha(h)Tp/|zr \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation } 3$$

Where:

α(h) is a lessening component to represent water and oxygen shortfall (-).

Tp is the potential transpiration (cm/d);

zr is the establishing profundity (cm).

The SWAP model represents the catchment to be simulated and was developed based on the agricultural sector of San Francisco. Additionally, it is a complex framework. In light of economic situations, advancing information, variable hydrology and administering foundations, a huge number of decision-makers are continually modifying their use of land, labour, innovation and various sources of information in the generation of agrarian items, with an end goal to yield the maximal return on investment. The model does not clarify the situation of groundwater in the catchment, but its inclusion is based on its uniqueness of a one-dimension physically-based approach to modelling, which is partly reflected and important to the sustainability index model of this study.

2.8.4 Blue Water Sustainability Index model

The Blue Water Sustainability Index (BIWSI) model is described as a summation of blue water use, non-renewable groundwater reflection and surface water abstraction (Wada, 2016). Cumulative blue water use is the result of agricultural (domesticated animals and water system), industrial and domestic water use. Non-inexhaustible groundwater reproduction is the after-effect of the subtraction between groundwater abstraction and normal groundwater use and recharge from the water system in the semi-arid and arid zones (Wada et al., 2010).

The BIWSI value is computed using three parameters; consumptive blue water use (CBWU), non-renewable groundwater abstraction ($NRGW_A$), and surface water over-abstraction (SW_{OA}). The *CBWU* parameter defines the water consumption for agricultural (livestock and irrigation), industrial, and domestic. The $NRGW_A$ parameter calculates by subtracting the groundwater abstraction (GW_A) from the sum of the natural groundwater recharge value (GWR_{Nat}) and the additional recharge from irrigation return flow (GWR_{Irr}). Thus the BIWSI can be presented as an equation:

$$BIWSI = \frac{\sum^{N}_{i-1} (NRGW_{A,i} + SW_{OA,i})}{\sum^{N}_{i=1} CBWU_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 4$$

$$NRGW_{A,i} = \max [0, GW_{A,i} - (GWR_{Nat.i} + GWR_{Irr,i})] \quad (Q_{Out,i} \geq Q_{Env}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 5$$

$$SW_{OA,I} = \begin{cases} \max\ (O, Q_{Env,i} - Q_{Out,i}) \left(Q_{In,i} \geq Q_{Env,i}\right) and \left(Q_{Out,i} < Q_{Env,i}\right) \\ \max\ (Q_{QIn,i} - Q_{Out,i}) \left(Q_{In,i} \geq Q_{Env,i}\right) and \left(Q_{Out,i} < Q_{Env,i}\right) \end{cases} \quad \ldots\ldots Equation\ 6$$

In the above calculation,

Q_{in} is the inflow;

Q_{out} is the outflow.

They are calculated from simulated stream flow (during the river routing) that may be reduced by upstream human water consumption from all sectors.

The BIWSI model, however, without taking specific measurements, evaluates extended spatial scales. Its weakness is that it merely takes a short review on a few hydrological parameters and it disregards the social financial matters or situations in the catchment. The BIWSI model tends to measure water quantity and not water quality, for example, water contamination that affects the amount of water over a catchment is not accounted for. BWISI is viewed as a low-end human water use and management model.

2.8.5 Global Hydrological and Water Resources model

As indicated by Wada et al. (2010; 2011) and Wada and Bierkens (2014), the Global Hydrological and Water Resources Model is used to mirror the earth's water balance (wetlands, soil water, water stores, lakes, waterways, and wetlands). The model calculates the water trade-offs between different layers of soil. Specifically, it takes a look at the topsoil layer and the climate. Other layers such as the deep soil, comprising groundwater aquifers fed by active recharge, are not considered. The Global Hydrological and Water Resources Model is a highly parameterised simulation within a linear reservoir model (Kraaijenhoff van de Leur, 1958).

According to Vörösmarty et al. (2000) and Wada (2016), the model further populates groundwater abstraction, sectorial water demand, surface water, water allocation, consumptive use and return flows to get a picture of the water balance in a catchment. Its weakness is that it does not look at vulnerability of the aquifer to shocks, such as reduced rainfall and droughts or the economic aspects of sustainable use of the aquifer. The model combines both surface water and groundwater, making isolated groundwater analysis impossible.

2.8.6 Modflow modelling

In Modflow is a model exclusive to groundwater modelling (Lautz & Siegel, 2006). Modflow is a US Geological Survey modular finite-difference flow model, specifically aimed at solving groundwater flows through aquifers. Fortran is the main programming language for this model, which is designed to run on Windows and Linux operating systems. The limitations of this model are that it focuses on transportation problems and water quality and not necessarily sustainability challenges. Many factors should be constant such as density, dynamic viscosity (and consequently temperature), making analysis non-dynamic when modelling (Chu et al., 2010).

2.8.7 Soil and Water Assessment Tool

Soil and Water Assessment Tool (SWAT) is mainly a surface water tool. It comprises hydrology, sedimentation, weather, soil temperature, nutrients, crop growth, agricultural management, pesticides, channel water transfers, reservoir routing and water transfer.

The SWAT modelling system is popular with water practitioners. It assists the user in approximating water amounts available for abstraction by analysing the soil water dynamics (Schattenberg, 2011). In the SWAT model the catchment is analysed using soil characteristics, general water management and homogenous land use. The SWAT simulations identify these factors in the catchment at the lowest level (Gassman et al., 2007; Winchell et al., 2007).

The SWAT model has shortcomings in that it is used mainly for accessing water quantity and quality issues at catchment level (Arnold & Allen, 1996; Bouraoui et al., 2005; Butts et al., 2004; Chaplot et al., 2005; Kim & Pachepsky, 2010; Molina-Navarro et al., 2014; Mutenyo et al., 2013; Oeurng et al., 2011). As discussed earlier, sustainability is wider than water quality and water quantity analysis. In South Africa, its application has been to understand the impact of land use on catchment hydrology (Govender & Everson, 2005; Welderufael et al., 2013; Zang et al., 2008a). According to Gassman et al. (2007), SWAT simulations may be grouped into hydrologic only, hydrologic and pollutant loss, or pollutant loss only.

2.8.8 MIKE SHE

MIKE SHE (powered by DHI) is a model with its strength in surface water analysis. It comprises evapotranspiration, channel flow, overland flow, saturated zone, aquifer exchange unsaturated zone, snowmelt, advection, geochemical processes, nitrogen processes, dispersion of solutes, crop growth, porosity, irrigation, and soil erosion. Its weakness is its lack of focus on all angles of sustainability. It is used for the assessment of water quantity and water quality (Doummar et al., 2012). According to various studies and authors, the MIKE SHE application has been quantification of hydrologic effects to land use change and climate change variability (McMichael et al., 2006; Sahoo et al., 2006; Thompson et al., 2004; Zhang et al., 2008b).

2.8.9 Application of artificial intelligence in groundwater monitoring

The general use of technologies may affect the whole economy at a massive scale, be it at global or national level. General use of technology has the potential to significantly change societies by impacting social and economic structures. The latest examples of such disruptive technology include the internet, computers and block chain (Bresnahan et al., 1995; Landes, 1976; Rosenberg, 1982).

Statistics have shown that cell phone use has improved globally from 2013 to 2019 (Ramamoorthy and Yampolskiy, 2018). In 2013, 56.5% of the world population used cell phones (Andreas, 1994). Mobile phones rely on artificial neural networks (ANNs). An ANN is a system of basic components, called counterfeit neurons. These neurons input and change the interior state (actuation) as indicated by the input information and create yields contingent upon the information and initiation. The system frames, by interfacing the yield of specific neurons to the contribution of different neurons, shape a coordinated, weighted chart. The weights, as well as the capacities that figures the actuation, may be changed by a procedure called realising, which is represented by a learning rule (Andreas, 1994).

ANNs are currently connectable to androids. Androids are open-source operating systems used for smartphones and tablet computers (Sakamoto et al., 2018). On the other hand, Sharma et al. (2018) defined toll-free lines as provisions of subsidised or free Short Message Services (SMS). This is also a short code to receive and send SMS messages from and to the users or consumers, as and when necessary. A toll-free line allows for the information exchanged through all telecommunication networks free of charge, by using an appropriate short code or Unstructured Supplementary Service Data (USSD). ANNs are taking centre stage as proposals in applications for groundwater monitoring, particularly in water quantity and quality.

Consumer behaviour regarding groundwater in South Africa is driven by the following (Mukheibir, 2008):

- Abstraction and access to sustainable water resources.
- Creating employment for community members.
- Providing hope and a dignified life for the users.
- Ensuring safe water usage.
- Need for adequate infrastructural services such as water and sanitation services.

- Creating awareness in the community about more desirable and sustainable water solutions through communication.
- Preserving the water and environment by reinforcing positive water consumption behaviour.

There are various groundwater databases, for example the National Groundwater Archive, Water Use Authorisation and Registration Management System and Hydstra (Olianti & Smit, 2019). Groundwater monitoring has been challenging for the water administrative authorities in the southern African region. Water clients do not submit the required compulsory critical data to effectively monitor water use. This, combined with an absence of restrictions by water authorities on the number of boreholes dug by permit holders, have led to difficulties in decision-making and groundwater conservation.

All SADC nations have hydrogeological maps on various scales. Most maps were produced in the mid-eighties to mid-nineties. The hydrogeological guide of the SADC nations is at a size of 1:2 500 000, and relies upon commitment from hydrogeologists from the member states for updating (Houghton-Carr et al., 2006). The openness and nature of groundwater data and groundwater databases differ between countries. A few of the SADC countries will require capacity building in setting up and improving their groundwater databases.

Technical programming for handling information is accessible, for example for groundwater development, pumping test examination, hydrochemical investigation and GIS. Even though South Africa has the most effective monitoring frameworks (Nomquphu et al., 2007), groundwater monitoring is weak throughout Southern Africa (Moseki, 2013). The groundwater monitoring frameworks change in a number of perspectives, for instance the spatial thickness of monitoring wells; the regularity of estimations; measure of metadata; and in its data organisation and coordination (IGRAC, 2013). According to Haasbroek et al. (2016), the South African groundwater monitoring frameworks have the following issues:

- Gaps in the data records.
- Necessity for training and equipping of monitoring staff, and perhaps formal accreditation of monitoring capacities and equipment.
- Lack of regulation terms, for example meters that can regulate according to terms set.
- Necessity for a segment of the regions to construct the number of groundwater level monitoring stations, as per typical densities in various areas and considering operational necessities and human requirements.

- Conversion of 'rough' groundwater level monitoring data into learning tools, for instance, short reports on delicate areas such as dolomite compartments, wetlands, sole source aquifers.
- Vandalism and theft of groundwater monitoring infrastructure.

2.8.10 Artificial intelligence in hydrological and hydrogeological decision support

Sustainability models may be used to govern aquifers through AI. AI extensively supports hydrological predictions and hydrological systems analyses (Chow et al., 1988). AI, used to provide predictions that assist in decision-making, supports the estimation of sustainability with regard to aquifer properties, which is one of the components of resource management models. Common problems solved using AI include the evaluation of flow in saturated materials and transport of non-reactive contaminants. In the application of all models, and particularly of groundwater quality (transport) models, a high degree of judgement based on a broad experience of field observation, is desirable to produce sound interpretations. This is where AI supports hydrological and hydrogeological decision-making support. This is further becoming significant as sustainability takes centre stage (Molina et al., 2013).

ANNs depend on an accumulation of associated units or hubs, called counterfeit neurons, which freely display the neurons in an organic mind. Every association, similar to the neuro-transmitters in a natural cerebrum, may transmit a flag starting with one artificial neuron onto the next. An artificial neuron that receives a flag may process it and thereafter flags off extra artificial neurons associated with it towards a specific action (Moorthy & Gandhi, 2018).

ANNs are flexible and less assumption-dependent and, thus, they find applications in modelling significantly complex domains such as groundwater flows, rainfall run-off, stream flows, water quality of aquifers and precipitation estimation. In most hydrological applications, a multi-layer perceptron neural network model is adopted with a feed-forward back propagation network (BPN). The ANN models presented in this section are based on BPN. The monitoring system has three components; namely knowledge/data capturing, monitoring and prediction, and information dissemination. While ANNs are used for the monitoring and prediction part, mobile phone technologies (SMS and mobile applications) and wireless sensors are used for knowledge and data capturing, and information dissemination purposes (Mehrotra et al., 2003).

Similar to ANN executions, the action at an association of counterfeit neurons is a genuine number and the yield of each artificial neuron is figured by some non-straight capacity of the aggregate of its sources of information (Julie et al., 2018). Julie et al. (2018) further stated that the associations between artificial neurons are called 'edges'. Counterfeit neurons and edges commonly have a weight that modifies as learning continues. The weight increments, or reductions are the quality of the flag at an association. According to Commons (2018), artificial neurons may have a limit with the end goal. The flag is simply sent if the total flag crosses that edge. Usually, artificial neurons are amassed into layers. Distinctive layers may perform various forms of changes on their data sources. Signs travel from the main layer (the info layer), to the last layer (the yield layer), potentially subsequent to navigating the layers on various occasions.

The objective of groundwater monitoring using an ANN approach is to take care of issues similar to prediction estimation as typical groundwater yield phenomena. In any case, after some time, consideration moved to perform particular errands and prompting deviations from science. Lessons were learnt from the use artificial neural network on an assortment of assignments, including personal computer vision, discourse acknowledgment, machine interpretation, informal community separating, playing board and computer games and medicinal findings, considering the information flow shown in Figure 2.7.

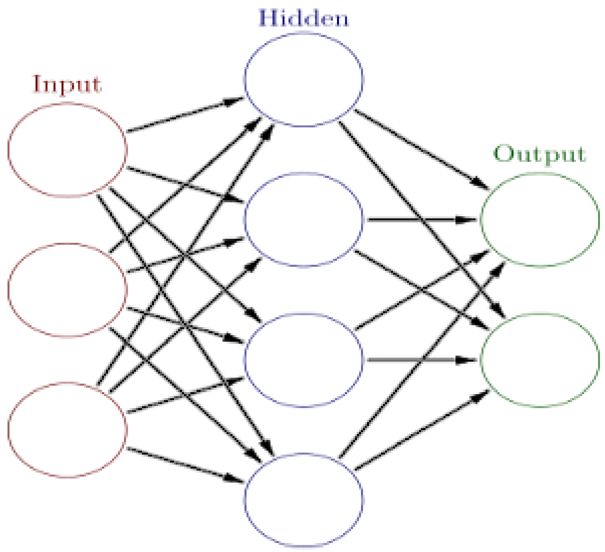


Figure 2.7: Information flow of an artificial neuron

Source: Antonić et al. (2001)

According to Wang et al. (2009), cloud computing is the act of using a system of remote servers facilitated on the Web to store, oversee and process information, as opposed to a nearby server or a personal computer. It keenly supports hydrological gauging models that anticipate yields from inputs in view of past records of groundwater levels. There are no settled standards for building up these AI procedures (ANNs), despite the fact that a general system may be taken in light of past fruitful applications in designing them (Cheng et al., 2005; Lin et al., 2006; Nayak et al., 2004; Sudheer et al., 2002). The goal of studies centred on foreseeing water releases, using forerunner esteems, is to sum up a relationship of the accompanying structure or cloud required in Equation 9:

$$Y = f(X^m) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 9$$

In the formula above,

X^m is an m-dimensional information vector comprising factors $x_1 \ldots x_i \ldots x_m$, and

Y is the yield variable.

In release demonstrating, estimations of x_{im} might be stream esteems, with various time slacks, and the esteem Y is, by and large, the stream in the following time frame. For the most part, the quantity of predecessor esteems incorporated into the vector X^m is not known from the previous result.

According to Sakala et al. (2018), Equation 10 represents the scientific portrayal of the connection between the actuation work, sources of information, weights, and the inclination:

$$y(k) = f(\sum_{i=1}^{m} i(k) * Wi(k) + b) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 10$$

In the above formula,

$X_i(k)$ is the input of a given time k and i ranges from zero to infinity;

$W_i(k)$ is the value assigned to a weight in a given time k where i ranges from zero to infinity.

b denotes bias value.

f denotes transfer function.

$y(k)$ denotes the output in each time k.

The plan and methodological highlights are bolstered by android innovation and Java programming. Man-made consciousness (AI) is used to depict the figuring worldview in this ICT-based framework, whose arrangements mirror human learning, recognition and dissuading the point of taking care of complex issues. The two primary AI procedures that have an effect on everything in this groundwater monitoring framework, are ANNs and canny specialists (Wang et al., 2009).

The technique additionally considers human instigated parameters of rights and values in terms of licenses, pumping rates every year, number of issued permits allowed in the catchment annually and number of boreholes in the sub-catchment. In addition, financial and land use (populace in the catchment, use per capita, water uses and duties) are considered.

ANNs are adaptable, less presumptive wards. This has seen them discovered in applications displaying, to a great degree, of complex spaces; for example, precipitation overflow, streams, water quality aquifers and precipitation estimation (Govindaraju 2000; Joorabchi et al., 2009; Taormina et al., 2012). In most hydrological applications, a multi-layer perceptron neural system display is received with feed-forward back engendering (BPN), as the preparation calculation that the ANN models exhibited in this section depends on the BPN (Antonić et al., 2001; Chang-Shian et al., 2010; Freitas & Billib 1997; Kung et al., 2006; Mishra & Desai 2006). The observation framework has three parts, namely learning/information catching, monitoring and forecast, and data scattering. ANNs are used for the observation and forecast part, while cell phone innovations (SMS and portable applications) and remote sensors are used for learning/information catching and data scattering purposes. The framework depends on ANNs.

Using an android telephone, well information, water levels and climate-related information such as precipitation are, thus, assembled and sent to a composed store through a sort code/USSD/instrument-free line in texts (SMS). This is proficient through a third generation global system for mobile communications, General Packet Radio Service (3G/GSM/GPRS) module that is part of the sensor equipment used for this procedure. Once in the store, requests are used to recuperate data in the required design. Additionally, it shows a cloud framework at the point where a long-lasting file is followed up.

In the Internet of Things (IoT) domain, billions of day-to-day things, extending from physical articles and gadgets to virtual items and gadgets are joined on the web; this has made IoT a modern occurrence (Atzori et al., 2010). Subsequently, IoT has turned out to be a standout among the most sought-after research subjects today. Empowering advancements required for various evaluations drive the achievement of IoT; these incorporate the web itself, radio recurrence identification/detection and remote sensor systems such as wireless sensor networks.

Wireless sensor networks have turned into significant parts of acknowledging the IoT; they provide the detecting abilities to gather data about the physical condition and remote correspondence that empowers impromptu systems administration, with no pre-set physical framework. Wireless sensor networks are particularly instrumental in acquainting insight with the IoT, due to their capacity to participate and team-up in completing undertakings. Be that as it may, the fundamental empowering factor for this promising worldview of the IoT is the interoperability of a few innovations, consistent information sharing and the simplicity of correspondence.

Theoretically, the most practical arrangement that may encourage viable information sharing and coordination is the portrayal of information in a machine discernible arrangement. That is, change of the data into semantically explained information with itemised metadata portrayal for consistent correspondence between assets or things, independent of the space, as connected to sustainability or aquifer assessment application.

The ICT framework may be used to assess the sustainability of groundwater in different catchments throughout South Africa and Southern African countries. This will thus bolster changes and practices among water consumers and water catchments. AI may be a coherent premise behind the groundwater catchment innovation, showcased as an inventive innovation arrangement that adds to the accomplishment of water programmes.

2.9 Factors determining groundwater sustainability

2.9.1 Hydrological cycle

In reference to Chow et al. (1988), hydrology is the study of the water cycle or hydrological cycle. That is, in more specific terms, the distribution of water within the earth's atmosphere. The hydrological cycle is the transgression of water naturally across the different layers, inclusive of land and oceans (Brutsaert, 2005). Chow et al. (1988) described the hydrologic cycle as follows:

> *The cycle has no starting or ending point. Water evaporates from the oceans and lifted into the atmosphere until it condenses and precipitates on the land or the oceans; precipitated water may be intercepted by vegetation, become overland flow over the ground surface, infiltrate into ground, flow through the soil as subsurface flow, and discharge into streams as surface run-off. Much of the intercepted water and surface run-off returns to the atmosphere through evaporation. The infiltrated water may percolate deeper to recharge groundwater, later emerging in springs or seeping into streams to form surface run-off, and finally flowing out to the sea or evaporating into the atmosphere as the hydrologic cycle continues.*

Figure 2.8 illustrates the hydrological cycle and its major components.

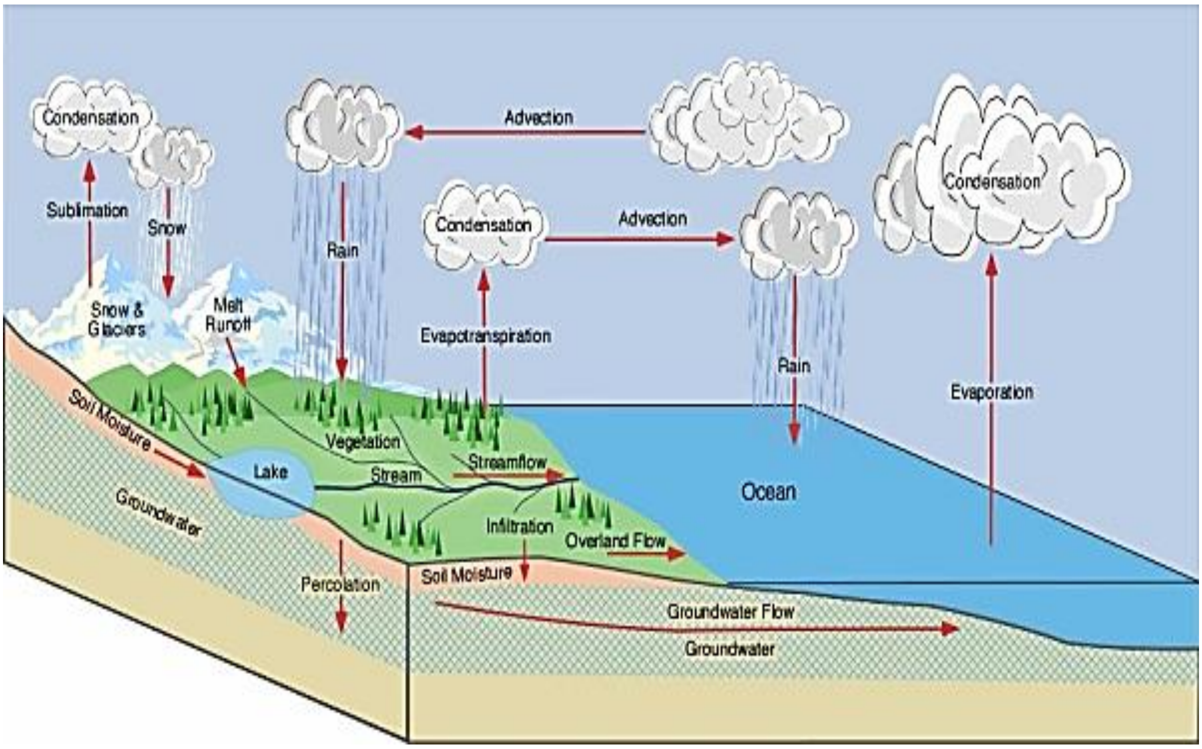


Figure 2.8: Hydrological cycle
Source: Pidwirny (2006b)

2.9.2 Catchment hydrology

Catchment hydrology deals with surface water and groundwater on a landscape scale, where the unit of interest is the catchment. Catchment refers to the land area that is drained by the tributaries of a river. A catchment, in most recent times, has been defined as an area drained by a stream or stream channel network in such a way that all the surface run-off from that area is concentrated as flow in a single outlet (Reddy, 2006). Quantitative assessment of hydrological parameters, such as precipitation, evaporation, infiltration and run-off and their use in water balance studies or in the problems of design and forecasting, will be rational only when they are applied to an area with well-defined boundaries (Reddy, 2006).

Run-off is regularly mentioned in discussions about catchment hydrology. Run-off is the result of a hydrological cycle and processes. Its main influences are physiographic factors and climatic factors. Physiographic factors are in two forms: catchment and channel characteristics. Catchment characteristics are broken down into land use and cover, topography, slope, and soil type. Channel characteristics, on the other hand, are associated with hydraulic processes and properties. This means that channels govern the motion streams and their storage capacity (Chow, 1964). Climatic factors are mainly categorised as rainfall type, distribution, duration, and intensity. These in turn affect evaporation and transpiration (Reddy, 2006).

2.9.3 Climate

Rainfall is not the only climatic factor that affects hydrology. In this study, rainfall is used as a component of the climatic conditions, because its data is easily accessible. Sanfo et al. (2017) described three types of rainfall: orographic, cyclonic, and convectional. Orographic rainfall is as result of airstreams forced to rise over a mountain range where the air is cooled. After this action, rain falls. The orographic effect has been underpinned to the windward slope of large topographical configurations typically receiving more rain than the leeward slope (Zhao et al., 2017). Cyclonic rainfall forms when warm air rises over cold air. The cold air condenses the warm air and the cooling effect results in rainfall. Convectional rainfall is synonymous with a tropical climate. Its formation is as result of rising and abrupt cooling of hot air. The hot ground is responsible for this heat exchange. The degree of heat determines if there will be thunderstorms. Some forms of rainfall, such as convectional rainfall, generate more downpour and, therefore, further available precipitation to contribute to recharge. Rainfall is an important groundwater sustainability factor as it is the key to assessing any rainfall-fed models (Tetsoane, 2013). The availability of precipitation data and its duration is vital for hydrological analyses during the design and management of water resources systems (Zulkafli et al., 2017). Other climatic factors considered are sunshine and evapotranspiration.

2.9.4 Slopes

Larger slopes generate more surface flow speed than smaller slopes. This may create faster run-off. Slopes dictate the amount of water filtered and retained in the ground as recharge. Smaller slopes balance rainfall input and the run-off rate that is stored temporally over the area. With time, it is able to drain out gradually. This is an important consideration for groundwater sustainability. According to Haggard et al. (2005), Khan et al. (2007), Tetsoane (2013) and Xanke et al. (2017), a rise in the surface slope shows a rise in surface water run-off.

2.9.5 Land use and cover

Land cover refers to natural vegetation cover and human impact through a number of activities directly related to land occupation. Human activities use land resources and interfere in the ecological processes that determine the functioning of land cover (Niehoff et al., 2002; Tetsoane, 2013). Land cover, and therefore land use, is one of the key parameters in groundwater sustainability, particularly in the hydrological cycle (Giertz et al., 2005; Tetsoane, 2013). The effect of land use changes, land cover changes and urbanisation on the hydrologic modalities and processes in catchments, were studied in South Africa in terms of vegetation conversion during the 1980s and 1990s (Giertz et al., 2005; Tetsoane, 2013). An investigation carried out by Hundecha and Bárdossy (2004) in Germany, Italy and South Africa, found that urbanisation led to a 2.9% rise in peak flow, but a decrease of 14% in peak flows due to increased afforestation. Tang et al. (2005) reported a 5% to 12% increase on run-off due to urbanisation. Klöcking and Haberlandt (2002) found that urbanisation causes an increase of storm flows in relation to the increased amount of surface run-off. There have been reports of alien plants drying some wetlands.

An assessment into the negative effects of farming on hydrological processes is important for groundwater sustainability. Most assessments concluded that high grazing pressure lowers infiltration rates, increases run-off from the ground surface as it lowers vegetation cover, and increases soil/ground compaction (Girmay et al., 2009; Tetsoane, 2013). Kashaigili (2008) concluded that the changes of land use and cover resulted in changes in distribution of surface run-off within the catchment in his study, therefore affecting water infiltration rates. Furthermore, Giertz and Diekkrüger (2003) studied the effects of land use on run-off generation by taking infiltration measurements on different land use categories. The results were that surface run-off was generated in varying magnitudes for different land use types, with farmland being the highest. Wei et al. (2007) reported high run-off coefficients for different land uses of farmland: 8.40% for cropland, 7.16% for pastureland, 2.61% for shrubland, 5.46% for woodland and 3.91% for grassland.

2.9.6 Soil type

Soil is an important factor for groundwater sustainability. The texture of a particular soil indicates much about the hydraulic conductivity and its particle size distribution (Jensen et al., 2017; Pidwirny, 2006a; Tetsoane, 2013). Soil texture and coarse fragment content are the most significant properties of soil that affect groundwater sustainability as they affect water flow through the soil. In addition, they further set out the amount of water retained in the soil, contributing to the water table of the catchment (Schaetzl & Anderson, 2005; Tetsoane, 2013). Soil type also affect run-off generation and characteristics. In an analysis of -Al-Baha region soils, Mahmoud and Alazba (2015) reported runoff coefficients of various soils types as 0.74, 0.67, 0.80 for loamy sandy, loamy clay and clays respectively. Clay soil had the highest value, which was much higher than sandy soil.

2.9.7 Topography

Topography defines the formation of land surface. This includes its relief and the position of its natural and man-made features (Krause, 2008; Tetsoane, 2013). Topographic maps are generally used to show areas of various elevations in a place. The elevations of mountains and valleys, steepness of slopes and the direction of stream flow may be determined by studying topographic maps (Gabler et al., 2004; Tetsoane, 2013). Topography is a key factor in groundwater sustainability because hydrologists use topographic and soil maps to understand an area (Hasanuzzaman et al., 2017; Tetsoane, 2013; Ward & Robinson, 1990). In groundwater sustainability, topography dictates the direction of groundwater flow. Topography further affects groundwater recharge and discharge (Krause, 2008). The impact of topography on rainfall distribution may be linked to different mechanisms, such as wind-driven effects and the small-scale topographic effect (Zhao et al., 2017).

2.9.8 Permits or licencing system

The permit or licencing system forms part of a groundwater sustainability system. Permits are used as a regulatory tool to guard accessibility of groundwater resources and monitoring of groundwater extractions. The permits further ensure that distribution rates, sizes and/or magnitudes remain within limits that are politically acceptable, socially and environmentally viable and technically feasible. Groundwater licensing guarantees groundwater abstraction with water management plans. The basic importance of permits with regard to groundwater sustainability is economic instruments, demarcating groundwater rights and groundwater licensing (Riemann et al., 2012). Groundwater restrictions and rights enable effective groundwater management if properly regulated (Pandey et al., 2011). Economic instruments are important as they conserve groundwater quality and control extraction of groundwater. Various methods have been used to lessen abstraction. These include enabling water right trading, subsidies and taxation. Caution is advised when taking water licensing measures.

These measures must take into account the intrinsic value of groundwater for all sectors of the economy (Pandey et al., 2011).

The National Water Act, Act 36 of 1998, of South Africa states that the country has ownership of water resources. The country links groundwater directly to surface water. As such, whoever owns the land has the right to the groundwater. To date, arrangements and provision for trading groundwater rights do not exist. This is important to note in regard to groundwater sustainability because the National Water Act promotes efficiency, equity and sustainability as paramount to the management of water resources development in South Africa. However, equity has not received the desired attention, according to the National Water Amendment Act, Act 27 of 2014, resulting in inequitable water allocation. The government has deemed equity as necessary for promoting sustainable economic growth and the eradication of poverty.

Table 2.3 shows an evaluation tool used for compulsory licensing. Compulsory licensing is a means by which all water users in an area are given water based on their requirements and assessed needs. Compulsory licensing was introduced for several reasons (Kidd, 2016) among which are:

- Fairness in water allocations.
- Preserving water quality.
- Serving public interest.
- Promoting efficient water resources.

Table 2.3 further shows the model used by the DWS to grant permits for water uses. The table assists in calculating the amount of water available in the sub-catchment, which is represented as water balance from the recharge. The table is the current licensing tool used by the government of South Africa to allocate how much groundwater can be abstracted by applicants. All groundwater use applications are assessed against this table. Any application with a recharge below the average of the sub-catchment recharge value is awarded. Those who apply for abstraction with a value above the catchment recharge value are declined. If the suitable yield is above the catchment recharge values, it becomes challenging to limit the applicant. Therefore, this further justifies the importance to study the groundwater sustainability of the catchments, which becomes additional tools to guide groundwater licencing.

Table 2.3: Water license evaluation template/tool

This is a typical example of the groundwater balance assessment used during a Water Use License Application and focus strictly on the groundwater recharge potential of the property on which the water use is to be developed and used.				
Software will calculate the components for the assessment				Only insert data in THESE coloured boxes
A21F	Kaalfontein 44 IQ (sub- Quaternary Catchment)			Quaternary Catchment and Farm Name/Number/Portion
Size (ha) of Property (Deed)	3816	38.160	km² [Area in Km²]	Area (ha) of Property as per Transport Deeds Registrar
General Authorisation on Quaternary (m³/ha/a)	60	228 960	m³/ha/a on Area	First General Authorisation (DWAF)
General Authorisation on Quaternary (m3/ha/a)	0	0		Total volume as per General Authorisation (#2) on Area
License (Water Use required)	1500 000	1500 000	m³/a	Water use requested by licensee for Area
Harvest Potential $_{MAP}$ - Min	10 000	m³/km²/a	Harvest Potential as per Vegter's Map (Including lateral Recharge) -Minimum	
Harvest Potential $_{MAP}$ - Max	15 000	m³/km²/a	Harvest Potential as per Vegter's Map (Including lateral Recharge) - Maximum	
Available Volume/a: Lower Harvest Potential value		381 600	m³/a	Volume of groundwater that can be authorised with Harvest Potential evaluation. (Maximum - Minimum)
Available Volume/a: Highest Harvest Potential Value		572 400	m³/a	
Average Harvest Potential volume		477 000	m³/a	
Average Harvest Potential ratio		2.9	: 1	Ratio: This allocation VS Harvest Potential.
Exploitation Potential (Haupt) for Quaternary Catchment		8 781	m³/km²/a	This is: Harvest Potential corrected for abstraction, recharge and hydraulic characteristics of aquifer(s) in Quaternary Catchment
Exploitation Potential (Haupt) for Area		335 070	m³/a	
Exploitation Potential ratio		4.5	: 1	Ratio: This allocation VS Exploitation Potential (by WSM-Haupt)
GRA II Information	A21F		m³ on Area	
Volume water Stored in Aquifer	585.980	Mm³/a	18 618 648	Total volume (m³) of groundwater stored in aquifer systems within QC (i.e. WZ + FZ) [Repeat from Project 1].
Harvest Potential (as in GRA II)	15.336		487 266	Annual volume (m³) of groundwater per km² available for exploitation according to Harvest Potential (Baron, Seward & Seymour, 1998)
Baseflow (MACBf)	8.159		259 231	Mean annual volume (m³) of groundwater discharge (baseflow) to rivers in Quaternary Catchment [output Project 3].
Average Annual Potential Recharge (Dry)	34.695		1 102 376	Mean annual volume (m³) of groundwater recharge from rainfall per Quaternary Catchment under 'drought' conditions, i.e. rainfall < MAP x %CV.
Groundwater Resource Pot (AGRP - Dry)	154.818		4 919 113	Mean annual Groundwater Resource Potential (AGRP in m³) per Quaternary Catchment under 'drought' recharge conditions (Re Dry).
Average Groundwater Exploitation Potential (AGEP - Dry)	68.380		2 172 677	Mean annual Groundwater Exploitation Potential (AGRP in m3) per Quaternary Catchment under 'drought' recharge conditions (AGEPDry = AGRPDry x Ef). INCLUDING SOME STORAGE!
Potential Groundwater Exploitation Potential (PGEP - Dry)	66.999		2 128 788	Mean annual Potable Groundwater Exploitation Potential (PGEP in m³) per Quaternary Catchment under 'drought' recharge conditions ($PGEP_{Dry}$ = $AGEP_{Dry}$ x Pf).
Utilisable Groundwater Resource Potential(UGRP - Dry)	18.713		594 591	Mean annual Utilisable Groundwater Resource Potential (UGRP in m³) per Quaternary Catchment under 'drought' recharge conditions ($UGRP_{Dry}$ = $AGRP_{Dry}$ using max. allowable drawdown [Project 4]).
Annual Recharge required		39.3	mm	Recharge required to sustain THIS water use on Area
Annual Recharge from av. Harvest Potential		12.5	mm	Recharge available On Area to sustain Harvest Potential
Annual Recharge from Exploitation Potential				Recharge available On Area to sustain Max Utilisable
Annual Recharge from GR... Estimation.		28.9	mm	Recharge available On Area to ... AGEP (GRA II)
Average Rech... Sub-QC (Mm³/a)	1.46	38.2	mm/a on s-QC	Source: From Reserve determination by Groundwater Consulting Services (March 2007).
Sub-...aternary Catchment Area	38.16	<Km² / m²>	38 160 000	
B...se flow	0.1031		Mm³/a	
In...tream Flow Requirements	0.0000		Mm³/a	
Basic Huma... Needs	0.0037		Mm³/a	
Amount of Recharge a...able for allocation		38	mm/a	
Recharge in reserve on this Area				Difference betw... ...rge in Reserve and Required for ... use (deficit if printed in red!!!)
➔ Land area required to sustain thus Use		8970	ha	Based on mean recharge of: 17 mm/a
THIS ALLOCATION	1.5000		Mm³/a	
Already allocated in Quaternary Catchment	1.051		Mm³/a	Updated from WARMS data base on:
TOTAL ALLOCATION	2.5547		Mm³/a	Total allocation for Quaternary Catchment, this water use included
Summary: Reserve volume in Quaternary Catchment	-1.1	Mm³	175%	<< ALREADY allocated in A21F - Quaternary Catchment

Source: DWA (2016)

2.9.9 Water policy and rights

Water rights is a factor that affects groundwater sustainability as it declares the country's ownership of water resources by linking groundwater to surface water. The right to groundwater is in line with the right to land. There are no practices and legal provisions for trading groundwater rights. For the purposes of this study, the National Water Act stresses efficiency, equity, and sustainability. The tenets of groundwater development are the guiding principles for water resources management in South Africa. Equitable access to groundwater is critical for transformation in the water sector of South Africa. Groundwater is a means to eradicate poverty and equitable sustainable growth.

2.9.10 Population, demographics, socio-economics, and anthropology

Population growth in arid and semi-arid zones of South Africa means that farmers and eco-systems have predetermined limited water resources, such as groundwater. In relation to groundwater sustainability, this has increased the need for access to groundwater and expanded the quantity of wells and boreholes being drilled to get to groundwater, which is required for various purposes, particularly for agribusinesses and drinking water. The restricted assets of water arrangements have put undue weight on aquifers, for example, the aquifers in the C52 Modder River basin catchment as a tributary of the larger Orange River system.

The undue pressure in the catchment has prompted extreme pumping and expanded use of groundwater. The capacity to supply water directly from aquifers to agriculturists and other water consumers depends largely on the precipitation recharging such aquifers. With the low precipitation in South Africa, groundwater recovery is certainly low. The net impact has been over-consumption made worse by prolonged dry seasons (Postel, 1997). There is subsequently a need to create groundwater sustainability techniques, models, and solutions to make informed choices for enhanced groundwater management.

According to Woodford and Chevallier (2002b), a detailed study was conducted on population distribution in South Africa to estimate the future water demand and requirements. An estimated 5% of the population of South Africa lives in the Modder River catchment (DWS, 2016). Approximately 80% of these people are concentrated in Bloemfontein, Botshabelo and Thaba 'Nchu. The main attraction of the population to these places has been as a result of the economic opportunities created to catalyse growth. With regard to the population distribution in the C52 catchment, the drier parts are sparsely populated, while the areas with higher rainfall, to the east of the catchment, are more densely populated. The population growth is projected to increase with economic growth.

2.10 Challenges of sustainable groundwater uses

2.10.1 Groundwater depletion

There are many impacts of groundwater depletion. The largest impact is loss of base flow. Base flow is water that has filtered into the earth's crust and then pumped. Figure 2.5 shows a stream that has turned out to be somewhat profluent (losing) towards the pumping, decreasing its base stream.

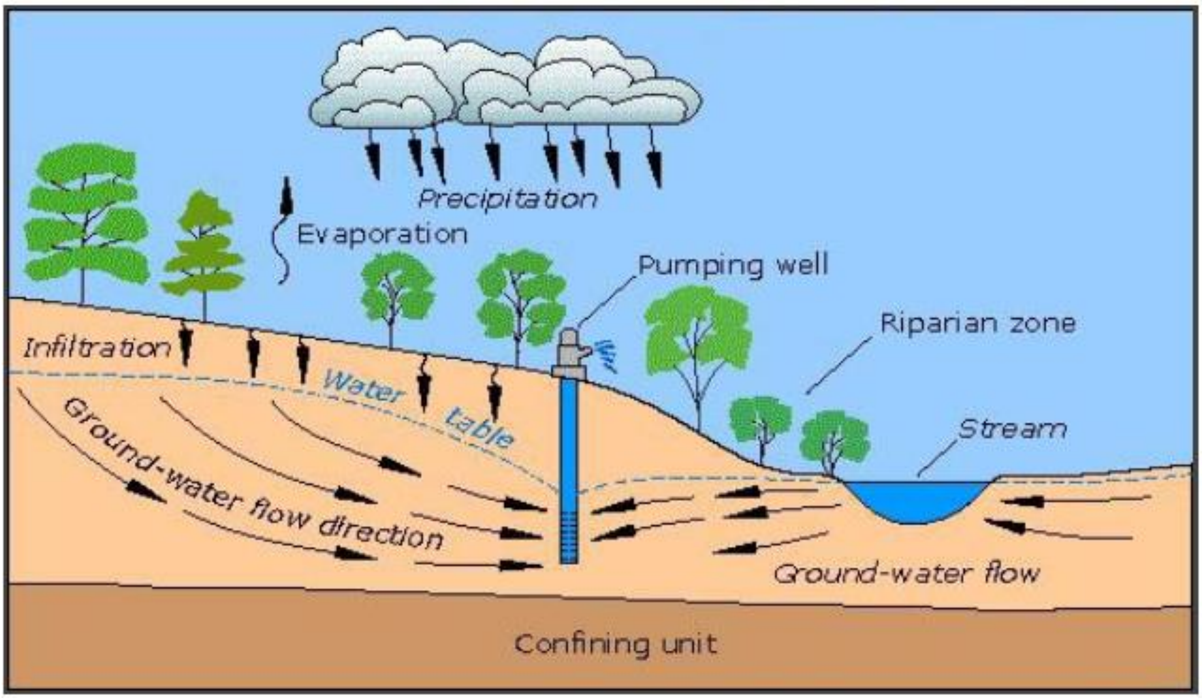


Figure 2.9: Base flow water that has filtered into the earth's crust and then pumped out
Source: Ponce (2006)

The National Research Council (2000) suggested that the impact on base flow depends on the pumping rate of the groundwater. The loss of base flow furthermore depends on the interaction between surface water and groundwater. Perennial flow of rivers is achieved through enhanced base flow. This is lost with a high groundwater pumping rate (Leschik et al., 2009). This effect of increased groundwater pumping decreases recharge. High base flow loss has a number of negative impacts (Hoffmann et al., 2001; Ponce et al., 1997) such as:

- Wells drying up.
- The cost of pumping and infrastructure framework expansion.
- Subsidence of land.
- Saltwater intrusion and enrichment.
- Climate change related impact such as low evapotranspiration.

2.10.2 Groundwater usage

Bear (2012) stated that groundwater usage has an impact on net recharge and net groundwater discharge. Net recharge by definition is the difference between discharge and recharge. When groundwater is stagnant, recharge is the same as the discharge; at this point net recharge is zero (see Figure 2.10). When groundwater is being abstracted for an economic activity, the pumping rate of a borehole is synonymous with artificial discharge (Mazzoni et al., 2018). At this point the artificial discharge reduces the natural discharge to a value of zero. The calculated value of the net recharge is the difference between the increase in recharge, the pumping rate, and the decrease of the discharge. If the difference is positive, the water table will rise; if the difference is zero, the water table is said to be in a steady state. If the difference is negative, the water table gradually drops over time.

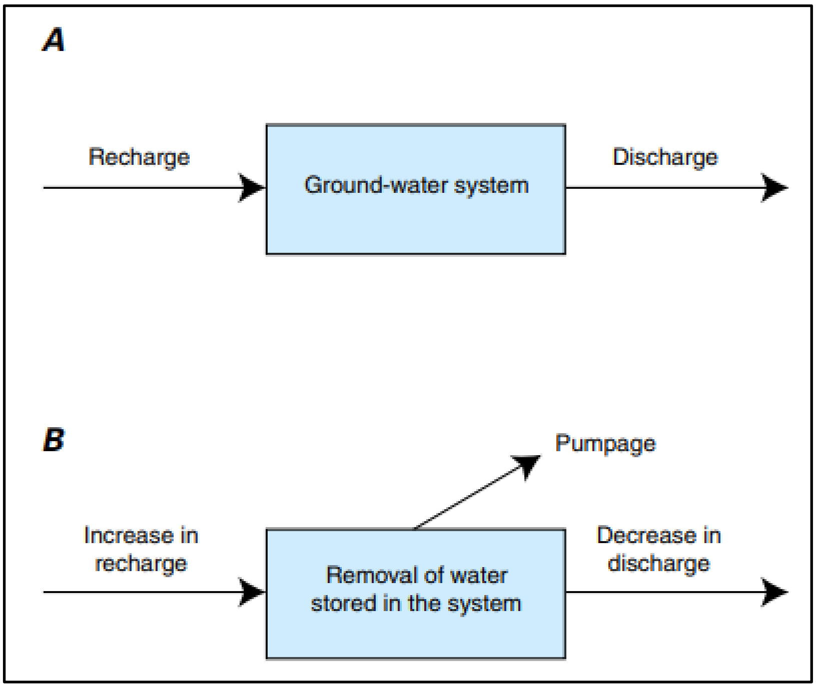


Figure 2.10: Net recharge when a well is not in development and when in development conditions

Source: Alley et al. (1999)

Another impact of groundwater usage is through assessing the effects of pumping (Martínez-Santos et al., 2018). This may be studied by investigating whether all the water pumped for irrigation is lost through evapotranspiration, plant use or returned to the ground as ground-water. In the cases where the uses are excessive and not returned as groundwater, the intensive withdrawals cause the surface water to reduce, leading to degraded ecosystems.

The key hydrological parameter subject to pumping of groundwater for socio-economic activity is the hydraulic gradient. According to Darcy's Law, the hydraulic gradient regulates the flow of groundwater (Pyne, 2017). Figure 2.11 shows a hydraulic gradient that is proportional to recharge. This is a result of recharge drawn from neighbouring connected aquifers.

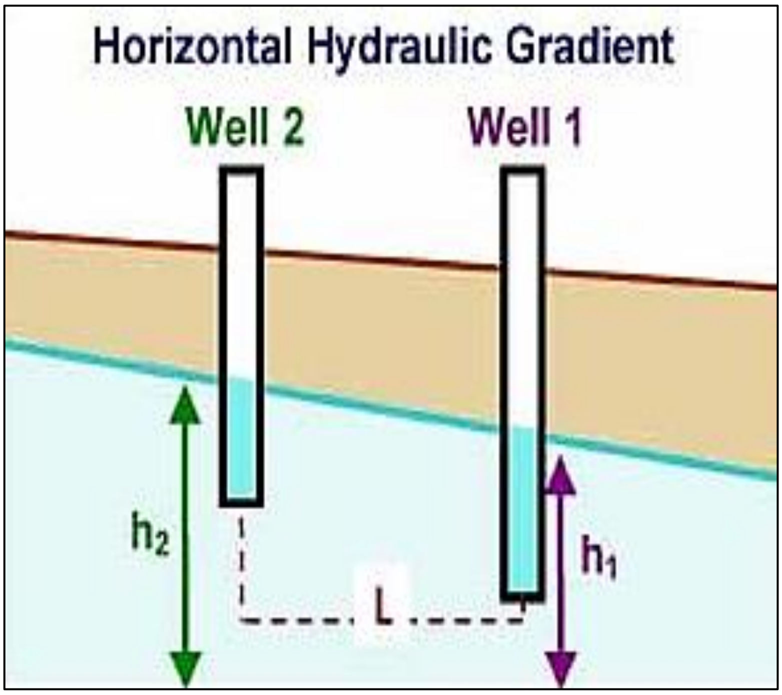


Figure 2.11: The horizontal hydraulic gradient

Source: Holt (1965)

It is demanded that hydrogeological and geophysical studies determine aquifer connectivity (Kelly & Locke, 2018). This is required because when aquifers are connected high pumping rates tend to have large areas of influence based on the slope and hydraulic gradient.

2.10.3 Borehole failure

The causes of failure of groundwater-dependent rural water supplies are complex and are likely to result from a number of interrelated contributory factors, ranging from changes in demand for water, reduction in rainfall, inappropriate engineering to weak governance and institutions. These factors have significantly different levels of importance and contribution to source failure in various physical and socio-economic settings. Unravelling the causes of supply failure requires in-depth knowledge of financing, management, and backstopping arrangements; groundwater conditions and trends; water point siting, design, construction, and maintenance; and seasonal changes and demand pressures.

2.10.4 Poor management of groundwater resources

Much political interference exists around groundwater management and development (Mukherji & Shah, 2005). As much as the realisation that sustainable groundwater management is required, low scientific knowledge of physical, hydrogeological and chemical characteristics of groundwater remain a challenge. Not much is known regarding the policies and institutions that govern issues to do with groundwater (Mukherji & Shah, 2005).

The incentives to make changes in groundwater management practices are driven by decline in groundwater yields, complaints about water quality and risks to water services (Tuinhof et al., 2003). Unfortunately, at this stage, recognition of these impacts will have happened when it is too late for effective remedial action to be taken, therefore associating these negative results with failure in governance (Bakker et al., 2008; Rogers & Hall, 2007).

Acceptable groundwater governance enables sustainability and embodies economic, technical, institutional, social, administrative, policy and judicial aspects. These tenets ensure that groundwater systems and eco-systems are used responsibly. Turton et al. (2007) defined acceptable groundwater governance as processes of informed decision-making, enabling trade-offs among competing water users so that groundwater resources are in balance, protected, mitigating conflict, enhancing security, ensuring sustainability, and holding government accountable.

According to the Council of Canadian Academies (2009), the context of groundwater governance involves both issues of quantity and quality and, as such, they stated that legal frameworks for groundwater management should separate future management requirements into decisions regarding resource allocation and use. The Council further recommended transparency and public participatory approaches in accountability of eco-systems, pre-cautionary principles and intergenerational equity. Both Pahl-Wostl (2015) and the United

Nations Environmental Programme (2003) supported a paradigm shift towards groundwater research, integration of water use across sectors, access to groundwater information and clear water laws and rights.

2.10.5 Groundwater allocation gaps in South Africa

It is still unclear if groundwater allocations in South Africa are based on individuals who have previously been advantaged. The DWS (2016) stated that the majority of the current water use licence applications are from this advantaged group, usually with no indication of how the allocations will contribute to redressing equity. Before the National Water Act was passed, the regulator also allowed borehole owners to continue to use unregistered groundwater.

The DWS (2016) further stated that the implementation of the water assessment programme did not cover allocation that was equitable to all groups. For example, compulsory licensing categories, as shown in Table 2.4, have not been implemented fully in South Africa. Pilot studies were undertaken and completed in the Jan Dissels catchment in the Western Cape province (van der Berg, 2008) and the Tosca Molopo groundwater area in the North West province (Kidd, 2016). This programme was planned to be implemented in all water stressed areas of the country.

Table 2.4: Category of water licenses issued

Regional - Initial

- Size of property ($AREA_{PROP}$)
- Recharge - HP (RE)
- Existing use volume (ABS_{EX})
- New use volume (ABS_{NEW})
- Scale of abstractions (ABS_{SCALE})

Calculation:

$AREA_{PROP} * RE = RE_{AREA}$ (m^3/a)

$ABS_{EX} + ABS_{NEW} = ABS_{TOTAL}$ (m^3/a)

$ABS_{SCALE} = (ABS_{TOTAL} / RE_{AREA}) * 100$

Small-scale abstractions (<60% recharge on property)	Category A
Medium-scale abstractions (60-100% recharge on property)	Category B
Large-scale abstractions (>100% of recharge on property)	Category C

Source: DWS (2016)

2.10.6 Groundwater management information gaps

According to the DWS (2016), there is a gap regarding current coverage of water data and information. There are insufficient spatial distributions and number of groundwater monitoring programmes. This resulted in inadequate data sharing among stakeholders in the water sector. The result has been unmet information needs for sound day-to-day decision-making. There is, therefore, a requirement for adequately designed, managed and coordinated systems for collection, assessment and dissemination of data and information on groundwater. Such data is currently being recorded by various entities in the water sector, such as provincial governments, state departments, municipalities, water services authorities and water management institutions (DWS, 2016).

2.10.7 Lack of knowledge of quantification of recharge

The DWS conducted a study to generate a groundwater recharge map for South Africa at a cell size of 1 km by 1 km grid (DWS, 2016). The method used to produce the recharge map is GIS-based, while quaternary catchments were used as the unit of measure. The recharge method essentially comprises four main complex components:

- Chloride mass balance approach.
- Empirical rainfall/recharge relationships.
- Layer model (GIS-based) approach.
- Cross-calibration of the results with field measurements and detailed catchment studies.

The results obtained from the recharge study by the DWS were in agreement with results obtained from earlier recharge studies (Department of Water Affairs and Forestry [DWAF], 2006). Though the approach did not differentiate between preferred path and matrix diffusion recharge, it was GIS-based, making it sufficiently flexible to include updates and new datasets. Recharge estimation was significantly hard to carry out.

2.10.8 Limitations of models

Numeric models have certain limitations and uncertainties related to the accepted hydro-geological parameters and limiting conditions. They incorporate weaknesses in identifying hydrogeological conditions, changes in groundwater recharge and modifications of mining schedules. Appropriate identification of hydraulic parameters, the nature of faults and fissures, as well as karstic formation phenomena, are decisive for reliability of modelling studies. For example, natural hydraulic barriers, such as faults filled with semi-permeable material or rock formations with low hydraulic conductivity compared to adjacent rock layers, may decrease the water inflow, as well as diminishing the negative environmental impact of dewatering. Under natural conditions, namely those existing before the drainage commencement, the most efficient method to identify hydrogeological structures and parameters of rock layers is a trial pumping. Despite the fundamental importance of recharge in the water balance, it is an element with the highest uncertainty, since its volume primarily depends on the accuracy assumed when calculating other elements of the balanced equation (Sophocleous, 2005).

Changes in the recharge may be a consequence of many factors, which were not accurately estimated or identified. These may include unidentified leakage of surface water into aquifers, water losses from the water supply and sewage disposal systems, technological waters recharging the rock mass during drilling and changes of recharge caused by land management. Assuming the amount of recharge, based on average multi-annual precipitations, does not account for the cyclic deviations and trends resulting from climate variability. For instance, small precipitation may lead to an increase of the groundwater table below a level, referred to as the evapotranspiration extinction depth, which causes an increase in effective infiltration.

On the other hand, the change of water deficit, namely the difference between potential evaporation from a reservoir and the precipitation, affects the rate at which post-mining reservoirs are filled with water. It particularly applies to long-term forecasts, which sometimes cover more than 100 years. Mining and power generation activity, including the formation of large open pits, and overburdening of dumping areas, as well as the existence of powerful heat and steam emitters at nearby power plants, may lead to changes of hydraulic parameters of layers, as well as local climate variations, influencing recharge form precipitation.

Post-audit analyses imply that groundwater sustainability models may fail to forecast the future due to the incorrect input parameters or different boundary conditions, which are not compatible with the actual conditions. Due to changes in schedules of mining activities or reclamation of post-mining excavations, the input data used in the model should be verified and updated with reference to the most recent recommendations and assumptions.

When the prescribed criteria are applied in groundwater analyses, the outcomes are simplistic, compared to the operation of real-life systems. According to De Carvalho et al. (2009), indices allow for complex analyses and the outcomes of these analyses depend on the number of factors, parameters, type of index, and indictors. Using indices, accommodate the analyses of complex, multidisciplinary, transboundary, and multidimensional issues (Talukder, 2016).

Indices are recognised for their key contribution to policymaking, public communication, and transfer of groundwater information (Singh et al., 2006).

2.11 Conclusion

The purpose of this chapter was to conduct a review on groundwater sustainability and its different components. Emphases were highlighting the concept of groundwater sustainability, how groundwater sustainability is reported, review of the various existing models on groundwater and hydrology, and factors affecting groundwater sustainability. Since groundwater sustainability is a management issue, this chapter analysed the gaps in the various popular models available for managing groundwater. Furthermore, the literature review provided a narrative of the application of AI in modelling hydrological factors. The review found that AI extensively supports hydrologic predictions and hydrologic systems analyses. The review concluded that several assessment tools may be applied to determine the progress in attaining groundwater sustainability.

A review of the factors affecting groundwater sustainability were discussed. From the hydrological cycle to catchment hydrology, slope, topography, climate, land use, permits and licencing system, populations, and water rights were highlighted. The review discussed the existing regulatory framework used in South Africa to manage groundwater resources, the gaps in allocation, challenges to groundwater management such as borehole failure, poor management strategies, maintaining balance in net recharge and groundwater depletion. These are all important issues to achieve a sustainable groundwater system.

Chapter 3

HYDROLOGICAL AND HYDROGEOLOGICAL SETTINGS OF THE MODDER RIVER BASIN

3.1 Introduction

This chapter presents a review of the C52 Modder River catchment. It focuses specifically on the C52 geology, hydrology, hydrogeological conditions, topography, formations and soil types. This chapter characterises the catchment study area. This is important in getting an understanding of the catchment's water-bearing capacity. The chapter is also important in guiding the rating and scoring of the sustainability index model that was developed in Chapter 4.

Woyessa et al. (2006) provided a comprehensive description of the Modder River catchment. The total area is 1 736 000 ha, with a mean annual precipitation of 537 mm. The mean annual run-off from the total area was estimated at 94.42×10^6 m^3. Of the 1 736 000 ha, around 70 000 is communal land occupied by subsistence farmers with a low standard of living.

Regarding land use of the catchment, the upper catchment is dominated by unimproved natural grassland. In this part of the catchment, irrigated cropland is insignificant. The middle and lower parts of the catchment are largely used for crop production, with commercial irrigation farming dominating the lower part of the catchment. Large portions of the middle part of the catchment are used for urbanisation, consisting of the city of Bloemfontein and the Botshabelo township (Woyessa et al., 2011).

3.2 Study area description

3.2.1 Location

The Modder River Basin is situated in the southwestern part of the Free State province in South Africa, forming some portion of the Upper Orange Water Management Area (WMA) (Figure 3.1). The Upper Orange WMA expands further into parts of the Eastern and Northern Cape provinces.

The Modder River catchment is within the Karoo Basin of South Africa. Groundwater in the Karoo is found in contact zones of dykes, sills, intrusive rocks, and weathered rock sections

(Usher et al., 2006). The major rock types underlying the Modder River catchment are dolerite, mudstone, sandstone and shale. The geology comprises of the Ecca group and the Beaufort group (Usher et al., 2006). The groundwater yield of the Karoo Basin is generally limited (0.3 ℓ/s), except in some areas where large volumes are pumped to supply towns and mines (Woodford & Chevallier, 2002a).

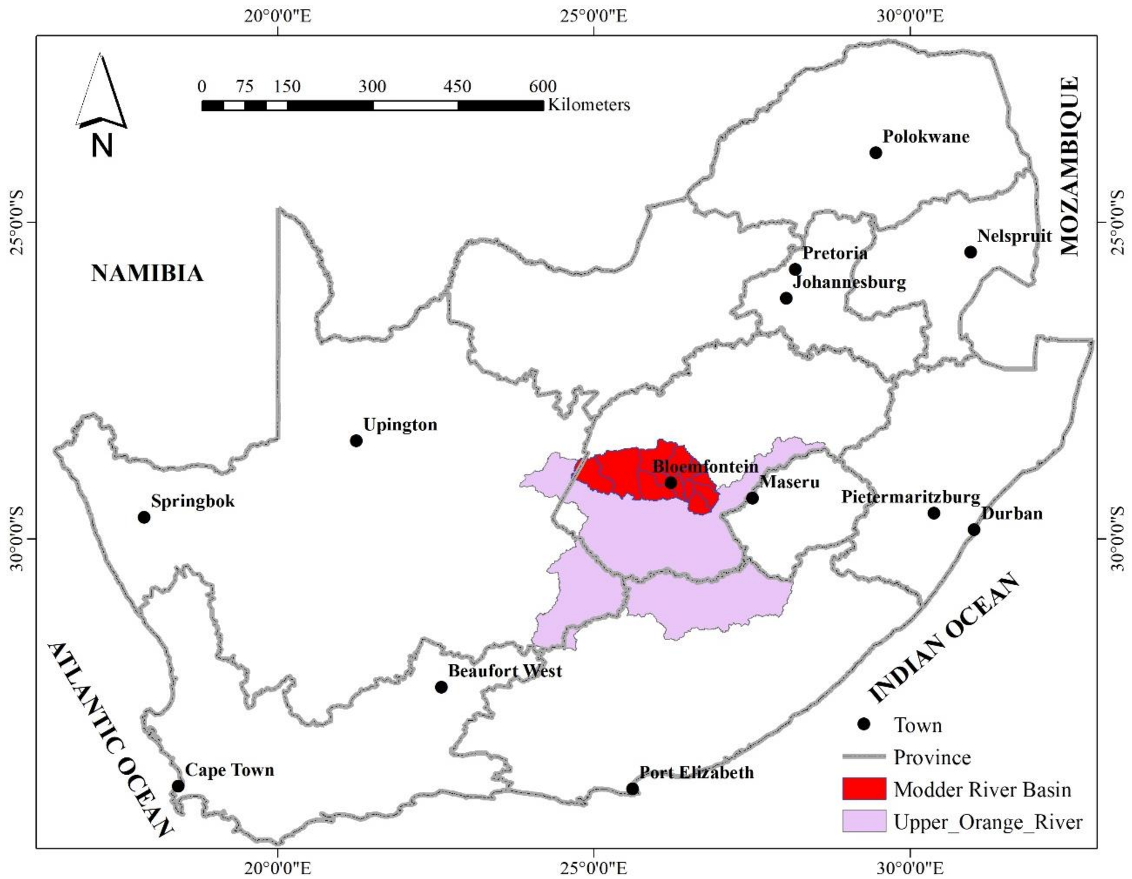


Figure 3.1: Location of the Modder River catchment showing boundaries within the Upper Orange River catchment and the Free State province of South Africa

Source: Modified by author

Figure 3.2 shows the boreholes available in the Modder River catchment. The boreholes include both government monitoring boreholes (orange) and private boreholes (green).

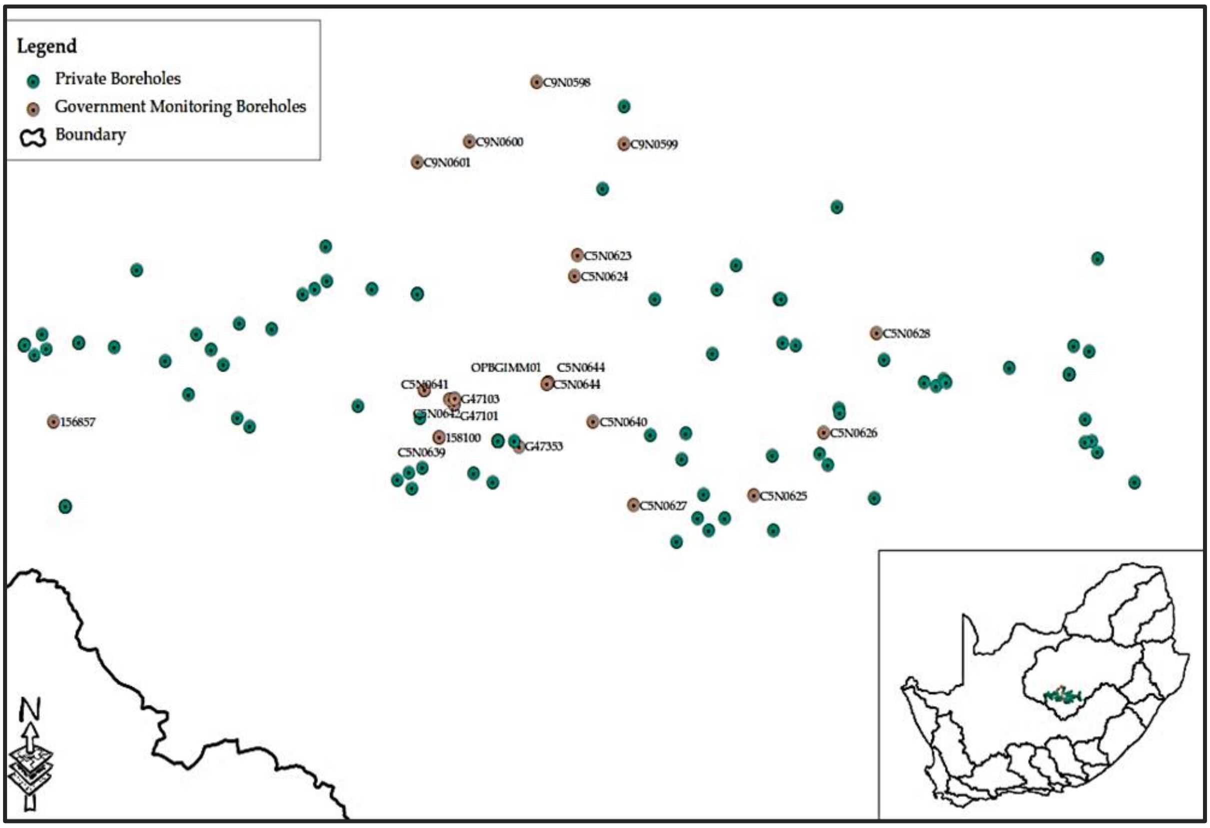


Figure 3.2: Map showing borehole distribution in the Modder River catchment

Source: Obtained from DWA in 2017

The Modder River Basin is located at latitudes 28°50" to 29°40" South and longitudes 24°40" West to 27°00" East. The altitude ranges from 1 057 masl to 2 106 masl. The Modder River and its tributaries form the main drainage system. The highest areas are at the north-eastern end of the basin (Maluti Mountains), characterised by flat-topped hills, and at the south-eastern end of the basin (Dewetsdorp). The lowest area lies to the southern side of Kimberley. The Modder River originates near Dewetsdorp and then flows north, thereafter heading west. After about 340 km, the river flows into the Riet River that joins the Orange-Vaal River. The Modder River was generally, like most inland rivers in South Africa, a regular stream, yet because of the development of three critical dams, namely the Rustfontein, Mockes and Krugersdrift, the waterway currently looks like a perpetual stream. However, the dam levels may drop to as low as 30% during the dry season. Water in the lower side stagnates in winter.

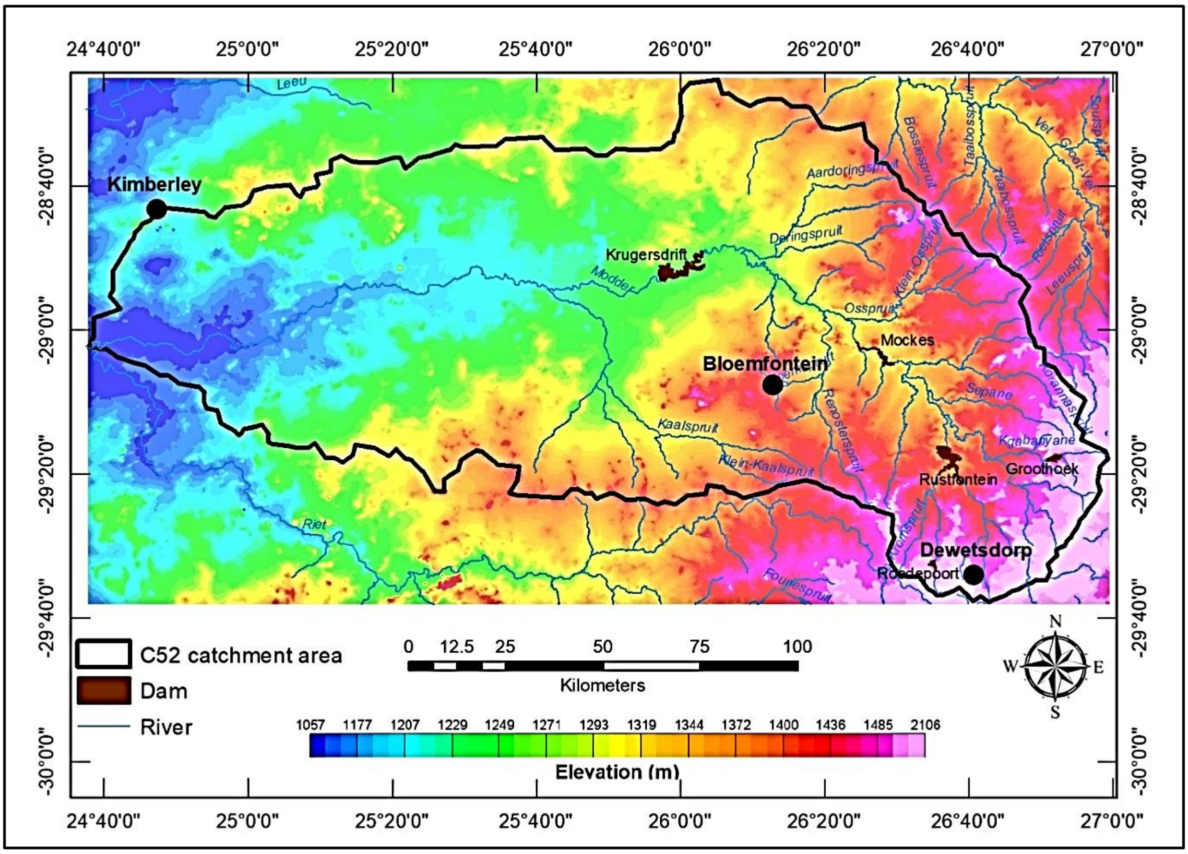


Figure 3.3: Digital elevation model of the Modder River Basin

Source: Author

According to Oldknow and Hooke (2017), Savannah grassland is predominant in the eastern part of the catchment. The result is a Karoo shrubbery to the south and west of the catchment.

3.2.2 Physiography

According to the Köppen climate classification, the study area falls in the BSk class, which is characterised by a cold semi-arid climate. A semi-arid environment, or steppe zone, is a climatic location with precipitation beneath potential evapotranspiration; however, not as low as a desert climate. There are various types of semi-arid zones, contingent upon factors, for example temperature and influencing various biomes (Peel et al., 2007). Figure 3.4 indicates the typical temperature and rainfall distribution throughout the year.

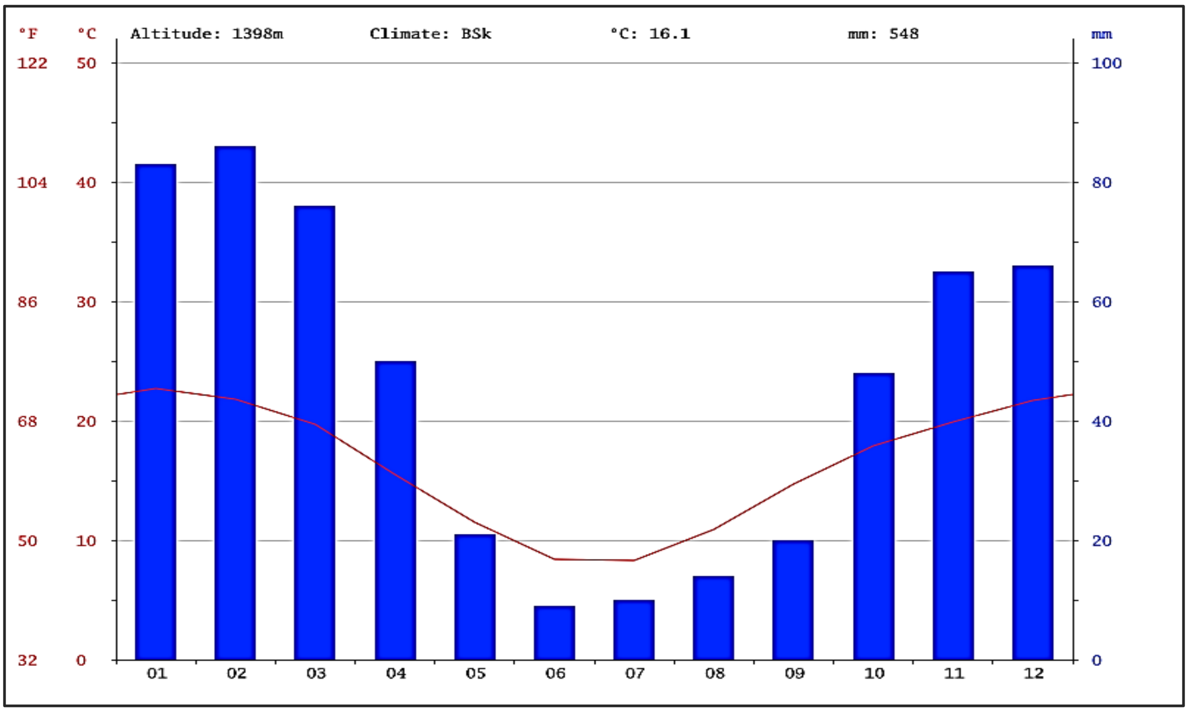


Figure 3.4: Climatic condition of the Modder River area
Source: Climate-data.org (2017).

The area receives long-term rainfall of between 300 mm and 600 mm, characterised by a decrease in rainfall from an eastern to western direction (Agricultural Research Council, 2014), as shown in Figure 3.4.

With a semi-arid climate, the study site has a mean annual precipitation of 563 mm. The winters are ordinarily dry and chilly, with periodic ice and snow, while the summers, between October and March, are sweltering hot (Barnard, 2000). With reference to climatic data collected between 1982 and 2012 recorded at the Bloemfontein weather stations, the study area receives a monthly rainfall of between 9 mm in June and 86 mm in February (Climate-data.org, 2017). The month-to-month circulation of normal daily highest temperatures demonstrates that the normal midday temperatures for the study area range between 0°C and 30°C, with July as the coldest month (South African Weather Service, 2016). Evapotranspiration exceeds rainfall, as shown in Figure 3.5 and Figure 3.6.

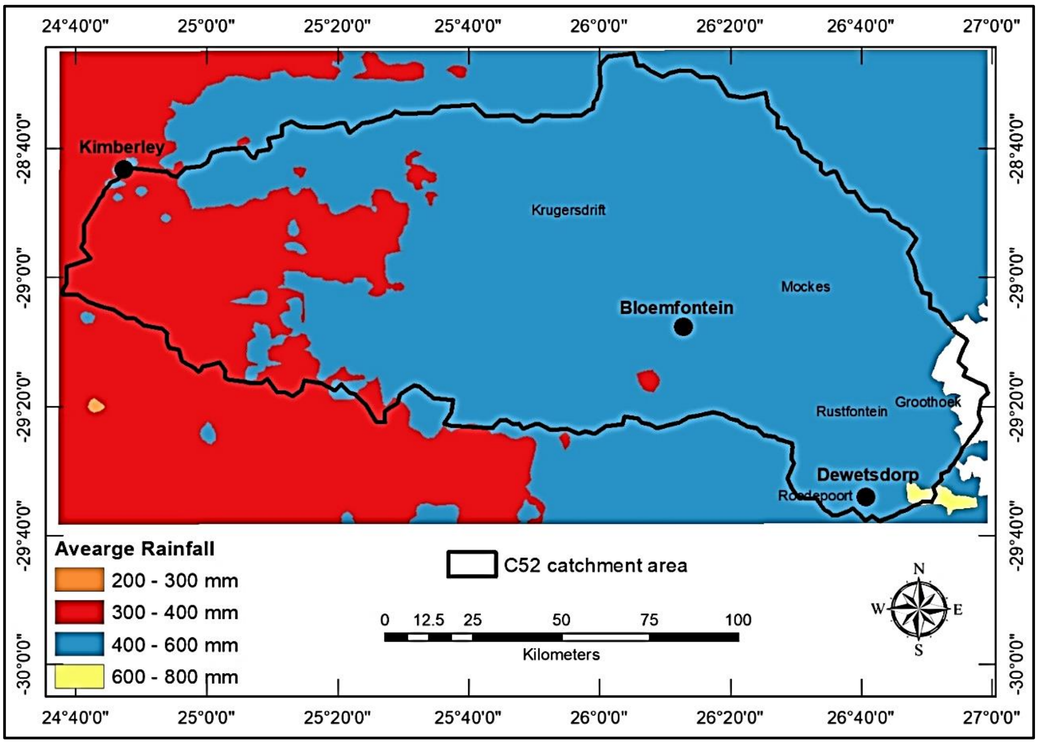


Figure 3.5: Map showing mean annual precipitation of the Modder River catchment

Source: South African Weather Service (2016)

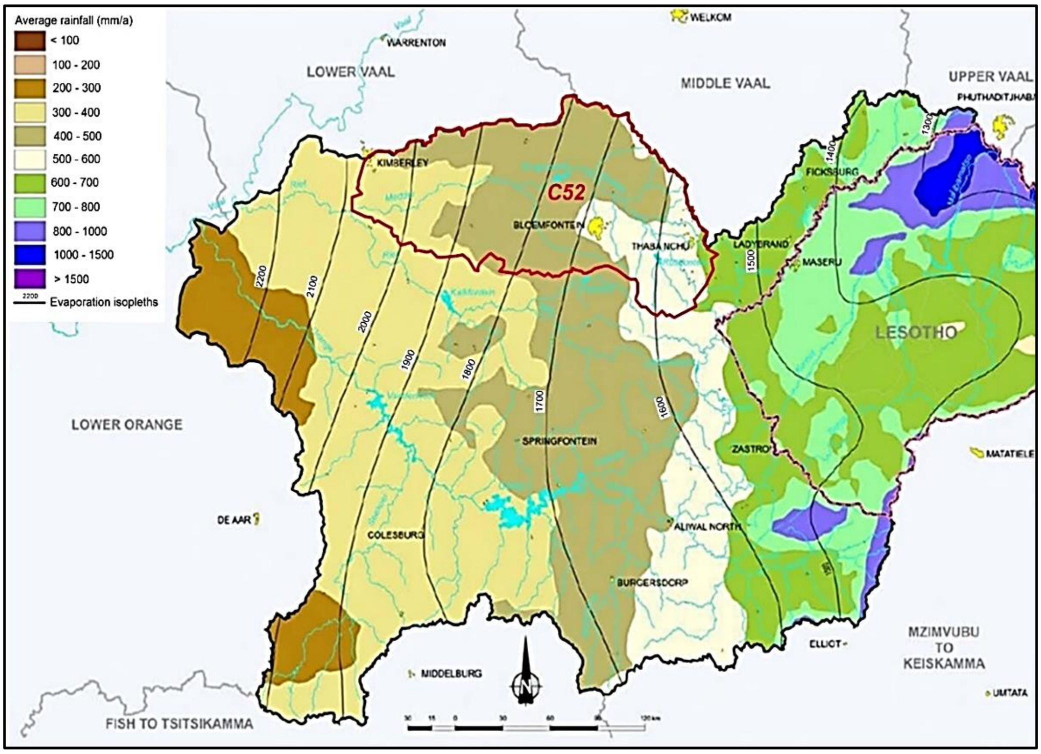


Figure 3.6: Mean annual precipitation with evaporation isopleths of the greater Upper Orange River catchment with an insert of Modder River catchment

Source: Basson and Rossouw (2003)

3.3 Hydrology

3.3.1 Catchments

The Modder River Basin is divided into three sub-basins: Upper Modder, Middle Modder and Lower Modder and is all referred to as C52. The water in the Modder River originates in the Maluti highlands. The water supply in the upper and middle parts of the Modder River is stabilised at the Mockes and Rustfontein dams, while to the west of Bloemfontein, the river is stabilised at the Krugersdrift Dam. Figure 3.7 shows the C52 quaternary catchment as a sub-catchment in the Upper Orange tertiary catchment.

Figure 3.7: Map showing the position of C52 catchment within the Upper Orange tertiary

Source: Basson and Rossouw (2003)

The mean annual run-off of the Modder River Basin is 39×10^6 m^3 (Midgley et al., 1994). The C52 catchment is marked by a high density of rivers on the eastern side, while the Modder River is the only river in the western side of the basin (Figure 3.8)

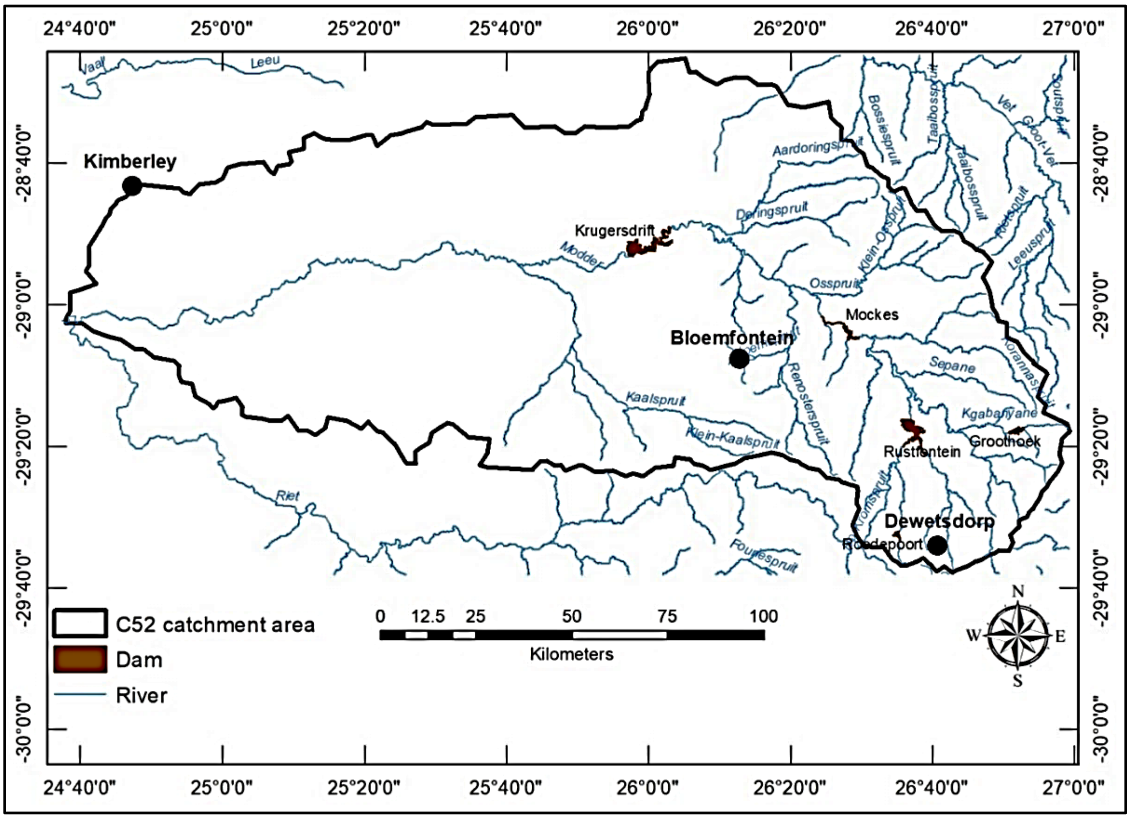


Figure 3.8: Detailed river network found within and surrounding the Modder River catchment

Source: Modified by author

Delineation of the catchment was based on acknowledging that groundwater delineation was still based on surface water geography and zoning. It was carried out based on the geographical boundaries and smaller surface water bodies (streams and rivers) contributing to flows into a bigger river. The topography, rainfall, evaporation, and river flow directions were some of the important factors considered in surface water delineation. These factors have been discussed in Chapter 2. Currently, groundwater in South Africa is delineated based on surface water delineation. On this basis, groundwater uses are monitored and data captured. This is a general limitation to the study of groundwater in South Africa because rock types and other factors, which serve as hosts to groundwater, do not follow the delineation of surface water.

The Water Resources Management Act of 1998 supports the delineation of the catchments in South Africa into water management zones. C52 is a sub-catchment that falls within the Upper Orange River catchment. The C52 catchment is part of the wider catchment of the Orange

Water Management Area, which has been shown in Figure 3.7 and explained in section 3.2.1. Delineated watersheds are required for modelling and basin watershed characterisation (Siddiqui et al., 2020). For the C52 catchment, this was carried out to allow for characterisation and investigation of the processes in the catchment. Delineation accounts for interconnection of the groundwater in the catchment.

Delineation for the C52 catchment was carried out through a process of watershed segmentation in which the watershed was divided into discrete land and channel segments to allow for analysis of the watershed behaviour. This means that the impact of over-abstraction in one area of the C52 catchment was compensated by recharge in another part of the wider Upper Orange catchment and was accounted for. The two main methods of delineation of catchments used and triangulated for C52 were the following:

- Digital elevation method (automatic delineation) which refers to water streams flowing downhill on a grid cell-based methodology and the boundaries are consequently completed by computer.
- Manual delineation involves the illustration of watersheds by tapping on the guide. It requires fundamental information for exactness, limiting it to the contributing zone for a specific control point or outlet (Martinez-Casasnovas & Stuiver, 1998).
-

3.4 Geology setting of the Modder River Basin

In order to create sustainable groundwater management strategies for the Modder River Basin, it was important to understand the geological setting from a regional to a local scale.

3.4.1 Regional geological setting

According to Bicca et al. (2017), the general geology of the C52 catchment consists mainly of sedimentary rocks of the Karoo Supergroup which were formed before the break-up of the Gondwana supercontinent. The Karoo Supergroup covers around 66% of the present land surface of Southern Africa (Kent, 1980). Its strata records a relatively endless glacio-marine to terrestrial succession. It started in the Permo-Carboniferous era (280 Ma) and ended 100 million years after the early Jurassic era. Its silt achieved an extreme combined depth of up to 12 km in some places. The overlying basaltic magmas, which denote the Lesotho area, are 1.4 km thick. These were collected in a retro-circular segmented basin (Cole, 1992), named the 'Karoo Basin'. Along its southern fringe, the Karoo Basin is bordered by the Cape

Fold Belt. It was created amid a progression of compressional beats, beginning in the Late Carboniferous era and ending in the Late Triassic era (Hälbich et al., 1983).

The Late Palaeozoic advancement was started by plate assembly, subduction, and growth along the Palaeo-Pacific edge in the south-western part of Gondwana. The Cape Fold Belt consists of an East-West striking southern branch, with north-skirting folds and an North-South striking the western part of open folds, which converge into a 100 km wide syntaxis zone (Figure 3.9). Its mountain ranges consist of siliciclastic silt, with an aggregate thickness of 8 000 m, placing it within the Ordovician-Carboniferous Cape Supergroup.

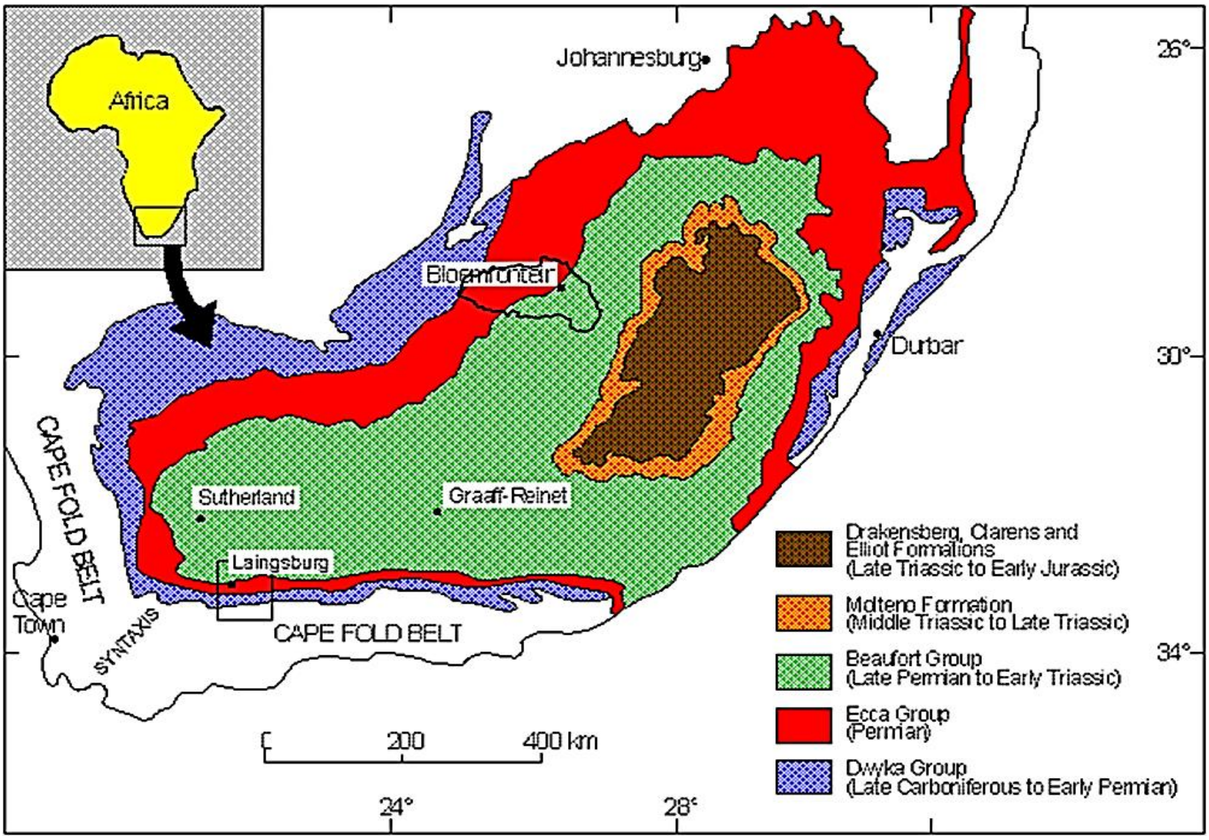


Figure 3.9: Regional geology of the Karoo Basin

Source: Modified by author

The deposition of the Karoo Supergroup began after a rest at the Cape/Karoo Supergroup limit with the Dwyka Group. After glaciation, a broad sea remained, facilitated by the melted water. Clays and muds of the Lower Ecca Group were aggregated. Deformation of the southern edge of the basin brought about elevation and disintegration of mountains towards the south. Quick down-warping of the basin was the result of thrust sheets in the nearby Cape Fold Belt (Cole, 1992). The south-western part of the Karoo Basin was isolated by the Cape Fold Belt syntaxis (Figure 3.10) into the Laingsburg and Tanqua sub-basins (Wickens, 1992). Deltaic progradation involved the filling of the sub-basins by a thick submarine fan and deltaic silt of the Upper Ecca Group (Kingsley, 1981).

Progressive shallowing of the fore took place within the Late Permian timeframe because of the rate of sedimentation surpassing the rate of subsidence. The expansive scale backward succession ended in the formation of the fluvial-lacustrin Beaufort Group. The Early Triassic lifted the Cape Fold Belt deposition in wide regions of the Karoo Basin. Just in the focal piece of the Karoo Basin, the fluvial, alluvial and aeolian residues of the Triassic Molteno, Elliot and Clarens Formations were stored. Regionally, the study area lies beneath the Beaufort Group on the east, the Ecca Group in the centre and the Wyka Group on the western side. The Main Karoo Basin becomes thinner from the south to the north, as shown in Figure 3.10 (Catuneanu et al., 1998).

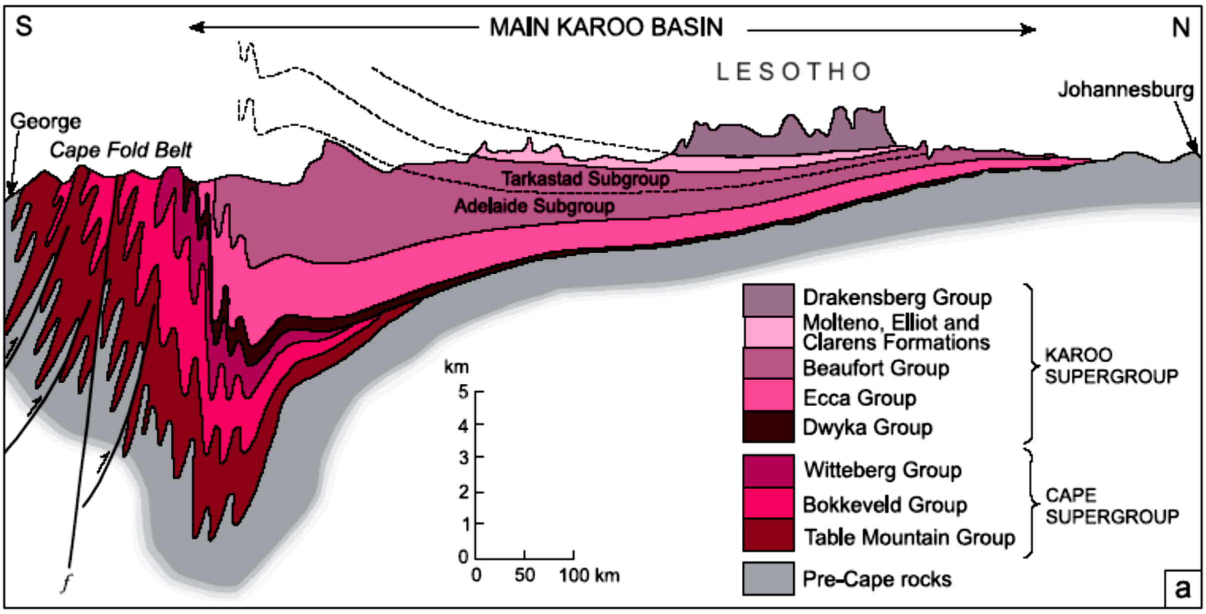


Figure 3.10: Sectional view of Karoo Supergroup

Source: Johnson et al. (1996)

A small exposed outcrop of the Transvaal Supergroup is found on the western part of the study catchment. The Transvaal Supergroup is a stratigraphic unit in the northern parts of South Africa and southern Botswana, arranged on the Kaapvaal Craton. It is dated to the limit between the Archean and Proterozoic times, approximately 2 500 Ma. It is delimited by the Witwatersrand Basin (2 700 Ma) and the Bushveld Igneous Complex (2 050 Ma) (Eriksson & Reczko, 1995). It comprises three sections, namely the Transvaal Basin in the east; the Griqualand Basin in the west, and the smaller Kanye Basin in southern Botswana.

Figure 3.11 provides a schematic presentation of the geological succession of the Karoo Supergroup. It should be noted that only the Beaufort, Ecca and Dwyka groups can be found in the Modder River catchment and their compositions are discussed in detailed in section 3.4.2.

Drakensberg Volcanics			Basaltic	Jurassic
Stromberg Group	Clarens		Cross bedded sandstone	Triassic
	Elliot		Red mudstone and sandstone	
	Molteno		Sandstone, conglomerate, mudstone	
Beaufort Group	Tarkastad Subgroup		Burgersdrop Formation	
			Katberg Sandstone	
	Adelaide Subgroup		Green, grey and purple mudstones	
			Sandstone	Permian
Ecca Group			Shale and sandstone	Permian
Dwyka Group			Tillite and diamictite	Carboniferous

Figure 3.11: Schematic presentation of the Karoo Supergroup sequence
Source: Gomo (2011).

The Transvaal sedimentation started with transcendently clastic sedimentary rocks (Black Reef-Vryburg Formations) trailed via carbonate shakes and joined iron developments (Chuniespoort-Ghaap-Taupone Groups). After an erosional break, the clastic sedimentary rocks and volcanics of the Pretoria-Postmasburg-Segwagwa Groups were stored within the three basins, to a great extent, under closed basin conditions. A last phase of transcendently volcanic progression (Rooiberg Group-Loskop Formation) was constrained to the Transvaal Basin.

The Campbellrand-Malmani carbonate stage is a part of the Chuniespoort Group and initially secured the majority of the Kaapvaal Craton. It has a thickness of more than 1 km in both the Malmani and Campbellrand Subgroups. The Malmani Subgroup comprises of dolomite and chert, with just minor clastic residues and is northwest of Johannesburg.

3.4.2 Local geological setting

For the local geology and according to Geoscience Australia (n.d.), 1:1 million freely available geological information pieces covering the C52 catchment basin, including five Karoo-aged rocks and Transvaal rocks, are found in the catchment area. A typical idealised illustration is shown in Figure 3.12. The Karoo-aged rocks are the Beaufort (Adelaide and Tarkastad), Dwyka, and Ecca Groups, as well as dolerite intrusive rocks. The Karoo mafic intrusive rocks (dykes and sills) are scattered throughout the basin, including the Modder River catchment. The intrusive rocks are most pronounced on the north-eastern side of Bloemfontein and areas surrounding Kimberley.

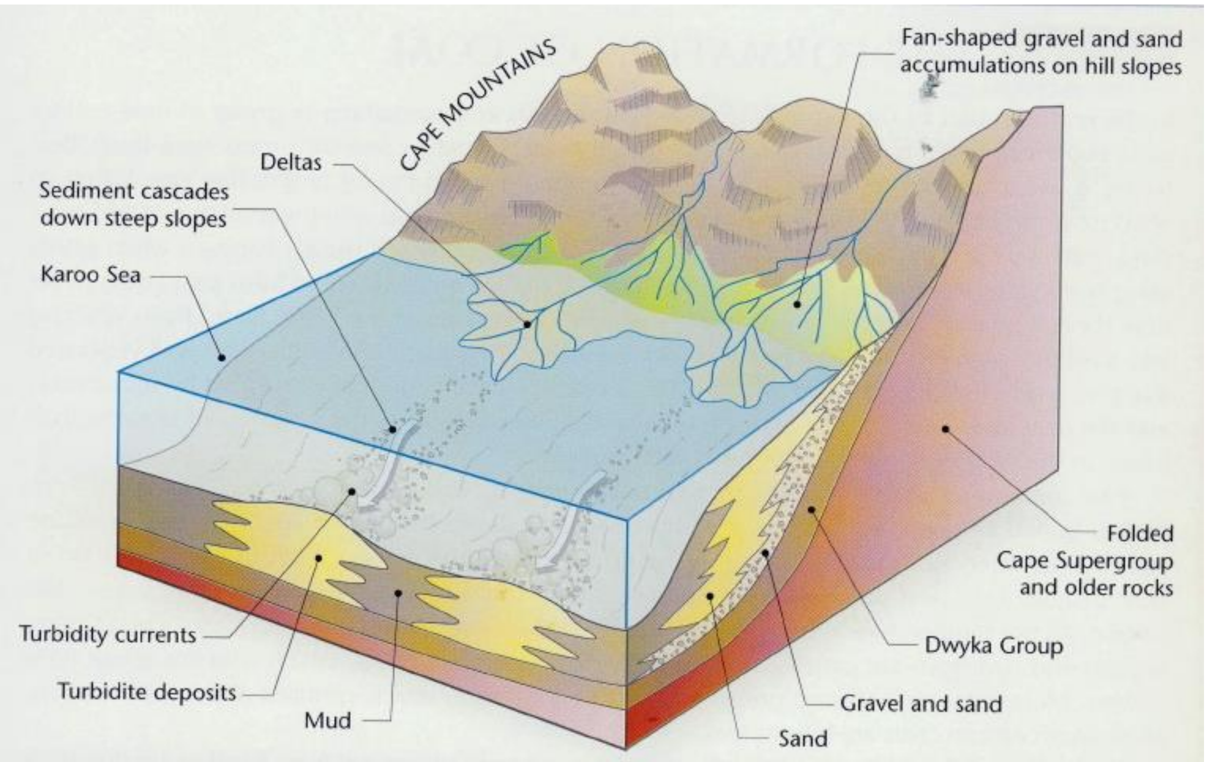


Figure 3.12: Conceptual illustration of Karoo sedimentary rocks formation

Source: Trailrider (2009)

The Dwyka Group sediments consist mainly of diamictite (tillite) which is generally immense, with little jointing which may be stratified in a few places (Woodford & Chevallier, 2002a). The Ecca Group (Tierberg) consists of undifferentiated shales, with interbedded siltstone. Between Bloemfontein and Kimberley, Transvaal calcareous (limestone and calcarenite) rocks are exposed. A small exposure of Transvaal Ventersdorp lava is found south of Kimberley.

3.5 Aquifer types of the Modder River Basin

This section defines the key geological attributes of the C52 catchment. The section further provides an explanation on the characteristics of the study area and their influence on the occurrence of groundwater. It describes the features of the aquifers and geology of C52, explaining how dolerite occurrence affects the catchment water availability.

In terms of definition, an aquifer is a geological formation that contains adequate immersed porous material to yield large amounts of water to a well (Melanés Murcia, 2020). An aquifer is an underground layer of water-bearing porous rock or unconsolidated materials (rock, sand, residue, or clay), from which groundwater may be extracted using a well (Karamouz et al., 2020). Aquifers may be permeable as in sandy rivers, fractured as in crystalline bedrock or fractured and intergranular as in sedimentary rocks such as the Karoo.

Usually, aquifers are classified by their limiting or boundary conditions, including confined and unconfined aquifers. Unconfined aquifers indicate a condition in which groundwater is influenced by the atmospheric pressure. Unconfined aquifers have the water table or phreatic surface as their upper boundary. In general, the shallowest aquifer at a given area is unconfined, meaning it does not have a confining layer (an aquitard or aquiclude) sandwiched between it and on the surface (Figure 3.13). Unconfined aquifers, more often than not, are recharged directly from the surface, from precipitation or from a collection of surface water, for example a river, stream, or lake, which is hydraulically linked to it.

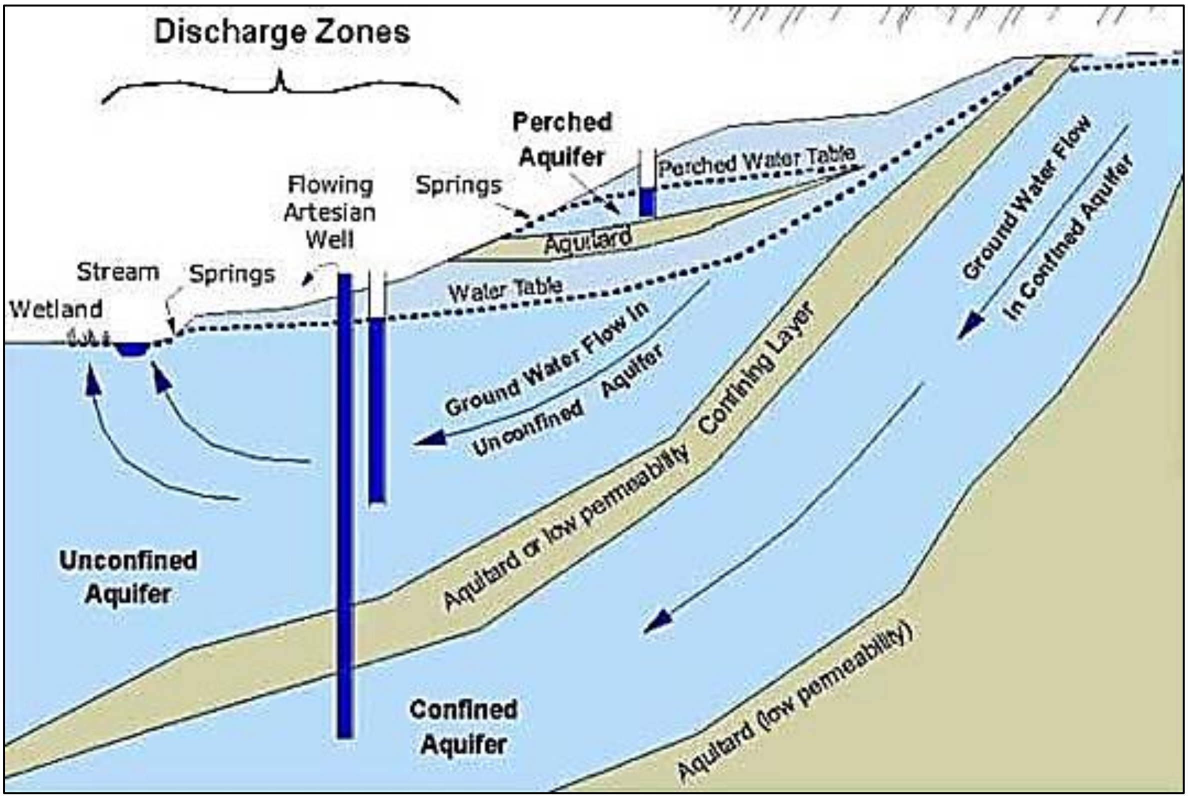


Figure 3.13: Conceptual illustration of aquifer systems

Source: Idaho State University (2018)

Confined aquifers have the water table below their upper boundary (an aquitard or aquiclude) and are ordinarily found underneath unconfined aquifers (this is in reference to low permeable aquifers) or below a confining layer. The water here totally fills a rock that is overlain by a limiting quaint. When these aquifer types give water under high pressure to the surface, they are referred to as artesian aquifers. Aquifers may be generally divided into four classes based on their host rocks, namely fractured, fractured and intergranular, intergranular, and karst.

According to Dalton et al. (2017), the geology of Modder River Basin is mostly hard geological formations without large porous aquifers in the catchment. Thus, large amounts of groundwater can be abstracted, mostly from intergranular and fractured dolerite zones. This means that the recharge rates and sustainable yields are relatively low (Usher et al., 2006). In dry parts of the catchment such as Colesberg and surrounding towns, groundwater is the sole source of rural domestic as well as stock watering supply. According to the DWS (2016), severe over-exploitation of groundwater is rampant in the peri-urban areas of Bainsvlei and smallholdings close to Bloemfontein. The areas around Petrusburg in the Modder River catchment are further over-exploited with regard to groundwater extraction due to an increase in the demand for irrigation water. As a result of the rock type, the quality of groundwater in the C52 catchment is naturally satisfactory. The eastern parts of the catchment have high rainfall with acceptable quality regarding taste, smell, and colour. The drier parts of the catchment are highly mineralised; therefore, the water is relatively brackish. The same applies to the areas with salt pans.

3.5.1 Fractured aquifers

Fractured or secondary aquifers refer to conditions where groundwater travels through an assortment of joints, fractures, cracks, and fissures. In fractured aquifers, groundwater is contained fundamentally in fractures, joints and crevices, including the critical jointed transitional zone between weathered and solid rock segments and on bedding planes. Over geological time, rocks are subjected to forces largely related to gravity and the movement of large rock masses in the crust and upper mantle. With applied force, a set of stresses is produced. The activity of a connected pressure field will result in the deformation (change in shape and size) of a body. Strain is the geometrical expression of the amount of deformation, which is a function of the type of material, temperature, pressure, fluids and period exposed to stress. Within the rocks, there is a combination of elastic and viscous strain when forces are applied.

When elastic deformation leads to failure, the material loses cohesion by the development of a fracture or fractures across which the continuity of the material is broken. This is called brittle behaviour and leads to the development of faults and joints (Park, 1984). When there are essentially no primary pore spaces and the water is stored in fractures, joints, bedding planes and cavities within the solid rock mass, the aquifer is called fractured or secondary. Fractured aquifers are found in sedimentary, igneous, and metamorphic rocks. The fractured regime is represented by the Dwyka Group, Ecca Group and portions of the Tarkastad Subgroup of the Beaufort Group, south of the Orange River.

3.5.1.1 Dwyka Group aquifer

The Dwyka Group, which comprises consolidated products of glaciation (with high amounts of clay) is normally considered to be an aquiclude owing to low permeability values associated with the rocks of this group. However, where the Dwyka Group is highly weathered, permeability increases and when a borehole is drilled in such areas, the rocks may supply a reasonable yield for a household (Barnard, 2000). The chemistry of the groundwater in the Dwyka Group is generally considered suitable for domestic and irrigation uses. Background sulphate values range between 1 mg/ℓ and 93 mg/ℓ, based on 46 samples extracted from boreholes drilled in the Dwyka Group in South Africa, but not necessarily within the study area (Ellington, 2003). These values may vary owing to other factors such as variability in the mineral composition of the Dwyka Group rocks, depending on their depositional location.

3.5.1.2 Ecca Group aquifer

The aquifers of the Ecca Group are classed as fractured as well as fractured and intergranular. Yields range between 0.5 ℓ/s and 2 ℓ/s (Ndlovu, 2018). Burger (2012) concluded that the chances of obtaining adequate groundwater supplies are more favourable where there are interlayered coal layers in the sediments than where there are solely sandstone and ordinary shale layers. A few boreholes drilled alongside dolerites dykes, intrusive into sediments of the Ecca Group, indicated that yields become progressively smaller the closer boreholes are drilled to the contact. The poor yields generally obtained in the Ecca Group may be ascribed to the fact that the small potential water-bearing fractures are filled up with secondary material. This was observed in dry riverbeds where the various layers were exposed (King, 1997). Dolerite intrusions, as well as fractured sediments occurring at depth are the most suitable targets for successful groundwater development in this geohydrological unit. The water is a sodium-chloride water type, indicating an end-point of discharge or stagnation of water. The Ecca Aquifer Group has shown that it is of low yield and cannot give an appreciable amount of groundwater for sustainable uses.

3.5.2 Intergranular and fractured aquifers

The terms 'intergranular' and 'fractured' describe aquifers within the same lithology in which groundwater occurs in both the above modes, with the exception that the intergranular interstices are secondary. Secondary intergranular interstices usually result where less-resistant material in a medium- to coarse-grained hard rock lithology, such as granite and gneiss, is removed by weathering, leaving intergranular interstices between the remaining more resistant granules. The same restricting factors, as mentioned above, are valid for this type of aquifer in the Karoo where there is dolerite. Limited information regarding water levels and depths of weathering has rendered it impossible to accurately delineate aquifers of this type. This type, as indicated on the map in Figure 3.14, rather refers to the property of the lithology to contain groundwater in both modes than to the actual condition at any given locality. The distribution of the intergranular and fractured aquifers is shown in Figure 3.14.

The hydrogeological units of Figure 3.14 predominantly exhibit intergranular and fractured aquifer characteristics. The intergranular and fractured mode of groundwater occurrence was represented by Adelaide and Tarkastad Subgroups of the Beaufort Group, Ventersdorp lava and widespread dolerites.

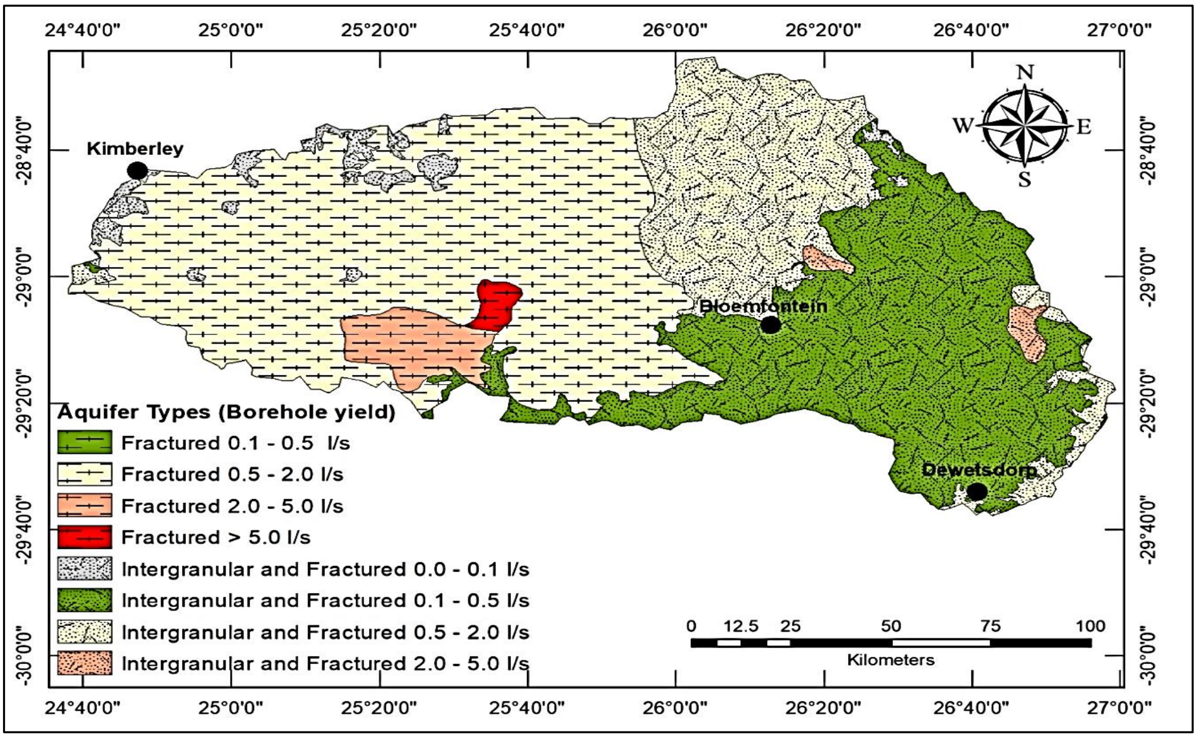


Figure 3.14: Aquifer types found within the C52 catchment area

Source: Modified by author

3.5.2.1 Beaufort Group

The Beaufort Group aquifers are multi-layered, as well as multi-porous, with different thicknesses, owing to the complex geology of the formations of the Beaufort Group (Steyl et al., 2011). The contact plane between two different sedimentary layers will cause a discontinuity in the hydraulic properties of the composite aquifer. The pumping of a multi-layered aquifer will consequently cause the piezometric pressure in the more permeable layers to drop more rapidly than in the less permeable layers (Steyl et al., 2011). It is therefore possible to completely extract the more permeable layers of the multi-layered Beaufort aquifers, without materially affecting the piezometric pressure in the less permeable layers (Molaba, 2017). This complex behaviour of aquifers in the Beaufort Group is further complicated by the fact that many of the coarser and thus more permeable sedimentary bodies are lens-shaped. The lifespan of a high-yielding borehole in the Beaufort Group may therefore be limited if the aquifer is not recharged frequently (Molaba, 2017; Steyl et al., 2011).

3.5.2.2 Dolerite

Dolerite intrusions occur predominantly as sills and dykes throughout the Karoo sequence, with typical borehole yields of less than 2 ℓ/s (Du Toit & Sonnekus, 2014). If the contact (side of the sill) is targeted, the factors to consider will be more or less the same as when targeting a dyke, namely dip, recharge potential, static water level and the type of host rock, and the distance to drill from the contact zone. When a source needs to be developed on a sill, three main targets should be investigated, namely the upper weathered and fractured zone, the upper contact zone and the lower contact zone. Factors that will influence the success rate on such a sill environment are as follows:

- The depth of the buried sill and the static water table – the overlaying formation should be weathered and fractured to a depth that exceeds the static water table in the area. Depth of the upper contact zone should further exceed the static water level.
- The type of rock overlying and underlying a sill.
- The thickness of the sill – if the sill is too thick, it will not be economically feasible to target the lower contact for possible secondary fracturing.
- The weathering and fracturing pattern of the upper part of the sill.
- The possibility of geological lineaments transecting the sill, such as fault zones and younger intrusions.

The water type is the magnesium-sodium-calcium-bicarbonate-chloride water type with electrical conductivity values falling within the ranges for ideal domestic water quality (Du Toit & Sonnekus, 2014).

3.5.2.3 Ventersdorp lava

The Ventersdorp upper group is dominated by andesitic lavas, interlayered with subordinate agglomerate and conglomerate tuff units. Groundwater is generally shallow, with high yields in lavas, due to deep weathering and large fractures which were created during the cooling process (DWS, 2018). Yield is generally directly related to rainfall.

3.5.3 Intergranular aquifers

'Intergranular' describes aquifers where the groundwater occurs in openings between granules and grains of unconsolidated material, such as sand and gravel (Du Toit & Sonnekus, 2014). Such openings may either be of a primary or secondary nature. Primary openings refer to the voids left during the deposition of the material (Du Toit & Sonnekus, 2014). The aquifers marked as 'intergranular' in Figure 3.14, refer to this type. The capacity of intergranular aquifers to store or yield water is influenced by factors such as grain size, roundness of grains, ratios of different grain sizes, clay content and the density of compaction.

A water-saturated zone is generally unconsolidated; however, occasionally semi-consolidated. Groundwater is stored and flows through intergranular interstices in porous and permeable media. Alluvial deposits of limited extent occur along river terraces such as sand and gravel. Weathered crystalline rock, with a principal water strike, occurs in the weathered intergranular zone. Groundwater occurs in tertiary-quaternary alluvial deposits of limited lateral extent and thickness along many riverbeds, such as the Modder River. These deposits vary in thickness from a few centimetres to tens of metres. Accumulatively, the alluvium solely covers a small percentage of the study area and, in general, consists of alternating layers of clay and poorly to well sorted sand and gravel layers (Van Aardt, 2015). Forty percent of boreholes drilled in this unit were observed to yield 0,5 ℓ/s to 2.0 ℓ/s (Du Toit & Sonnekus, 2014). Chemical analyses indicate that groundwater in the alluvial deposits is unsuitable for domestic use.

The alluvial deposits relate to the upstream regional geology and the sorting, grain size distribution and extent of the deposits are influenced by the flow of the river. The intensity of the flow of the rivers within the study area is only rapid during floods. During these times, the dumping and re-working of river sediments are most active. The water is classified as predominantly calcium-magnesium-chloride, indicating a water type related to reverse ion exchange (replacement of Na^+ with Ca^{2+} and Mg^{2+}).

3.5.4 Karst aquifer

Karst aquifers are water-bearing, solvent rock layers, at or close to the earth's surface, in which groundwater flow is focused along auxiliary developed cracks, gaps, courses and other interconnected openings. They are formed by the compound disintegration activity of somewhat acidic water, on exceedingly dissolvable rocks, most strikingly limestone and dolomite and, to a lesser degree, gypsum, anhydrite and halite. For the procedures of karst to be active, water should flow through these dissolvable rocks, presenting the rock to dissolve with water and empowering transport of solutes, and the water should be undersaturated for the mixture's constituents of the stone-empowering disintegration to happen. This interchange of flow (hydrology) and disintegration (geochemistry) removes rock, creating progressively larger voids along the groundwater pathway. The karst aquifers in the study zone of the Modder River catchment comprise the accompanying Transvaal calcareous rocks of hydro-geological units.

3.5.4.1 Transvaal calcareous rocks

Groundwater occurs along fault and shear zones associated with intense deformation, resulting in the occurrence of fractures, joints, and cavities, subsequently enlarged by dissolution processes in the calcareous rocks. Groundwater is further found at the contact zones of dykes and sills, and in fractures of diverse origin. The yield ranges between 2.0 ℓ/s to 16.0 ℓ/s with the greatest yield frequency being greater than 5.0 ℓ/s, and yields of over 16.0 ℓ/s have been encountered within this lithology (Du Toit & Sonnekus, 2014). The high yield suggests that it can give appreciable quantity of water that may support further groundwater development. The water displays a calcium-magnesium-bicarbonate character with elevated sodium levels and HCO_3^- as the predominant anion (Du Toit & Sonnekus, 2014). All the available chemical analyses within the lithology fall within the ideal drinking water quality range (Du Toit & Sonnekus, 2014) which suggests that it will be sustainable for use.

Section 3.5.5 discusses the various methods of estimating and quantifying recharge. These methods were not all used to estimate groundwater recharge in the study catchment, but they were discussed in order to give an indication of all the ways of catchment-scale characterisation using recharge. This section also sets out the recharge value of the C52 catchment quantified using the mass chloride method, which is currently of much interest. The mass chloride method is reliable, available and the data is readily accessible. All the known methods of recharge mode and value estimation are discussed in this section because it was necessary to triangulate and validate the recharge values of the C52 determined in this study.

A key measure of groundwater is recharge. Recharge is a key parameter for sustainability, particularly in arid to semi-arid areas. It is indicated that it is not yet possible to accurately measure the hydrological quantity of recharge; an accurate direct measure of groundwater recharge is not yet established. Several indirect measurements of recharge exist and how it is used in this research will be presented in subsequent chapters. However, these methods also introduce errors and uncertainties (Karamouz et al., 2020). Recharge methods vary because of the variations in rainfall and recharge events (Sami & Hughes, 1996; Sophocleous, 1991).

Most quantification techniques require familiarity with the concepts of safe/sustainable yields, borehole capacity evaluation through Jacob's extrapolation method, pump testing specifically, recovery, extended and constant discharge step (Helweg, 1994).

3.5.5 Chloride mass balance

The chloride mass balance method was applied to the C52 catchment and represents one of the indirect third method of measuring groundwater recharge. According to Aishlin (2006), it takes more than two years to measure the variability of recharge. This routing is the basis of the estimate of the net recharge of the catchment. For C52, this is a collection from the slopes and channels without the losses through base flow discharged from the catchment.

The researcher obtained the chloride mass balance data for C52 from the Council of Geo-science in South Africa, which was from an earlier work of DWAF (2006). The researcher analysed this data and the results are produced a GIS-based recharge map for the C52 catchment (Figure 3.15). In the study catchment, high recharge areas (19 mm to 34 mm) were found in the eastern and south-eastern parts. The central and western parts were marked by lower recharge values (0.1 mm to 7 mm).

As indicated in section 2.10.7, the DWS groundwater recharge values for South Africa at 1km by 1km grid cell is based on water balance method (DWS, 2016). The method is what DWS use for granting permits and was used in Chapter 4 and 5 of this research since it is derived from the boreholes used in the study and it was the basis for granting the permit upon which the boreholes covered in this thesis were dug. The quaternary catchments were used as the unit of measure. It should however be noted that this is an oversimplified way of recharge calculation.

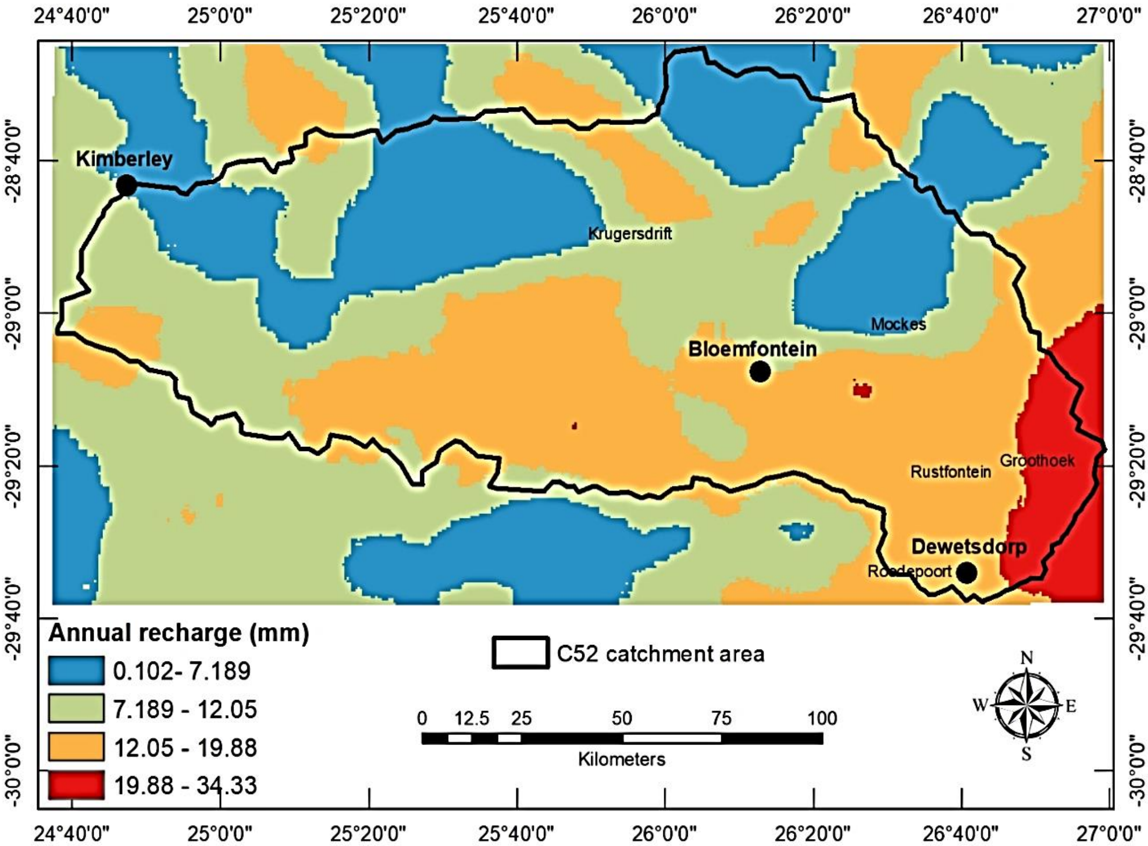


Figure 3.15: Recharge map of the C52 catchment area
Source: Author

The findings of the GIS map are in agreement with results obtained from an earlier recharge study that the DWS conducted on a national scale. Although the DWS approach did not differentiate between preferred path and matrix diffusion recharge, the GIS approach used by the researcher allowed sufficient flexibility for the inclusion of updates and new datasets.

3.6 Population of the Modder River Basin

A detailed study on the population distribution in South Africa was conducted by Woodford and Chevallier (2002a) to estimate future water demand and requirements. An estimated 5%

(25 500 families or 1 127 000 people) of the population of South Africa lives in the Modder River catchment (DWS, 2016). Majority of this population are concentrated in Bloemfontein, Botshabelo and Thaba 'Nchu. The main attraction of the population to these places is the economic opportunities created to catalyse growth. With regard to population distribution in the C52 catchment, the drier parts are sparsely populated, while the areas with high rainfall, to the east within the catchment, are more densely populated. The population growth is projected to increase with economic growth.

3.7 Water allocations of the C52 Modder River Basin

In cross-reference to Table 1.1 in Chapter 1, the DWS (2016) stated that water requirements within the C52 are mainly for irrigation which accounts for 80% of the local needs for water. Table 1.1 provided the quantities of water demand and available supply. The local and industrial needs in the C52 catchment are in the Modder River catchment, where Thaba 'Nchu and Bloemfontein are situated. With regard to a further breakdown of the requirements in the C52, none of the large industries have their own bulk water supplies. The water demand for mining and power generation are insignificant. According to the DWS (2016), all the requirements are given at a standard 98% assurance of supply. The water supply system of greater Bloemfontein provides the water required by the Mangaung Metropolitan Municipality.

Figure 3.16 shows the historical trend for water requirements and the demand for the greater Bloemfontein. This historical trend shows a rise based on the economy and population. This trend further suggests that the population of the Modder River area will tend to move towards other water sources available such as groundwater. Large-scale groundwater development is under consideration as an option for town supply. Farmers are mainly using groundwater for irrigation and this has had a definite impact on the area.

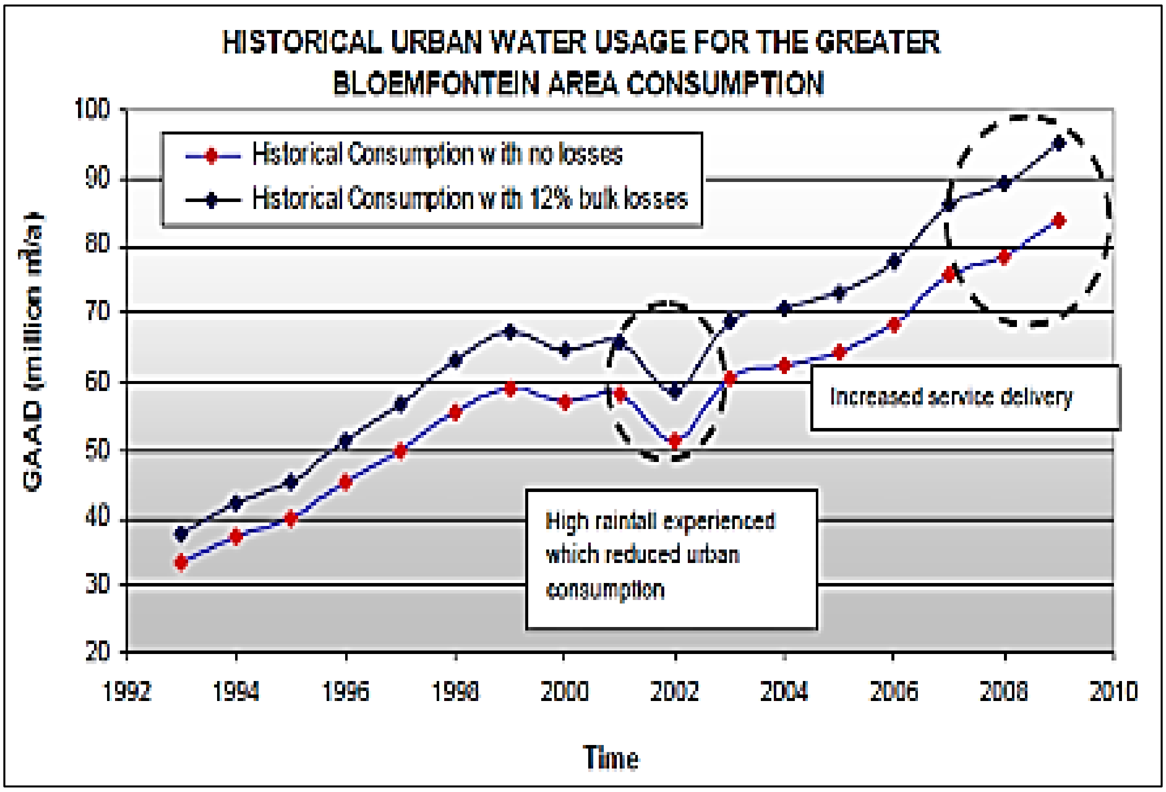


Figure 3.16: Historical urban water usage

Source: DWS (2016)

3.8 Conclusion

The purpose of this chapter was to review the C52 catchment groundwater and related conditions. It focused on the C52 geology, hydrology, hydrogeological conditions, topography, formations, and soil types. This chapter characterised the catchment study area, so that an understanding of the catchment's water-bearing capacity could be generated. It was also important as a sustainability prediction for the catchment because aquifers with low recharge will have poor yields and a subsequent groundwater sustainability potential. Also, aquifers with low water quality will behave likewise since the water will be deemed unsuitable for use.

The chapter concluded that the catchment is predominately a dolerite laden aquifer. The study area was a high groundwater recharge area found in the eastern and south-eastern parts of the study area which correlates with areas having high presence of surface water, while the central and western parts of the study area are marked by lower recharge values.

In the next chapter, the information on the hydrology and hydrogeology of the Modder River Basin detailed in this chapter will serve as a guide in developing a framework with sustainability index scores, while the specific hydrological and geohydrological details of this chapter will be applied to Chapter 5 to model the developed sustainability scores.

Chapter 4

DEVELOPMENT OF THE GROUNDWATER SUSTAINABILITY INDEX METHODOLOGY

4.1 Introduction

This chapter captures the elements underpinning the development of a groundwater sustainability index methodology. The specific methodology and data acquisition processes are described and the weighting and rating of parameters are explained.

The study adopted principles of sustainability reporting (Rossi and Luque-Vilchez, 2020) in the design of the study's sustainability index/methodology. Sustainability reporting is the process of assessing the groundwater status by objectively reflecting on the condition on the ground as best as possible, based on the data that can be gathered (Fraser et al., 2006). The sustainability standards of this research were the following:

- Stakeholder inclusiveness was designed into the research.
- An analysis of groundwater sustainability context was done.
- Materiality – reflecting the significant economic, environmental, and social impacts of the groundwater.
- Covers aspects of groundwater sustainability that substantively influence the assessments and decisions of stakeholders.
- Completeness – boundaries of the catchment set for sufficient analysis.
- Timeliness, clarity, accuracy, and balance were considered.
- The research information has been presented in a manner that enables stakeholders to analyse changes in groundwater in the catchment and that could support analysis relative to other catchments or aquifers.

As already stated, hydrological models help with a given objective of addressing issues to do with, for example, sustainability, water quantity, water quality and deep percolation. According to Chow et al. (1988), the hydrological systems analysis was used to process and predict a given output. Hydrological models require measured data (Senent-Aparicio et al., 2015). The observed data simulates or predicts the outcome in the catchment (Ndomba et al., 2008; Das and Pal, 2020; Liu et al., 2020). Beven (2001) and Baalousha (2016) gave three steps in the development of models:

- Determining the purpose and processes of the model.

- Developing the relationships within the model based on the catchment processes.
- Assigning the mathematical description of the equations to make quantitative predictions in the model.

These three steps were used in the conceptual framework. The conceptual framework further accounted for other aspects, such as rights to groundwater and socio-economic conditions, which was necessary, using the techniques of numerical analysis to define a procedural model in the form of codes that will run on a computer.

Groundwater sustainability builds on groundwater vulnerability, which is a relative dimensionless parameter of the natural attenuation of pollutants by the surface and/or subsurface, which cannot be measured directly in the field. Assessments are often done to understand the natural conditions of the geology, hydrogeology and may be expanded to include the nature of pollutants and their migration into, and interaction with surface water and groundwater. Table 4.1 shows the evaluations of various approaches to typical groundwater assessment.

Table 4.1: Evaluation of various approaches to typical groundwater assessment

Assessment approach	Brief outline of approach
Overlay and Index Approach	This assessment approach is based on combining various geological, hydrogeological, and other physical attributes deemed to be major factors controlling groundwater pollution. Weights are assigned to each attribute by comparing the relative importance of each attribute with groundwater vulnerability and its spatial resolution. The attributes are then combined manually or in a GIS environment to produce a groundwater vulnerability model (National Research Council, 1993, cited by Oke, 2015). This approach is preferred because of its relative simplicity. Although data can be obtained easily, the approach includes all the important factors of groundwater vulnerability. The most commonly used approaches are the DRASTIC, GOD, SINTACS and AVI.
Process-Based Simulation Modelling	This approach involves solving mathematical equations that govern pollution transport by stimulating models. Thus, an attempt is made to predict pollution transport in space and time which could include a one, two or three dimensional model of the unsaturated and saturated conditions (Oke, 2015). The modelling is mainly specific to a certain hydrogeological condition. The limitations of the process-based simulation include a failure to account for flow and transport processes at spatial scales regionally. The approach often requires a large amount of data which are sometimes very difficult or very costly to acquire over a large area.

Assessment approach	Brief outline of approach
Statistical Approaches	Statistical approaches involve the calculation of the probability distribution of groundwater pollution based on the frequency of the pollution, pollution concentrations or pollution probability over an aerial extent, for example logistical regression, principal component analysis, fuzzy logic, analytical hierarchical process and kriging (Magiera, 2000; National Research Council, 1993; Oke, 2015; Oke et al., 2017). While statistical methods, similar to other approaches, rely heavy on the quality of data, for statistical methods the model is derived from the data. Thus, the higher the data quality the better the model is able to represent the actual conditions. In modelling using statistical approaches, some modelling may be complex and may require experts in that statistical method to help in the model development. Advantages of the statistical approach are that they deal more effectively with differences in scale than other approaches and there is a myriad of statistical methods from which to choose to suit a given dataset and the current knowledge of the system to be modelled. Thus, the approach is most flexible. AI approach mirror the statistical approaches.

Source: Oke (2015) and Sakala et al. (2018)

4.2 Conceptual framework

The conceptual framework (Figure 4.1) in which the groundwater sustainability model in this study was framed, was based on the physical processes governing hydrological cycles in relation to groundwater sustainability in the Modder River catchment. These processes are shown as follows in Figure 4.1:

- Climate-surface water-groundwater interactions.
- Land use-surface water-groundwater interactions.
- Climate-land use-groundwater interactions.
- Climate-groundwater interactions.

The processes and their interactions were grouped as factors, which include climatic, socio-economic aspects, land use, aquifer sustainability, right and equity of resources (Figure 4.1). The amount of groundwater recharge and discharge is of interest with regard to sustainability. Sustainability is a link between these interactions because any amount of water extracted from groundwater as a result of irrigation, ownership, and groundwater development rights effectively shortcut the natural process.

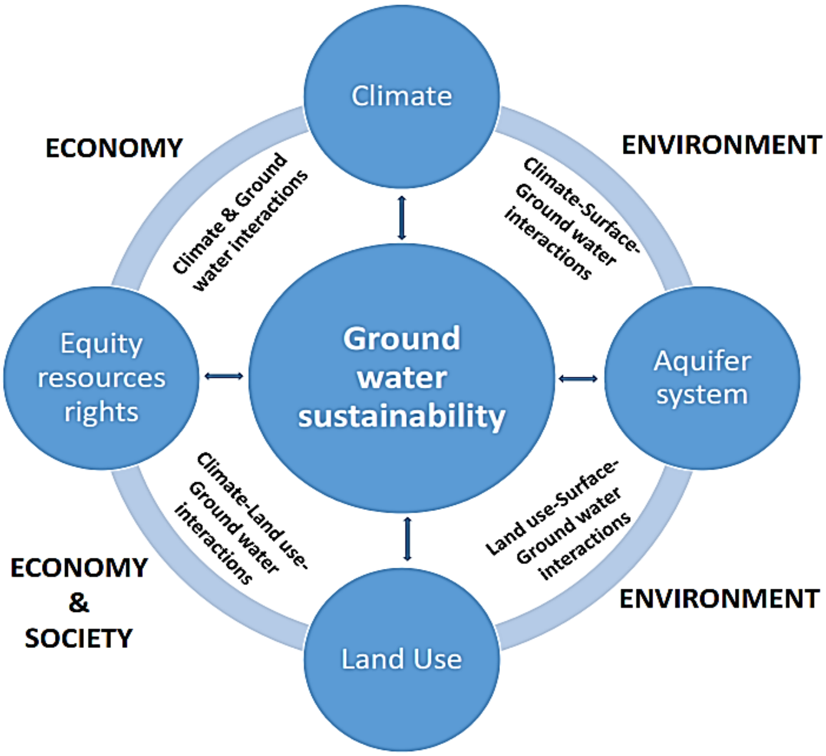


Figure 4.1: Conceptual framework
Source: Author

4.2.1 Climate-surface water-groundwater interactions

Rainfall is the main source of groundwater. Rainfall either forms part of the surface run-off or filters into the ground and later percolates into the ground. The amount collected into the ground has three paths:

- Capillary action leading to an unsaturated (vadose) zone.
- Evaporate, therefore furnishing evapotranspiration.
- Flows and contributes to the water table as groundwater.

As groundwater accumulates, it seeps slowly in the direction of oceans, lakes, and rivers. This facilitates the groundwater-surface water interaction. Figure 4.2 shows this interaction. Through this interaction the flow of groundwater is divided into flow that is deep (deep groundwater flow) and flow that is shallow (shallow groundwater flow).

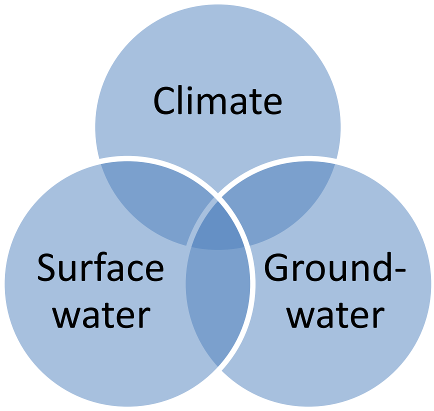


Figure 4.2: Interactions of climate–surface water–groundwater

Source: Author

4.2.1.1 Climate-surface water-groundwater interactions of the C52 catchment

Regarding the climate-surface water-groundwater interactions of the C52 catchment, a wider application in assessing the impact of land use changes on water resources, namely the SWAT model, was applied (Woyessa et al., 2011). The main aim being to evaluate the impact of land use change on water resources, with particular emphasis on the flow of water into the Rustfontein Dam. The model simulated several parameters among which the direct flow, the base flow or the groundwater flow, water yield and evapotranspiration were selected for evaluation purposes. The results showed variations of the water yield for the C52 catchment.

4.2.2 Land use-surface water-groundwater interactions

Human activity determines much of the groundwater discharge. For example, socio-economic needs lead to abstraction of groundwater. There are instances where a few communities artificially recharge their aquifers as conservation measures of groundwater resources (Figure 4.3). In general, when groundwater is recharged, low-lying groundwater flow also occurs and other cases the groundwater can be discharged back to the land surfaces. At interception, springs are fed and much of the water seeps back as surface water. This is termed base flow of water bodies. The percolated groundwater flows into the oceans without interception by land.

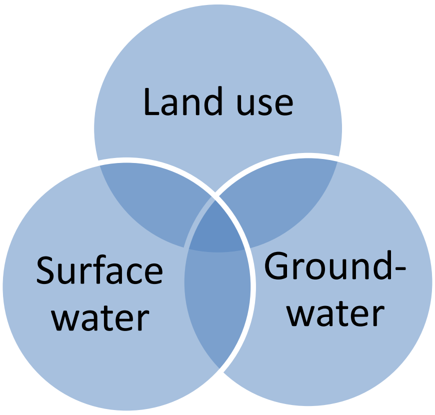


Figure 4.3: Land use-surface water-groundwater interactions

Source: Author

4.2.2.1 Land use-surface water-groundwater interactions of the C52 catchment

the hydrological balance of any river basin is directly and indirectly influenced by the spatial and temporal distribution of land use and land cover changes. Changes in land cover modify crucial hydrological processes, such as evapotranspiration and groundwater recharge. Upstream land use change could have a significant on-site effect on catchment water resources and an off-site effect on downstream users (Woyessa et al., 2011).

4.2.3 Climate-land use-groundwater interactions

Percolated groundwater is just a portion of water that reaches the ground and contributes to the water table. According to L'vovich (1979), the amount of rainfall that percolates into the ground is approximately $1/20^{th}$ of stream flow, which means that percolated groundwater is about 2% of rainfall globally. The 2% value vary with land use and scale of area, namely local to regional. Filtered groundwater flow intercepts the land surface. The amount that is intercepted by the land surface depends on the use of the land. Farmland intercepts more filtered groundwater. Percolated groundwater does not intercept the land surface. Percolated groundwater is usually pumped out for irrigation purposes. Figure 4.4 represents the climate-land use and groundwater interactions that support this process.

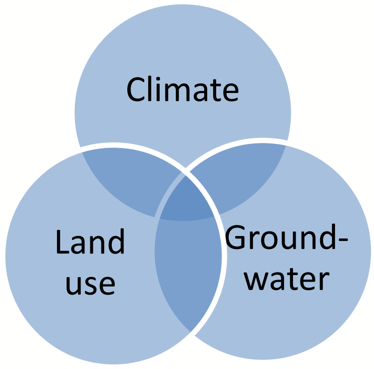


Figure 4.4: Land use-surface water-groundwater interactions
Source: Author

4.2.3.1 Climate-land use-groundwater interactions of the C52 catchment

Regarding the climate-land use-groundwater interactions of the C52 catchment, land use of the basin, especially the upper basin, is dominated by unimproved natural grassland. In this part of the basin irrigated crop land is insignificant. The middle and lower part of the basin are largely used for crop production, with commercial irrigation farming dominating the lower part of the basin. A large portion of the middle part of the basin area is used for urbanisation, which includes Bloemfontein and Botshabelo. The lower part of the basin consists of large areas of bush lands and low fynbos in addition to croplands. Quaternary catchment C52 is located on the Upper Modder River Basin. A land use map of 2000 indicates that 84% of the C52 area is covered by grassland, while only about 8% was used by agriculture (Woyessa et al., 2011).

4.2.4 Climate-groundwater interactions

Low water level groundwater is the source of low-lying groundwater flow. Globally, as a result of climatic conditions such as low rainfall, the amount of low-level groundwater is equal to a summation of the annual quantity of base flow that is discharged into river systems (World Water Balance, 1978). As such, base flow constitutes 30% of river systems that are at 40% rainfall. Base flow constitutes 12% of rainfall (L'vovich, 1979).

4.2.4.1 Climate-groundwater interactions of the C52 Modder River catchment

Rainfall and evapotranspiration are the main components of the climate that have major influences on the water balance of the C52 catchment. High rainfall contributes to increased stream flow, while on the contrary, high evapotranspiration reduces the amount of overland water considered as blue water (Jewitt et al., 2004). Physical and chemical soil properties, such as soil texture and infiltration rate, affect the amount of surface water considerably. Soils with high silt and clay content and soils with a low infiltration rate contribute to high surface run-off and less groundwater percolation. On the other hand, sandy soils and soils with a high infiltration rate reduce run-off; thus more groundwater (Woyessa et al., 2011).

4.3 Ratings of the sustainability factors

There is much similarity between vulnerability and sustainability assessments. With this in mind, the aim of the framework was for sustainable groundwater management in the Modder River catchment through development of a holistic hydrological and geohydrological model. Oke (2015) presented a major decision in the development of vulnerability assessments that can be adapted in sustainability assessments depending on the availability of input data for the hydrogeological system under consideration. As sustainability assessments of catchments build on the vulnerability of aquifers, different hydrogeological environments require different methods. For example, in aquifer vulnerability assessments, karst landforms or fractured terrains, require techniques which factor the nature of the fractures (Goldscheider, 2002; Goldscheider et al., 2000; Oke, 2015).

There are challenges when using the least and most established data to assess areas. The developed sustainability method has been designed to use a few climate-based hydro-geological parameters, fuzzy logic parameters such as rights and social economic data to assess groundwater sustainability of a delineated catchment such as the C52. Delineation exercises cater for inflows and outflows from the catchments and furthermore cater for other processes that affect the characteristics of a sub-catchment. This allows for identification of a unit of analysis, such as the C52 that is representative of the rest of the larger catchment such as the Upper Orange. According to Goldscheider et al. (2000), most vulnerability or sustainability methods target the assessment of groundwater resources such as catchment water tables or sources, which include wells or springs, with the aim to protect the groundwater resources for activities in the pathways and layers above the groundwater table.

4.3.1 Factor A: Climate

Boundary conditions were determined, based on global world meteorological reports and databases such as the Project Report No. 52 of the World Meteorological Organization [WMO] (2019). The highest and lowest global values that have ever been recorded were used as boundaries. Rainfall is critical in the catchment hydrological processes. It was given a maximum score of five for areas of rainfall above 3 000 mm per year (which is a global high value) and a low score of one for areas with rainfall less than 400 mm (which is also a global low value. A similar approach was taken to assigning maximum and minimum scores to evapotranspiration, sunshine, slope, vegetation, and climate zones. The boundary values were obtained from meteorological centres. In areas where the annual rainfall was significantly low (less than 400 mm per year), a lowest value of one was still assigned. As discussed in Chapter 2, when rainfall intensity is higher than the infiltration rate, more run-off is expected. As such, infiltration and recharge will be low. This, as discussed in section 2.9 in Chapter 2, will be further influenced by the nature of the surface topography.

In terms of theory, slope/topography is the result of the difference between topographic points (the highest to lowest) of an area. As discussed previously (section 2.9.4 and 2.9.7), recharge based on run-off and infiltration is influenced by the slope of an area. Low slopes result in ponding and water retention. This increases the infiltration and percolation. Steep slopes encourage increased run-off and low infiltration.

For Factor A, the resultant slope/topography is from the differences in contour values (Oke, 2015). Table 4.2 illustrates the values/scores assigned by the researcher based on global high and low amounts recorded. A look at slope and other parameters shows assignment of values from lowest to highest. A low score of one corresponds to an area with a high slope gradient beyond 50 %. This means these places encourage low infiltration and more run-off. Low slopes between zero to five correspond to places with contours, which are the same as that of surface water or water bodies, as a result ponding occurs. The ponding increases infiltration; therefore, a score of five was assigned. All the parameters under the climatic factor in Table 4.2 were treated in the same way, given the theory, linkages and relationships between them and aspects such as recharge. Evapotranspiration of greater than 2400 mm got a low score of one because it was not an ideal situation. In summary, the equation that represents the evaluation of Factor A is:

$$A = \sum_{k=0}^{n} k(R + E + S + T + V + C) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 12$$

Where:

A is the total score of all the parameters considered under Factor A;

K is the sum of the score of all the parameters considered under Factor A;

R is the rainfall;

E is the evapotranspiration;

S is the sunshine;

T is the topography;

V is the prevailing vegetation type;

C is the climatic zones assessed.

Table 4.2: Idealised illustration Factor A

Rainfall (mm)	**Score**
>1 600	5
1 200–1 600	4
800–1 200	3
400–800	2
<400	1
Evapotranspiration (mm)	**Score**
>2400	1
2400–1800	2
1800–1200	3
1200–600	4
<600	5
Sunshine (centigrade)	**Score**
0–5	5
5–10	4
10–25	3
25–50	2
>50	1
Slope/Topography (m)	**Score**
0–5	5
5–10	4
10–25	3
25–50	2
>50	1
Climatic zones	**Score**
Desert	1
Arid to semi-arid	2
Temperate	3
Monsoon	4
Tropics	5
Vegetation	**Score**
Tropical forest	5
Temperate forest	4

Savanah grassland	3
Semi dessert shrub	2
Dessert shrub	1

Source: Author

4.3.2 Factor B: Rights and equity versus resources

The boundary conditions for all factors was based on the highest and lowest global values that have ever been recorded. The values/scores were then assigned by the researcher based on these global high and low amounts. This was done so that the index would be applicable to any catchment or any part of the world. For Factor B, the values were checked against World Bank databases and DWS reports. All the parameters under the rights and equity versus resources factor in Table 4.3 were given the same treatment, given the theory, linkages and relationships between them and aspects such as recharge.

The parameters are based on information at borehole locations interpolated to cover the whole catchment. This is independent of the area of the catchment. The number of permits issued in the catchment per year was assumed to be of importance as it represents the abstraction activity in the catchment. The maximum score value of five was assigned if the number of permits issued was low (for example one). The lowest score of one was assigned to areas receiving more than five permits. The same was considered in the assignment of scores for the duration of permits, number of boreholes and pumping rate. Based on global databases (WMO, 2019), the values and scores were assigned as shown in Table 4.3, with the lowest scores corresponding to poor practises and the highest scores of five to mean good practices (these refer to permits issued for boreholes). During the analysis and application of the model on the Modder River catchment, the figures were obtained from the DWS data bases. A pumping rate of 1 000 000 cubic metres per year was given a low score of one by the researcher because that was not an ideal situation, while a pumping rate of 400 000 cubic metres per year gets a score of five because a lower pumping rate was a more desirable situation. As mentioned before, the parameters are based on information at borehole locations interpolated to cover the whole catchment, it is independent of the area of the catchment. In summary, the equation that represents the evaluation of Factor B is:

$$\mathrm{B} = \sum_{k=0}^{n} k\,(N + L + B + P) \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\ Equation\ 13$$

Where:

B is the total score of all the parameters considered under Factor B;

K is the score of all the parameters considered under Factor B;

N is the number of the permit;

L is the length or duration of permit years;

B is the number of boreholes in the sub-catchment;

P is the pumping rate.

Table 4.3: Idealised illustration Factor B

Number of permits issued in the catchment per year	Score
0-1	5
1–2	4
2–3	3
3–4	2
>5	1
Length or duration of permit years	**Score**
0–5	5
5–10	4
10–15	3
15–20	2
20	1
Number of boreholes in the sub-catchment	**Score**
0–25	5
25–50	4
50–75	3
75–100	2
>100	1
Pumping rate (1 000 cubic metres per year)	**Score**
>1 000 000	1
800 000–1 000 000	2
600 000–800 000	3
400 000–600 000	4
<400 000	5

Source: Author

4.3.3 Factor C: Socio-economics

Use per capita of the catchment was assigned a maximum score of five to a use of less than 25 ℓ/c/d, which is an acceptable practice of low use of water (Mkwalo, 2011). A per capita use of more than 100 was assigned a score of one. This was the lowest score and it indicates over-abstracting or using too much water. The scoring for the population in the catchment, water uses and tariffs, was the same trend as the per capita use. These values were from global reports and data bases (Messerschmid et al., 2018). However, in terms of an analysis of the Modder River catchment, the values assigned were derived from the DWS data bases (Lange et al., 2007). Based on this, data scores were assigned as shown in Table 4.4, with the lowest scores corresponding to poor practises, while the highest score of five denotes an acceptable practice.

As with previous boundary conditions for Factors A and B, boundary conditions for all factors are based on the global highest and lowest values ever recorded. The values/scores were assigned by the researcher based on the global high and low amounts ever recorded. This was done so that the index would be applicable to any catchment or any part of the world. For Factor C in particular, the values were checked against DWS reports. All the parameters under the socio-economic factor in Table 4.4 were given the same treatment, given the theory, linkages and relationships between them and aspects such as recharge. The parameters are based on information at borehole locations interpolated to cover the whole catchment. It (the parameters) is independent of the area of the catchment. In addition, as an example, a population in the catchment of greater than 2 000 000 was assigned a score of one because it was not a desired situation. This means that two million people are using the groundwater directly on a daily basis, while a population of less than 500 000 received a score of five because it is a low value and it is deemed a desired situation because a lower population uses the groundwater resources. In this situation as well, the parameters are based on information at borehole locations interpolated to cover the whole catchment, which is independent of the area of the catchment. The score of one to five were ranged equally according to the differences between these two sets of boundaries as shown in Table 4.4.

Furthermore, some activities such as irrigation and power generation use more water than others such as for domestic use. Water uses for large-scale activities such as mining scored higher compared to domestic use. Also, the higher the tariff, the lower the water use. This is a global management practise of ensuring sustainability. If people pay more, they use less. The National Water Act (1998) set the amount to be charged and gave the municipality the right to adjust this amount as it deemed fit.

In summary, the equation that represents the evaluation of Factor C is:

$$\mathrm{C} = \sum_{k=0}^{n} k\,(U + P + W + T) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathit{Equation}\ 14$$

Where:

C is the total score of all the parameters considered under Factor C;

k is the score of all the parameters considered under Factor C.

U is the use per capital of the catchment;

P is the population present in the catchment;

W is the water uses;

T is the tariffs.

Table 4.4: Idealised illustration factor C

Use per capita of the catchment (ℓ/c/d)	Score
<25	5
25–50	4
50–75	3
75–100	2
>100	1
Population in the catchment	**Score**
>2 000 000	1
1 500 000–2 000 000	2
1 000 000–1 500 000	3
500 000–1 000 000	4
<500 000	5
Water uses (ℓ/d)	**Score**
Domestic (<2)	5
Afforestation (2–20)	4
Mining and bulk industrial (20–100)	3
Irrigation (100–300)	2
Power generation (>300)	1
Tariffs (rand)	**Score**
<2	1
2–20	2
20–100	3
100–300	4
>300	5

Source: Author

4.3.4 Factor D: Aquifer sustainability

Groundwater naturally recharges upstream and discharges downstream. Most of the recharge areas are near mountain peaks, where rainfall is higher, compared to adjacent lowlands. Infiltrated groundwater is discharged at valleys and at the earth's crust or low-lying zones. The extent by which rock type affects groundwater sustainability, is dependent on hydraulic conductivity and permeability. Unfractured basement rock has little sustainability. Sustainability of fractured basement rock depends on frequency variation, distribution and range of widths of the fractures (Oke, 2015). Since fractured rock sustainability depends on the rock's hydraulic conductivity, the weighting of fractured rock in Table 4.5 was low, compared to unfractured, unconfined rocks.

A score of five was assigned to intergranular rock as infiltration of water through it to the water table takes longer (see Table 4.5). The water that percolates densely consolidated rock is assumed to originate from surface run-off and not vertical infiltration, irrespective of topsoil permeability. The dolerite presents the lowest percolation in all geological rocks, as presented in Table 4.5, and the low infiltration is due to the small pore spaces and lower permeability present in most of them. The dolerite formation was given a low score of 0.5 to a maximum of 1.0.

The water quality scoring will depend on the state of the water. If the water smells, taste bad and coloured it is not fit for use and will frequently be wasted, therefore a score of one was assigned, but if the water is good in taste with no smell and colour, it is good and sustainable. A high recharge aquifer (above 300 mm) is regarded as a sustainable aquifer and was assigned a high score, while a recharge of below 2 mm per year is unsustainable and was assigned a low score.

In summary, the equation that represents the evaluation of Factor D is:

$$\mathrm{D} = \sum_{k=0}^{n} k\,(A + R + W + Y + R + S) \ldots \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 15$$

Where:

D is the total score of all the parameters considered under factor D;

k is the score of the parameter.

A is the aquifer system in place;

R is the rock type present;

W is the water quality;

Y is the aquifer yield.

R is the recharge condition;

S is the storage volume of the aquifer.

It should be noted that the values corresponding to the scores were gauged with the global low and high as reported (Messerschmid et al., 2018), while a comparison was made to the prevailing indicators in the Modder River catchment. The Modder River data values were obtained from data bases of the DWS and similar studies (Lange et al., 2007).

Table 4.5: Idealised illustration Factor D

Factor D (Aquifer system)		**Score**
Unconfined		5
Perched		4
Confined		3
Semi-confined		2
Fractured		1
Rock type/lithology		**Score**
Intergranular	0–5	5
Fractured	5–10	4
Karst	10–25	3
Intergranular and fractured	25–50	2
Dolerite	>50	1
Water quality		**Score**
Smell		(yes=1, no=5)
Taste		(yes=1, no=5)
Colour		(yes=1, no=5)
Aquifer yields of the catchment (ℓ/s)		**Score**
>1		5
0.8–1.0		4
0.6–0.8		3
0.4–0.6		2
<0.4		1
Recharge (mm/year)		**Score**
<2		1
2–20		2
20–100		3
100–300		4
>300		5
Storage volume of aquifer (1 000 cubic metres)		**Score**
>1 000 000		5
800 000–1 000 000		4
600 000–800 000		3
400 000–600 000		2

<400 000	1

Source: Author

4.4 Concept of the sustainability index method

This method is based on using the indicators' index method to understand a set of selected parameters, namely economic, policy, geological, social dynamics, and groundwater (Karathanassi et al., 2007). The index method of analysis is popular and applicable to data sets that are readily available. The sustainability index method, as shown in Figure 4.5, is based on the fact that the parameters and various rates are known or are part of routinely measured/collected data, therefore largely available information.

Factor (A) Climate

Rainfall (mm)	Score
>3000	5
1600-1200	4
1200-800	3
800-400	2
<400	1
Evapotranspiration (mm)	**Score**
>200	1
200-150	2
150-100	3
100-50	4
<50	5
Sunshine (centigrade)	**Score**
0-5	5
5-10	4
10-25	3
25-50	2
>50	1
Slope / Topography (m)	**Score**
0-5	5
5-10	4
10-25	3
25-50	2
>50	1
Climatic zones	**Score**
Desert	1
Arid – semi arid	2
Temperate	3
Monsoon	4
Tropics	5
Vegetation	**Score**
Tropical forest	1
Temperate forest	2
Savanah Grassland	3
Semi dessert shrub	4
Dessert shrub	5

Factor (B) Rights/equity verse resources

Number of permits issued in the catchment per year	Score
<1	5
1-2	4
2-3	3
3-4	2
>5	1
Length or duration of permit years	**Score**
0-5	5
5-10	4
10-15	3
15-20	2
20	1
Number of boreholes in the sub catchment	**Score**
0-25	5
25-50	4
50-75	3
75-100	2
>100	1
Pump rate (1000 cubic meters per year)	**Score**
>1,000,000	1
1000000-800000	2
800000-600000	3
600000-400000	4
<400000	5

Sustainability (S) S= ∑A.B.C.D

Sustainability Index	Sustainability class	Sustainability map
19-35	Very low	
35-51	Low	
51-67	Moderate	
67-83	High	
83-100	Very high	

Factor (C) Socio economics

Use per capita of the catchment (l/c/d)	Score
<25	5
25-50	4
50-75	3
75-100	2
>100	1
Population in the catchment	**Score**
>2,000,000	1
2000000-1500000	2
1500000-1000000	3
1000000-500000	4
<500000	5
Water uses (l/d)	**Score**
Domestic (<2)	5
Afforestation (2-20)	4
Mining & bulk industrial (20-100)	3
Irrigation (100-300)	2
Power generation (>300)	1
Tariffs (rand)	**Score**
<2	5
2-20	4
20-100	3
100-300	2
>300	1

Factor (D) Aquifer sustainability

Aquifer system		Score
Unconfined		5
Perched		4
Confined		3
Semi confined		2
Fractured		1
Rock type / lithology		**Score**
Intergranular	0-5	5
Fractured	5-10	4
Karst	10-25	3
Intergranular and fractured	25-50	2
Dolomite	>50	1
Water quality		**Score**
Smell		(yes=1, no =5)
Taste		(yes=1, no =5)
Colour		(yes=1, no =5)
Aquifer yields of the catchment (l/s)		**Score**
>1		5
1-0.8		4
0.8-0.6		3
0.6-0.4		2
<0.4		1
Recharge (mm/year)		**Score**
<2		1
2-20		2
20-100		3
100-300		4
>300		5
Storage volume of aquifer (1000 cubic meters)		**Score**
>1,000,000		5
1000000-800000		4
800000-600000		3
600000-400000		2
<400000		1

Figure 4.5: Idealised illustration of the sustainability index/model

Source: Author

The methodology used was to consider a detailed understanding of the indicators/parameters and scoring/ranking, against the following set weights:

- Aquifer system (recharge, yields, storativity, aquifer types, lithology/rock types).
- Physical processes affecting the groundwater system of the Modder River catchment, namely climatic factors such as climatic zones, precipitation, sunshine, evapo-transpiration, slope and topography.
- Human-induced parameters of rights and equity such as duration of the permits, pumping rate per year, number of issued permits per year in the catchment, number of boreholes in the sub-catchment.
- Socio-economic and land use such as population in the catchment, use per capita, water uses and tariffs.

Following the approach defined by Oke (2015), the sustainability index acronym was derived from the initial letters of the factors used in the formulae (Equations 10, 11, 12 and 13) as A, B, C and D. The status of sustainability in C52 is a summation of the factors A, B, C and D. Factors A, B, C and D have equal weighting as the principle of sustainability analysis, discussed earlier in Chapter 2, assigns equal importance to all views and paradigms. These paradigms, directly and indirectly, consider economic, social, policy and all fuzzy logic to be of equal importance and contribution to achieving sustainability of a resource. For this research, the sustainability index method was designed for the groundwater sustainability analyses on a corresponding spreadsheet (Figure 4.5), calculating the value of the groundwater sustainability impact, which is then presented in the form of outcome GIS maps.

The A-factor is the **climate** of the study area, such as the rainfall that the Modder River receives, which feeds infiltration and percolation into the aquifer. This determination is a measure of the mean rainfall dependent on climatic conditions, as measured by means of the rain gauges/stations by the South African Weather Service. Evapotranspiration in the catchment was high, it was reported to be around an average value of 1 800 mm per year (DWS, 2016) as presented in Figure 3.6. This is higher than the average rainfall of 400 mm per year for this region (DWS, 2016) as presented in Figure 3.6. The sunshine, measured as temperature, ranged from 15 to 50°C, which led to the arid and semi-arid climatic zones present in the area. Further indicators considered in the climatic conditions, were and climatic zones. The data used in modelling the Factor A framework were sourced from the South African Weather Service.

The B-factor is the **rights and equity versus resources** of the study area and includes aspects such as issuing of permits in the Modder River catchment, which therefore represents the abstraction activity in the aquifer. The factor considers the rights and equity of the water users regarding the groundwater resources in the catchment; and constitute the number of borehole permits issued per year, duration or length of the borehole permits issued, number of actual boreholes drilled and pumping rate per year currently in the Upper Orange River. These were determined by the regulations of the DWS in the Free State province. These indicators are being monitored and available at the DWS. Factor B, therefore, represents the groundwater abstraction rate in the aquifer.

The C-factor is the **socio-economic activities** of the study area. Factor C is the socio-economic activities of the catchment related to their impact on the groundwater resources. It includes aspects such as tariffs and commercial use of water in the Modder River catchment, which therefore represents the abstraction activity in the aquifer that supports economic growth. The indicators considered in this factor consist of the per capita use of the catchment, where boreholes are located, the population of the C52 catchment, tariffs paid based on use, the economic activities of the users and the purpose of the groundwater use such as mining, agriculture, domestic and power generation. Factor C further represents the potential use of the water, the economic growth that relies on the groundwater abstracted and the activities that impact on the abstraction of groundwater. Generally, these indicators represent the main activities that influence the groundwater sustainability of the C52 catchment. These indicators are being monitored and available at the DWS.

The D-factor is **aquifer sustainability** that represents the groundwater interactions and processes in the aquifer and it cannot underscore the extent of how the rock type affects groundwater sustainability. Furthermore, aquifer sustainability depends on the hydraulic conductivity and permeability of the rocks. Hydraulic conductivity, in turn, determines recharge. Fractured basement rock has little sustainability. The sustainability of unfractured basement rock depends on rock distribution, frequency of unfractured variations and rock width. Key indicators/parameters of importance, which affect aquifer system sustainability, are the rock type hosting the groundwater and type of aquifer system in place such as confined, unconfined, semi-confined, and fractured. Non-fractured basement rock has no water and no sustainability. The sustainability of fractured basement rock depends on joints, faults, lineaments and cavities. The indicators that further affect the sustainability of the aquifer system are aquifer yields (in litres per seconds, recharge (in millimetre per year), aquifer storage (measured as storage gross volume in cubic metres per year) and water quality. Concepts of safe/sustainable yield, borehole capacity evaluation through Jacob's extrapolation method (the easiest method known to date), pump testing, specifically recovery, and extended and constant discharge steps were considered.

It is important to explore the sustainability of the aquifer system in the catchment separately, as there is a possibility of some aquifers sustaining themselves, irrespective of the socio-economic activities that the aquifer supports. Aquifers are recharged through several processes, including rainfall, infiltration and percolation, recharge mechanisms and other hydrological processes that affect groundwater sustainability. The higher the population number in a catchment, the higher the socio-economic activities such as agriculture, mining, industry, and domestic use; the higher their demands, the more permits are issued, which puts the aquifers in a vulnerable and less sustainable condition.

The developed framework was proposed in a sustainability index. The sustainability indices were ranked based on a percentile system. The percentile system sets a range from the highest score of 100, which implies a highly sustainable system, to the lowest score of 19, which suggests the least sustainable system. A rating of one was assigned to ‘severe impact’ and a rating of five was assigned to ‘least impact’ on the groundwater sustainability status.Table 4.6 shows the description of the sustainability index values regarding to climatic and environmental condition and abstraction..

Table 4.6: Description of various groundwater sustainability index

<table>
<tr><th>Groundwater Sustainability Index</th><th>Groundwater Sustainability Status</th><th>Description</th></tr>
<tr><td>19−35</td><td>very low sustainability</td><td rowspan="3">Too much abstraction activity, unfavourable climatic conditions.

Slow to little groundwater processes and interactions such as high or steep slopes and low rainfall.</td></tr>
<tr><td>35−51</td><td>low sustainability</td></tr>
<tr><td>51−67</td><td>moderate sustainability</td></tr>
<tr><td>67−83</td><td>high sustainability</td><td rowspan="2">Correspond to areas with favourable climatic conditions, and favourable groundwater interaction and processes, namely fast rate aquifer system, particularly recharge.

The high classes further have less abstraction and socio-economic activity.</td></tr>
<tr><td>83−100</td><td>very high sustainability</td></tr>
</table>

4.5 Conclusion

The purpose of this chapter was to explain the elements underpinning the development of the groundwater sustainability index methodology. The specific methodology and data acquisition were described and weighting and rating of parameters were explained. The proposed sustainability method was presented as a simple concept. The sustainability index method use both subjective techniques and physically-based techniques.

Boundary conditions for all factors were based on the global highest and lowest values ever recorded. The values/scores were assigned by the researcher based on the global high and low amounts ever recorded. This was done so that the indices would be applicable to any catchment in any part of the world. For all factors, the values were checked against DWS reports. All the parameters under study were assessed in the same way, given the theory, linkages, and relationships between them.

Under steady state conditions, evapotranspiration is subtracted from rainfall to get a value of recharge. The conclusion of the chapter is that in real-life events, infiltration and percolation of rainfall contribute to groundwater pools. Regarding the sustainability index, the sustainability classes that were derived follow other methods of analysis of complex sustainability challenges around water resource management studies. These methods offer a range of sustainability classes from very high to very low. The resulting sustainability model/index is easy to collate and use. It is designed for zones such as the Modder River Basin and areas with similar sustainability challenges in South Africa and globally.

Chapter 5

APPLICATION OF THE DESIGNED SUSTAINABILITY METHOD TO THE C52 CATCHMENT

5.1 Introduction

Chapter 5 gives an account of the application of the sustainability index concept to 51 boreholes in the C52 catchment of the Modder River Upper Orange Basin. This chapter further details the production of maps for all the factors under study in this thesis. A final sustainability map is plotted from the climate, aquifer sustainability, socio-economic aspects, and rights maps.

A hydrological model is adopted based on its effectiveness, namely its accuracy and ability to simulate the hydrology and represent various other processes in the catchment (Rattanaviwatpong, 2001). Currently, a wide range of hydrological models depends on data availability, economic constraints and fitness for purpose (Beven et al., 1980).

Beven (2001) suggested the following steps in applying a model:

- Prepare and review the list of available models. Create your own model if none is available for the modelling purpose.
- List the predictable and required parameters/variables. Determine the strategy and purpose of the model required.
- List out the assumptions to be made by the model, based on rejected models that do not represent the catchment processes.
- List out the inputs, boundaries, conditions and specify the parameter values required by the model.
- Review the list of available models in the first step if predictions are required for an application.

The sustainability index was subjected to the steps outlined above, which use both subjective and physically-based techniques. The parameters of the sustainability model have been designed for application to evaluate, collate and calculate the groundwater sustainability of areas such as the C52 Modder River Basin and other catchments globally, with similar challenges.

5.2 Data collection

A list of study parameters was identified and collected, and is shown in Table 5.1. In Chapter 4, a detailed desk review was conducted to understand the historical evolution of existing frameworks on groundwater sustainability (Table 4.1) where written, electronic, photographic and video sources were reviewed.

Table 5.1: Types of data and parameters collected for the study

Parameter		Method of collection	Source	Form	Method of analysis	Validation
Yield and recharge of groundwater	Use per capita of catchment water, evapotranspiration potential	Requested in writing for access to data base	Data bases in DWS and South African Weather Affairs	Text tables	Graphs and infinite series	Observed data, expert view, model system checks
Evapotranspiration potential	Intensity and duration of rainfall	Requested in writing for access to data base	Data bases in DWS and South African Weather Affairs	Text	Graphs and infinite series	Observed data, expert view, model system checks
All parameters		Requested in writing for access to data base	Data bases in DWS and South African Weather Affairs	Text	Graphs and infinite series	Observed data, expert view, model system checks
Yield and recharge of groundwater, length/duration of permits	Number of permits issues in the catchment	Dipper meters, sensor equipment	Private farms	Text	Graphs and infinite series	Observed data, expert view, model system checks
Water levels	Aquifer data	Literature review, aquifer data	Private farms	Text	Graphs and infinite series	Observed data, expert view, model system checks
Lithology and geology	Lithology and geology, depth of soil encountered	Review of reports and data bases	Private farms	Text	Graphs and infinite series	Observed data, expert view, model system checks
Population or people/livestock served	Yield and recharge of groundwater	Field	DWS	Text	Graphs and infinite series	Observed data, expert view, model system checks
Recharge of aquifer, storativity (volume and area), GPS coordinates of sampling points, area of land used for mining irrigation	Length/duration of permits	Field	DWS	Text	Graphs and infinite series	Observed data, expert view, model system checks
Distribution of rainfall, evapo-transpiration potential	Number of boreholes in the catchment	Review of data bases	DWS	Text	Absolute number	Observed data, expert view, model system checks
	Aquifer yield of the catchment	Review of data bases	DWS	Text		Observed data, expert view, model system checks
Distribution of rainfall, evapo-transpiration potential		Review of data bases	DWS	Text		Observed data, expert view, model system checks

Parameter		Method of collection	Source	Form	Method of analysis	Validation
Number of permits issued in the catchment	Spatial analysis of permits/boreholes	Review of data bases	DWS	Coordinates	GIS mapping	Observed data, expert view, model system checks
Design, geology, construction	Per capita use of catchment water		DWS		Absolute number	Observed data, expert view, model system checks
All parameters		Interviews, literature review	DWS, Mangaung data bases in meteorology			Observed data, expert view, model system checks
Parameter		Method of collection	Source	Form	Method of analysis	Validation

Source: Author

Interviews and focus discussions were held with the key people/informants in the organisations using a guiding set of questions (Appendix A). DWS personnel and selected farmers were consulted. The guiding questions were refined through pre-tests until the answers presented permitted an appropriate level of analysis. The interviews were used to acquire key quantitative data and to mine relevant data to feed into the modelling work. The interviews were critical to better understand the study.

5.3 Data

The data was obtained from the DWS, various data bases, semi-structured interviews, case studies and a literature review (see Appendix A). The following hydrogeological parameters were collected:

- Physical processes affecting the groundwater system of the Modder River catchment, such as climatic factors, including climatic zone precipitation, sunshine, evapo-transpiration, slope, and topography.
- Aquifer system such as recharge, yields, storativity, aquifer types, lithology and rock types.
- Socio-economic aspects and land use such as population in the catchment, use per capita, water uses and tariffs.
- Human induced parameters of rights and equity such as duration of the permits, pumping rate per year, number of issued permits per year in the catchment, number of boreholes in the sub-catchment.

A number of databases covering major national water monitoring systems and programmes were accessed. These included:

- Groundwater information in different databases (National Groundwater Archive, Water Registration Management System, GRIP, Hydstra, and hydrogeological maps).
- Surface water information/Hydstra database. This considered streams, rainfall, and evapotranspiration.
- Gauged precipitation information, from the South African Weather Service database, water sheets, neighbourhood, and area regions, and water use management systems.
- Rivers' data base, water management systems, and geological data frameworks (GIS).
- Water-use information captured by the DWS on the Water Registration Management System.
- Compliance and monitoring information in the Regulatory Performance Management System.

5.4 Assignment of scores to parameters

As an example, places where contours were the same as that of surface water/water bodies resulted in ponding. The ponding increased infiltration. For this reason, a score of five was assigned. A low value of one corresponded to undesirable situations.

The latitudes and longitudes were consistent with the DWS, GIS and GPS coordinate systems. The scores were colour-coded as shown in Table 5.2.

Table 5.2: Corresponding sustainability classification for Factor A

Score	Class of sustainability	Colour code
0–5	Very low	Red
5–15	Low	Orange
15–20	Moderate	Yellow
20–25	High	Green
25–30	Very high	Blue

Source: Author

The A-factor is the climatic conditions dominant in the C52 catchment area. The Factor A score was the result of an average rainfall of 534 mm in the Modder River C52 catchment. This value and that of evapotranspiration, were averages obtained from the South African Weather Service for 2016. This rainfall average received a score of two. Evapotranspiration in the catchment ranges was 1 570 mm to 2 000 mm (DWS, 2016), which received a score of one as high evapotranspiration is not desirable as it depletes the soil of the soil water, which is supposed to contribute to groundwater. Sunshine hour's information was not available so a proxy for air temperature was used. In the study area, the average air temperature is 15 °C and was assigned a value of three. Other indicators considered was the slope, as a proxy indicator of topography, received a score of five.

The data used in modelling Factor A was sourced from the South African Weather Service and the DWS. Table 5.2 and Appendix C (Factor A) show the scoring of Factor A and the corresponding sustainability classification. According to the sustainability index, the Factor A total score was 11.

The B-factor considers the rights/equity, as related to groundwater resources of the catchment. The total score from the mapping for the 51 boreholes was in the range of 8–13. This range of scores was the result of adding the weights of actual values for each borehole. The weights for the number of borehole permits issued per year, duration or length of the borehole permit issued, number of actual boreholes drilled and pumping rate per year currently in the Modder River catchment, were added and ranked. These indicators are being monitored and available at the DWS. Table 5.3 reflects the scoring of Factor B. Appendix C (Factor B) shows the corresponding sustainability classification.

Table 5.3: Corresponding sustainability classification for Factor B

Score	Class of sustainability	Colour code
0–4	Very low	Red
4–8	Low	Orange
8–12	Moderate	Yellow
12–16	High	Green
16–20	Very high	Blue

Source: Author

Generally, the C-factor represent the main activities that influenced the groundwater sustainability of the C52 catchment. The score considered in this factor consisted of the values of water use per capita of the catchment, where boreholes are located, the population of the catchment, tariffs paid based on the use and their economic activities and the purpose of the groundwater use such as mining, agriculture, domestic and power generation, against the weighting of the sustainability index. The score range for Factor C was from 7–11. Table 5.4

reflects the corresponding sustainability classification. The parameters were monitored and available at the DWS as shown in Appendix C (Factor C) for the 51 boreholes.

Table 5.4: Corresponding sustainability classification for Factor C

Score	Class of sustainability	Colour code
0–4	Very low	Red
4–8	Low	Orange
8–12	Moderate	Yellow
12–16	High	Green
16–20	Very high	Blue

Source: Author

The score for the 51 boreholes is presented against the aquifer system, rock type, aquifer yields in litres per second, recharge in millimetres per year, aquifer storage (measured as storage gross volume in cubic metres per year) and the water quality. The sustainability range of the score was 10.5–16.5. All boreholes located in the fractured aquifer type and the dolerite rock type, received a score of one. The Modder River is recharged in the range of 2–20 mm/year and this scored a two, according to the sustainability index rating. Table 5.5 shows the scoring of Factor D. The scoring followed the same method as that applied to Factors A, B and C. Appendix C (Factor D) shows the corresponding sustainability classification for Factor D.

Table 5.5: Corresponding sustainability classification for Factor D

Score	Class of sustainability	Colour code
0–5	Very low	Red
5–15	Low	Orange
15–20	Moderate	Yellow
20–25	High	Green
25–30	Very high	Blue

Source: Author

5.5 Preparation of sustainability maps

The results of the mapping were generated using an ArcView GIS platform. The ArcView GIS platform has been significantly applied globally to address water quality and water quantity issues (Arnold & Allen, 1996; Bouraoui et al., 2005; Butts et al., 2004; Chaplot et al., 2005;

Kim & Pachepsky, 2010; Oeurng et al., 2011; Molina-Navarro et al., 2014; Mutenyo et al., 2013). ArcView GIS has further been applied in South Africa to model the effects of land use variation on the hydrology of catchments (Gassman et al., 2007; Govender & Everson, 2005; Welderufael et al., 2013). Data selection used in this study incorporated data from Microsoft Excel© files received from the DWS.

A shape file of the C52 Modder River Basin was collected from the DWS. It included the Modder River shape files, as well as files created for all the maps that were produced from these base maps. The borehole coordinates were provided by the DWS in Bloemfontein. The coordinate system output and input mapped projections on the World Geodetic System as of 1984 (Decker, 1986).

Contouring of maps was achieved using a gridding system. Factors A, B, C and D (the calculated weighted parameters) were overlaid after contouring on a gridded map. To take advantage of ArcView GIS, other elements such as shape files presented as multiple data layers (in Microsoft Excel©) were contoured and imposed on the same maps. These were plotted against factors scores, GPS coordinates of boreholes, as well as towns and centres on the map.

The contours joined boreholes and places with the same sustainability or factor score. The contouring led to smoothing of the map, using additional features and functions of the ArcView GIS software. Smoothing involved the interpolation of boundaries within two contours. The final step was to colour-code the points/scores, to facilitate interpretation and identification.

5.6 Sustainability maps of the C52 Modder River catchment

Chapters 2, 3 and 4 highlighted that rainfall is critical in the catchment hydrological processes. It was given the maximum score of five to areas of rainfall above 3 000 mm and a low score of one for areas with rainfall less than 400 mm per year. A similar approach was taken to assign the maximum and minimum scores to evapotranspiration, sunshine, slope, vegetation, and climate zones. These values for Factor A (Appendix B) were from meteorological centres. As discussed in Chapter 2, where rainfall intensity is higher than infiltration rates, run-off is expected to result as opposed to infiltration and later recharge of groundwater. This (also as discussed under section 2.9 in Chapter 2) will be further influenced by the nature of the surface topography.

In theory, slope/topography is the result of the difference between topographic points (the highest to lowest) of an area. Again, as discussed previously (Figure 3.3), recharge based on run-off and infiltration are influenced by slope. Low slopes result in ponding and water retention, which increase percolation and infiltration. Steep slopes encourage increased run-off and low infiltration.

For Factor A, the resultant slope/topography is from the differences in contour values (Oke, 2015). As explained earlier in section 5.5, the topography of an area can significantly influences other climatic parameters such as rainfall and evapotranspiration. Mountain ranges are natural barriers to air movement. For example, coastal ranges allow for some condensation and light precipitation. Again, a low score of one corresponds to an area with a high slope beyond 50 %. This means that these places encourage low infiltration and more run-off. Low slopes of zero to five correspond to places with contours that are the same as that of surface water/water bodies, and result in ponding. The ponding increases infiltration. For this reason, a score of five was assigned to those areas within the catchment.

The map of Factor A, shown in Figure 5.1 shows areas of a moderate class of sustainability. The moderate classes suggest areas with more abstraction activity, unfavourable climatic conditions and slow too little groundwater processes and interactions (high or steep slopes and low rainfall).

Table 5.6: Factor A assigned values/scores for interpreting Figure 5.1

Score	Class of sustainability	Colour code
0–5	Very low	Red
5–15	Low	Orange
15–20	Moderate	Yellow
20–25	High	Green
25–30	Very high	Blue

Source: Author

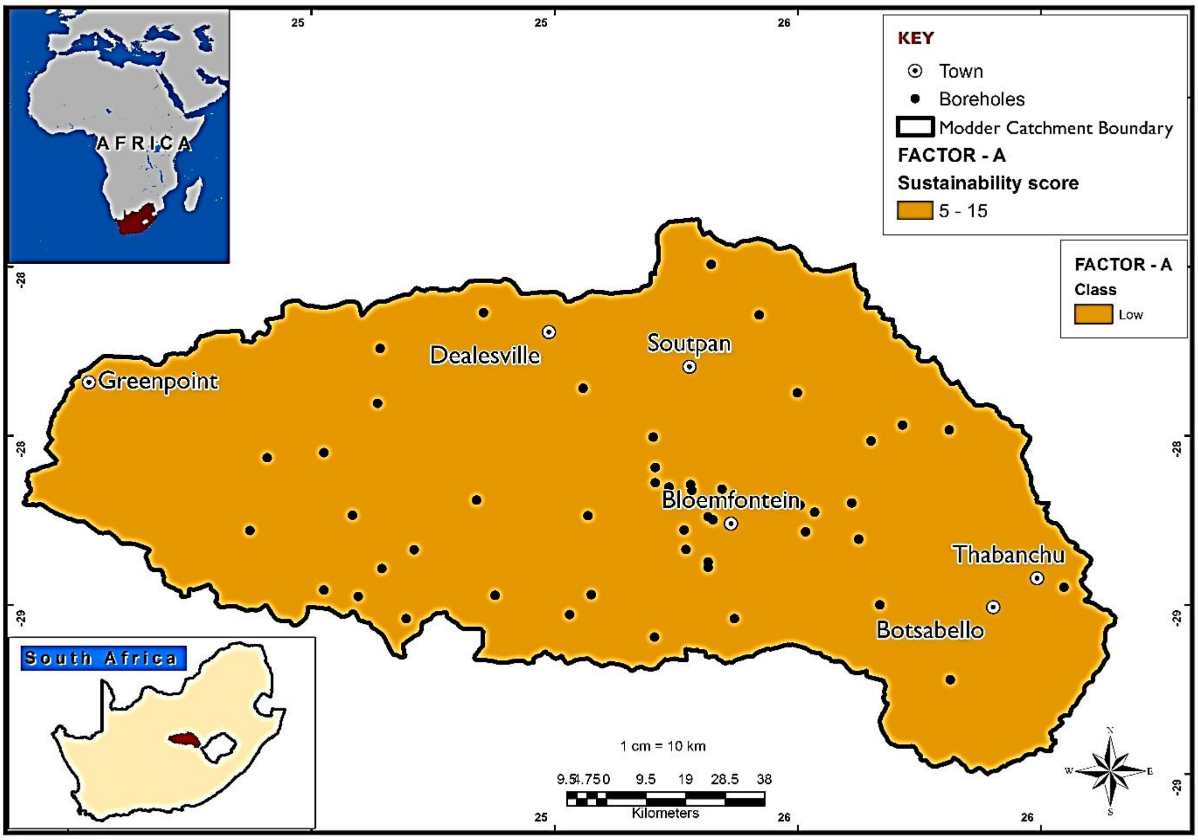


Figure 5.1: The A-factor: Climatic conditions map
Source: Author

The number of permits issued in the catchment per year represents the abstraction activity in the catchment. The maximum score of five was assigned to the number of permits equal to one, and the lowest score of one to areas receiving more than five permits. The same was considered in the assignment of scores for the duration of permits, number of boreholes and pumping rates. Based on global reports and data bases, values and scores were assigned, as shown in Table 5.6, with the lowest scores corresponding to poor practises and the highest score of five to mean good practices. During analysis and application of the model on the Modder River catchment, the figures were obtained from the DWS data bases. As stated in Chapter 4, the boundary conditions for all factors were based on the global highest and lowest values ever recorded. The values/scores were assigned by the researcher based on global high and low amounts ever recorded. This was done so that the indices can be applied to any catchment or any part of the world. For all factors, the values were checked against DWS reports. All the parameters under study were given the same treatment, given the theory, linkages and relationships between them and aspects such as recharge.

Figure 5.2 depicts the scoring of Factor B displayed spatially. The sustainability class of the boreholes marked mostly orange, yellow, and green, suggest areas that were the opposite of the desired scenario: too much abstraction activity, unfavourable climatic conditions and slow to little groundwater processes and interactions (high or steep slopes and low rainfall). Yellow are moderate, while green represents a desirable situation. These places had government intervention for restrictions in abstraction through permits, tariffs, and pumping rates.

Table 5.7: Factor B assigned values/scores for interpreting Figure 5.2

Score	Class of sustainability	Colour code
0–4	Very low	Red
4–8	Low	Orange
8–12	Moderate	Yellow
12–16	High	Green
16–20	Very high	Blue

Source: Author

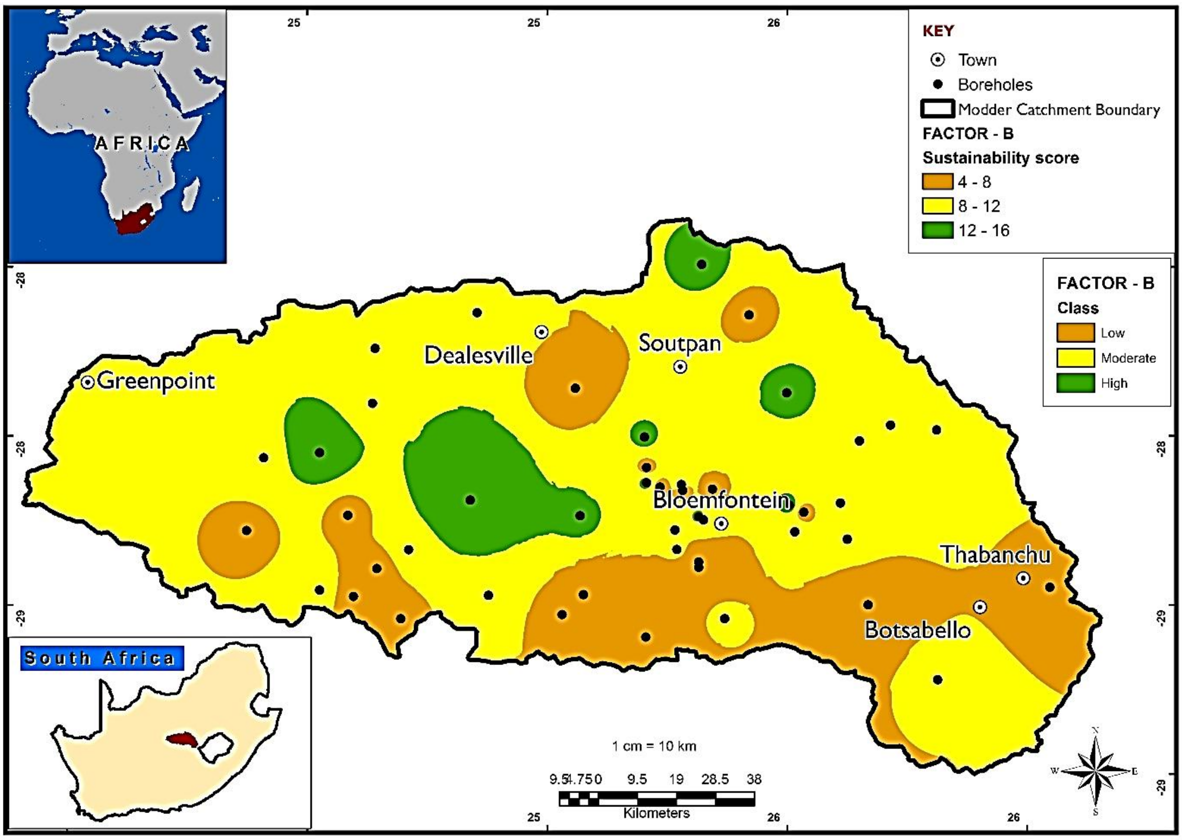


Figure 5.2: The B-factor: Rights and equity map
Source: Author

A use per capita of groundwater in the catchment was assigned the maximum score of five, to usage of less than 25 ℓ/c/d, which is an acceptable practice of low use of water. A per capita use of more than 100 ℓ/c/d was assigned a score of one. This was the lowest score and it indicated over-abstracting or using too much water. The scoring for the population in the catchment, water uses and tariffs, showed the same trend as the per capita use. The catchment values were weighed against the values in Chapter 4.

In terms of the analysis of the Modder River catchment, the values assigned and scored were derived from the DWS database. Based on this data, scores were assigned as shown in Table 5.7 with the lowest scores corresponding to poor practises, while the highest score of greater than five, denotes an acceptable practice. The values/scores were assigned by the researcher after comparing the catchment value to the global high and low amounts ever recorded, as shown in Chapter 4. This was done so that the index would be applicable to any catchment or any part of the world. For all factors, the values were checked against DWS reports.

Figure 5.3 shows the scoring of Factor C displayed spatially. The sustainability class of the boreholes marked mostly in orange, suggest areas with too much abstraction activity, unfavourable climatic conditions and slow to little groundwater processes and interactions (high or steep slopes and low rainfall). The green spots represent areas with a low number of permits issued, short duration of the permits, few boreholes constructed in the area, and significantly low pumping rates.

Table 5.8: Factor C assigned values/scores

Score	Class of sustainability	Colour code
0–4	Very low	Red
4–8	Low	Orange
8–12	Moderate	Yellow
12–16	High	Green
16–20	Very high	Blue

Source: Author

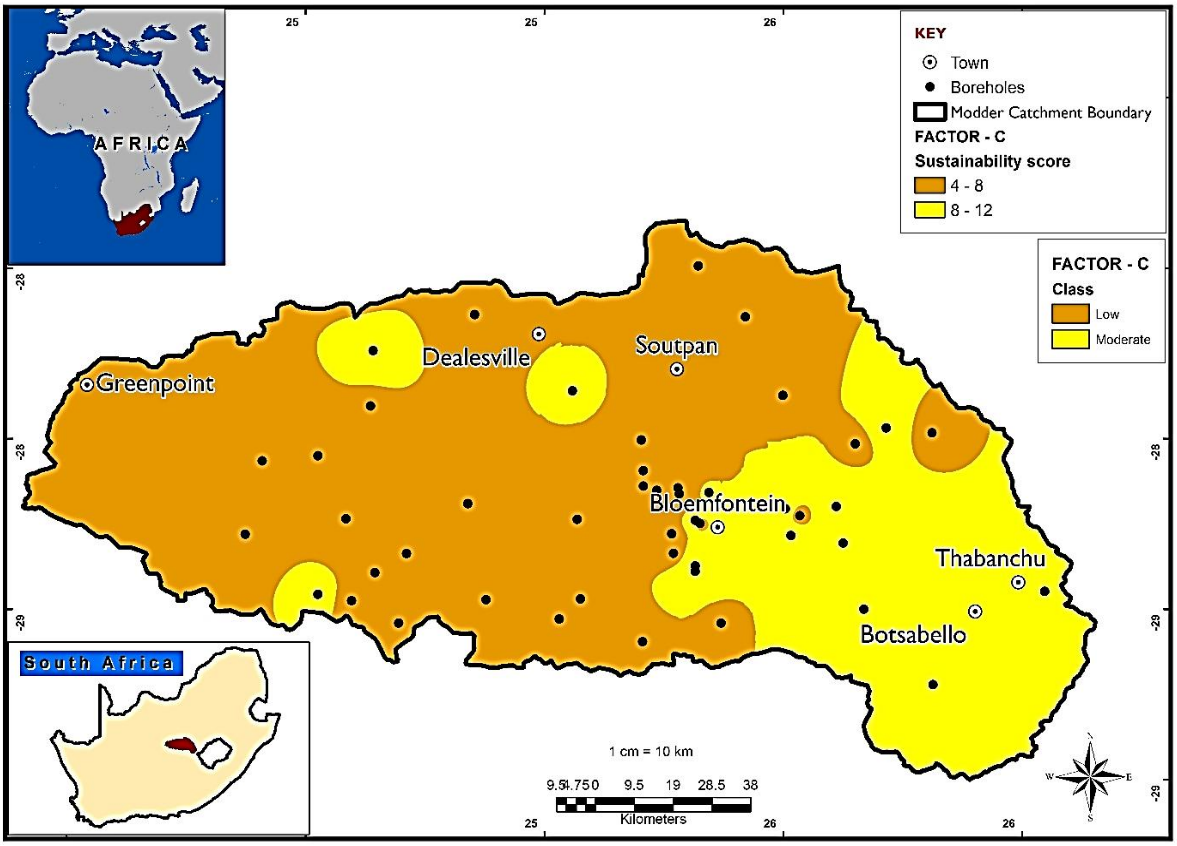


Figure 5.3: The C-factor: Socio-economics map of the catchment

Source: Author

As mentioned in Chapter 4, groundwater naturally recharges upstream and discharges downstream. The majority of the recharge areas are found near mountain peaks, where rainfall is higher compared to adjacent lowlands. Infiltrated groundwater is discharged at valleys and at the earth's low-lying zones.

Chapter 4 explained that a score of five was assigned to intergranular rock because infiltration of water through it to the water table takes more time (see Table 4.8). The water that percolates densely consolidated rock was assumed to originate from surface run-off and not vertical infiltration, irrespective of topsoil permeability. Dolerite presented the lowest percolation in all geological rocks presented in Table 4.8 and the low infiltration was due to the small pore spaces and lower permeability present in most of them. The dolerite formation was given a low score of 0.5.

Figure 5.4 indicates the scoring of Factor D displayed spatially. The sustainability class of the boreholes was also marked mostly orange and suggests areas with too much abstraction activity, unfavourable climatic conditions and slow to little groundwater processes and interactions (high or steep slopes and low rainfall).

Table 5.9: Factor D assigned values/scores interpreting Figure 5.4

Score	Class of sustainability	Colour code
0–5	Very low	Red
5–15	Low	Orange
15–20	Moderate	Yellow
20–25	High	Green
25–30	Very high	Blue

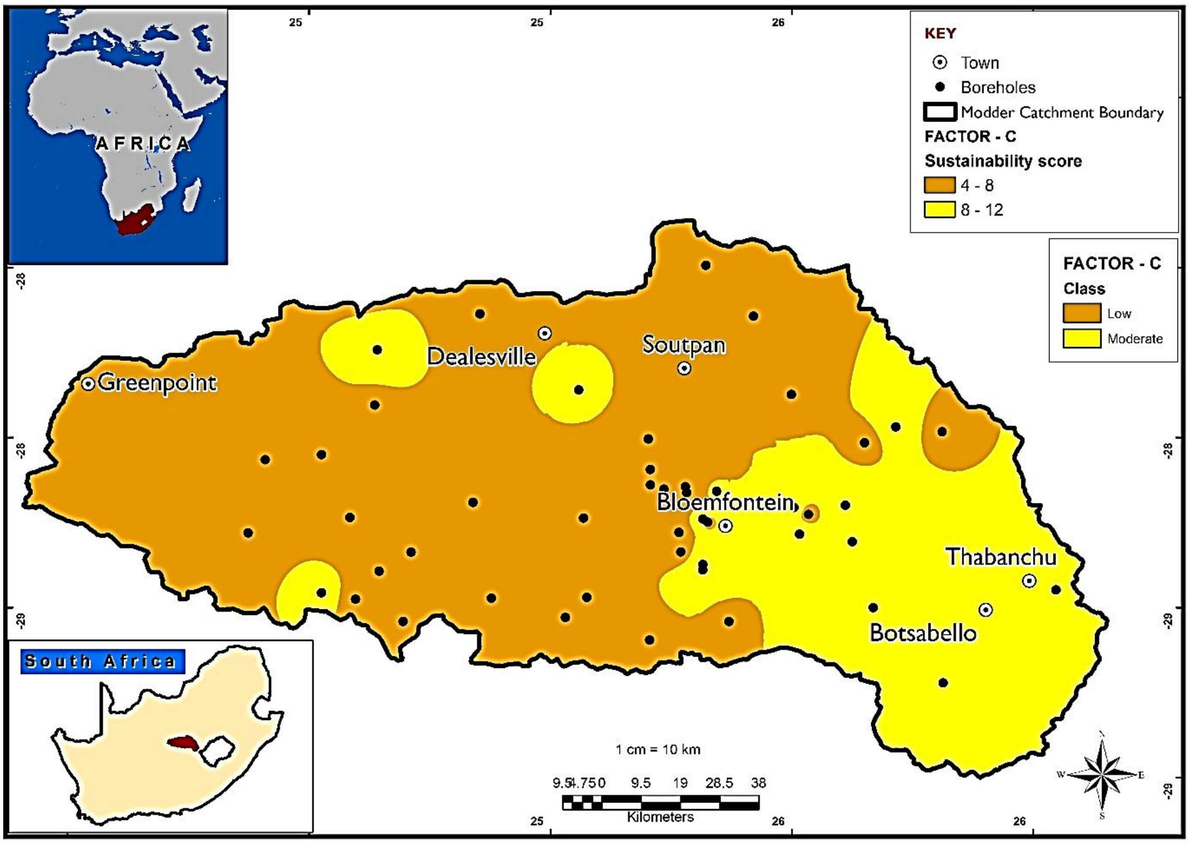


Figure 5.4: The D-factor: Aquifer sustainability map of the catchment

Source: Author

The final sustainability map (Figure 5.5) was derived from the sustainability index calculations, which was computed, based on the principles behind sustainability by combining the factors of climatic conditions, rights and equity as related to the groundwater resources, socio-economics, and the aquifer system sustainability. All factors were given equal weighting prior to the addition as sustainability gives an equal weighting to factors considered with resource conservation issues. The final sustainability score was calculated as follows:

$$Sustainability\ S = \sum A + B + C + D \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation\ 16$$

A = Climatic condition score;

B = Rights and equity score;

C = Socio-economic score;

D = Aquifer system score.

The final sustainability factors were added up because they all impacted the groundwater sustainability. Factor D and A elements (aquifer system and climatic conditions) were complex in the natural context and responsible for percolation and infiltration.

As stated earlier, all factors carried equal weights. For Factor A and D six parameters were considered for each of Factor A and Factor D, thereby carrying equal weights of 30. Aside from the higher parameters considered for these two factors, the sustainability method further assumes rainfall as the principle climatic condition for groundwater availability in the catchment, initiator of the infiltration and, later, percolation, which contributes to recharge and later becomes groundwater. The implication is that, if rainfall or another recharge mode is absent, there is no groundwater formation and sustainability is low. The impact of Factor B and C on groundwater sustainability may be higher or lower depending on whether human activity will deplete whatever groundwater is available and not replenish it. For this reason, equal parameters and weights were assigned and considered for these two factors.

The sustainability index was grouped into five classes. The classes and sustainability values are presented in Figure 5.5. The final groundwater sustainability index class score of 19−35 meant a class of very low sustainability, 35−51 meant a class of low sustainability, 51−67 meant a class of moderate sustainability, 67−83 meant a class of high sustainability and 83−100 meant very high sustainability.

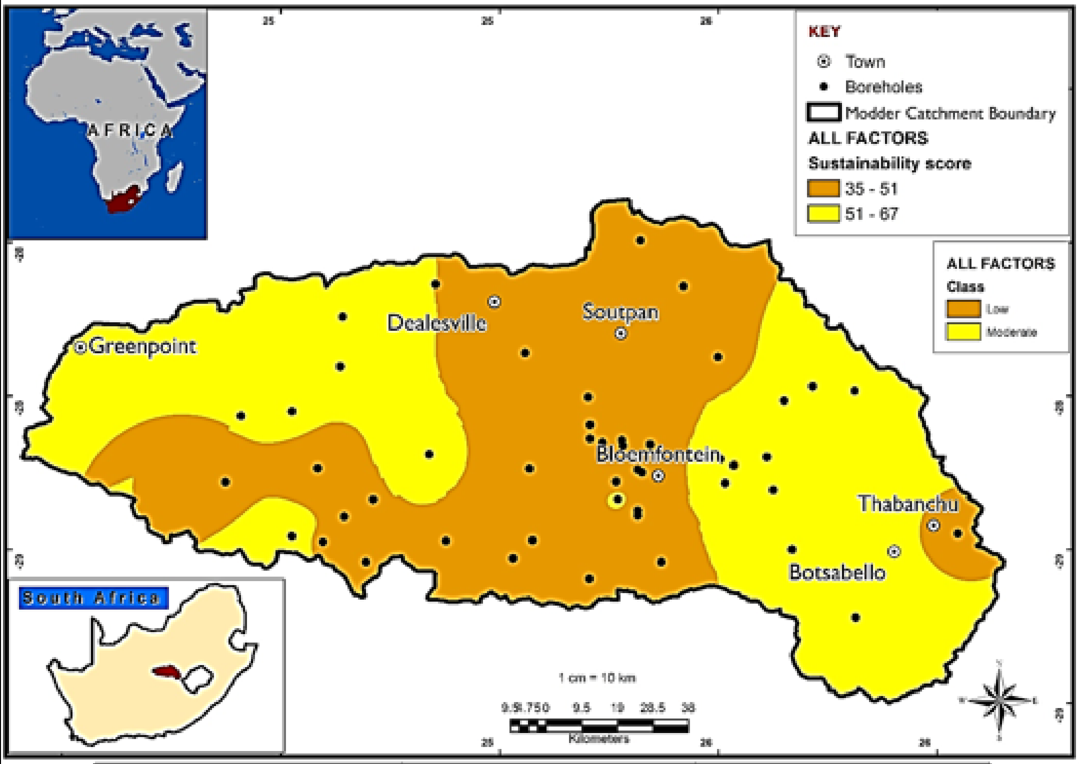
The rankings were based on a scoring system (see Table 5.10) from the highest score of 100, which implies a highly sustainable system to the lowest score of 19, which suggest the least sustainable system. The high and very high sustainability classes correspond to areas with favourable climatic conditions, and favourable groundwater interaction and processes (a fast rate aquifer system, especially recharge). They further have less abstraction and socio-economic activity. The moderate to low classes represent areas that are opposite to the favourable scenario, suggesting too much abstraction activity, unfavourable climatic conditions and slow to little groundwater processes and interactions (high or steep slopes and low rainfall).

Table 5.10: Combined sustainability score for all factors: A, B, C & D

Bore-hole	Latitude	Longitude	Score A	Score B	Score C	Score D	Sustainability index	Sustainability class	Colour
1	-28.867897	26.302778	11	11	12	10,5	44,5	Low	Orange
2	-29.567891	26.072222	11	10	12	10,5	43,5	Low	Orange
3	-29.098889	26.058333	11	11	12	10,5	44,5	Low	Orange
4	-29.014567	26.144565	11	11	12	10,5	44,5	Low	Orange
5	-29.012578	26.075565	11	9	12	10,5	42,5	Low	Orange
6	-29.005556	26.025898	11	9	12	10,5	42,5	Low	Orange
7	-29.292361	26.166667	11	10	12	10,5	43,5	Low	Orange
8	-29.076946	26.120568	11	11	12	10,5	44,5	Low	Orange
9	-28.995833	25.995833	11	11	12	10,5	44,5	Low	Orange
10	-29.168446	26.112233	11	14	11	10,5	46,5	Low	Orange
11	-29.075321	26.113345	11	11	12	13,5	47,5	Low	Orange
12	-29.067528	25.850528	11	11	12	10,5	44,5	Low	Orange
13	-29.182341	26.110765	11	11	11	10,5	43,5	Low	Orange
14	-29.239611	25.857694	11	8	12	10,5	42,5	Low	Orange
15	-29.283324	25.811056	11	9	12	10,5	42,5	Low	Orange
16	-29.332056	25.994028	11	9	12	10,5	42,5	Low	Orange
17	-28.519876	26.116667	11	11	12	10,5	44,5	Low	Orange
18	-28.896223	25.991389	11	11	12	10,5	44,5	Low	Orange
19	-29.007389	25.905608	11	8	12	10,5	41,5	Low	Orange
20	-28.791234	25.849082	11	12	10	10,5	44,5	Low	Orange
21	-29.066667	25.341667	11	8	12	10,5	42,5	Low	Orange
22	-28.962778	25.995833	11	8	12	10,5	42,5	Low	Orange
23	-28.633241	26.220044	11	12	10	10,5	43,5	Low	Orange
24	-29.223557	26.878324	11	12	10	12,5	45,5	Low	Orange
25	-29.141083	26.062083	11	9	13	16,5	49,5	Low	Orange
26	-29.425139	26.632917	11	9	10	16,5	46,5	Low	Orange
27	-29.262148	26.480619	11	10	14	16,5	51,5	Moderate	Yellow
28	-28.973456	28.978757	11	10	11	15,5	47,5	Low	Yellow
29	-28.904639	26.462567	11	9	13	15,5	48,5	Low	Orange

Bore-hole	Latitude	Longitude	Score A	Score B	Score C	Score D	Sustainability index	Sustainability class	Colour
30	-28.880806	26.630833	11	9	7	15,5	42,5	Low	Orange
31	-28.876754	26.535642	11	12	13	16,5	52,5	Moderate	Yellow
32	-29.046543	26.425678	11	12	13	16,5	52,5	Moderate	Yellow
33	-29.044944	26.308056	11	12	13	16,5	52,5	Moderate	Yellow
34	-29.063256	26.345673	11	13	11	16,5	51,5	Moderate	Yellow
35	-29.103864	29.103089	11	8	7	14,5	40,5	Low	Orange
36	-29.102778	26.320278	11	9	11	14,5	46,5	Low	Orange
37	-29.118826	26.434841	11	12	14	14,5	51,5	Moderate	Yellow
38	-28.551254	25.373452	11	11	13	16,5	51,5	Moderate	Yellow
39	-28.625321	25.625765	11	9	13	14,5	47,5	Low	Orange
40	-29.243806	25.354222	11	8	8	14,5	41,5	Low	Orange
41	-28.941111	25.157778	11	9	7	14,5	41,5	Low	Orange
42	-29.233333	25.284567	11	9	11	14,5	45,5	Low	Orange
43	-29.122222	25.120872	11	10	14	16,5	51,5	Moderate	Yellow
44	-28.702785	25.401392	11	9	11	14,5	45,5	Low	Orange
45	-29.182972	25.405139	11	11	13	16,5	51,5	Moderate	Yellow
46	-28.822567	25.395757	11	9	8	14,5	48,5	Low	Orange
47	-29.291972	25.457528	11	8	7	14,5	46,5	Low	Orange
48	-29.141667	25.475567	11	9	7	14,5	47,5	Low	Orange
49	-29.241667	25.654352	11	9	7	14,5	47,5	Low	Orange
50	-29.033861	25.609833	11	13	11	16,5	51,5	Moderate	Yellow
51	-28.936565	25.283421	11	11	7	14,5	49,5	Low	Orange

Source: Author



Sustainability index	Sustainability class	Colour code
19-35	Very low	Red
35-51	Low	Orange
51-67	Moderate	Yellow
67--83	High	Green
84-100	Very high	Blue

Figure 5.5: The final groundwater sustainability map of the Modder River catchment

Source: Author

5.7 Conclusion

The intention of Chapter 5 was to give an account of the application of the sustainability index concept to 51 boreholes in the Modder River catchment of the Upper Orange Basin. This chapter detailed the production of maps for all the factors under study in this thesis. The climatic conditions, rights/equity (as related to the groundwater resources), socio-economics and the aquifer system sustainability maps were produced. The underlying conditions responsible for the sustainability score of each factor were discussed under each factor's map rather than a general description for ease of comprehension.

Sources of data were identified and presented. It was important to present some of the tables used in attaining the sustainability score in this chapter for clarity, logical flow of ideas and verification. The rest of the tables are placed in the appendix. It should also be noted that the tables presented in this chapter were derived from the recalculated raw data. The raw data is presented in Appendix C. Generally, the sustainability index developed in the current study is adaptable, simple and understandable. The generated sustainability map were influenced by rainfall, geology and topography of the overlying layers of C52 Modder River catchment.

In conclusion, the sustainability class in the Modder River Basin ranges from low sustainability to moderate sustainability. The moderate sustainability class is typical of areas with extensive dolerite, low slopes and low recharge. In Chapter 6, a validation exercise using rainfall, recharge and yield is applied to the C52 Modder River catchment in order to compare and verify the correctness of the sustainability map.

Chapter 6

VALIDATION OF THE MODDER RIVER CATCHMENT SUSTAINABILITY INDEX MAPS

6.1 Introduction

Validation of the sustainability index map of the C52 Modder River catchment is set out in this chapter. An explanation of the scores is given according to the classes presented. In addition, the correlation graphs shine some light on the strengths and weaknesses of the sustainability index map.

The most common validation analyses carried out in groundwater studies, as specified by Daly et al. (2002), Saidi et al. (2011), Oke (2015) and Oke et al. (2017, 2018), include analogical studies, water balance, tracer techniques, bacteriology, calibrated numerical simulations and hydrographs of chemical properties. Validation allows for comparison of calculated indices and physically measured parameters (Xanke et al., 2017). Validation is of importance as models need to calculate values that are close to the physically measured values, as part of more exact predictions. Therefore, the sustainability index should calculate values that are close to the physically measured values of the C52 Modder River catchment. The sustainability model should further test the results of the sustainability maps. The validation for this research was therefore carried out by:

- using existing knowledge such as expert views (face validity) and observing similar systems;
- checking model assumptions – system components, structure of the system, input parameters and data; and
- input–output transformations.

The data required to run a groundwater model was discussed in Chapters 2, 3, 4 and 5. This chapter presents a discussion of spatial interpolation, as well as the impact of the average values of a chosen set of parameters of given factors A, B, C and D of the C52 catchment, as modelled in Chapter 5. The analysis to test errors and uncertainty of output for the sustainability index/simple model is presented in this chapter, using traditional relationship curves. The graphs in this chapter further assess sensitivities when a given parameter is varied. In other words, this chapter tests and correlates the results from the model with observed geohydrological parameters. Therefore, the following specific validations are presented in this chapter:

- Comparison of evapotranspiration and rainfall of the catchment in relation to the sustainability maps.
- Comparison of the modelled sustainability map with the field estimated groundwater recharge map using the chloride mass balance method and the river network map.
- The plot of the relationship between licensed volume abstracted against the calculated storativity volume.
- The plot of modelled aquifer sustainability index scores for the catchment against the storativity of the catchment.

6.2 Recharge over 70 years for the C52 catchment

This section discusses the climate implications of the study area. It is described in terms of the precipitation that the Modder River receives, which represents infiltration and percolation of rainfall into the aquifer. This determination is a measure of the mean rainfall dependent on climatic conditions, as measured by the South African Weather Service's rain gauges/stations. From the plot in Figure 6.1, evapotranspiration is on average 1 070 mm higher than rainfall. Figure 6.1 further shows that the annual rainfall is significantly lower than evapotranspiration. The Modder River catchment received its highest rainfall in 1974/1975 with an estimated amount of 945 mm. Based on the rainfall in this period, it means that recharge was significantly lower across all other years. The final sustainability map shows areas with low sustainability scores (see Figure 5.1 and 5.5). Low recharge relates to the low sustainability scores. This is consistent with Figure 6.1. This implies a low sustainability factor score. Therefore, the aquifer sustainability Factor A is driven by the recharge values. There is a positive correlation between the rainfall and evapotranspiration for the C52 catchment.

As explained in Chapters 4 and 5, rainfall is the dominant climatic condition that drives the other hydrological processes in the C52 catchment area. This means that rainfall is central to the sustainability of the catchment's groundwater. Furthermore, evapotranspiration in the catchment ranged from a lowest recorded total of 1 165 mm in 1969 to a highest recorded total of 2 497 mm in 1995 (Figure 6.1). This is much higher than the average rainfall of 450 mm per year for this region (DWS, 2016). This means that there was a negative water balance available for groundwater recharge. The sunshine, measured as temperature in degrees

Celsius, in the range of 15 to 50°C, led to the arid and semi-arid climatic zones present in the area. The data used in modelling were sourced from the South African Weather Service.

Rainfall is an important groundwater sustainability factor as it is key to assessing any rain-fed models (Tetsoane, 2013). Excess run-off leads to a reduced amount of rainfall infiltrating and percolating into the ground as groundwater. Less groundwater recharge is expected when run-off is high.

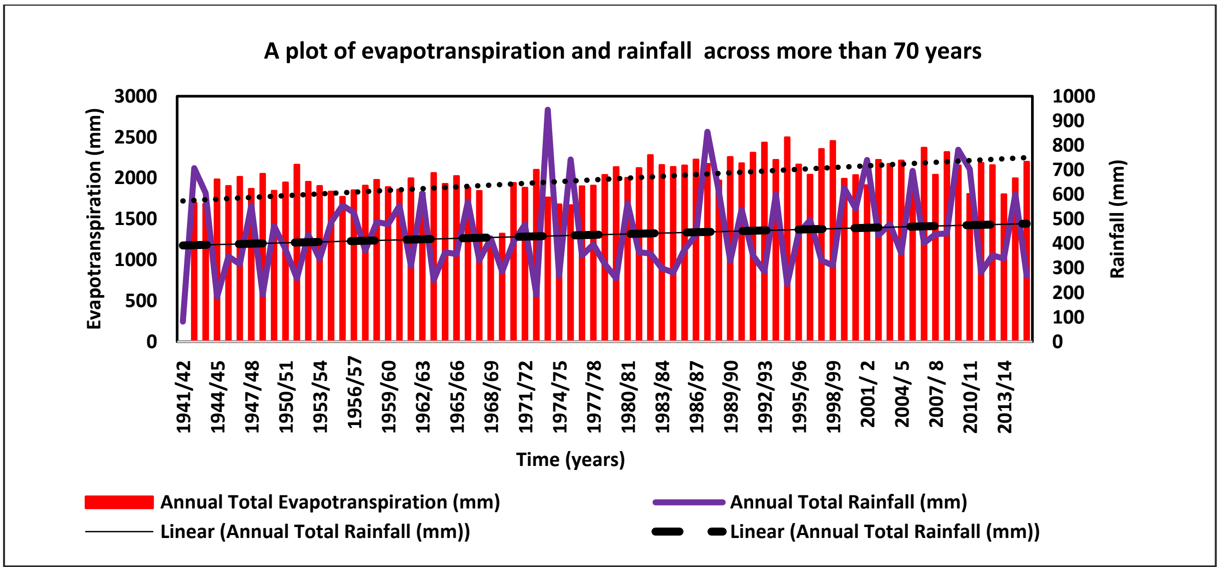


Figure 6.1: Relationship between evapotranspiration and rainfall across more than 70 years

Source: Author

6.3 Comparison of sustainability map with catchment groundwater recharge map

This section discusses the validation of the sustainability results of the study, using the maps that were previously derived in Chapters 3, using the chloride mass balance for actual recharge estimation and comparing it with the sustainability index map generated in Chapter 5. Figure 6.1 shows the final sustainability map for this study (Figure 6.2a), the river network map (Figure 6.2b) and the actual groundwater recharge map (Figure 6.2c) of the study area. The three maps were placed together to assist in the comparison and to identify their commonalities.

It should be noted that generally, there is low groundwater recharge across the C52 catchment. This is due to the highest actual recharge value of 37 mm. The highest groundwater recharge (areas having over 37 mm) were found in the easternmost end of the study area, while the south-eastern areas of Bloemfontein showed considerable recharge. The central areas west of Bloemfontein and the western areas showed a poor groundwater recharge of below 12 mm. The low recharge area suggests a low aquifer sustainability of that part of the catchment as shown in the final sustainability map (Figure 6.2a).

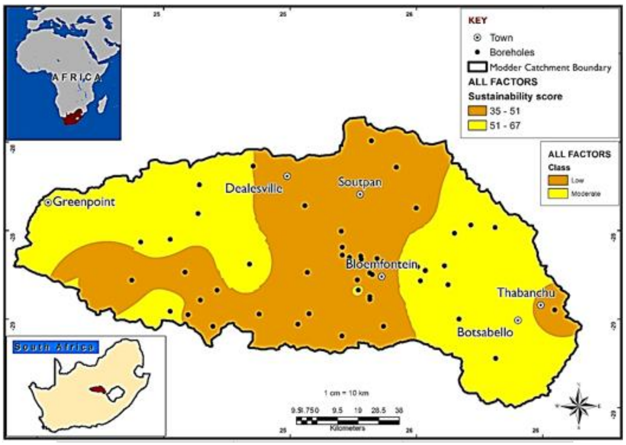


Figure 6.2a: Sustainability map

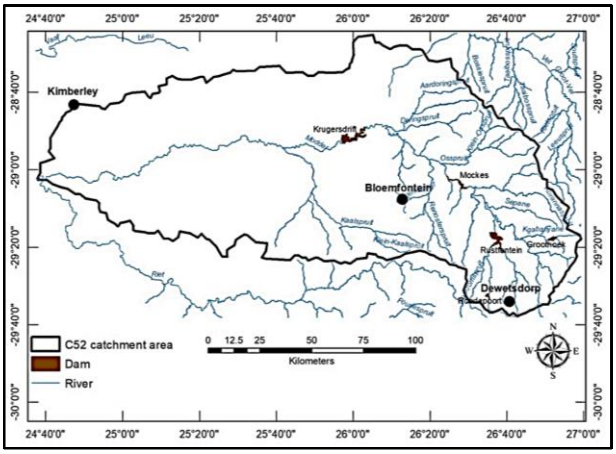


Figure 6.2b: River network map

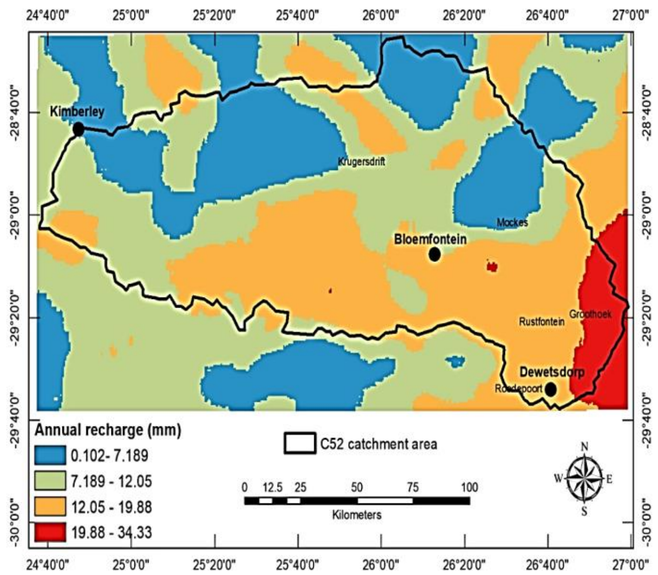


Figure 6.2c: Recharge map

Figure 6.2: Comparison maps validating the sustainability of the Modder River Catchment

Source: Author

Likewise, there are similarities in the final sustainability index map (Figure 6.2a), and the detailed river network map (Figure 6.2b). Most of the areas on Figures 6.2a with moderates sustainable areas records heavy presence of surface water such as dams as the Rustfontein Dam, Groothoek Dam, Maselspoort Dam and Mockes Dam, while river networks and streams such as the Sepane River, Kgabanyane River and Koranspruit drain these areas. More so, areas drained by the Modder River west of the catchment showed a moderate sustainability class. Therefore, it can be inferred that there were some bases for the semblance of base flow interaction. To confirm this assertion would require further studies beyond the scope of the present research. The central areas north and south of Bloemfontein showed a low groundwater sustainable area, and when compared to the surface water showed little or no presence of surface water in this area. It was noticed that due to the massive development of dams along the upper catchment of the Modder River, little surface water flow is experienced around the central areas.

It is important at this point to indicate and clarify the similarities and differences in the recharge values used at different stages of the study as recharge is the most important parameter for achieving groundwater sustainability in the catchment. Table 6.1 is a summary of the recharge values used in the study, which set the tone of the study, as it attempted to streamline the values used to perform the following:

1. A general design of the sustainability index

2. Analyses of the C52 catchment using the designed sustainability index, and applying specific parameters related strictly to the catchment
3. Validation of the sustainability class of the C52 catchment

The groundwater recharge values were calculated using chloride mass balance method, the water balance method, recharge values from rainfall, and calculation of the evapotranspiration all formed part of the validation tools. These values are all in millimetres. Likewise, the differences were that while chloride mass balance is a direct method of calculating groundwater recharge, the water balance method is an indirect method of calculating the catchment recharge value. Therefore, the best validating method adopted in this study was the chloride mass balance method. This was used to validate the original model designed using the water balance method.

Table 6.1: Summary of the recharge values used in the study

Actual groundwater recharge			Hydrological parameters linked to groundwater recharge			
Recharge based on chloride mass balance	Recharge based on DWS	Recharge based on global high and low	Rainfall data (SA Weather Service)	Rainfall based on global high and low	Evapotranspiration (SA Weather Service)	Evapotranspiration based on global high and low
<0.1 mm		<2 mm		<400 mm		<50 mm
0.102–7.189 mm		2–20 mm		400–800 mm		100–50 mm
7.189–12.05 mm	2–20 mm	20–100 mm	450 mm	800–1 200 mm	1 570 mm	150–200 mm
12.05–19.88 mm		100–300 mm		1 200–1 600 mm		200–150 mm
19.88–34.33 mm		>300 mm		>1 600 mm		>200 mm
Catchment average:						
12.05 mm	12 mm		450 mm		1 570 mm	
Comments:						
Most of the C52 catchment falls within the ground-water recharge value of the ranges above (DWS as of 2018)	Groundwater recharge of the C52 catchment is given in the DWS spreadsheet based on water balance method (DWS, 2016)	Groundwater recharge based on global highs and lows (Paliwal, 2017; WMO, 2019)		WMO (2019)		WMO (2019)
See description in Chapter 3 & Chapter 6 for validation	Used in Chapter 5 for application	Used in Chapter 4 in designing the index	Used in Chapter 5 as C52 catchment value	Used in Chapter 4 in the index design	Used in Chapter 5 as C52 catchment value	Used in Chapter 4 in the index design

Source: Author

6.4 Relationship between water abstraction volumes issued and storativity of the C52 catchment

This section looks at the study validation from a socio-economic aspect of the study area. This includes aspects such as tariffs and commercial use of water in the Modder River catchment, which, therefore, represents the abstraction activity of the aquifer that supports economic growth. This is highly significant and should be considered as part of the validation tool of the sustainability results. The plot (Figure 6.3) presented in this section details the socio-economic activities of the catchment related to their overall impact on the groundwater resources used. As explained in Chapter 4, per capita use of the catchment, where boreholes are located, population of the C52 catchment, tariffs paid based on the use, economic activities of the users and purpose of the groundwater/land use for mining, agriculture, domestic use and energy development, influence the relationship between water abstraction volumes issued and storativity of the catchment.

Furthermore, from the plot (Figure 6.3) of the relationship between water abstraction volumes issued and the storativity of the C52 catchment, the following can be inferred:

- The potential use of the water
- The economic growth that relies on the groundwater abstracted
- The activities that impact the groundwater abstraction

Generally, these are the main activities that influenced the groundwater sustainability of the C52 catchment. Regarding the relationship between water abstraction volumes issued and the storativity of the C52 catchment, the plotted data is being monitored and available at the DWS.

The graph of storativity versus licensed volume (Figure 6.3) shows that higher volume as compared to the storage volume of the aquifer was licensed. This is unsustainable and the findings on the final sustainability map in Chapter 5 further correlate with this assertion. There was no correlation between the pumping rate and the storativity of C52 as will be shown later in Figure 7.4. The correlation coefficient value was 0.0052.

It can be argued that there are negative effects of human activities such as farming and irrigation on hydrological processes. Most studies, for example Girmay et al. (2009) and Tetsoane (2013), concluded that high grazing pressure and lower infiltration rates increase soil run-off as it lowers vegetation cover and increases soil compaction. Kashaigili (2008) concluded that the changes of land use and cover result in changes in distribution of surface run-off within the catchment, therefore, affecting water infiltration rates and thereby decreasing the storativity potential.

A further step in the plotted relationship in this section involved a comparison of the measured physical variables, such as abstracted volume and the storativity of the C52 catchment. This was checked against the responses of the farmers in the catchment. The farmer responses were captured in the questionnaire that was designed for the study (A sample of the questionnaire is attached in Appendix A.)

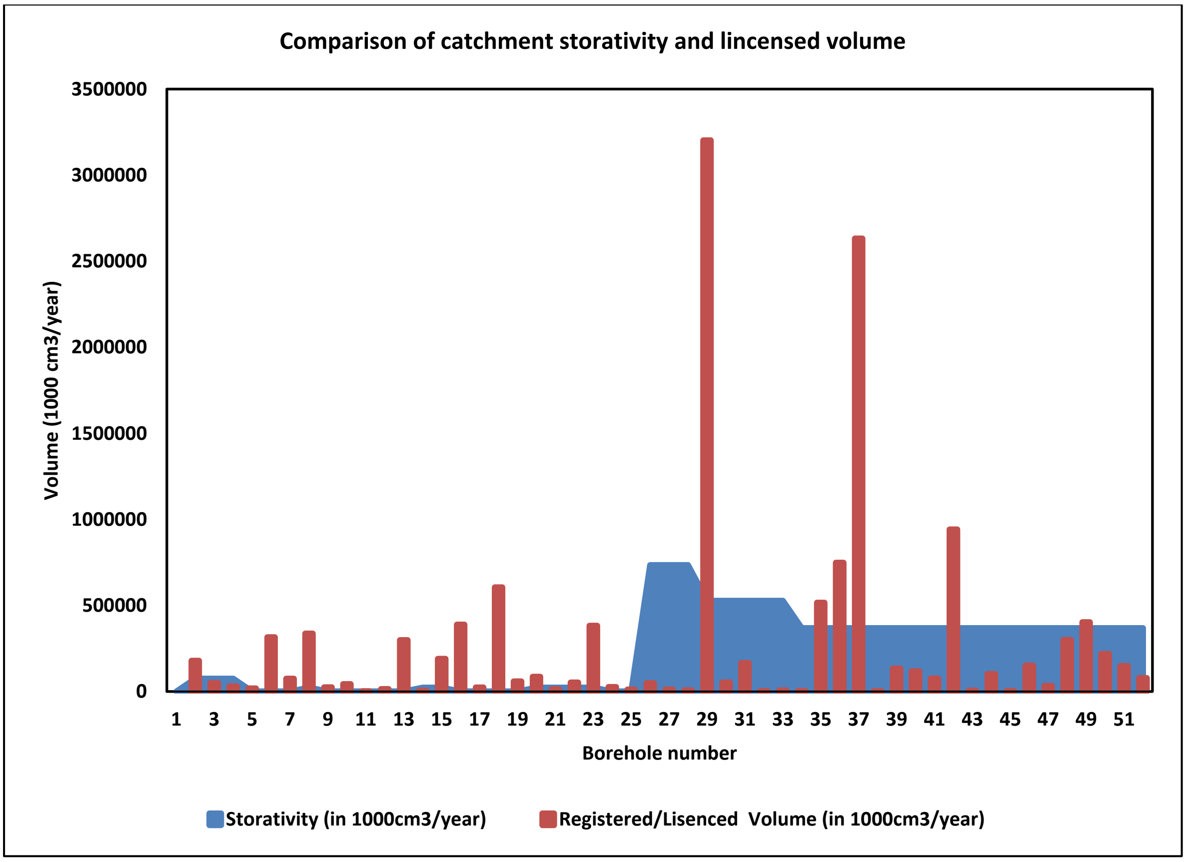


Figure 6.3: Relationship between storativity and licensed volume

Source: Author

6.5 Plot of sustainability index scores versus storativity

The higher the population number in a catchment, the higher the socio-economic activities (agriculture, mining, industrial and domestic), the higher their demands for groundwater and the more permits are issued, which put aquifers in vulnerable and less sustainable conditions. It was explained in Chapters 4 and 6 that it was important to explore the sustainability of the aquifer system in the catchment because of the possibility that some aquifers being self-sustaining irrespective of the socio-economic activities that the aquifer supports.

In cross-reference with Chapter 4, the sustainability index scores of the study area (Table 4.3 and Table 5.10), consisted of aspects such as issuing of permits in the Modder River catchment, which therefore represented the abstraction activity in the aquifer. The sustainability index scores considered the rights and equity of the water users relating to the groundwater resources of the catchment. These were made up of the number of borehole permits issued per year, the duration or length of the borehole permit issued, the number of actual boreholes drilled and the pumping rate per year currently in the Upper Orange River. The sustainability index, therefore, represents the groundwater abstraction rate in the aquifer.

In addition to the DWS regulating the rights of the water users to exploit the groundwater resources, it further issues permits and keeps records of groundwater yields. Table 6.2 reflects the drainage region within the C52 catchment, storativity values of C52 catchment drainage regions, borehole number, the sustainability index score of the boreholes in the C52 catchment and its final sustainability class. This table was put together so that a comparison of storativity and final sustainability index score could be carried out.

Table 6.2: Comparison of sustainability index score and storativity value of the C52 catchment

Drainage region	Storativity (in 1 000 cm^3/year)	Borehole	Sustainability index	Sustainability class
C52G	74 320.5	1	44,5	Low
C52G	74 320.5	2	43,5	Low
C52G	74 320.5	3	44,5	Low
C52H	160.51	4	44,5	Low
C52H	160.51	5	42,5	Low
C52H	160.51	6	42,5	Low
C52J	22 668.67	7	43,5	Low
C52H	160.51	8	44,5	Low
C52H	160.51	9	44,5	Low
C52H	160.51	10	46,5	Low
C52H	160.51	11	47,5	Low
C52H	160.51	12	44,5	Low
C52J	22 668.67	13	43,5	Low
C52J	22 668.67	14	42,5	Low
C52H	160.51	15	42,5	Low
C52H	160.51	16	42,5	Low
C52H	160.51	17	44,5	Low
C52H	160.51	18	44,5	Low
C52J	22 668.67	19	41,5	Low
C52J	22 668.67	20	44,5	Low
C52J	22 668.67	21	42,5	Low
C52J	22 668.67	22	42,5	Low
C52H	160.51	23	43,5	Low
C52B	62.58	24	45,5	Low
C52A	734 547.6	25	49,5	Low
C52A	734 547.6	26	46,5	Low
C52A	734 547.6	27	51,5	Moderate
C52E	527 202.8	28	47,5	Low
C52E	527 202.8	29	48,5	Low
C52E	527 202.8	30	42,5	Low

Drainage region	Storativity (in 1 000 cm^3/year)	Borehole	Sustainability index	Sustainability class
C52E	527 202.8	31	52,5	Moderate
C52E	527 202.8	32	52,5	Moderate
C52F	368 407.7	33	52,5	Moderate
C52F	368 407.7	34	51,5	Moderate
C52F	368 407.7	35	40,5	Low
C52F	368 407.7	36	46,5	Low
C52F	368 407.7	37	51,5	Moderate
C52F	368 407.7	38	51,5	Moderate
C52F	368 407.7	39	47,5	Low
C52F	368 407.7	40	41,5	Low
C52F	368 407.7	41	41,5	Low
C52F	368 407.7	42	45,5	Low
C52F	368 407.7	43	51,5	Moderate
C52F	368 407.7	44	45,5	Low
C52F	368 407.7	45	51,5	Moderate
C52F	368 407.7	46	48,5	Low
C52F	368 407.7	47	46,5	Low
C52F	368 407.7	48	47,5	Low
C52F	368 407.7	49	47,5	Low
C52F	368 407.7	50	51,5	Moderate
C52F	368 407.7	51	49,5	Low

Source: Author

The sustainability index, as explained earlier in Chapter 4, also reflects the tariffs and commercial use of water in the Modder River catchment, which therefore further represents the abstraction activity in the aquifer that supports economic growth. The sustainability index is the socio-economic activities of the catchment, as related to their impact on the groundwater resources. The indicators considered in the sustainability index consisted of the per capita use of the catchment, where boreholes are located, the population of the C52 catchment, tariffs paid based on the use, the economic activities of the users and the purpose of the groundwater use such as mining, agriculture, domestic and energy development. The sustainability index represents the potential use of the water, the economic growth that relies on the groundwater abstracted and the activities that impact the groundwater abstraction. Generally, these indicators represent the main activities that influence the groundwater sustainability of the C52 catchment. This makes a plot of sustainability index scores versus pumping rate of great significance.

A further step in this plot involves a comparison of the calculated indices (provided in Table 6.2) with the measured physical values, with an analysis of the actual end users' validation carried out to assess the ability of the sustainability index to determine values that are a close reflection of the physical system. Figure 6.4 shows a plot of the final sustainability map value against a measurable parameter (storativity/aquifer yield). Boreholes 1 to 24 had low sustainability index scores. Boreholes 25 to 54 had higher sustainability indices. This presented a point at which to ask further questions or compare it with a timeline of events to see what could have influenced the situation (further recommendations from the study). There was a high correlation between the storativity and the sustainability index as shown in Figure 6.4.

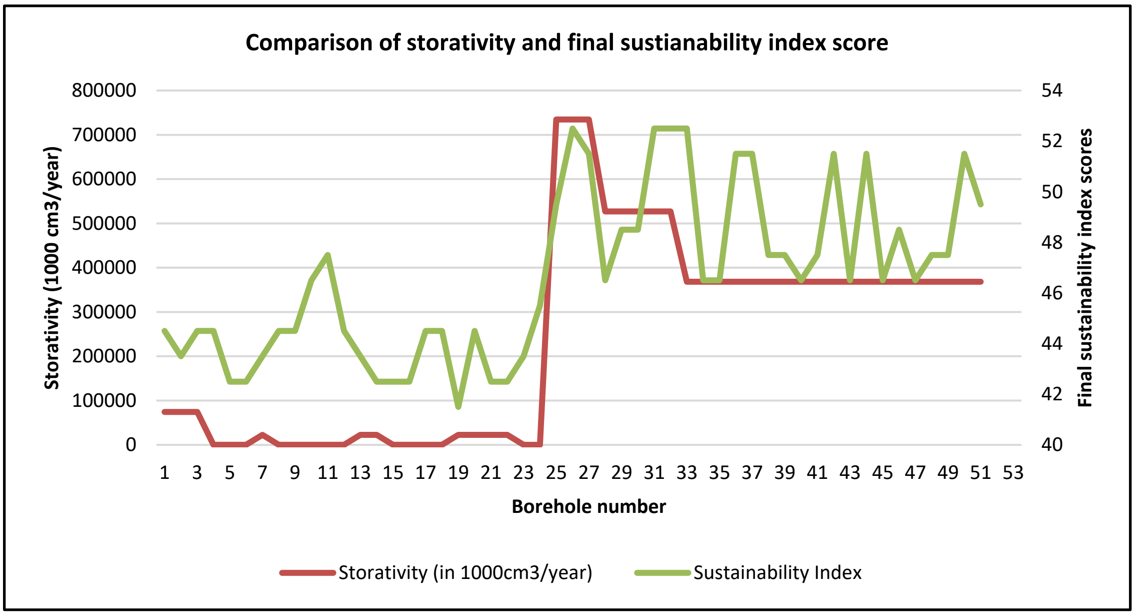


Figure 6.4: Comparison of storativity and final sustainability index score
Source: Author

6.6 Strengths and weaknesses of the sustainability index map

The strength is that it is applicable to all catchments and particularly those with limited data. Another strength of the index is that it allows spatial analysis and visual representation of results for easy decision-making by non-scientists. The sustainability index method uses both subjective techniques and physically-based techniques. This is a strength. Indices are easy to use and validation using any other method is possible. This is a strength. The weakness of the sustainability index is that it requires GIS mapping skills and technology. It requires knowledge of hydrological modelling so it is not suitable for unskilled people. This is a weakness.

6.7 Conclusion

The purpose of this chapter was to validate the sustainability index map. An explanation of the scores was given according to the classes presented. An attempt was made to use comparison and correlation graphs, where possible, to shed some light on the strengths and weaknesses of the sustainability index map. Validation was carried out to triangulate the C52 catchment findings using other methods and other maps that are not the final sustainability index map.

Validation as done in this research to determine whether the model was a meaningful and accurate representation (in important aspects) of the real system (the Modder River catchment). The findings agreed with the representation and results on the sustainability map.

Validation is an important aspect of the modelling process. The validity (or significance) of a model should be judged by its suitability for a particular purpose. This chapter concluded that a model is sound and dependable if it accomplishes what is expected of it. This means that validity, as an abstract concept divorced from purpose, is meaningless. What may be an excellent model for one purpose or study area's conditions may be misleading and useless for another.

It can be concluded that sustainability depends more on the storativity, which is determined by recharge of the aquifer, than pumping rate and register volumes in the C52 catchment. In summary, it would be interesting to use recommendations from this study in future studies to support claims that low sustainability of the aquifer is due to climate change and human activities in the catchment.

Chapter 7

SIGNIFICANCE OF THE STUDY BASED ON THE RESULTS

7.1 Introduction

This chapter describes the contribution of this thesis to new knowledge. The major contribution of this thesis was the development of a groundwater sustainability index that supports an ICT improved groundwater monitoring system such as AI. The sustainability index makes use of both subjective and physically-based techniques. The variables for evaluation are easy to collate and calculate, especially when data is readily available. The proposed sustainability tool may be used to evaluate the sustainability of groundwater in other catchments. The set conditions under which the tool can be used are as follows:

- For catchments that have limited but readily available data
- Where monitoring systems are planned to function
- Where the required modelling capacity is available
- Where there is consensus and buy-in among the users in the water system
- Where the required technology is available

7.2 Water resources management

A review of the C52 catchment aquifer yields point to the first significant aspect of this study. Aquifer yield demonstrates the prolific characteristics of an aquifer. An aquifer is a geological formation that contains adequate immersed porous material to yield large amounts of water to a well. It means an aquifer is an underground layer of water-bearing porous rock or unconsolidated materials (rock, sand, residue, or clay) from which groundwater may be extracted by using a well. In cross-reference to section 3.5, aquifers may be permeable as in sandy rivers, fractured as in crystalline bedrock or fractured and intergranular as in sedimentary rocks such as limestone and sandstone, which are either permeable or fractured systems.

Aquifer sustainability cannot be underscored. The study has shown that aquifer sustainability depends on pumping rate, aquifer yield, hydraulic conductivity and permeability of the aquifer under review. Even though permeability and hydraulic conductivity were not directly considered in the designed index, they primarily account for recharge of the groundwater. It is obvious that fractured basement rock has little sustainability, as depicted by the low score in the study, due to due to percolation of water to deeper layers because the basement rock is fractured and not capable of holding water for a long period of time. The correlation between pumping rate and aquifer yield can further be explored to sustain the aquifer system's sustainability concept. The correlation, in the study was negative. This explains the low C52 catchment aquifer sustainability. The implication of the correlation obtained on aquifer sustainability was that groundwater in the C52 needs to be regulated.

7.2.1 Importance of Aquifer type to Aquifer sustainability

Key indicators or parameters of importance, which affect aquifer system sustainability, are type of rock hosting the groundwater and the type of aquifer system in place such as confined, unconfined, semi-confined or fractured. The sustainability of fractured basement rock depends on joints, faults, lineaments and cavities. In this section, the significance of groundwater sustainability mapping in the context of a farmer's reporting tool and AI were discussed. A basic validation was carried out to test and correlate the maps and results of the model with observed geohydrological parameters borehole yield and pumping rate data, while keeping recharge in mind.

7.2.2 Effects of pumping rate on Aquifer sustainability

Important keys to the sustainability of the C52 catchment aquifer system was the established relationship between aquifer yields in litre per second, recharge in millimetre per year, aquifer storage measured as gross storage volume in cubic metres per year and water quality. As the pumping rate of boreholes is identical to artificial discharge (Mazzoni et al., 2018). So when groundwater is abstracted for economic purposes, the water table deceases over time and if prolonged for much longer some fractures network might collapse leading to a reduction in aquifer yield. This will affect the sustainability of the catchment aquifer system.

7.2.3 Determination of pumping rate

The second significance of this study was the determination of safe/ideal pumping rate for C52 catchment, as shown in Figure 7.1. The figure further shows that the average aquifer yield for the catchment was 0.7 ℓ/s, which translated to around 248 2599 m^3 per year. The highest yield recorded was 1.4 ℓ/s, while many boreholes recorded a yield below 0.1 ℓ/s. The recommended safe pumping rates for the catchment should be between the minimum (153 820 m^3 per year) and the average (248 259 m^3 per year) values as most borehole have very low yields. This would ensure that pumping will not disturb the dynamic equilibrium of the aquifer to achieve sustainability.

The pumping rates have been recalculated and recommended in Table 7.1. The formula correlating pumping rate to aquifer yield was automatically derived by using Microsoft Excel©. The gradient and curve constant can also be read from the graph generated by Microsoft Excel©. The formula (Pumping rate = 157 397x + 138 080) was used to determine the ideal pumping rate for each borehole in the C52 catchment, which are presented in Table 7.1. For example:

Pumping rate for borehole 1 = (157 397 (0.141401256) + 138 080

= 160336.1335

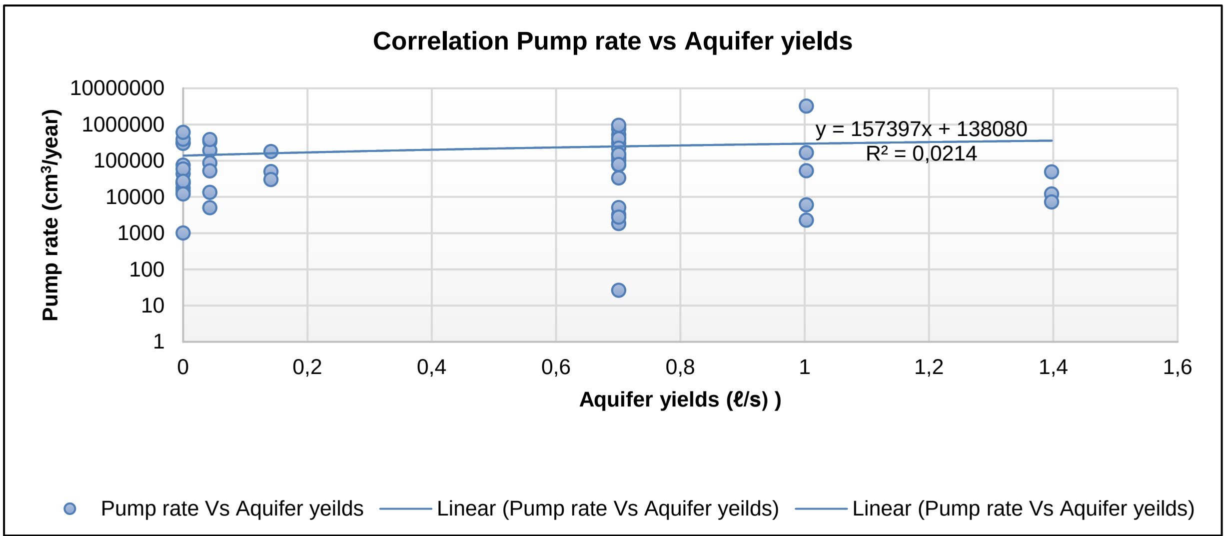


Figure 7.1: Correlation between pumping rate and aquifer yield
Source: Author

A further significant test done was when the pumping rate, as plotted on the x and y axes, is switched. Another significant test done involves swiping the axes for Figures 7.1 such that the x-axis becomes the pumping rate and y-axis becomes aquifer yield. This test was performed to determine the boreholes pumping above the yields allocated and to observe the sustainability behaviour of the abstraction. For this reason, both Figures 7.1 and 7.2, though representing the same data set, were presented differently. It was obvious from Figure 7.2 that even though the yield for the borehole was the same, the rate of groundwater pumping increased exponentially. That meant that most boreholes in the catchment were pumping at higher rates as compared to the individual borehole yields. It can further be explained that the boreholes were abstracting water at rates that were higher than the rate at which the aquifer can be recharged. This was an unsustainable practice.

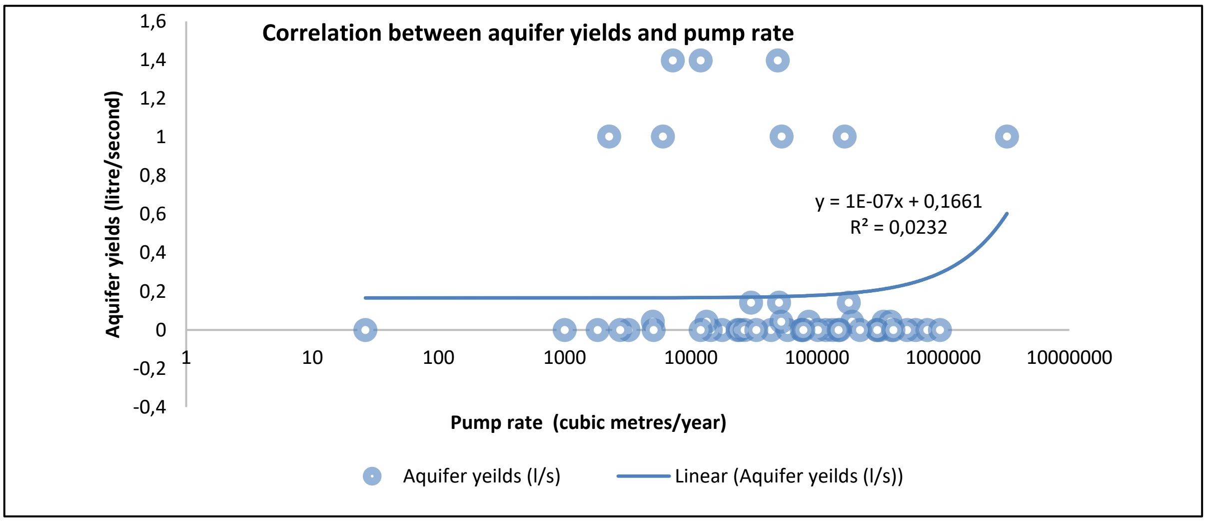


Figure 7.2: Correlation between aquifer yield and pumping rate
Source: Author

Table 7.1, therefore, presents the recommended pumping rates for each borehole. These pumping rates are suggested as moderate to low classes representing areas that were the opposite of the favourable scenario, i.e. too much abstraction activity, unfavourable climatic conditions and slow to little groundwater process and interactions, namely high or steep slopes and low rainfall.

Table 7.1: Recommended pumping rates

Borehole	Aquifer yields (ℓ/s)	Previous pumping rate (cubic metres per year)	Recommended pumping rate (cubic metres per year)
1	0.141401256	178 470	160 336
2	0.141401256	50 000	160 336
3	0.141401256	30 000	160 336
4	0.000305384	17 693	138 128
5	0.000305384	315 000	138 128
6	0.000305384	75 000	138 128
7	0.043129129	336 520	144 868
8	0.000305384	24 420	138 128
9	0.000305384	43 200	138 128-
10	0.000305384	1 000	138 128

Borehole	Aquifer yields (ℓ/s)	Previous pumping rate (cubic metres per year)	Recommended pumping rate (cubic metres per year)
11	0.000305384	14 362	138 128
12	0.000305384	298 480	138 128
13	0.043129129	5 000	144 868
14	0.043129129	189 900	144 868
15	0.000305384	388 818	138 128
16	0.000305384	23 470	138 128
17	0.000305384	605 000	138 128
18	0.000305384	58 536	138 128
19	0.043129129	86 088	144 868
20	0.043129129	13 320	144 868
21	0.043129129	52 000	144 868
22	0.043129129	382 500	144 868
23	0.000305384	26 654	138 128
24	0.000119064	11 937	138 099
25	1.397541096	48 886	358 049
26	1.397541096	11 948	358 049
27	1.397541096	7 200	358 049
28	1.003049467	3 202 700	295 957
29	1.003049467	52 400	295 957
30	1.003049467	165 600	295 957
31	1.003049467	2 250	295 957
32	1.003049467	6 000	295 957
33	0.700927892	3 206	248 404
34	0.700927893	515 974	248 404
35	0.700927894	748 128	248 404
36	0.700927895	2 632 027	248 404
37	0.700927896	1 825	248 404
38	0.700927897	132 990	248 404
39	0.700927898	117627	248 404
40	0.700927899	75 675	248 404
41	0.700927900	941 296	248 404
42	0.700927901	5 060	248 404
43	0.700927902	101 686	248 404
44	0.700927903	2 750	248 404
45	0.700927904	151 125	248 404
46	0.700927905	33 065	248 404
47	0.700927906	300 000	248 404
48	0.700927907	402 492	248 404
49	0.700927908	219 000	248 404
50	0.700927909	148 200	248 404
51	0.700927910	78 000	248 404

Source: Author

The graph of storativity versus licensed volume (Figures 7.3 and 7.4) shows that higher volumes were licensed in the Modder River catchment compared to the storage volume of the aquifer. The findings on the final sustainability map provided in Chapter 5 further correlate with this.

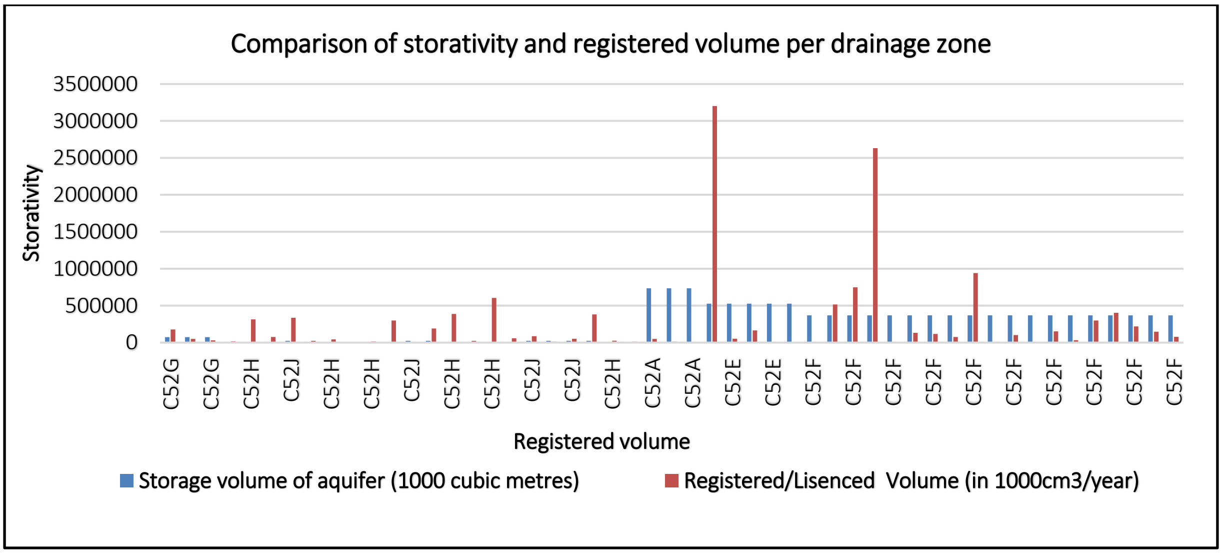


Figure 7.3: Relationship between storativity and licensed volume of the C52 sub-catchment
Source: Author

Drainage zones C52A, C52E, C52F, C52B and C52C had a good storativity potential. This was also shown in the river network map (Figure 3.8). Also, the chloride groundwater recharge map (Figure 3.15) showed appreciable groundwater presence. Therefore, these areas still support further groundwater development. Other areas in the catchment such as C52I, C52J, C52H and C52G, showed low storativity and higher licences issued, as well as low sustainability. Therefore, they did not support further groundwater development.

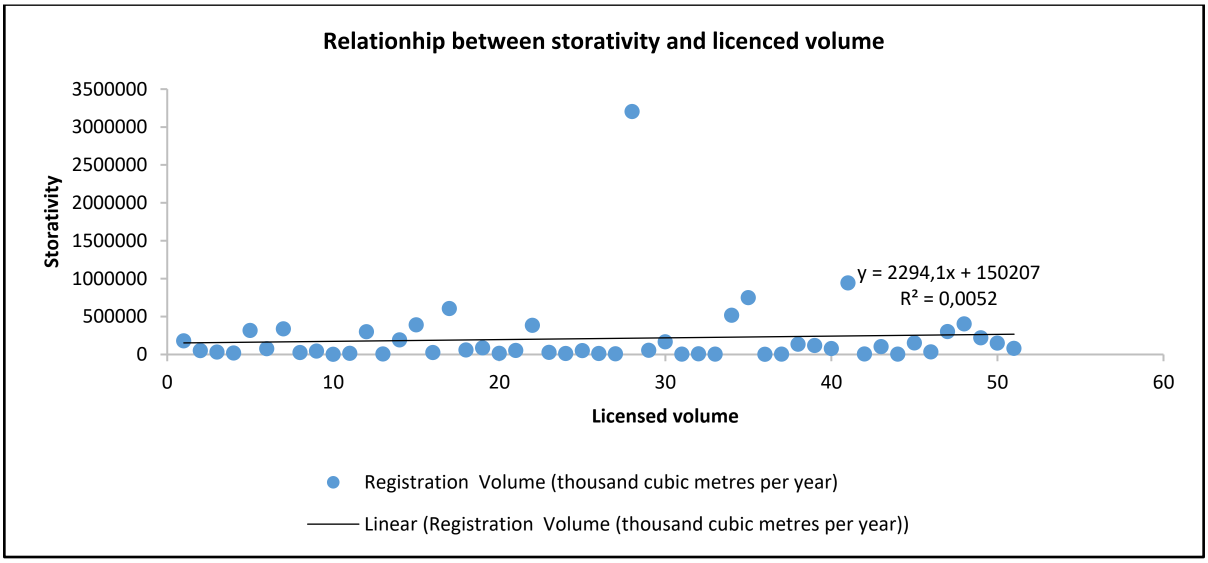


Figure 7.4: Regression curve of relationship between storativity and licensed volume

Source: Author

The value/scores of the final sustainability map index was plotted against a measurable parameters, namely pumping rate and aquifer yield. Figure 7.5 depicts a low correlation coefficient value of 1.04%, which indicated no positive correlation or reinforcement. These pumping rates were suggested as moderate to low classes, representing areas that are opposite of the favourable scenario: too much abstraction activity, unfavourable climatic conditions and slow to little groundwater processes and interactions such as high or steep slopes and low rainfall.

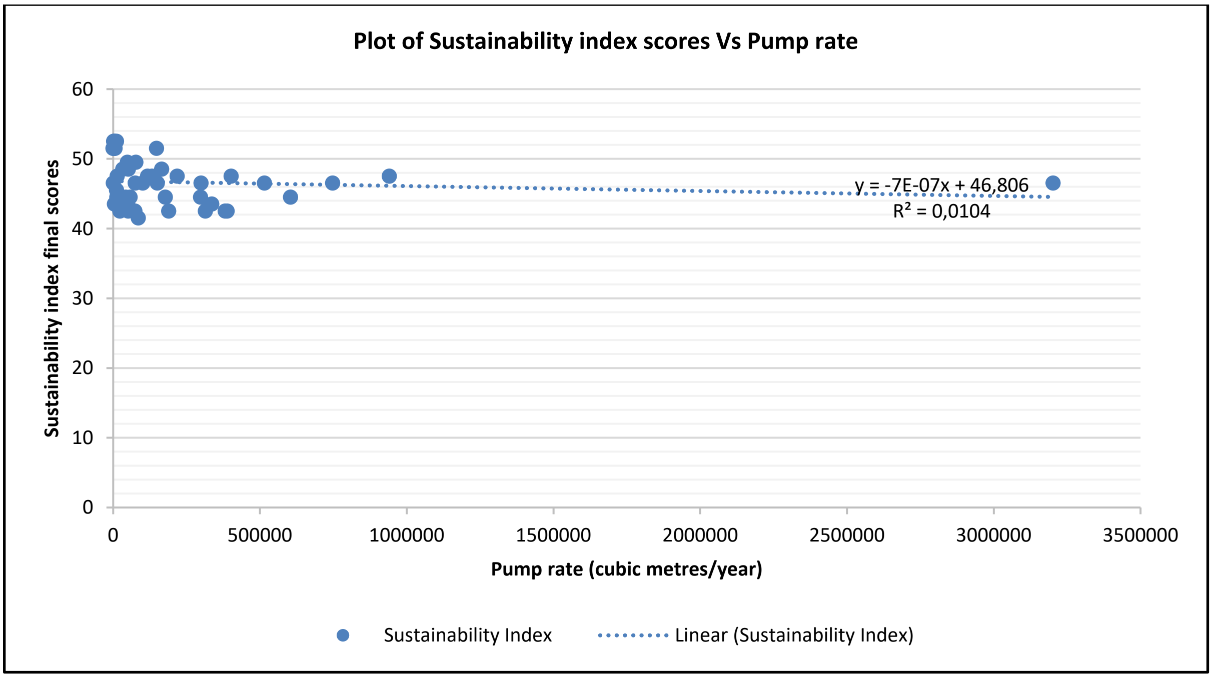


Figure 7.5: Calculation of the correlation coefficient values
Source: Author

7.3 Proposed groundwater users' reporting tool as a sustainability tool

The third significant aspect of the study was the proposed groundwater user' reporting tool (see Questions 1 to 9 in Appendix D) which was derived from the study for achieving aquifer sustainability. Borehole information such as water levels is critical to regulators in groundwater maintenance. From the study, it was obvious that the regulators played a vital role in groundwater sustainability since they issued licences and permits. The DWS emphasised the application for water licenses and grants permit for borehole drilling based on the required/requested volume of water. However, the study has shown that too much groundwater was abstracted compared to the storativity of the system. This problem arose from the fact that the DWS licenced boreholes to get the required/requested volume instead of allocating volume based on storativity of the system. This practise, therefore, leads a misalignment between was is licenced and what the groundwater system can offer which is mismanagement of the groundwater system.The question that arise is how do regulators ascertain that groundwater use does not exceed the approved water license? (MacDonald et al., 2012). On this basis, the groundwater users' reporting tool was developed in conjunction with the aim of studying the sustainability of the system.

Research on the development of an application was necessary and was done using scores and ranking of the factors by means of a Microsoft Excel© monitoring spreadsheet. This was carried out with the aim of creating an analysis application for sustainability reporting. Based on this, an application for monitoring and evaluation of groundwater level, storativity and quality should be considered so that the sustainable yield could be routinely adjusted. This further justified the reason why a reporting or monitoring tool proposed for farmers was required.

The points below summarise and justify the proposed reporting tool as extracted from the study:

- Number of permits issued in the catchment per year is important because it represents the abstraction activities in the catchment, which directly affect the sustainability of the system
- The same importance is considered with regard to level of activity indicator as revealed by duration of permits, number of boreholes approved and pumping rate
- The reporting tool considers the rights/equity permitted by law as related to the groundwater resources of the catchment
- The tool reflects sustainability classification. It gives a picture of the number of borehole permits issued per year, duration or length of the borehole permits issued, number of actual boreholes drilled and pumping rate per year currently in the Modder River catchment
- For effective monitoring of the groundwater system by the DWS, these indicators are required.

Groundwater monitoring has been difficult in the catchment and Southern African region in general for the water administrative authorities. Water clients do not submit the required compulsory critical data for effective monitoring of water use. This, combined with the absence of limits to boreholes dug by permit holders, has led to challenges in decision-making and groundwater conservation.

7.4 Application of the artificial intelligence system to monitor the groundwater sustainability use of the Modder River catchment

The fourth significant aspect of the study is filling of the gap in monitoring groundwater sustainability of the C52 catchment system using an innovative element of technology such as the AI system. The use of an innovative technology, its primary output, and potential commercial value contributes to new knowledge and ways in the future development of the catchment groundwater resources and its sustainability. Technology can also support the application of the designed sustainability framework, through an ICT support mechanism, in order to improve the groundwater monitoring system. Since the sustainability framework uses physical and subjective techniques, the variables in the sustainability index could easily be adaptable to an ICT system. The solution proposed in this research takes the form of a generic early warning system consisting of four components, namely gathering of the risk knowledge; monitoring and predicting the situation; communicating the warning messages; and responding to the warning (International Strategy for Disaster Reduction [ISDR], 2006). The ISDR model was adapted to incorporate the various ICT systems (AI, wireless sensor networks, mobile phones) in the three-elements' early warning system, as was the case with ITIKI (Information Technology and Indigenous Knowledge with Intelligence) framework by Masinde et al. (2018). The design features are supported by android technology and Java programming. Figures 7.6 and 7.7 represent the application's architecture.

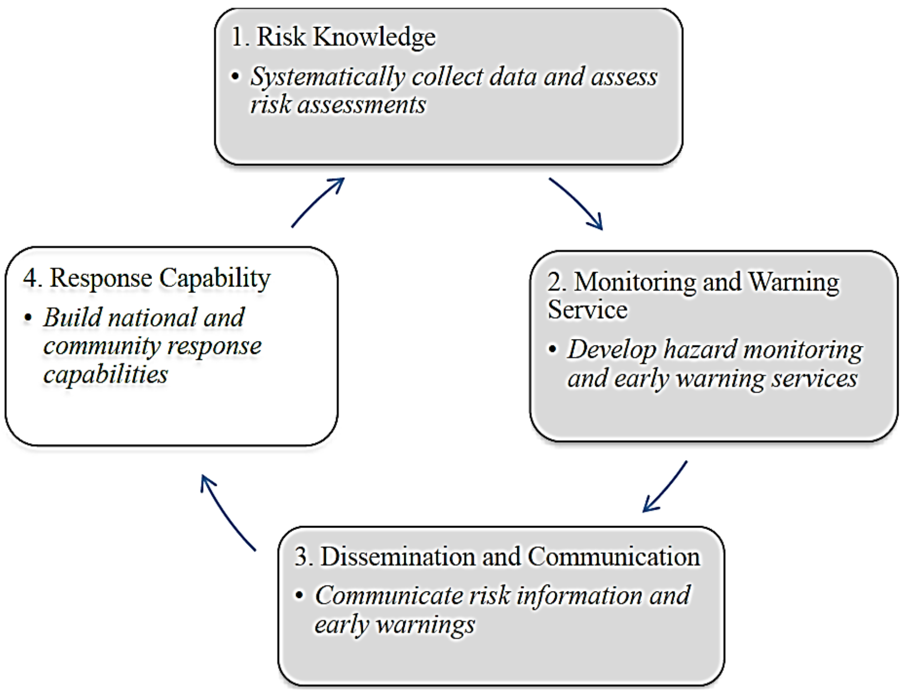


Figure 7.6: Elements of an early warning system

Source: Adapted from ISDR (2006)

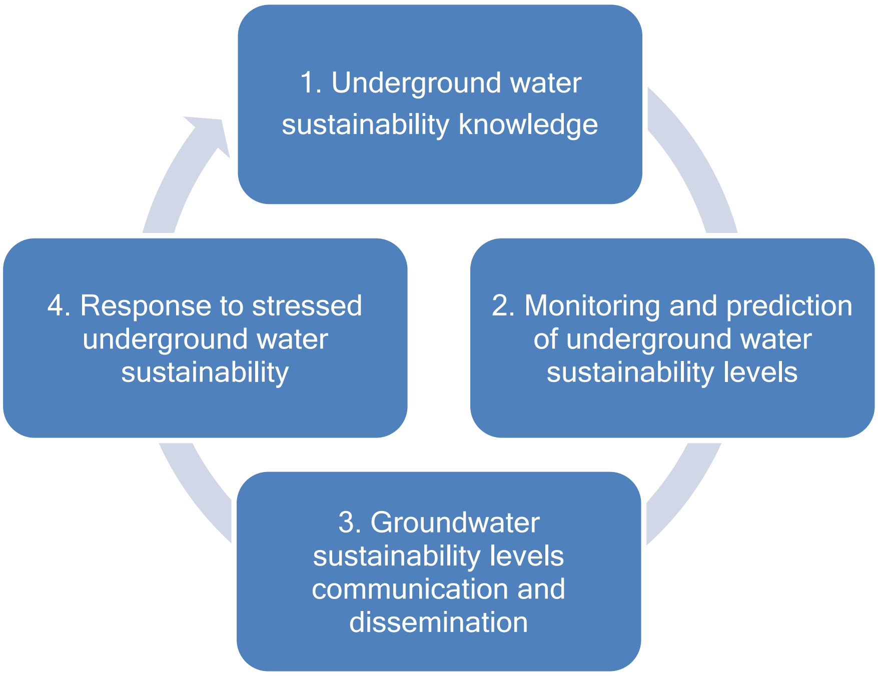


Figure 7.7: Groundwater sustainability early warning system
Source: Author

This section provides a brief description of how the framework in Figure 7.7 can be translated into a working AI system for the C52 Modder River catchment. The advanced components of innovation, its essential yield and potential business esteem, are that they should add to new information and improvement of a groundwater sustainability structure that backs an ICT enhanced groundwater monitoring framework. The sustainability structure uses physical and cognitive strategies.

The reason for AI in groundwater administration is to increase the protection and sustainability of groundwater through a framework that constantly submits updates and early warning signs to the water administrators. It also strengthens positive actions regarding water abstraction and viable water use. Groundwater users will have the capacity to check excessive use of water and any regional government will have the capacity to assess if a catchment is over-exploited. The net pick-up or effect will be water investment funds, cost reserve funds and better execution of groundwater administration in regions and offices. The application will collect real-time information posed as questions reviewing the knowledge, attitude and practices of the water consumers with regard to water consumption.

In summary, the advantages, as shown in Figure 7.6 and 7.7, are that it makes use of autonomous technologies such sensors incorporated within the Internet of Things (IoT) paradigm. For this, 3D innovation is adopted to deal with substantial informational indexes. It is a cutting-edge data-gathering system for use by groundwater use clients or groundwater specialist organisations. Furthermore, the system provides real-time updates and early warning signals to groundwater management. This reinforces positive good behavioural practices on water abstraction and effective water use. The information from the proposed exploratory system may be used in evaluating the sustainability of groundwater systems in various catchments throughout South Africa and the southern African region. This, in turn, will support behavioural changes and practices among groundwater consumers and municipalities. Figure 7.8 highlights the conditions for using this tool in other catchments.

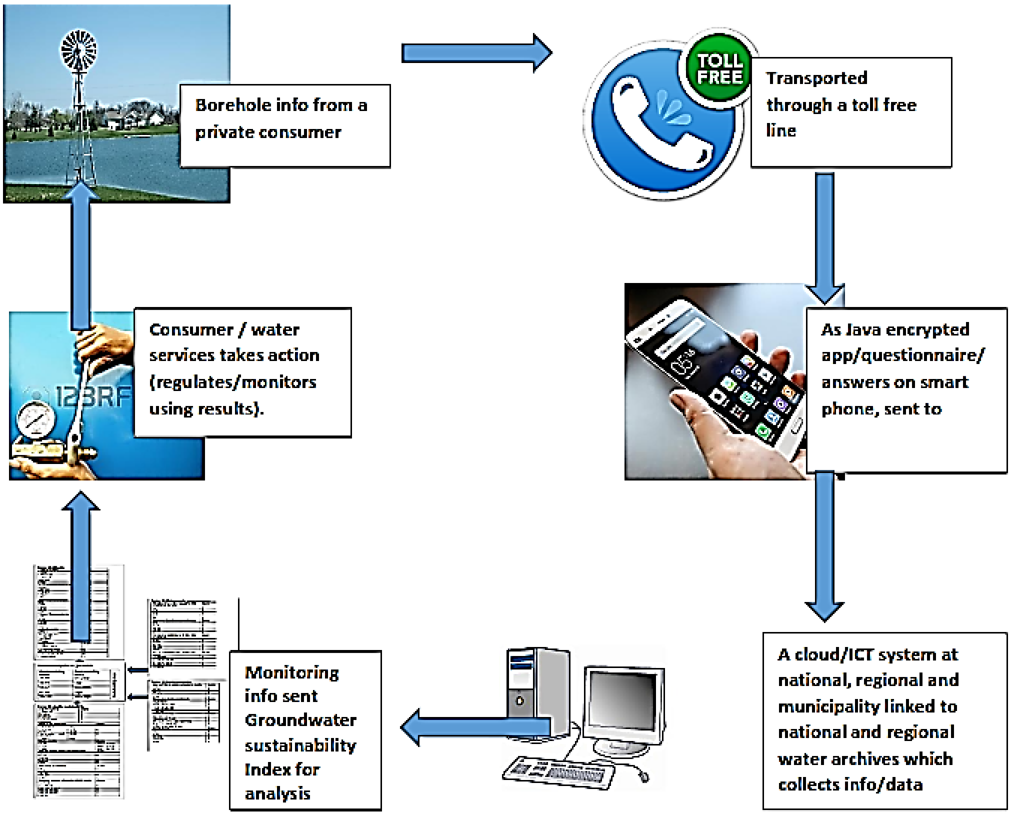


Figure 7.8: Proposed application architecture
Source: Author

7.4.1 Implication of the artificial intelligence system on the community of practice

The fifth significant aspect of the study is a research and coming up with a proposed workflow for an AI system for groundwater management and its implications on the community. The purpose of AI in groundwater management is to increase groundwater conservation and sustainability through a monitoring system that promotes real-time updates and early warning signals to water management and reinforces positive, acceptable behavioural practices on water abstraction and effective water use. Groundwater consumers will be able to gauge when their water usage is too high, and municipalities will be able to gauge if a catchment is over-abstracted. The net gain or impact will be water savings, cost savings and improved water management performance by provinces, municipalities and responsible departments.

The proposed workflow sustainability tool (sustainability index, AI, and ICT) may be used to evaluate the sustainability of groundwater in various catchments throughout South Africa, provided they can access accurate data as used in this study. This, in turn, will support the national water strategy of having a balanced water system. AI may be a descriptive logical basis behind the groundwater catchment technology showcased as an innovative technology solution that contributes to achieving the objectives of water sector programmes.

7.5 Implications for groundwater sustainability

The sixth significant aspect of the study is the identification of the implications for groundwater sustainability practitioners, summarised from the researcher's participation and reflections on the research. These implications are as follows:

- Need to mark out and enforce buffer zones
- Need for revisions of the 'sustainable yield' value
- The age of data used in designs as a result of the licensing evaluation tool, needs review
- Some catchments need restrictions in pumping rates
- Designs need to conform to some sort of groundwater sustainability codes
- Need to support clients in making the links between the hydrological cycle and abstracted amounts
- Need for a polluters/abstractor pays principle
- Need for information-based initiatives mandated by disclosure (applications)
- Need for increased financing for regulation and streamlining licensing
- Key shifts and strategic choices regarding groundwater infrastructure (enforced protocol on shared aquifers)
- Need for disrupting innovations (effective research and development)

7.6 Outstanding groundwater infrastructure concerns at industry/sector level

The seventh significant aspect of the study is the framing of the outstanding concerns regarding groundwater concerns, collected and summarised from the study participants' reflections. These are:

- How do we get the water industry, social planners, and researchers to cooperate in identifying and planning future groundwater needs?
- How do we ensure take-up of, and should we subsidise new technologies and services to ensure sustainable abstraction of groundwater?
- Do we need a new approach to planning so that planners, the water industry, infrastructure providers, and service providers work more closely together and share information?
- Are we doing enough to set research priorities for new products in groundwater management?
- How do we best 'value' the benefits of potential new groundwater industry products and materials?
- How do we encourage more industry research into new products and improved management processes?
- What steps are required to encourage rapid investment and development of factory-produced, on-site assembly of modular components for groundwater management?
- How do we ensure that the industry captures and shares its growing 'evidence-based' knowledge of groundwater performance data?

7.7 Conclusion

Sustainability reporting is the procedure of objectively appraising the groundwater asset management status and, as ideally as possible, reflect on the circumstances on the ground. Additionally, as an approach, it is considered to be the best practice.

AI may increase the understanding of policies and practices of groundwater sustainability. It may further increase the improvement in groundwater resource understanding, sustainable groundwater management and conservation. AI may expand the approach and work on the comprehension of groundwater sustainability. AI may likewise expand the change in groundwater asset understanding, feasible groundwater administration and preservation.

Going forward, a key preface for the appraisal strategy is that groundwater management should occur within a sustainability structure. To accomplish this, all options and tools should be used as a measure for the evaluation in order to take stock of institutional improvement and administrative measures for groundwater development.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This last chapter outlines the recommendations and conclusions based on the findings of this research. It also provides recommendations for further work and research.

The aim and objectives of the research were largely met. The research aim was to design and model a framework of important hydrological parameters governing the sustainability of groundwater in the C52 catchment of the Modder River in South Africa. The Modder River is part of the broad Orange River system. Due to the adverse impact of climatic change and increased dependence on the groundwater systems in the catchment, there was a need to develop a framework for sustainable groundwater management, by modelling hydrological and human induced factors affecting the sustainability of the groundwater system.

The aim and the set objectives were achieved. Sustainability was more dependent on the storativity of the aquifer than the pumping rate/registered volumes in the C52 catchment. In summary, the low sustainability of the aquifer was rather due to climate impact induced low recharge from rainfall and less due to human activities in the catchment.

8.2 Conclusions

Three objectives were set to reach the aim of the study. The conclusions are presented under the objectives as follows:

8.2.1 Objective 1: To set up, calibrate and validate a model to predict groundwater sustainability at catchment scale

The elements underpinning development of the groundwater sustainability index methodology and the specific methodology and data acquisition were explained in chapter 2, 4 and 5. Furthermore, weighting and rating of the parameters were explained and the proposed sustainability method was presented as a simple concept. The sustainability index method uses both subjective techniques and physically-based techniques.

To set up the model, boundary conditions for all factors were developed based on the global highest and lowest values that have ever been recorded. Scores were assigned by the researcher based on these global highest and lowest amounts ever recorded values. This was done so that the developed sustainability index could be applicable to any catchment or any part of the world. For all factors, the values were checked against DWS reports to investigate parameters that influenced the C52 catchment groundwater. This has been stated explicitly in chapter 4. All the parameters under study were given the same treatment (scoring and rating), given the theory, linkages and relationships between them and aspects such as recharge.

Sustainability classes that were derived followed other methods of analysing complex sustainability challenges around resource mitigation. These methods offer a range of sustainability classes from very high to very low. The resulting sustainability model/index would be easy to collate and use. Since the parameters affecting groundwater sustainability in Modder River Basin was used, it finds best applicability to investigate groundwater sustainability in arid areas of South Africa and elsewhere.

To validate the sustainability index map, an explanation of the scores was given according to the classes presented. An attempt was made to use comparison graphs and correlation graphs where possible to shine some light on the strengths and weaknesses of the sustainability index map. Validation was carried to triangulate the C52 catchment findings using other methods and other maps that were not the final sustainability index map.

The study found that aquifers were classified by their limiting/boundary conditions, including confined and unconfined aquifers. Unconfined aquifers alluded to phreatic aquifers, which have the water table or phreatic surface as their upper boundaries. Usually, the shallowest aquifer in a given area is unconfined, meaning that it does not have a confining layer (an aquitard or aquiclude) sandwiching it with the underlying bedrock. Unconfined aquifers, more often than not, are recharged directly from the surface i.e. from precipitation or from a collection of surface water, for example a river, stream or lake hydraulically linked to it. This warrants and supports the validation process.

Validation is the process conducted to determine whether the model, as a conceptualisation or an abstraction, would be a meaningful and accurate representation (in important aspects) of the real system (the Modder River catchment). The findings agreed with the representation and results on the sustainability map. Validation of groundwater models is currently a popular aspect of groundwater studies. The validity (or significance) of a model should be judged by its suitability for a particular purpose. This chapter concludes that a model is sound and dependable if it accomplishes what is expected of it. This means that validity as an abstract concept divorced from purpose is meaningless. What may be an excellent model for one purpose may be misleading and useless for another.

The study concludes that sustainability depended more on the storativity of the aquifer than the pumping rate/registered volumes in the C52 catchment. In summary, it would be interesting to use this study's recommendations for future studies to support claims that the low sustainability of the aquifer was due to impact of climate as a result of low rainfall and recharge than human activities in the catchment.

The study further explained sustainability reporting as the procedure of appraising the groundwater asset management status objectively and reflecting on the circumstances on the ground, as ideally as possible. Additionally, as an approach, it was considered to be a best practice.

An additional conclusion is that AI may increase the understanding of policies and practices of groundwater sustainability. It may further increase the improvement in groundwater resource understanding, sustainable groundwater management and conservation. AI may expand the approach and work on the comprehension of groundwater sustainability. AI may likewise expand the change in groundwater asset understanding, feasible groundwater administration and preservation.

The information on the hydrology and hydrogeology of the Modder River Basin, as a result of this objective, has been used to develop a framework/sustainability index, which is discussed here. The index has been developed to model important parameters governing the sustainability of groundwater systems in the C52 catchment of the Modder River system of South Africa. A validation exercise using rainfall, recharge and yield data collected, was applied to the C52 Modder River catchment. This was carried out in order to compare and verify the correctness of the sustainability map.

The designed model is a simplified concept; the sustainability model makes use of both subjective and physically-based techniques. In the field, infiltration and percolation of rainfall, and less evapotranspiration is assumed as recharge under steady state conditions. The sustainability class is similar to that of other methods and the sustainability classes range from very low to very high sustainability. The sustainability model/method parameters for evaluation are easy to collate and calculate and is designed for data limited or scarce areas such as the Modder River Basin and areas with similar challenges globally, particularly those in South Africa.

8.2.2 Objective 2: To apply the developed model to predict the sustainability of the groundwater of the Modder C52 catchment of the Upper Orange River system, using observed data from the Department of Water and Sanitation

The intention of this objective was to give an account of the application of the sustainability index concept to 51 boreholes in the C52 catchment in the Modder River Upper Orange River Basin. This is presented in chapter 5 and it details the production of maps for all the factors under study in this thesis.

The climatic conditions, rights/equity as related to the groundwater resources, the socio-economics and the aquifer system sustainability maps were produced and a final sustainability map was generated. The sources of data were identified and the applications of the data were described. Generally, the sustainability index is adaptable, simple, and understandable. The generated sustainability map was influenced by the rainfall, geology, and topography of overlying layers of the C52 Modder River catchment.

The sustainability method discussed in Chapter 4 was used to assess the sustainability of groundwater in the C52 Modder River catchment. Sources of data and their application were highlighted. The conclusion of the chapter is that the sustainability class in the Modder River Basin ranged from low sustainability to moderate sustainability. The moderate sustainability class is typical of areas with extensive dolerite, low slopes, and low recharge.

The adaptability of the sustainability model is simple and easily understandable. The generated sustainability map is influenced by the geology, topography, and rainfall of the overlying layers of the C52 Modder River Orange catchment. The second objective becomes the basis of the third objective on validation. A validation exercise using rainfall data collected was applied to the Modder River Basin. This was carried out in order to verify and compare the accuracy of the sustainability index map.

8.2.3 Objective 3: To test and correlate the results from the model with observed geohydrological parameters of recharge, borehole yield and pumping rate data

The sustainability index maps were compared with the recharge maps developed in Chapter 3 using the DWS chloride mass balance data, presented in Figure 6.2. The results obtained from the recharge study by the DWS agreed with the results obtained from the model presented in the final sustainability map. Figure 6.2 shows the final sustainability map, the river network map and recharge map of the study area extracted from the countrywide recharge map of South Africa. In the study area, high recharge areas were found in the eastern and south-eastern parts of the study area. The central and western parts of the study area were marked by lower recharge values. This is consistent with the sustainability final index maps. There is a lot of similarity in the outcomes of the final sustainability index map (Figure 6.2a), the detailed river network map (Figure 6.2b) and the recharge map (Figure 6.2c). The three maps were placed together to assist comparison. The reason was to identify commonalities.

Figure 6.2a has yellow shaded areas that indicate moderate sustainability zones. Figure 6.2b indicates that the river network concentration in the east of the Modder catchment is high. This suggests that the rivers influence recharge of the aquifers in the yellow zone. This augment is supported by Figure 6.2c, which shows high groundwater recharge marked by red zones and orange. This require further detailed studies to compare the groundwater chemistry and river network in that area.

Figure 6.2c further shows red and orange zones which have higher recharge. This is consistent with areas with high surface water and the yellow zones in Figure 6.2a are consistent with moderate sustainability. The implications are that the orange zones on the Modder River catchment (Figure 6.2a) has low groundwater sustainability in the densely populated area. New developments are not viable in the orange zones (see Figure 6.2a). This corresponds with the decision of water affairs to stop the drilling of new boreholes north and west of Bloemfontein. Coincidently, it is in the orange zone.

The relationship between pumping rate and aquifer yields was tested. Tests were carried out when the pumping rate is plotted on the x and y axes. The same was repeated when aquifer yields were plotted on both x and y axes as well. This was carried out to determine if the behaviour of the plots was different. For this reason, both Figures 7.1 and 7.2 was presented. The pumping rates were higher than the aquifer yields. This means that the boreholes that were abstracted at a rate that was higher than the aquifer yield, could be recharged. The majority points on the graph (Figure 7.2) were below the best fit line.

According to Figure 7.1, the ideal pumping rate was defined by the equation: Pumping rate = 157 397x + 138 080. As such, the pumping rates have been recalculated and recommended in Table 7.1. This means that this amount may be pumped without disturbing the dynamic equilibrium of the aquifer. This pumping rate would support the capture principle approach for the C52 catchment. These pumping rates were derived by applying the formula: Pumping rate = 157 397x + 138 080; this formula was derived at using Figure 7.1. It was automatically derived by using Microsoft Excel©. The gradient and curve constant could also be read from the graph generated by Microsoft Excel©. The formula – Pumping rate = 157 397x + 138 080 – can be used to determine the ideal pumping rate for each borehole in the C52 catchment. The application of in safe/ideal pumping rate determination supports the capture principle approach.

8.3 Recommendations

The sustainability map of the Modder River Basin presents an alarming picture of the risk that is taken if groundwater in the basin remained unprotected. Restrictions are needed to control over-abstractions of sources for non-domestic activities. The recommendations and measures in the research thesis were based on the findings and challenges encountered during the research for the protection of the Modder River Basin aquifers. These recommendations were presented under two categories, namely those on further studies and those to government as a major contributing factor to groundwater sustainability in the Modder River Basin; the continuous monitoring of improper land-use patterns across the basin; and education that is necessary to safeguard the vulnerable groundwater resources of the Modder River Basin.

8.3.1 Recommendations for further studies on modelling and prediction of groundwater sustainability on catchment scale or level

The research aim was to design and model a framework of important hydrological parameters governing the sustainability of groundwater in the C52 catchment of the Modder River system in South Africa. Some of the outcomes have been a proposed reporting tool for farmers and an innovative element of technology such as the AI system proposed for the C52 catchment of the Modder River. To add value to future studies and implementation, the study recommends the following:

- Pre-testing of the aquifer sustainability system through an application with the Microsoft Excel© monitoring spreadsheet, using the scores and ranking of the factors. This should be done with the aim of creating an analysis application for sustainability.
- The groundwater sustainability methodological evaluation is a practical and applicable tool for land-use planning and risk assessment. This method may be used to investigate aquifer sustainability in a similar basin with limited data. Recommendations for further studies are to evaluate other high priority catchments like that in Cape Town.

8.3.2 Recommendations on sustainability of the groundwater of the Modder River C52 catchment of the Upper Orange River system using observed data from DWS, other government departments and general groundwater users in the Modder River Basin

- A survey regarding the groundwater assets management status in the SADC in view of accessible groundwater records and logically written reports in the region are required to acquire a proportion of the groundwater management status.
- The age of data used for the licensing evaluation tool needs to be reviewed as the figures used were from 2007 (refer to reserve determination on the licensing evaluation tool, Table 2.3, section 2.9.8).
- An application for monitoring and evaluation of groundwater levels should be considered so that the sustainable yield is routinely adjusted.
- Investment in a routine assessment of the status of groundwater abstraction that should be regularly conducted.
- Implementation of the groundwater strategy should be expedited.
- Investment in groundwater sustainability models is required.
- Groundwater abstraction/use rights should be granted to groundwater users under government control. These rights systems should be clarified in statutory forms in the relevant laws. This should be strengthened by government.
- Land use plans should integrate groundwater concerns, to maintain sustainability of the resources.
- Collection and accumulation of scientific data on groundwater should be promoted as the basis for sound groundwater management.
- Government should prevent lowering of groundwater levels due to over-extraction by passing appropriate laws.
- There should be an improvement in public water distribution. This will reduce the dependency on groundwater.
- Government should formulate an appropriate land-use management act, particularly for vulnerable aquifer areas. Farmers could be monitored for over-abstraction.

8.3.3 Recommendations based on results from the model with observed geohydrological parameters of recharge, borehole yield and pumping rate data

- Strict borehole regulations, particularly in vulnerable aquifers in over-congested areas in the Modder River Basin should be formulated and enforced.

- Groundwater sustainability zoning, based on the methods used in this research, should be established with matrices that indicate what activities are possible where and at what acceptable risk to groundwater.

8.4 Final conclusion

This research therefore supports recommendations for aquifer sustainability assessment on a national scale, with local and municipal governments embarking on similar projects based on the resources available. The sustainability maps produced in this thesis are recommended for use by groundwater managers and decision-makers in the realisation of programmes and/or measures aimed at protecting groundwater resources.

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Appendix A:

FOCUSED INTERVIEW GUIDE

FARMERS' QUESTIONNAIRE- WATER LEVEL MONITORING

Introduction: I am Rebecca Alowo, a PdD student at the Central University of Technology. I am carrying out research into to what extent a region's groundwater resources can be exploited without unduly compromising the principle of sustainable development. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (The World Commission on Environment and Development, 1987).

Please note that I am trying to obtain your views based on your experience and later under general comments as you wish the situation to be (Taylor-Powell, 1998). I would therefore be grateful for any feedback I can get. Individual or organisational names will be held in confidence and used only in reports with permission please state your preference)

HOW TO ANSWER THIS QUESTIONNAIRE – Please indicate by ticking where appropriate *

SECTION A:

Name Contact phone number:

Town: Province:

SECTION B: Borehole data

1. What is the monthly water level?

2. What is the monthly rainfall?

3. What is the amount of water abstracted, weekly / monthly?

4. What is the borehole behaviour (tick as appropriate)

Very good	
Good	
Fair	
Poor	
Very poor	

5. What is the water geochemistry?

Smell	
Taste	
Colour	

6. Do you have a monitoring programme?
7. Are monitoring holes available to monitor the groundwater flow regime with relation to water use activity on your land?
8. Do the monitoring holes penetrate the whole aquifer?
9. Do you have historical groundwater monitoring data to present?
10. Do you have a maintenance plan for monitoring during decommission and post-closure phases?
11. Do you have a geo-referenced map of the property with boreholes, surface water features, physical structures (irrigation equipment)?
12. What is the depth of the borehole(s)?
13. What is the borehole yield?
14. At what depth is the pump installed?

SECTION C GENERAL

1. In terms of technology and policies, how can groundwater be sustained?
2. It terms of financial input, what kind of financial support is required for groundwater sustainability?
3. What skills are necessary to implement a suitable abstraction system?
4. What would you want to see in terms of groundwater sustainability working differently, which have not been considered above?

What recommendations would you give for general stakeholders such a farmers?

Would you object to receiving a follow-up phone call ________ would you like your participation acknowledged in the final report __________ __________

Thank you for your time.

References: Ellen Taylor-Powell (May 1998): Questionnaire design: Asking questions with a purpose: Programme Development and Evaluation series G3658-.

Appendix B

DATA OF C52 CATCHMENTS

Bore-hole	Latitude	Longitude	Rainfall (mm)	Evapo-transpiration (mm)	Sunshine (Centi-grade)	Slope (m)	Climatic Zone	Number of permits issued in the catchment (per year)	Length of permits (years)	Number of boreholes in the catchment	Pumping rate (Cubic metres per year)	Use per capita of the catchment (l/c/d)	Population in the Catchment	Water Uses	Tariffs (Rand per Month)	Aquifer System	Rock Type	Water quality	Aquifer yields (ℓ/s)	Recharge (mm/year)	Storage volume of aquifer (1000 cubic metres)
1	-28.867897	26.302778	534	1570	15	0 to 5	Arid to Semi-Arid	1	20	97	178470	490,3	2,205,000	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,141401256	2 to 20	74320,5
2	-29.567891	26.072222	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	50000	137,36	2,205,001	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,141401256	2 to 20	74320,5
3	-29.098889	26.058333	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	30000	82,42	2,205,002	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,141401256	2 to 20	74320,5
4	-29.014567	26.144565	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	17693	48,61	2,205,003	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
5	-29.012578	26.075565	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	315000	865,38	2,205,004	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
6	-29.005556	26.025898	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	75000	206,04	2,205,005	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
7	-29.292361	26.166667	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	336520	924,51	2,205,006	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67
8	-29.076946	26.120568	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	24420	67,09	2,205,007	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
9	-28.995833	25.995833	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	43200	118,68	2,205,008	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
10	-29.168446	26.112233	534	1570	15	0 to 5	Arid to Semi-Arid	2	20	97	1000	2,75	2,205,009	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
11	-29.075321	26.113345	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	14362	39,46	2,205,010	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
12	-29.067528	25.850528	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	298480	820	2,205,011	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
13	-29.182341	26.110765	534	1570	15	0 to 5	Arid to Semi-Arid	5	60	97	5000	13,74	2,205,012	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67
14	-29.239611	25.857694	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	189900	521,7	2,205,013	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67
15	-29.283324	25.811056	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	388818	1068,18	2,205,014	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
16	-29.332056	25.994028	534	1570	15	0 to 5	Arid to Semi-Arid	3	60	97	23470	64,48	2,205,015	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
17	-28.519876	26.116667	534	1570	15	0 to 5	Arid to Semi-Arid	1	20	97	605000	1662,09	2,205,016	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
18	-28.896223	25.991389	534	1570	15	0 to 5	Arid to Semi-Arid	6	20	97	58536	160,81	2,205,017	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
19	-29.007389	-29.007389	534	1570	15	0 to 5	Arid to	3	60	97	86088	236,51	2,205,018	Agriculture:	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67

Bore-hole	Latitude	Longitude	Rainfall (mm)	Evapo-transpiration (mm)	Sunshine (Centi-grade)	Slope (m)	Climatic Zone	Number of permits issued in the catchment (per year)	Length of permits (years)	Number of boreholes in the catchment	Pumping rate (Cubic metres per year)	Use per capita of the catchment (l/c/d)	Population in the Catchment	Water Uses	Tariffs (Rand per Month)	Aquifer System	Rock Type	Water quality	Aquifer yields (ℓ/s)	Recharge (mm/year)	Storage volume of aquifer (1000 cubic metres)
							Semi-Arid							Irrigation							
20	-28.791234	25.849082	534	1570	15	0 to 5	Arid to Semi-Arid	3	60	97	13320	36,59	2,205,019	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67
21	-29.066667	25.341667	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	52000	142,86	2,205,020	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67
22	-28.962778	25.995833	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	382500	1050,82	2,205,021	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0,043129129	2 to 20	22668,67
23	-28.633241	26.220044	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	26654	73,23	2,205,022	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.000305384	2 to 20	160,51
24	-29.223557	26.878324	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	11937	32,79	2,205,023	Mining	27,43	Fractured	Dolerite	Good	0,000119064	2 to 20	62,58
25	-29.141083	26.062083	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	48886	134,3	2,205,024	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,397541096	2 to 20	734547,6
26	-29.425139	26.632917	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	11948	32,82	2,205,025	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,397541096	2 to 20	734547,6
27	-29.262148	26.480619	534	1570	15	0 to 5	Arid to Semi-Arid	3	60	97	7200	19,78	2,205,026	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,397541096	2 to 20	734547,6
28	-28.973456	-28.978757	534	1570	15	0 to 5	Arid to Semi-Arid	3	60	97	3202700	8798,63	2,205,027	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,003049467	2 to 20	527202,8
29	-28.904639	26.462567	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	52400	143,96	2,205,028	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,003049467	2 to 20	527202,8
30	-28.880806	26.630833	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	165600	454,95	2,205,029	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,003049467	2 to 20	527202,8
31	-28.876754	26.535642	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	2250	6,18	2,205,030	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,003049467	2 to 20	527202,8
32	-29.046543	26.425678	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	6000	16,48	2,205,031	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	1,003049467	2 to 20	527202,8
33	-29.044944	26.308056	534	1570	15	0 to 5	Arid to Semi-Arid	1	20	97	3206	8,81	2,205,032	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927892	2 to 20	368407,7
34	-29.063256	26.345673	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	515974	1417,51	2,205,033	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927893	2 to 20	368407,7
35	-29.103864	-29.103089	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	748128	2055,3	2,205,034	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927894	2 to 20	368407,7
36	-29.102778	26.320278	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	26,320278	0,07	2,205,035	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927895	2 to 20	368407,7
37	-29.118826	26.434841	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	1825	5,01	2,205,036	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927896	2 to 20	368407,7
38	-28.551254	25.373452	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	132990	365,36	2,205,037	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927897	2 to 20	368407,7
39	-28.625321	25.625765	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	117627	323,15	2,205,038	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927898	2 to 20	368407,7
40	-29.243806	25.354222	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	75675	207,9	2,205,039	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927899	2 to 20	368407,7
41	-28.941111	25.157778	534	1570	15	0 to 5	Arid to Semi-Arid	2	20	97	941296	2585,98	2,205,040	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927900	2 to 20	368407,7
42	-29.233333	25.284567	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	5060	13,9	2,205,041	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927901	2 to 20	368407,7

Bore-hole	Latitude	Longitude	Rainfall (mm)	Evapo-transpiration (mm)	Sunshine (Centi-grade)	Slope (m)	Climatic Zone	Number of permits issued in the catchment (per year)	Length of permits (years)	Number of boreholes in the catchment	Pumping rate (Cubic metres per year)	Use per capita of the catchment (l/c/d)	Population in the Catchment	Water Uses	Tariffs (Rand per Month)	Aquifer System	Rock Type	Water quality	Aquifer yields (ℓ/s)	Recharge (mm/year)	Storage volume of aquifer (1000 cubic metres)
43	-29.122222	25.120872	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	101686	279,36	2,205,042	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927902	2 to 20	368407,7
44	-28.702785	25.401392	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	2750	7,55	2,205,043	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927903	2 to 20	368407,7
45	-29.182972	25.405139	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	151125	415,18	2,205,044	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927904	2 to 20	368407,7
46	-28.822567	25.395757	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	33065	90,84	2,205,045	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927905	2 to 20	368407,7
47	-29.291972	25.457528	534	1570	15	0 to 5	Arid to Semi-Arid	2	60	97	300000	824,18	2,205,046	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927906	2 to 20	368407,7
48	-29.141667	25.475567	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	402492	1105,75	2,205,047	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927907	2 to 20	368407,7
49	-29.241667	25.654352	534	1570	15	0 to 5	Arid to Semi-Arid	1	60	97	219000	601,65	2,205,048	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927908	2 to 20	368407,7
50	-29.033861	25.609833	534	1570	15	0 to 5	Arid to Semi-Arid	1	5	97	148200	407,14	2,205,049	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927909	2 to 20	368407,7
51	-28.936565	25.283421	534	1570	15	0 to 5	Arid to Semi-Arid	2	10	97	78000	214,29	2,205,050	Agriculture: Irrigation	27,43	Fractured	Dolerite	Good	0.700927910	2 to 20	368407,7

Appendix C

FACTOR SCORING

Factor A: Assignment of scores to factors

Bore-hole	Rainfall (mm) MAP	Score	Evapo-trans-piration (mm)	Score	Sunshine (Degrees Centigrade) MAT	Score	Slope (m)	Score	Climatic Zone	Score	Vegetation	Score	Total Score
1	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
2	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
3	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
4	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
5	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
6	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
7	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
8	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
9	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
10	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
11	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
12	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
13	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
14	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
15	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
16	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
17	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
18	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
19	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
20	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
21	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
22	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
23	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
24	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
25	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14

Bore-hole	Rainfall (mm) MAP	Score	Evapo-trans-piration (mm)	Score	Sunshine (Degrees Centigrade) MAT	Score	Slope (m)	Score	Climatic Zone	Score	Vegetation	Score	Total Score
26	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
27	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
28	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
29	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
30	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
31	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
32	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
33	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
34	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
35	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
36	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
37	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
38	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
39	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
40	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
41	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
42	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
43	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
44	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
45	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
46	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
47	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
48	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
49	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
50	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14
51	534	2	1570	1	15	3	0 to 5	5	Arid to semi-arid	2	Savanah grasslands	3	14

Scoring against Factor A

Borehole	Latitude	Longitude	Score A	Class	Colour
1	-28.867897	26.302778	11	Low	Orange
2	-29.567891	26.072222	11	Low	Orange
3	-29.098889	26.058333	11	Low	Orange
4	-29.014567	26.144565	11	Low	Orange
5	-29.012578	26.075565	11	Low	Orange
6	-29.005556	26.025898	11	Low	Orange
7	-29.292361	26.166667	11	Low	Orange
8	-29.076946	26.120568	11	Low	Orange
9	-28.995833	25.995833	11	Low	Orange
10	-29.168446	26.112233	11	Low	Orange
11	-29.075321	26.113345	11	Low	Orange
12	-29.067528	25.850528	11	Low	Orange
13	-29.182341	26.110765	11	Low	Orange
14	-29.239611	25.857694	11	Low	Orange
15	-29.283324	25.811056	11	Low	Orange
16	-29.332056	25.994028	11	Low	Orange
17	-28.519876	26.116667	11	Low	Orange
18	-28.896223	25.991389	11	Low	Orange
19	-29.007389	25.905608	11	Low	Orange
20	-28.791234	25.849082	11	Low	Orange
21	-29.066667	25.341667	11	Low	Orange
22	-28.962778	25.995833	11	Low	Orange
23	-28.633241	26.220044	11	Low	Orange
24	-29.223557	26.878324	11	Low	Orange
25	-29.141083	26.062083	11	Low	Orange
26	-29.425139	26.632917	11	Low	Orange
27	-29.262148	26.480619	11	Low	Orange
28	-28.973456	28.978757	11	Low	Orange
29	-28.904639	26.462567	11	Low	Orange
30	-28.880806	26.630833	11	Low	Orange
31	-28.876754	26.535642	11	Low	Orange
32	-29.046543	26.425678	11	Low	Orange
33	-29.044944	26.308056	11	Low	Orange
34	-29.063256	26.345673	11	Low	Orange
35	-29.103864	29.103089	11	Low	Orange
36	-29.102778	26.320278	11	Low	Orange
37	-29.118826	26.434841	11	Low	Orange
38	-28.551254	25.373452	11	Low	Orange
39	-28.625321	25.625765	11	Low	Orange
40	-29.243806	25.354222	11	Low	Orange
41	-28.941111	25.157778	11	Low	Orange
42	-29.233333	25.284567	11	Low	Orange
43	-29.122222	25.120872	11	Low	Orange

Borehole	Latitude	Longitude	Score A	Class	Colour
44	-28.702785	25.401392	11	Low	Orange
45	-29.182972	25.405139	11	Low	Orange
46	-28.822567	25.395757	11	Low	Orange
47	-29.291972	25.457528	11	Low	Orange
48	-29.141667	25.475567	11	Low	Orange
49	-29.241667	25.654352	11	Low	Orange
50	-29.033861	25.609833	11	Low	Orange
51	-28.936565	25.283421	11	Low	Orange

Factor B: Parameter scoring

Borehole	Number of permits issued in the catchment (per year)	Score	Length of permits (years)	Score	Number of boreholes in the catchment (of the 97 boreholes only 52 were approved by DWS/ consented to the study)	Score	Pumping rate (Cubic metres per year)	Score	Total Score
1	1	5	20	2	97	2	178470	1	10
2	1	5	60	1	97	2	50000	1	9
3	1	5	60	1	97	2	30000	1	9
4	2	4	60	1	97	2	17693	1	8
5	2	4	60	1	97	2	315000	1	8
6	2	4	60	1	97	2	75000	1	8
7	1	5	60	1	97	2	336520	1	9
8	1	5	60	1	97	2	24420	1	9
9	1	5	60	1	97	2	43200	1	10
10	2	4	20	2	97	2	1000	1	8
11	1	5	60	1	97	2	14362	1	10
12	1	5	60	1	97	2	298480	1	10
13	5	1	60	1	97	2	5000	1	5
14	2	4	60	1	97	2	189900	1	8
15	2	4	60	1	97	2	388818	1	8
16	3	3	60	1	97	2	23470	1	7
17	1	5	20	2	97	2	605000	1	10
18	6	5	20	2	97	2	58536	1	10
19	3	3	60	1	97	2	86088	1	7
20	3	3	60	1	97	2	13320	1	7
21	2	4	60	1	97	2	52000	1	8
22	2	4	60	1	97	2	382500	1	8
23	2	4	60	1	97	2	26654	1	8
24	2	4	60	1	97	2	11937	1	8
25	1	5	60	1	97	2	48886	1	9
26	1	5	60	1	97	2	11948	1	9
27	3	3	60	1	97	2	7200	1	7
28	3	3	60	1	97	2	3202700	1	7
29	1	5	60	1	97	2	52400	1	9
30	1	5	60	1	97	2	165600	1	9
31	1	5	60	1	97	2	2250	1	9
32	1	5	60	1	97	2	6000	1	9
33	1	5	20	2	97	2	3206	1	10
34	2	4	60	1	97	2	515974	1	8
35	2	4	60	1	97	2	748128	1	8
36	1	5	60	1	97	2	26,32028	1	9
37	1	5	60	1	97	2	1825	1	9
38	1	5	60	1	97	2	132990	1	9
39	1	5	60	1	97	2	117627	1	9
40	2	4	60	1	97	2	75675	1	8
41	2	4	20	2	97	2	941296	1	9
42	1	5	60	1	97	2	5060	1	9

Borehole	Number of permits issued in the catchment (per year)	Score	Length of permits (years)	Score	Number of boreholes in the catchment (of the 97 boreholes only 52 were approved by DWS/ consented to the study)	Score	Pumping rate (Cubic metres per year)	Score	Total Score
43	2	4	60	1	97	2	101686	1	8
44	1	5	60	1	97	2	2750	1	9
45	2	4	60	1	97	2	151125	1	8
46	1	5	60	1	97	2	33065	1	9
47	2	4	60	1	97	2	300000	1	8
48	1	5	60	1	97	2	402492	1	9
49	1	5	60	1	97	2	219000	1	9
50	1	5	5	5	97	2	148200	1	13
51	2	4	10	4	97	2	78000	1	11

Score againt Factor B

Borehole	Latitude	Longitude	Score B	Class	Colour
1	-28.867897	26.302778	10	Moderate	Yellow
2	-29.567891	26.072222	9	Moderate	Yellow
3	-29.098889	26.058333	9	Moderate	Yellow
4	-29.014567	26.144565	8	Low	Orange
5	-29.012578	26.075565	8	Low	Orange
6	-29.005556	26.025898	8	Low	Orange
7	-29.292361	26.166667	9	Moderate	Yellow
8	-29.076946	26.120568	9	Moderate	Yellow
9	-28.995833	25.995833	10	Moderate	Yellow
10	-29.168446	26.112233	8	Low	Orange
11	-29.075321	26.113345	10	Moderate	Yellow
12	-29.067528	25.850528	10	Moderate	Yellow
13	-29.182341	26.110765	5	Low	Orange
14	-29.239611	25.857694	8	Low	Orange
15	-29.283324	25.811056	8	Low	Orange
16	-29.332056	25.994028	7	Low	Orange
17	-28.519876	26.116667	10	Moderate	Yellow
18	-28.896223	25.991389	10	Moderate	Yellow
19	-29.007389	25.905608	7	Low	Orange
20	-28.791234	25.849082	7	Low	Orange
21	-29.066667	25.341667	8	Low	Orange
22	-28.962778	25.995833	8	Low	Orange
23	-28.633241	26.220044	8	Low	Orange
24	-29.223557	26.878324	8	Low	Orange
25	-29.141083	26.062083	9	Moderate	Yellow
26	-29.425139	26.632917	9	Moderate	Yellow

Borehole	Latitude	Longitude	Score B	Class	Colour
27	-29.262148	26.480619	7	Low	Orange
28	-28.973456	28.97875	7	Low	Orange
29	-28.904639	26.462567	9	Moderate	Yellow
30	-28.880806	26.630833	9	Moderate	Yellow
31	-28.876754	26.535642	9	Moderate	Yellow
32	-29.046543	26.425678	9	Moderate	Yellow
33	-29.044944	26.308056	10	Moderate	Yellow
34	-29.063256	26.345673	8	Low	Orange
35	-29.103864	-29.103089	8	Low	Orange
36	-29.102778	26.320278	9	Moderate	Yellow
37	-29.118826	26.434841	9	Moderate	Yellow
38	-28.551254	25.373452	9	Moderate	Yellow
39	-28.625321	25.625765	9	Moderate	Yellow
40	-29.243806	25.354222	8	Low	Orange
41	-28.941111	25.157778	9	Moderate	Yellow
42	-29.233333	25.284567	9	Moderate	Yellow
43	-29.122222	25.120872	8	Low	Orange
44	-28.702785	25.401392	9	Moderate	Yellow
45	-29.182972	25.405139	8	Low	Orange
46	-28.822567	25.395757	9	Moderate	Yellow
47	-29.291972	25.457528	8	Low	Orange
48	-29.141667	25.475567	9	Moderate	Yellow
49	-29.241667	25.654352	9	Moderate	Yellow
50	-29.033861	25.609833	13	High	Green
51	-28.936565	25.283421	11	Moderate	Yellow

Factor C: Parameter scoring

Borehole	Use per capita of the catchment (l/c/d)	Score	Population in the Catchment (population in the C52 sub-catchment)	Score	Water Uses as given in the licensed fact sheet from DWS	Score	Tariffs (Rand per Month)	Score	Total Score
1	490,3	1	2,205,000	1	Agriculture: Irrigation	2	27,43	3	7
2	137,36	1	2,205,001	1	Agriculture: Irrigation	2	27,43	3	7
3	82,42	2	2,205,002	1	Agriculture: Irrigation	2	27,43	3	8
4	48,61	3	2,205,003	1	Agriculture: Irrigation	2	27,43	3	9
5	865,38	1	2,205,004	1	Agriculture: Irrigation	2	27,43	3	7
6	206,04	1	2,205,005	1	Agriculture: Irrigation	2	27,43	3	7
7	924,51	1	2,205,006	1	Agriculture: Irrigation	2	27,43	3	7
8	67,09	2	2,205,007	1	Agriculture: Irrigation	2	27,43	3	8
9	118,68	1	2,205,008	1	Agriculture: Irrigation	2	27,43	3	7

Borehole	Use per capita of the catchment (l/c/d)	Score	Population in the Catchment (population in the C52 sub-catchment)	Score	Water Uses as given in the licensed fact sheet from DWS	Score	Tariffs (Rand per Month)	Score	Total Score
10	2,75	5	2,205,009	1	Agriculture: Irrigation	2	27,43	3	11
11	39,46	4	2,205,010	1	Agriculture: Irrigation	2	27,43	3	10
12	820	1	2,205,011	1	Agriculture: Irrigation	2	27,43	3	7
13	13,74	5	2,205,012	1	Agriculture: Irrigation	2	27,43	3	11
14	521,7	1	2,205,013	1	Agriculture: Irrigation	2	27,43	3	7
15	1068,2	1	2,205,014	1	Agriculture: Irrigation	2	27,43	3	7
16	64,48	2	2,205,015	1	Agriculture: Irrigation	2	27,43	3	8
17	1662,1	1	2,205,016	1	Agriculture: Irrigation	2	27,43	3	7
18	160,81	1	2,205,017	1	Agriculture: Irrigation	2	27,43	3	7
19	236,51	1	2,205,018	1	Agriculture: Irrigation	2	27,43	3	7
20	36,59	4	2,205,019	1	Agriculture: Irrigation	2	27,43	3	10
21	142,86	1	2,205,020	1	Agriculture: Irrigation	2	27,43	3	7
22	1050,8	1	2,205,021	1	Agriculture: Irrigation	2	27,43	3	7
23	73,23	2	2,205,022	1	Agriculture: Irrigation	2	27,43	3	8
24	32,79	4	2,205,023	1	Mining	3	27,43	3	10
25	134,3	1	2,205,024	1	Agriculture: Irrigation	2	27,43	3	7
26	32,82	4	2,205,025	1	Agriculture: Irrigation	2	27,43	3	10
27	19,78	5	2,205,026	1	Agriculture: Irrigation	2	27,43	3	11
28	8798,6	1	2,205,027	1	Agriculture: Irrigation	2	27,43	3	7
29	143,96	1	2,205,028	1	Agriculture: Irrigation	2	27,43	3	7
30	454,95	1	2,205,029	1	Agriculture: Irrigation	2	27,43	3	7
31	6,18	5	2,205,030	1	Agriculture: Irrigation	2	27,43	3	11
32	16,48	5	2,205,031	1	Agriculture: Irrigation	2	27,43	3	11
33	8,81	5	2,205,032	1	Agriculture: Irrigation	2	27,43	3	11
34	1417,5	1	2,205,033	1	Agriculture: Irrigation	2	27,43	3	7
35	2055,3	1	2,205,034	1	Agriculture: Irrigation	2	27,43	3	7
36	0,07	5	2,205,035	1	Agriculture: Irrigation	2	27,43	3	11
37	5,01	5	2,205,036	1	Agriculture: Irrigation	2	27,43	3	11
38	365,36	1	2,205,037	1	Agriculture: Irrigation	2	27,43	3	7
39	323,15	1	2,205,038	1	Agriculture: Irrigation	2	27,43	3	7
40	207,9	1	2,205,039	1	Agriculture: Irrigation	2	27,43	3	7
41	2586	1	2,205,040	1	Agriculture: Irrigation	2	27,43	3	7
42	13,9	5	2,205,041	1	Agriculture: Irrigation	2	27,43	3	11
43	279,36	1	2,205,042	1	Agriculture: Irrigation	2	27,43	3	7
44	7,55	5	2,205,043	1	Agriculture: Irrigation	2	27,43	3	11
45	415,18	1	2,205,044	1	Agriculture: Irrigation	2	27,43	3	7
46	90,84	2	2,205,045	1	Agriculture: Irrigation	2	27,43	3	8
47	824,18	1	2,205,046	1	Agriculture: Irrigation	2	27,43	3	7
48	1105,8	1	2,205,047	1	Agriculture: Irrigation	2	27,43	3	7
49	601,65	1	2,205,048	1	Agriculture: Irrigation	2	27,43	3	7
50	407,14	1	2,205,049	1	Agriculture: Irrigation	2	27,43	3	7
51	214,29	1	2,205,050	1	Agriculture: Irrigation	2	27,43	3	7

Score against Factor C

Borehole	Latitude	Longitude	Score C	Class	Colour
1	-28.867897	26.302778	7	Low	Orange
2	-29.567891	26.072222	7	Low	Orange
3	-29.098889	26.058333	8	Low	Orange
4	-29.014567	26.144565	9	Moderate	Yellow
5	-29.012578	26.075565	7	Low	Orange
6	-29.005556	26.025898	7	Low	Orange
7	-29.292361	26.166667	7	Low	Orange
8	-29.076946	26.120568	8	Low	Orange
9	-28.995833	25.995833	7	Low	Orange
10	-29.168446	26.112233	11	Moderate	Yellow
11	-29.075321	26.113345	10	Moderate	Yellow
12	-29.067528	25.850528	7	Low	Orange
13	-29.182341	26.110765	11	Moderate	Yellow
14	-29.239611	25.857694	7	Low	Orange
15	-29.283324	25.811056	7	Low	Orange
16	-29.332056	25.994028	8	Low	Orange
17	-28.519876	26.116667	7	Low	Orange
18	-28.896223	25.991389	7	Low	Orange
19	-29.007389	25.905608	7	Low	Orange
20	-28.791234	25.849082	10	Moderate	Yellow
21	-29.066667	25.341667	7	Low	Orange
22	-28.962778	25.995833	7	Low	Orange
23	-28.633241	26.220044	8	Low	Orange
24	-29.223557	26.878324	10	Moderate	Yellow
25	-29.141083	26.062083	7	Low	Orange
26	-29.425139	26.632917	10	Moderate	Yellow
27	-29.262148	26.480619	11	Moderate	Yellow
28	-28.973456	28.978757	7	Low	Orange
29	-28.904639	26.462567	7	Low	Orange
30	-28.880806	26.630833	7	Low	Orange
31	-28.876754	26.535642	11	Moderate	Yellow
32	-29.046543	26.425678	11	Moderate	Yellow
33	-29.044944	26.308056	11	Moderate	Yellow
34	-29.063256	26.345673	7	Low	Orange
35	-29.103864	29.103089	7	Low	Orange
36	-29.102778	26.320278	11	Moderate	Yellow
37	-29.118826	26.434841	11	Moderate	Yellow
38	-28.551254	25.373452	7	Low	Orange
39	-28.625321	25.625765	7	Low	Orange

Borehole	Latitude	Longitude	Score C	Class	Colour
40	-29.243806	25.354222	7	Low	Orange
41	-28.941111	25.157778	7	Low	Orange
42	-29.233333	25.284567	11	Moderate	Yellow
43	-29.122222	25.120872	7	Low	Orange
44	-28.702785	25.401392	11	Moderate	Yellow
45	-29.182972	25.405139	7	Low	Orange
46	-28.822567	25.395757	8	Low	Orange
47	-29.291972	25.457528	7	Low	Orange
48	-29.141667	25.475567	7	Low	Orange
49	-29.241667	25.654352	7	Low	Orange
50	-29.033861	25.609833	7	Low	Orange
51	-28.936565	25.283421	7	Low	Orange

Factor D: Parameter scoring

Bore-hole	Aquifer System	Score	Rock Type	Score	Water quality	Score	Aquifer yeilds (ℓ/s)	Score	Recharge (mm/year)	Score	Storage volume of aquifer (1000 cubic metres)	Score	Total Score
1	Fractured	1	Dolerite	1	Good	5	0,141401256	1	2 to 20	2	74320,5	2	11
2	Fractured	1	Dolerite	1	Good	5	0,141401256	1	2 to 20	2	74320,5	2	11
3	Fractured	1	Dolerite	1	Good	5	0,141401256	1	2 to 20	2	74320,5	2	11
	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
5	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
6	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
7	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11
8	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
9	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
10	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
11	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
12	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
13	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11
14	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11
15	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
16	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
17	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
18	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
19	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11
20	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11
21	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11

22	Fractured	1	Dolerite	1	Good	5	0,043129129	1	2 to 20	2	22668,67	2	11
23	Fractured	1	Dolerite	1	Good	5	0.000305384	1	2 to 20	2	160,51	2	11
24	Fractured	1	Dolerite	1	Good	5	0,000119064	1	2 to 20	2	62,58	2	11
25	Fractured	1	Dolerite	1	Good	5	1,397541096	5	2 to 20	2	734547,6	2	17
26	Fractured	1	Dolerite	1	Good	5	1,397541096	5	2 to 20	2	734547,6	2	17
27	Fractured	1	Dolerite	1	Good	5	1,397541096	5	2 to 20	2	734547,6	2	17
28	Fractured	1	Dolerite	1	Good	5	1,003049467	5	2 to 20	2	527202,8	2	16
29	Fractured	1	Dolerite	1	Good	5	1,003049467	5	2 to 20	2	527202,8	2	16
30	Fractured	1	Dolerite	1	Good	5	1,003049467	5	2 to 20	2	527202,8	2	16
31	Fractured	1	Dolerite	1	Good	5	1,003049467	5	2 to 20	2	527202,8	2	16
32	Fractured	1	Dolerite	1	Good	5	1,003049467	5	2 to 20	2	527202,8	2	16
33	Fractured	1	Dolerite	1	Good	5	0.700927892	2	2 to 20	2	368407,7	2	15
34	Fractured	1	Dolerite	1	Good	5	0.700927893	2	2 to 20	2	368407,7	2	15
35	Fractured	1	Dolerite	1	Good	5	0.700927894	2	2 to 20	2	368407,7	2	15
36	Fractured	1	Dolerite	1	Good	5	0.700927895	2	2 to 20	2	368407,7	2	15
37	Fractured	1	Dolerite	1	Good	5	0.700927896	2	2 to 20	2	368407,7	2	15
38	Fractured	1	Dolerite	1	Good	5	0.700927897	2	2 to 20	2	368407,7	2	15
39	Fractured	1	Dolerite	1	Good	5	0.700927898	2	2 to 20	2	368407,7	2	15
40	Fractured	1	Dolerite	1	Good	5	0.700927899	2	2 to 20	2	368407,7	2	15
41	Fractured	1	Dolerite	1	Good	5	0.700927900	2	2 to 20	2	368407,7	2	15
42	Fractured	1	Dolerite	1	Good	5	0.700927901	2	2 to 20	2	368407,7	2	15
43	Fractured	1	Dolerite	1	Good	5	0.700927902	2	2 to 20	2	368407,7	2	15
44	Fractured	1	Dolerite	1	Good	5	0.700927903	2	2 to 20	2	368407,7	2	15
45	Fractured	1	Dolerite	1	Good	5	0.700927904	2	2 to 20	2	368407,7	2	15
46	Fractured	1	Dolerite	1	Good	5	0.700927905	2	2 to 20	2	368407,7	2	15
47	Fractured	1	Dolerite	1	Good	5	0.700927906	2	2 to 20	2	368407,7	2	15
48	Fractured	1	Dolerite	1	Good	5	0.700927907	2	2 to 20	2	368407,7	2	15
49	Fractured	1	Dolerite	1	Good	5	0.700927908	2	2 to 20	2	368407,7	2	15
50	Fractured	1	Dolerite	1	Good	5	0.700927909	2	2 to 20	2	368407,7	2	15
51	Fractured	1	Dolerite	1	Good	5	0.700927910	2	2 to 20	2	368407,7	2	15

Scoring against Factor D

Borehole	Latitude	Longitude	Score D	Class	Colour
1	-28.867897	26.302778	10,5	Low	Orange
2	-29.567891	26.072222	10,5	Low	Orange
3	-29.098889	26.058333	10,5	Low	Orange
4	-29.014567	26.144565	10,5	Low	Orange
5	-29.012578	26.075565	10,5	Low	Orange
6	-29.005556	26.025898	10,5	Low	Orange
7	-29.292361	26.166667	10,5	Low	Orange
8	-29.076946	26.120568	10,5	Low	Orange
9	-28.995833	25.995833	10,5	Low	Orange
10	-29.168446	26.112233	10,5	Low	Orange

Borehole	Latitude	Longitude	Score D	Class	Colour
11	-29.075321	26.113345	10,5	Low	Orange
12	-29.067528	25.850528	10,5	Low	Orange
13	-29.182341	26.110765	10,5	Low	Orange
14	-29.239611	25.857694	10,5	Low	Orange
15	-29.283324	25.811056	10,5	Low	Orange
16	-29.332056	25.994028	10,5	Low	Orange
17	-28.519876	26.116667	10,5	Low	Orange
18	-28.896223	25.991389	10,5	Low	Orange
19	-29.007389	25.905608	10,5	Low	Orange
20	-28.791234	25.849082	10,5	Low	Orange
21	-29.066667	25.341667	10,5	Low	Orange
22	-28.962778	25.995833	10,5	Low	Orange
23	-28.633241	26.220044	10,5	Low	Orange
24	-29.223557	26.878324	10,5	Low	Orange
25	-29.141083	26.062083	16,5	Moderate	Yellow
26	-29.425139	26.632917	16,5	Moderate	Yellow
27	-29.262148	26.480619	16,5	Moderate	Yellow
28	-28.973456	28.978757	15,5	Moderate	Yellow
29	-28.904639	26.462567	15,5	Moderate	Yellow
30	-28.880806	26.630833	15,5	Moderate	Yellow
31	-28.876754	26.535642	15,5	Moderate	Yellow
32	-29.046543	26.425678	15,5	Moderate	Yellow
33	-29.044944	26.308056	14,5	Low	Orange
34	-29.063256	26.345673	14,5	Low	Orange
35	-29.103864	-29.103089	14,5	Low	Orange
36	-29.102778	26.320278	14,5	Low	Orange
37	-29.118826	26.434841	14,5	Low	Orange
38	-28.551254	25.373452	14,5	Low	Orange
39	-28.625321	25.625765	14,5	Low	Orange
40	-29.243806	25.354222	14,5	Low	Orange
41	-28.941111	25.157778	14,5	Low	Orange
42	-29.233333	25.284567	14,5	Low	Orange
43	-29.122222	25.120872	14,5	Low	Orange
44	-28.702785	25.401392	14,5	Low	Orange
45	-29.182972	25.405139	14,5	Low	Orange
46	-28.822567	25.395757	14,5	Low	Orange
47	-29.291972	25.457528	14,5	Low	Orange
48	-29.141667	25.475567	14,5	Low	Orange
49	-29.241667	25.654352	14,5	Low	Orange
50	-29.033861	25.609833	14,5	Low	Orange
51	-28.936565	25.283421	14,5	Low	Orange

Appendix D

QUESTIONS FOR GROUNDWATER USERS

Questions 1 to 9 were, therefore, proposed for all the groundwater users, especially the farmers who are the main users of groundwater.

1. What is the amount of water abstracted, weekly / monthly?

100–500 litres	
500–1 000 litres	
1 000–5 000 litres	
>5 000 litres	
Other	

2. What is the type and volume of water storage?

	Type	Volume
Groundwater tank		
Underground water tank		
Dam		

3. What is the pumping duration for your storage tank?

<30 minutes	
30 minutes to 1 hour	
1–2 hours	
>2 hours	
Other	

4. What is the capacity of your pump?

0.75 hp	
1.0 hp	
1.5 hp	
2.0 hp	
Other	

5. What is the water geochemistry?

Smell	
Taste	
Colour	

6.	What is the depth or the borehole(s)?	
7.	What is the yield of the borehole(s)?	

8.	At what depth was the pump installed?	
9.	What is the monthly water level?	