Effects of evapotranspiration on water quantity and quality along the Modder River catchment using remote sensing

Silent Ruzvidzo

Dissertation submitted in fulfilment of the requirements for the degree

Master of Technology in Environmental Health

in the

Department of Health Sciences

Faculty of Health and Environmental Sciences

at the

Central University of Technology, Free State

Supervisor: Dr S Oke, PhD (Geohydrology)
Co-supervisor: Dr NJ Malebo, PhD (Microbiology)

Bloemfontein

Declaration of Independent Work

I, Silent Ruzvidzo, identity number and student number , hereby declare that this research project submitted to the Central University of Technology, Free State for the degree Master of Technology: Environmental Health, is my own independent work; and 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 before to any institution by myself of any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

SIGNATURE OF STUDENT

21/12/2020
DATE

Acknowledgements

I would like to thank God, the almighty, who has given me this opportunity and made this research work possible.

My deepest appreciation goes to my family, my wife and children who cared for me and allowed me time to work on this project. My special thanks also go to my wife, Getrude, who assisted me with graphical work and referencing techniques for this research project.

I would also like to express my deepest gratitude to my research supervisor, Dr Oke Saheed, for his advice, patience, guidance, encouragement, and useful critique of this research work.

I would also like to thank Dr Malebo Ntsoaki, my co-supervisor, for her advice and guidance when starting this research work.

My deep appreciation also goes to Ms Palesa Moja who helped in processing the finances for my project expenses for laboratory analysis and software procurement.

Abstract

The effect of evapotranspiration on river catchments needs to be consistently monitored as water availability and usability affects the livelihood and health of all living organisms. The consistent monitoring of water quantity and quality at scale using ground based methods can however be costly and unsustainable. Alternative methods of monitoring such as Remote Sensing thus need to be explored and tested. The main aim of this study was to assess the seasonal water loss and variation in water quality in the Modder River due to evapotranspiration by using remote sensing techniques. Landsat 8 satellite images and data were used to compute remote sensing indices, such as the Normalised Difference Water Index and the Normalised Difference Vegetative Index, seasonally over three years (2017–2019). The remote sensing indices were used to evaluate the surface water area across the Mockes and Krugersdrift dams which are part of the Modder River catchment. The evapotranspiration values were then assessed against the surface water area. Seven water samples were taken across several points on the Modder River and the chemical and physical parameters of pH, electrical conductivity, total dissolved solids, calcium cations, magnesium cations, sodium, potassium, chlorine, nitrates, and sulphates, were used for calculating the seasonal Water Quality Index. The seasonal Water Quality Index was analysed against evapotranspiration, as well as the Normalised Difference Vegetative Index. The Pearson regression test results gave a strong r value of -0,9 between evapotranspiration and water quality relationship as well as a weak r value of -0.22 between evapotranspiration and surface water quantity, respectively. The spring and summer seasons had the maximum and minimun seasonal evapotranspiration average values of 10.1 mm and 7.8 mm respectively with corresponding poor water quality indices of 62.6 and 53.5 respectively. The average seasonal Normalised Difference Vegetative Index values for the Summer, Autumn, Winter, and Spring seasons across the 3 years were 0.34, 0,38, 0.22, and 0.26, respectively. The study outcome showed that potential evapotranspiration does have a significant effect on water quality but showed a weak correlation with surface water quantity. Furthermore, the study proved that remote sensing techniques can be used in assessing surface water quality and quantity parameters.

Key terms: evapotranspiration; remote sensing; water quantity; Water Quality Index

Definition of terms

- **Catchment area**: An area drained by a river basin.
- **Evaporation**: The process in which a liquid turns to vapour.
- **Evapotranspiration**: A combination of evaporation and transpiration, the process by which water is transferred from land and other surfaces to the atmosphere, as well as from plant surfaces.
- **Field capacity** is the amount of soil moisture that remains in the soil after excess water has drained away and the rate of downward water movement has decreased.
- **Remote sensing** is the art and science of acquiring information about an object without making physical contact with the object.
- **Saturation** refers to the state in which all the soil's water content is filled with water.
- **Transpiration**: The process by which water is lost from plant surfaces.

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List of Abbreviations

AOI	Area of interest
COVID-19	Coronavirus disease of 2019
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EC	Electrical conductivity
EOS	Earth Observing System
ET	Evapotranspiration
ET_0	Potential Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographical Information Systems
NDVI	Normalised Difference Vegetative Index
NDWI	Normalised Difference Water Index
NIR	Near-infrared
SAWS	South African Weather Service
SEBAL	Surface energy balance algorithm for land
SWIR	Short-Wave Infrared
TDS	Total dissolved solids
TSS	Total suspended solids
WHO	World Health Organization
WQI	Water Quality Index

Chapter 1
Introduction

1.1 Background

The Modder River catchment is a relatively small river catchment which is in the central region of the Free State province of South Africa (Gwate et al. 2015). It has a mean annual run-off of 184 × 106 m^3 and provides about 60% of the potable water supply of Bloemfontein and its surrounding areas (Koning and Roos 1999). Like most parts of South Africa, the Free State region is arid, with an annual mean rainfall of 407 mm (Bloemwater 2019). South Africa receives an average annual rainfall of 464 mm, well below the global average of 860 mm per annum (Koning and Roos 1999). The total renewable water available per inhabitant is just 1 106 m^3 per annum, placing South Africa among the driest quintile of countries in the world (Food and Agriculture Organization of the United Nations [FAO] 2005).

With the growing scarcity of potable water in most parts of South Africa, coupled with the persistent droughts due to the changing climatic conditions, the importance of water resource monitoring and management cannot be overemphasised. The application and use of technology such as remote sensing in the monitoring and management of water resources in developing countries such as South Africa is crucial as it provides efficient and affordable access to remote areas at large spatial scales as compared to ground based monitoring methods.

The management of water resources in the twenty-first century is one of the ultimate challenges facing the human global population (FAO 2005). As the global population rises, there is growing pressure to develop more innovative ways of monitoring and managing water as the natural supply, in the form of precipitation, is becoming increasingly variable and uncertain with climate change. It cannot be overemphasised that the management of water quantity and the quality of water resources is important for the sustenance of the rising global population (Grove et al. 2015).

Understanding the hydrological processes and closely monitoring the components of catchment water balance, such as evapotranspiration (ET) in relation to the physical and natural environment, provide the basis on which water quantity and quality can be better managed. The Modder River catchment is surrounded by large trees compared to its surroundings. According to Zhang et al. (2001), catchments with large trees have higher ET than grassed catchments.

Terrestrial ET forms a major part of the hydrological and climatic systems and links the major components of the carbon and energy cycles (Liang and Wang 2020). Accurate measurements or estimations of ET are thus crucial in understanding hydrological processes for water resource management. Continuous measurements of ET at spatial scale over long periods of time are limited in sub-Saharan Africa and there is a large knowledge gap in understanding hydrological processes as influenced by ET in this region (Ashaolu and Iroye 2018).

Water loss in hydrological systems can have a direct effect on water quality (Mamba et al. 2008). The quality of water pertains to the suitability of water to sustain various uses or processes such as drinking or supporting invertebrate communities (Chapman 1996; Hassimi et al. 2020). Each particular use has certain requirements for the physical, chemical, or biological characteristics of water, such as concentrations of toxic substances, restrictions on temperature and pH ranges (Koplin et al. 2004). Water quality can be affected by a wide range of natural and human influences. The most important of the natural influences are geological, hydrological, and climatic since these affect the quantity and the quality of the available water (Ratikane 2013). Their influence is generally greatest when available water quantities are low and maximum use must be made of the limited resource such as in arid and coastal areas where high salinity is often experienced.

Toxins in drinking water may pose serious health risks to consumers (Ratikane 2013; Jehan et al. 2019). The adverse health effects include various cancers, reproductive complications, cardiovascular diseases, and neurological disorders (Koplin et al. 2004). Similarly, the quality of water may be affected by salinisation, which could be because of excessive clearance of natural, deep-rooted vegetation from catchments, rising saline groundwater, discharge of saline agricultural wastewater and increasing climatic aridity (Ali 2014; Mahim 2014).

1.2 Study rationale

The effects of ET on water quantity has been widely studied in agriculture to determine how much water is lost by crops through ET. While many studies focused on how much water is lost from plants through ET ,very little attention has been given to the analysis of terrestrial water loss at catchment scale. The major limitation to studying water loss at catchment scale is the availability of resources required by most ground-based methods to make the necessary measurements. To avert this limitation, this study has employed the use of remote sensing technology to try and estimate potential ET at catchment level. The study also investigated the degree of association between ET and surface water quality at catchment scale using remote sensing technology, a technique that few studies have exploited for assessing water loss and water quality. These hypotheses will be tested in this study and will be described in the following section.

1.3 Research aims and objectives

The main aim of this research is to investigate the effects of potential evapotranspiration on the surface water quantity and water quality along the Modder River catchment using remote sensing technology. The study assessed the seasonal relationship between surface water quantity and potential ET, as well as establishing a relationship between remote sensing indices such as the Normalised Difference Vegetative Index (NDVI), and the Normalised Difference Water Index (NDWI) with water quality and water quantity, respectively. This broad aim was achieved through the following sub-aims and objectives:

Sub-aim 1: Assessing the hydrological loss in the Modder River catchment through potential evapotranspiration.

Objectives:

- To estimate the seasonal surface water quantity within the Modder River catchment using remote sensing indices.
- To establish the relationship between potential evapotranspiration and surface water quantity within the Modder River catchment.
- To assess the seasonal healthiness of vegetation along the Modder River catchment using remote sensing indices.

Sub-aim 2: Assessment of the effect of evapotranspiration on water quality in the Modder River.

Objectives:

- To investigate the relationship between potential evapotranspiration and water quality within the Modder River catchment.
- To assess the implications of the seasonal differences in potential evapotranspiration to water quality.
- To evaluate the use of remote sensing as a suitable and reliable method for estimating surface water quantity and water quality within the Modder River catchment.

1.4 Hypothesis

The following null hypotheses were put forward in this research project:

H_0 = Evapotranspiration has a significant impact on surface water quantity and quality within a river catchment.

H_0 = Remote sensing technology can be effectively used to estimate surface water quantity and quality within a river catchment.

1.5 Research scope

The purpose of this study was to investigate the extent to which the process of ET affects the quantity and quality of water in the Modder River catchment. The investigation made use of remote sensing techniques such as the NDWI and the NDVI to evaluate water quantity and vegetation healthiness within the catchment area.

The estimations of the seasonal ET data over the catchment are calculated using the Hargreaves and Samani method over a three-year period from 2017 to 2019. The estimated ET data is compared with the Water Quality Index (WQI), to determine the extent to which ET affects the concentration of solutes in catchment water.

1.6 Limitations of the study

The accuracy of the study outcomes might have been negatively affected by the nature of the methodology used in measuring potential ET, the choices made in selecting the sampling sites and the way the samples were collected, as well as in the time and timeframes from which the research was carried out.

The methodology of the research involved the use of estimation techniques such as the Hargreaves and Samani method to calculate the potential ET. The Hargreaves and Samani method uses estimates of weather parameters such as temperature and radiation from the sun to estimate ET. These estimates might not give a true indication of the actual values of potential ET as would have been with actual ground measurements which could compromise the outcome of this study.

Due to the imposed lockdown of the Coronavirus disease of 2019 (COVID-19) pandemic, the sampling of the water from the Modder River catchment for water quality analysis, which was scheduled for the month of July, could not take place as travelling was not permitted. A very limited number of samples which were obtained in 2019 were thus used to estimate the seasonal water quality for the autumn and winter seasons which were then used in this study. Furthermore, the period for which the research was conducted could have been extended to improve on the number of samples and hence accuracy of the results.

Chapter 2
An overview of the application of remote sensing in assessing the relationship between evapotranspiration, water, and environmental health

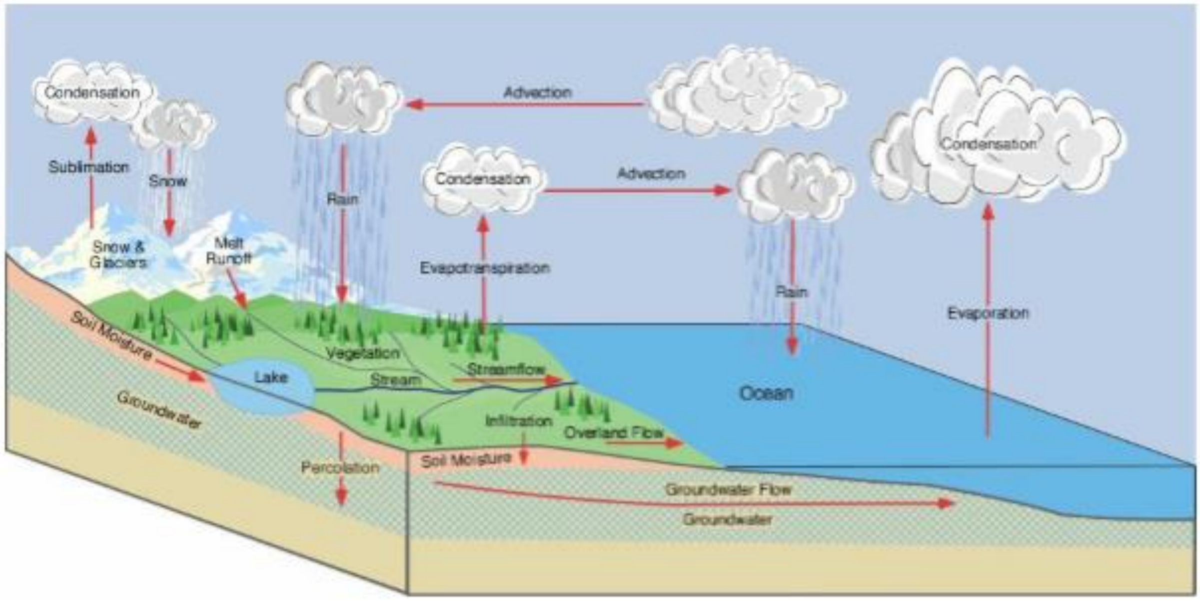
2.1 Introduction

The literature review presented in this chapter is discussed under nine main headings on evapotranspiration as an aspect of catchment water balance, sensitivity of evapotranspiration to climate and weather elements, estimating potential evapotranspiration, applications of remote sensing in environmental monitoring, water quality and environmental health, parameters used in evaluating water quality, application of the water quality index in assessing water quality, the Modder River catchment, and the research gap.

2.2 Evapotranspiration as an aspect of water catchment balance

The changing global climatic conditions coupled with the increasing populations has led to increasing demands for freshwater sources (Jana et al. 2016). As freshwater becomes scarcer, more shrewd measures are needed in planning and optimising the efficient use of the available water resources. Estimating ET in the natural environment is not an easy task as it is affected by some natural processes and cycles involving the vegetation, soil, and the atmosphere (Hellegers et al. 2010). The proficiency to calculate near accurate levels of ET will be of great benefit for water resource managers.

Evapotranspiration is a combination of two natural processes: evaporation and transpiration. In evaporation, water in the liquid state is converted to the gaseous state. The surface molecules of the water gain enough energy (usually from the sun or wind) to transform into a gaseous state (Allen et al. 1998; Collier 2016). Transpiration involves the vaporisation of water molecules from plant tissues, mainly leaves, into the atmosphere. Like evaporation, transpiration depends on energy supply, vapour pressure gradient and wind. According to Ndou et al. (2017), ET is one of the biggest components of the hydrological cycle with an estimated consumption of 60–90% of the annual precipitation. However, the extent to which ET affects water consumption within a river catchment has been rarely assessed across all four weather seasons in South Africa. This study focused on investigating the seasonal effects of ET on surface water. ET influences many ecological processes by playing an important role in balancing the energy and nutrient exchange in ecosystems (Xu et al. 2014). Figure 2.1 shows the detailed processes of the hydrological cycle.



Source: Pidwirny (2006)

Figure 2.1: Hydrological cycle

2.2.1 Water balance in a river catchment

Evapotranspiration is one of the main ways in which water is lost in a drainage catchment (Ali et al. 2016). The hydrological behaviour of a catchment can be reliably analysed with the water balance. The water balance is useful for assessing how changes in catchment conditions can alter the partitioning of rainfall into different components. The water balance for a catchment can be represented in mathematical terms as:

$$P = ET + R + D + AS \qquad (1)$$

Where P is precipitation, ET is evapotranspiration, R is surface run-off measured as streamflow, D is recharge to groundwater, and AS is the change in soil water storage.

The ET rate is normally expressed in millimetres (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth. The time unit can be an hour, day, month, decade, or even an entire growing period or year (Allen et al. 1998; Dadaser-Celik et al. 2016). Ali et al. (2016) described ET as the second-largest term in the water balance equation, and it is closely linked with vegetation characteristics. In arid and semi-arid regions such as Modder River catchment, ET is often nearly equal to precipitation, while in humid areas, it is limited by available energy (Gwate et al. 2018).

2.2.2 Understanding the impact of evaporation and transpiration on water sources

Understanding and measuring the distinction between evaporation from soil and water and transpiration from the leaves in plants are very challenging but crucial in managing scarce water resources. Generally, it is expected that the degree of evaporation is larger in sparsely vegetated systems, particularly in dry areas or in very wet systems such as wetlands.

Separately analysing ET is essential in correctly monitoring water systems to improve water management practices (Kool et al. 2014). In their studies on evaluating the impact of 'E' and 'T' in ET, Collier (2016), Kool et al. (2014) and Pidwirny (2006) concluded that in most cases 'E' often constitutes a larger fraction of ET than 'T'. This study, however, investigated the combined effects of ET on water quality and quantity as it will need more resources and time to investigate the separate components of ET.

2.2.3 Effects of evapotranspiration on surface water and groundwater

The quantity of water in a river catchment can directly affect the surface area covered by water. This can indirectly influence the rate of inflow, outflow, precipitation, and evaporation of a river catchment (Xu et al. 2014). ET can influence the change in the chemistry of groundwater (Humphries et al. 2011). The solutes in groundwater can become progressively concentrated due to ET, resulting in the saturation, precipitation, and accumulation of less soluble compounds (Ali 2013).

In a study conducted by Humphries et al. (2011) to identify the effects of ET on the chemistry of groundwater and pore-water collected from the Mkuze River floodplain in the Okavango Delta, Botswana, it was identified that mineral precipitation was an active process on the floodplain which resulted in the progressive development of salinity, particularly in areas dominated by deep-rooted trees. The study also highlighted that ET-induced chemical sedimentation is an important process in southern African wetlands, which has the potential to influence vegetation distribution, hydrological flows, and local topography. It is, however, unclear on how the process operates in arid environments. Part of this study focused on investigating the effect of ET on the concentration of surface water rather than groundwater.

2.2.4 Importance of land use management

Land use management has a great impact on catchment water balance, water yield and groundwater recharge (Zhang et al. 2001). Evapotranspiration in catchments can be affected by many factors, including rainfall interception, total leaf area and the number of plants available in the catchment. These factors also rely on other variables such as soil type, climate and the state of vegetation. Studies from more than 250 catchments around the world have shown that there is a good long-term relationship between the average ET and rainfall over the long term (Graham et al. 2016).

2.2.5 Measuring evapotranspiration

Evapotranspiration is one of the most important components of the hydrological balance and the most difficult to measure (Tang and Oki 2016). In recent times, the estimation of ET has benefitted from advances in remote sensing, particularly in the field of agriculture. Despite the advances in remote sensing technology, measuring ET from mixed landscape vegetation environments still possesses some challenges due to the heterogeneity of plant species, canopy covers, microclimate, and because of costly methodological requirements. Numerous studies have been conducted in agriculture and forestry, which should alternatively be borrowed for mixed landscape vegetation studies with some modifications (Nouri et al. 2013).

Measuring ET is an important aspect in the local and global assessment and management of climate change, land use, water budget and environmental management. As discussed, the loss of water through evaporation mainly occurs from three main sources, namely the soil, vegetation surface or atmosphere. The evaporation of water from the soil is affected by the soil moisture status, the physical and chemical characteristics of the soil, tilth conditions, soil cover and ecological parameters. On the other end, evaporation of vegetation surface moisture is influenced by vegetation type, species, canopy cover, microclimate, and water availability to the plants through precipitation (Arnell 2016).

The estimation of ET has improved over recent years through advances in technology which brought about the improvement in mechanisms and tools of measurements such as remote sensing. Remote sensing makes use of satellite imagery to evaluate ET for a broad range of pixels to global scales (Karpov et al. 2019). Remote sensing can also be used together with some empirical methods to simplify the ET measurement and shorten the input data requirements. Regardless of a wide range of applications of the remote sensing technology, the ET estimation of mixed catchment vegetation remains insufficiently characterised due to the diversity in water needs of the various vegetation systems and types (Drexler et al. 2004; Maitra 2011).

The use of hydrological methods, such as the water balance to estimate ET, and meteorological methods, such as energy balance, can only be considered as point measurements. The extrapolation of the ET rates from a single point to a large area dilutes the accuracy of the estimation (Gibson et al. 2018). Measuring ET by remote sensing provides an area-based estimation that can be updated frequently. Remote sensing has the capacity of quantifying vegetation characteristics, including species composition, moisture status and vegetative type over a large area (Arnell 2016; Nouri et al. 2013).

2.2.6 Weather parameters affecting evapotranspiration

The primary weather parameters affecting ET are plant exposure to sunshine, air temperature, humidity, and wind speed (Xing et al. 2016). Various techniques have been developed to assess the evaporation rate from these parameters. In this study, each of these weather parameters was assessed against ET within the Modder River catchment to give an overview of how each of these parameters affect ET in arid catchments.

In vegetation environments, ET is the main consumer of precipitation. Studies have indicated that more than 90% of annual rainfall in arid and semi-arid areas is consumed by ET (Glenn et al. 2007). For many years, weather-based methods such as the soil moisture measurements, and surface energy balance approaches have been the most used techniques for estimating ET in vegetation (Allen et al. 1998; Maina et al. 2018). Almost all these ET estimation models require detailed input data of vegetation, soil, and climate parameters to obtain regional and local ET estimations.

2.3 Sensitivity of evapotranspiration to climate and weather elements

Evapotranspiration is one of the major components of the hydrological cycle. According to Goyal et al. (2004), ET can be influenced by weather and climatic parameters such as air temperature, humidity, wind speed, sunshine hours and rainfall. This means that any sudden or long-term change in climatic parameters will affect ET or vegetation water requirements, thereby affecting the management of water resources. The sensitivity of ET to different climatic variables can differ significantly among climates (Tabari and Talaee 2014). The data on the sensitivity of ET to changing climatic conditions can also be used to assess the impact of climate change in agriculture and forestry.

2.3.1 Wind speed

The use of ET to describe the suitability of a given climate on determining transpiration from vegetation or evaporation from wet surfaces may lead to wrong conclusions about the consequences of climate and weather aspects on plant growth and water relations. Recent studies have shown that wind speed increases the rate of evaporation from surfaces but plays a big role in reducing transpiration (Schymanski and Or 2015). The effect of increasing wind speed may result in an increase in potential evaporation, which is commonly interpreted as increased "water stress". However, at the same time, the effect of increasing wind speed can reduce leaf transpiration, implying a decrease in water demand at the leaf scale (Akinola and Josiah 2016). Unlike the other weather and climate variables, the dual nature of wind on ET makes it difficult to analyse its wholistic effect on the ET process.

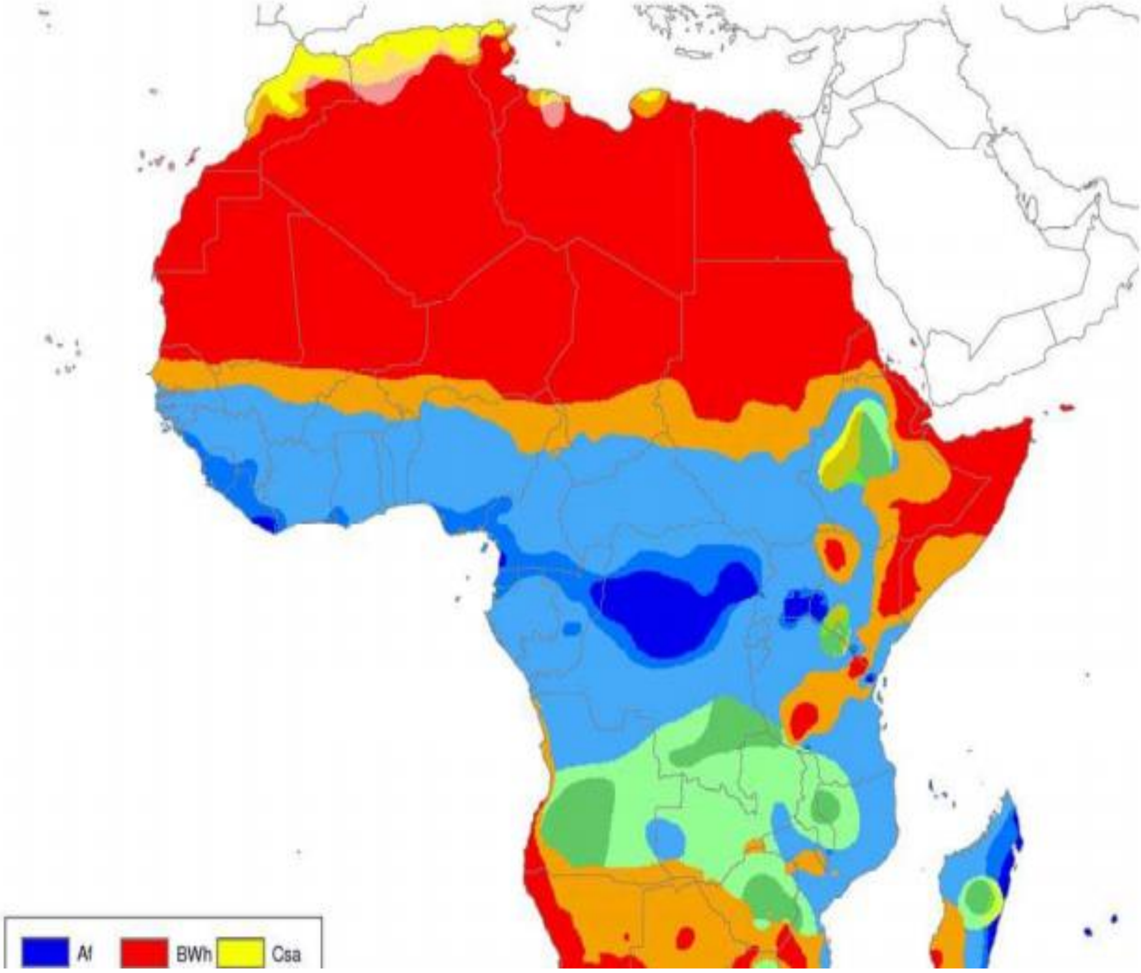
2.3.2 Precipitation

Precipitation has a strong impact on streamflow, and it is one of the most important elements of water balance within a catchment (Jarmain et al. 2009). Although increased precipitation can lead to an increase in streamflow, its impact on ET has been found to vary dis-proportionately. Increased rainfall has been shown to lead to larger increases in streamflow and comparatively smaller increases in ET (Garbrecht et al. 2004; Liu et al. 2015).

Precipitation and ET represent the volumes of incoming and outgoing water in the hydrological budget. This can be observed in terms of water balance which demonstrates the condition of water surplus or deficit at a place and time. The spatial and temporal variability in the amount of precipitation and ET can severely impact water resources management, agriculture, and all the major economic activities that depend on water (Ashaolu and Iroye 2018).

2.3.3 Temperature

According to the Köppen–Geiger climate classification system, the climate of the Modder River catchment can be classified as semi-arid (Peel et al. 2007; Wanders 2015). As shown in Figure 2.2, the African map of the Köppen–Geiger climate-type shows that the Modder River catchment area can be most likely classified under the Cwa (C=Temperate, w=dry winter and a=hot summer) category. The Cwa category is characterised by temperatures with very hot summers and average temperatures with a minimum of 22°C, with dry winters. The high temperatures, low rainfall, low humidity, and high wind speed conditions can be characterised by very high ET rates, especially in the summer months (MacLeod and Korycinska 2019).

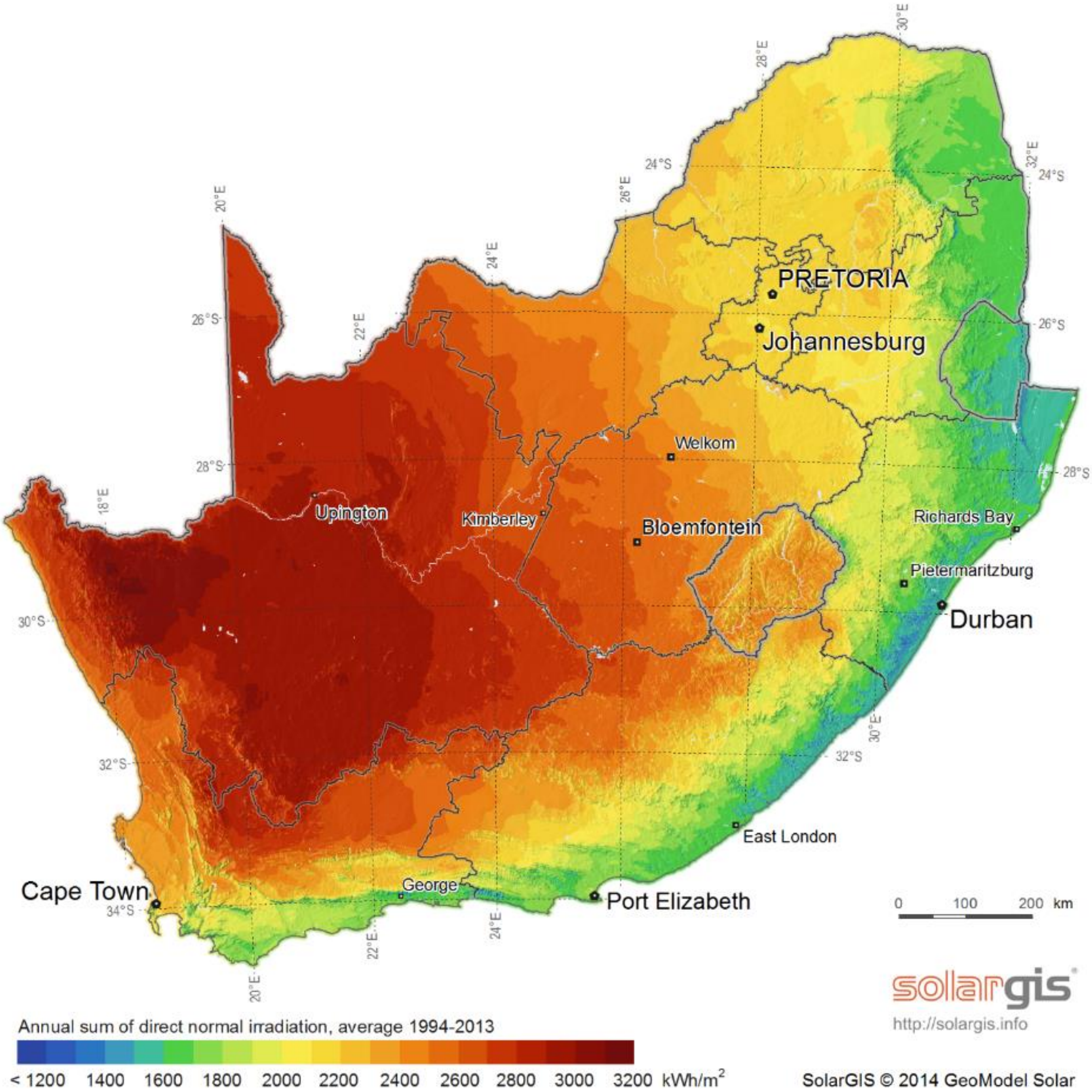


Source: Peel et al. (2007)

Figure 2.2: Köppen-Geiger climate-type map of Africa

2.3.4 Solar radiation

The Modder River catchment is in a region which is characterised by high solar radiation (Centre for Renewable and Sustainable Energy Studies 2014). Figure 2.3 shows the updated direct normal solar irradiation map of South Africa.



Source: Centre for Renewable and Sustainable Energy Studies (2014)

Figure 2.3: Updated direct normal solar irradiation map of South Africa, Lesotho and Swaziland

According to the map, the average solar radiation received by the area within the Modder River catchment ranges between 2 400 and 3 000 kWh/m^2. Solar radiation is the principal source of energy for the climate system. Variability in the amount of energy received at the earth's surface has implications for ET and water resources management.

According to Suri et al. (2015), the utilisation of incoming solar radiation by plants is limited by other factors, mainly water availability, either in the form of rainfall or underground capillary inflow. While most plants require radiation to grow, excessive radiation may disrupt the stomatal resistance. Stoma is a small air hole within the plant leaf that controls and adjusts water vapour levels leaving the plant. Too much radiation on plants leads to the stomata closing to reserve water (Gurjar et al. 2017). However, the prolonged exposure to radiation can lead to the stomata failing to open for a long period of time, leading to stunted growth and ultimately destroying the plant (Gurjar et al. 2017).

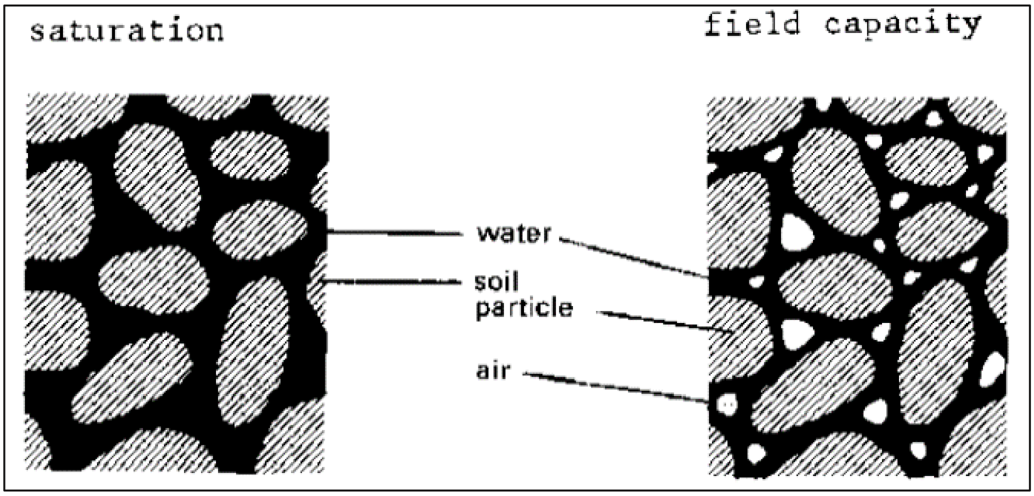
The changes in cloud cover, aerosol emissions, and air pollution associated with economic developments are widely considered to be responsible for a substantial part of solar radiation. In their studies on finding the relationship between solar radiation and ET, Xu and Usher (2006) discovered that changes in pan evaporation in the Yangtze River catchment in Asia were mainly caused by the changes in solar radiation.

2.4 Estimating potential evapotranspiration

Evapotranspiration is a key parameter of the hydrological budget which influences the terrestrial ecosystem processes such as surface run-off, soil moisture content and plant growth (Jovanovic et al. 2020). Reliable methods for estimating potential ET are critical for accurately assessing the water balance at catchment and regional scale.

2.4.1 Exploring methods for estimating potential evapotranspiration

In most cases, the direct field measurement of ET is not attainable because it is costly, time-consuming, and often requires expensive field instrumentation (Jarmain et al. 2009; Jovanovic et al. 2020). To circumvent these challenges, many researchers resort to using estimation methods to calculate the reference ET. The reference ET is often used to represent the potential ET in situations where the soil is at field capacity (Egwuonwu et al. 2012). This is because when the soil is at field capacity, the actual ET will equal the potential ET and moisture input will exceed potential evaporation. Figure 2.4 shows the soil particles at field capacity. Egwuonwu et al. (2012) explained that in such scenarios, the excess rainfall over ET is known as water surplus, while water deficit is represented by the condition of excess ET over rainfall. Because of this concept, this study has interchangeably used potential ET and actual ET.



Source: Brouwer et al. (1985)

Figure 2.4: Soil moisture characteristics with field capacity

Estimation of evapotranspiration remains one of the most important challenges for the agricultural and environmental sciences. The determination of reliable data collection and ET calculation methods is a key aspect to the determination of accurate ET. Most techniques for estimating ET around the world have been around for many decades. However, it is only in the last two decades that technology has allowed them to become reasonably affordable and practically applicable methodologies (Jarmain et al. 2009). The full potential for most of these technologies is yet to be realised in developing countries, while at the same time new opportunities also need to be explored for improved measurement, such as through the complementary use of ground-based and remote sensing techniques, especially for larger scale water resource-related applications.

Various methods are used to measure ET in arid and semi-arid catchments. These methods range from direct field measurements to computing ET using weather data such as temperature or radiation or a combination of both (Irmak et al. 2008; Watson and Burnett 1995; Xu and Singh 2002). ET can be estimated by using water balance methods such as atmometers, lysimeters, the eddy covariance techniques and the Bowen ratio energy balance system. However, although these direct methods might be more accurate in measuring ET compared to the estimation methods, the direct methods are costly and time-consuming (Hargreaves et al. 2003). Environmental and water managers need to develop and test reliable methods for estimating ET that can be conveniently utilised to quickly detect changes in water resources. This study explored and used an ET estimation method that requires limited weather data for arid and semi-arid regions.

2.4.2 Surface energy balance algorithm for land method

One of the most widely used methods in estimating and measuring ET is the surface energy balance algorithm for land (SEBAL) method (Jana et al. 2016). The SEBAL method comprises an image processing model with an average of 25 computational steps that calculate the potential and actual ET rates, as well as other energy exchanges between land and atmosphere (Kallarackal and Roby 2017). The SEBAL method has been widely used to measure the actual ET for crops in agriculture, as well as for measuring water loss through ET in open water sources. In the SEBAL method, satellite observations are used together with meteorological data in estimating the actual ET of a place (Jana et al. 2016; Patel et al. 2006).

The SEBAL method is based on a thermodynamic model that partitions between sensible heat flux and latent heat of vaporisation flux (Wageningen 2017). The SEBAL method had been used in various studies in agriculture and the results of the studies showed that satellite observations with meteorological information could yield satisfactory estimate values of ET in plants (Wageningen 2017). However, the use of the SEBAL method is limited in most cases in that it requires the use of complex mathematical calculations combined with some ground-based meteorological data, making it very unaffordable to employ in low budget studies.

2.4.3 Reflectance and derivative indices method

Understanding the biochemical and physiological processes of plants has enabled environmental scientists to exploit various ways of using remote sensing techniques in estimating terrestrial ET. In one of the studies conducted by Furuuchi et al. (2013), estimates of plant crown transpiration and water use efficiency were determined by using reflectance and derivative indices obtained from remotely sensed chlorophyll fluorescence measurements by using a portable spectrometer. The use of these techniques enhances the accuracy of the ET estimation but requires skill and expertise that in many cases may not always be available. However, in this study, the idea of using reflectance indices was employed on water extraction and estimating plant density.

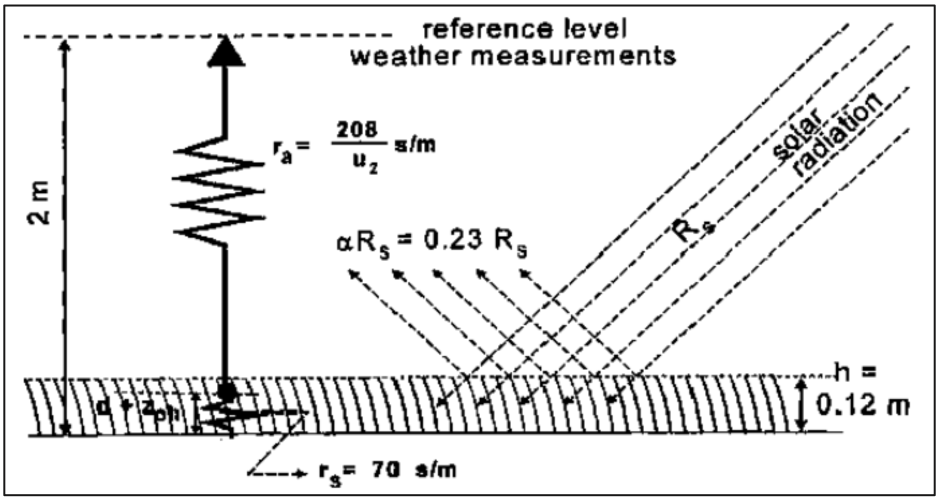
Over the last six decades, environmental and agricultural scientists throughout the world have developed numerous empirical and less empirical methods to estimate ET from different climate variables (Allen et al. 1998; Jovanovic et al. 2020; Nusantara and Nadiar 2020). The major challenges with most ET estimating methods were that the relationships between variables were often subject to rigorous local calibrations and proved to have limited global validity. To accommodate different data availabilities, four methods were earlier proposed for use to calculate the reference crop ET. These were the Blaney–Criddle, the modified Penman, and the radiation and pan evaporation methods (Djaman et al. 2015).

The modified Penman method is considered to offer the best results with a minimum possible error in relation to a living grass reference crop (Nusantara and Nadiar 2020). It was expected that the pan evaporation method would give acceptable estimates, depending on the location of the pan. The radiation method was suggested for areas where available climatic data include measured air temperature and sunshine, cloudiness, or radiation, but not measured wind speed and air humidity. The Blaney–Criddle method was recommended for areas where available climatic data covered air temperature only (Hargreaves et al. 2003).

Although no ET estimation method is error-proof, these four methods were considered to offer the best results with minimum errors. Methods such as the pan evaporation method were expected to supply acceptable estimates depending on the location of the pan, whereas the radiation method was suggested for areas with available climatic data, including measured sunshine, radiation, air temperature, but humidity and temperature were not measured (Tabari and Talaee 2014).

2.4.4 Penman–Monteith method

The Penman-Monteith method was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m and having a surface resistance of 70 s m^{-1} and an albedo of 0.23 (Al-Kazragy 2020; Allen et al. 1998). This standard was closely resembling the evaporation of an extension surface of green grass of uniform height and actively growing and adequately watered. Figure 2.5 shows some of the characteristics of the hypothetical crop/plant.



Source: Allen et al. (1998)

Figure 2.5: Characteristics of the hypothetical crop/plant

The adjustments of the original Penman-Monteith equation with respect to the aerodynamic and surface resistance parameters gave rise to the following new equation:

$$ET_0 = \frac{0.40\Delta(Rn - G) \quad + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

Where:

ET_0 = reference ET [mm day^{-1}]

R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}]

G = soil heat flux density [MJ m^{-2} day^{-1}]

T = mean daily air temperature at a 2 m height [°C]

u_2 = wind speed at a 2 m height [m s^{-1}]

e_s = saturation vapour pressure [kPa]

e_a = actual vapour pressure [kPa]

$e_s - e_a$ = saturation vapour pressure deficit [kPa]

D = slope vapour pressure curve [kPa °C^{-1}] and

γ = psychrometric constant [kPa °C^{-1}]

(Allen et al. 1998; Dengxiao et al. 2017; Hua et al. 2020).

Through the Penman–Monteith equation, the reference ET, ET_0 provides a standard to which ET at different periods of the year or in other places or regions can be compared and the ET of other plants can be related. The equation uses standard climatological records of sunshine or solar radiation, humidity, air temperature and wind speed. To ensure the integrity of computations, the weather measurements should be taken at a height of at least 2 m above the ground, or if not, should be converted to that height above an extensive surface of green grass.

Although various methods for estimating ET exist, the Penman–Monteith equation has been adopted and recommended by many studies because of its suitability for use under various climatic conditions (Dengxiao et al. 2017). However, the major challenge with using the Penman–Monteith method is that some of the climatological and weather data needed to compute ET might be difficult to gather, especially in developing countries. However, according to Tabari (2010), radiation-based methods can be used to provide better estimates for ET in semi-arid and arid regions. For the purposes of this study, numerous ET estimating methods were explored to determine the most appropriate method which would balance accuracy, efficiency, and data availability.

2.4.5 Hargreaves and Samani method

In most cases, it is not easy to acquire all the weather data required to calculate the estimated ET as required by the Penman–Monteith equation. The lack of data coupled with other factors such as the constant changing in climate and weather patterns compromise the quality of the measurements in agricultural and environmental studies (De Rooij 2018). To solve these and other problems, radiation-based methods for estimating ET were preferred for this study. These methods require simple meteorological input data, such as air temperature and sunshine radiation to compute potential ET. The Hargreaves and Samani equation is shown as follows:

$$ET_o = 0.0023\ Ra\ (Tmean + 17.8)(Tmax - Tmin)^{0.5} \quad (3)$$

Where, Ra = water equivalent of extraterrestrial vegetation; Tmean = mean air temperature; Tmax = daily maximum air temperature (ºC); Tmin = daily minimum air temperature (°C).

The Hargreaves and Samani equation have been widely adopted as the great alternative to the Penman–Monteith equation (Almorox and Grieser 2016). This is because the Hargreaves and Samani method requires very few weather data parameters and can be used in areas where weather data is not readily available. Several studies have recommended the use of the Hargreaves and Samani method for arid and semi-arid regions and its accuracy in these conditions has been comparable to that of the Penman–Monteith equation (Djaman et al. 2015).

The Hargreaves and Samani model was adopted in this study to estimate ET because of the quality of the weather data that was available, costs of accessing the weather data, site aridity, and the simplicity of conducting the computations.

2.4.6 Limitations of the evapotranspiration measuring methods

The recent advances in technology and analyses conducted by researchers has continued to expose shortcomings with regard to some ET measuring methods and techniques. In most instances, the ET estimating methods have shown great deviations between computed and observed ET values. The modified Penman method has been frequently found to overestimate ET_0 by up to 20% for low evaporative conditions (Hua et al. 2020). Numerous studies have shown that most ET estimating methods vary widely in their performance under different climate conditions (Gibson et al. 2018).

In some instances, the radiation methods show good results in humid climates where the aerodynamic term is relatively small, but performance in arid conditions such as the Modder River catchment is erratic and tends to underestimate ET (Djaman et al. 2015). Uddin et al. (2013) highlighted that most temperature-based methods are empirical and require local calibration to achieve satisfactory results, except for the 1985 Hargreaves method which has shown reasonable ET_0 results that are within global limits.

The pan ET methods clearly reflect the shortcomings of predicting crop ET from open water evaporation as their performance is erratic. The methods are susceptible to the microclimatic conditions under which the pans are operating and the rigour of station maintenance (Almorox and Grieser 2016). The analysis of the performance of the numerous ET calculation methods revealed the need for formulating a standard method for the computation of ET_0.

2.5 Applications of remote sensing in environmental monitoring

Remote sensing is the art and science of detecting, monitoring, and measuring the physical characteristics of an area or object by using spectral reflectance (Gandhi et al. 2015; Mather and Koch 2011). The spectral reflectance of the emitted and reflected radiation is recorded by using sensors mounted on satellites or aircraft and processed and analysed by computer software to identify and categorise objects by class, substance and spatial distribution (Mather and Koch 2011; Stone and Mohammed 2017).

Remote sensing techniques can be used to monitor physical and biological processes from satellite images (Peng 2019). The major advantage of using remote sensing in monitoring the environment is that it can be applied in large areas for various vegetation types with a minimum amount of ground data (Peng 2019). Remote sensing techniques have been widely used in agriculture and wildlife sanctuaries to monitor water loss from natural water sources as well as vegetation growth in forests (Sirisha et al. 2016).

Unlike most ground-based monitoring methods, the use of multispectral remote sensing images is very cost-effective for obtaining a better understanding of the environment. Remote sensing techniques make use of acquiring information through satellite data and extracting features in the nature of spatial and temporal images of objects such as vegetation, land cover for urban and agricultural use, and water resources without impending physical contact with these objects (Jung et al. 2020).

2.5.1 Remote sensing indices

Several indices have been developed to assist in analysing the vegetation and water features on the ground using remotely sensed images from various satellite stations. Some of the most important and commonly used indices used for analysing water and vegetation features are the NDVI and the NDWI (Tadesse et al. 2015; Sirisha et al. 2016). The use of these indices has been very popular among researchers due to their usefulness and convenience in estimating water and vegetation biomass in agriculture (Masocha et al. 2017).

2.5.1.1 Normalised Difference Vegetative Index

The NDVI is one of the most widely applied indices in monitoring vegetation at local and regional scales (Jana et al. 2016). The NDVI is frequently used to monitor drought, plant growth in agriculture as well as in forecasting fire zones in forests (Earth Observing System [EOS] 2020). The NDVI can be calculated by using the formula:

$$\text{NDVI}=\frac{NIR-Red}{NIR+Red} \tag{4}$$

Where NIR represents the reflection in the near infra-red spectrum; and Red represents reflection in the red range of the spectrum (Gessesse and Melesse 2019).

The NDVI value varies between -1 and +1. The negative values usually represent water, snow, or cloud cover, while the values close to zero represent bare soil or rocks. According to EOS (2020), the values ranging from 0.1 or less of the NDVI correspond to empty areas of sand, desert, rocks, glaciers, or snow; the values between 0.2 and 0.3 correspond with meadows or shrubs, while the large values between 0.6 and 0.8 represent temperate and tropical forests. Lower NDVI values represent stressed vegetation, while higher NDVI values represent higher density green and healthy vegetation (Gandhi et al. 2015).

Many studies involving the use of the NDVI in environmental monitoring have focused on drought monitoring, extraction of surface water and establishing the link between the NDVI and the physical water quality of surface water such as rivers, lakes, and dams (Acharya et al. 2018). In some studies, the NDVI has been shown to have a very good positive correlation to physical water quality (Calders et al. 2020; Masocha et al. 2017). This study aimed to find the relationship between the NDVI and NDWI to ET and non-physical water quality parameters, a relationship that has been rarely investigated by other studies.

2.5.1.2 Normalised Difference Water Index

The NDWI makes use of the reflected near-infrared radiation and visible green light which was used to provide estimations on available surface water (Chapungu and Nhamo 2016; Gao 1996; Mather and Koch 2011). The NDWI uses the formula:

$$\text{NDWI}=\frac{NIR-SWIR}{NIR+SWIR} \tag{5}$$

Where, NIR represents the near-infrared range with wavelengths in the range of 0.841 to 0.876 nm and the SWIR represents the short-wave infrared wavelengths in the range of 1.628 to 1.652 nm (EOS 2020). The SWIR reflectance shows the changes in both the plant water content and the spongy mesophyll structure in plant canopies. On the other hand, the NIR value for reflectance is affected by the internal structure of the plant leaf and not by water content. The combination of using the NIR with the SWIR helps improve the accuracy of the NDWI in identifying the water content of vegetation (Ceccato et al. 2001).

Near accurate estimations of surface water have been made possible by remote sensing. In their studies on testing the effectiveness of different remote sensing indices on water extraction, Acharya et al. (2018) concluded that NDWI was very efficient in detecting water bodies. This study also aimed at validating the reliability of using these remote sensing indices in the arid Modder River basin.

2.5.2 Usefulness of combining both the Normalised Difference Vegetative Index and Normalised Difference Water Index

According to Goyal (2004), ET is one of the most important components of the hydrological cycle, the outcome of establishing its effects on the NDVI and NDWI is crucial for the work of water and environmental monitors and managers.

The usefulness of using both the NDVI and NDWI in extracting the water content in vegetation has been shown in many studies. In their study on extracting water bodies and using time series to detect changes in the lake Burdur in Turkey, Gulcan and Mehmet (2016) highlighted the use of several remote sensing indices such as the NDVI, NDWI, the modified NDWI as well as the Automated Water Extraction Index. Statistical tests performed on these indices indicated that the NDWI was more reliable at detecting water bodies than the rest of the indices tested within the study area.

Remote sensing indices are commonly used for surface water estimation which separates water from the background based on a threshold value. However, according to Acharya et al. (2018), the challenge with using a threshold value is that it can be adversely affected by background environmental noise such as snow, clouds, shadows, forest cover and buildings. In response to this, this study has employed the use of validation techniques from which remote sensing values can be compared with ground-based measurements.

2.5.3 Limitations of remote sensing methods

In this study, remote sensing techniques were used for extracting water bodies and estimating surface water quantity. Remote sensing methods are convenient compared to ground-based assessment methods, however, their accuracy and reliability is still a cause of concern among researchers. In some instances, remote sensing indices have shown susceptibility to data errors during the rainy season (Sruthi and Mahommed 2015). Considering this, it is always better to merge the use of the indices with other parameters or ground-based methods to ensure more accuracy. As part of assessing the reliability of remote sensing methods, this study will also assess the suitability of using remote sensing as a reliable tool for estimating water quality variables within a river catchment.

2.6 Water quality and environmental health

The quantity and quality of water available in water resources play a significant role in the functioning of ecosystems as well as on the health of all living organisms, including humans (Gwate et al. 2015). Rivers and streamflows are crucial for the health and well-being of aquatic and terrestrial ecosystems. The combination of the factors such as soil type, land cover and climate within a river catchment affect the rainfall–run-off relationships and thereby the quantity and quality of water that ends up flowing in the rivers (Bloemwater 2019). It is therefore imperative to understand the relationship and the impact of natural processes such as ET on the water balance, as well as on the water quantity and quality, as all life depends on water.

According to the World Health Organization (WHO 2008), water resource management is the first barrier against drinking water contamination from chemical and microbial contaminants of the source water. Water resource management and possible polluting human activities in the catchment have the potential to influence water quality downstream. This can have a huge impact on the treatment steps required to ensure that the water is safe for drinking. In under-resourced countries, water resource management can mean a matter of life and death as the water treatment facilities do not usually meet the desirable standards. The regular assessment of water quality parameters in the source water is therefore crucial in analysing pollution activities within the areas surrounding the catchment.

2.6.1 Assessment of the water quality in river catchments

Water quality can be defined as the suitability of water to sustain various uses or processes (Bartram and Balance 1996; Daniel et al. 2020). Any particular use will have certain requirements for the physical, chemical or biological characteristics of water, such as limits on the concentrations of toxic substances for drinking water use, or restrictions on temperature and pH ranges for water supporting invertebrate communities (WHO 2003).

Water quality deterioration is a major threat to water resources in Southern Africa (Mare 2007). The prevalence of drought due to climate change has largely affected the hydrological processes leading to the deterioration of water quality in open source water (Nel et al. 2013). The dilapidation of river catchments is one of the most concerning environmental problems that is faced by developing countries in Southern Africa (Masocha et al. 2017). Environmental and water managers are constantly faced with challenges on how to constantly assess the water quality in river catchments at scale with minimum costs but better accuracy.

Target 7C stipulated under Goal 7 of the South African Millennium Development Goals specifies that the number of people without access to safe water sources should be halved by the year 2015 (Statistics South Africa 2015). However, according to the 2015 progress report on the Millennium Development Goals, the target had not been achieved by the end of 2015 (Statistics South Africa 2015). The quality of natural water intended for the purpose of using it as drinking water varies both temporally and spatially (Bilotta and Brazier 2008). This variation changes considerably in different seasons.

2.6.2 Factors affecting water quality

The concentration of dissolved oxygen in a river may vary as a result of input from run-offs, which may transport different types and concentrations of contaminants such as heavy metals from urban storm water drainage systems or chemicals from agricultural fields where only a single watercourse is involved (Grove et al. 2015). Factors such as the location of a river, its origin and climatic conditions can also affect the water quality (WHO 2006). The influence of these factors is generally greatest when available water quantities are low and maximum use must be made of the limited resources such as the high salinity commonly experienced as arid and coastal areas (Wu et al. 2020). Salinisation of surface water through evaporation in arid and semi-arid regions and the high salt content of some groundwater under certain geological conditions, may render the natural water unfit for drinking purposes (Wu et al. 2020).

2.6.2.1 Effects of natural processes on water quality

The composition and concentration of chemical elements and compounds in a river system are subject to changes by various types of natural biological, chemical, and physical processes (Gupta et al. 2017). The concentration of dissolved material in lakes and rivers is mainly through the processes of evaporation and transpiration. The decay of dead vegetation adjacent to water bodies can influence the quantity of organic and nitrogenous compounds in natural water (Xu and Usher 2006). The growth, death, and decay of aquatic plants such as algae also affect the concentration of nitrogenous and phosphorus nutrients, pH, and dissolved oxygen in water. Aquatic vegetation has varied effects on the chemistry of lake and river water. The chemistry of lake water is generally more affected than that of river water (Gupta et al. 2017; Xu and Usher 2006).

2.6.3 Using remote sensing to assess water quality in surface waters

Remote sensing tools provide spatial and temporal views of data of surface water quality parameters that are not readily available from in situ measurements (Nouri et al. 2013). This makes it possible to monitor the water bodies such as rivers, dams, and lakes more effectively and efficiently through identifying and quantifying water quality parameters. Some of the major factors affecting water quality in water bodies across the landscape are suspended sediments which affects the turbidity, algae with pigments such as chlorophylls and carotenoids, chemicals from pesticides, fertilisers, dissolved organic matter, thermal releases, aquatic vascular plants, pathogens, and oils (Chen et al. 2019). These pollutants change the energy spectra of reflected solar or emitting thermal radiation from surface waters which can be measured using remote sensing techniques. However, some chemicals and pathogens do not directly affect or change the spectral or thermal properties of surface waters, so they can only be inferred indirectly from measurements of other water quality parameters affected by these chemicals (Mackintosh and Colvin 2003).

In a study conducted by Masocha et al. (2017), the remotely sensed index, NDVI, was used to assess the level of the total suspended solids (TSS) in more than 32 sub-catchments in Zimbabwe. The results of the study showed a consistent negative curvilinear relationship between the Landsat 8 derived NDVI and TSS measured across the catchments under study. Jordan et al. (2014) highlighted that the NDVI and NDWI indexes can be used to distinguish water sources, depending on their purity as indicated by their spectral reflectance. The findings of these studies emphasised the usefulness of having readily available satellite data for near-real time monitoring of the physical water quality at river catchment scale, especially in resource-constrained areas, such as the sub-Saharan Africa.

2.6.4 Implications of drinking polluted water

Polluted drinking water can pose serious health risks to people if it is not well treated. According to Xu and Usher (2006), the major concerns of drinking water pollution in Africa are pathogens, organic agents, salinisation, and nitrates. It is estimated that more than seven million people in South Africa do not have access to clean drinking water and approximately 8 600 children under the age of five years die due to waterborne diseases each year (Mackintosh & Colvin, 2003). It is therefore necessary for all the stakeholders in water quality and management to initiate interventions to improve the quality of drinking water.

2.7 Parameters used in evaluating water quality

The monitoring of water quality in open water sources such as lakes, dams and rivers requires many parameters to be analysed (WHO 2006). The main water quality parameters that are considered for evaluating surface water quality include water temperature, dissolved solids, suspended solids, pH, turbidity, biological oxygen demand, chemical oxygen demand, phosphorus compounds and nitrogen compounds (Gupta et al. 2017). These water quality parameters can be categorised into physical, chemical, and microbiological parameters. The physical parameters include temperature, turbidity, and electrical conductivity (EC), while the chemical parameters include pH, alkalinity, dissolved oxygen, and the total hardness of the nitrogen containing compounds, phosphates, carbonates and sulphates (Hassan et al. 2008). The microbial water quality assessment involves the measure of the water conditions which are related to human and animal health requirements. It mainly involves the analysis of concentrations of pathogenic microorganisms, and the microbial indicators of possible pathogen contamination in water sources (Pachepsky et al. 2018).

For the purpose of this study, not all water quality parameters were tested as the objective was to find the relationship between water quality and ET. Parameters which do not have significant health risks, such as sulphates, and parameters which occur in very low quantities in water, such as fluorides, were just used entirely for concentration determination of surface water. Some of the parameters analysed in this study are explained below.

2.7.1 pH

The pH is a measure of the acidity or alkalinity of a solution. The pH scale is a logarithmic scale which ranges from 0 to 14. Pure water has a pH of 7 which is neutral, but is very difficult to find in natural water sources. Water with a pH below 7 is acidic, while water with a pH greater than 7 is considered basic (Gorde and Jadhav 2013). According to the standards and guidelines for drinking water quality of the Indian Council of Medical Research (2007) and the WHO (2006), the average healthy pH for water required by a human body lies between 6.5 to 8.5. A pH below 6.5 may result in the human body failing to process minerals, including vitamins, while a pH of more than 8.5 may result in people having skin disorders and eye irritations (Indian Council of Medical Research 2007; WHO 2006). Very acidic pH within the range of 3.5 to 4.5 have been observed to negatively affect the quality of aquatic life (Guo et al. 2017).

2.7.2 Electrical conductivity

Electrical conductivity is a numerical expression of the capacity of an aqueous solution to conduct an electric current (Yegül et al. 2020). The ability of an aqueous solution to conduct electricity depends on several factors, some of which are on the presence of dissolved ions, their concentrations, their electronic configuration, and the temperature of the water. The EC of a solution is proportional to the amount of dissolved ions or solute. The conductivity of pure water is very poor (less than 1 µmhos/cm), while the solutions of most inorganic acids, bases and salts are relatively good conductors (Gorde and Jadhav 2013).

2.7.3 Total dissolved solids

Total dissolved solids (TDS) is a parameter that is used for measuring the amount of solid materials that are dissolved in surface or groundwater (Bilotta and Brazier 2008). The presence of natural and anthropogenic organic materials in larger concentrations in surface water can have an impact on the odour, colour and taste of water which can be harmful to humans as well as to aquatic life (Brix et al. 2010). Some studies have also shown that the high TDS concentrations in water can have some harmful negative effects on human health such as the disruption of the central nervous system, irritability and dizziness (WHO 2006).

All rivers contain considerable quantities of suspended solids and dissolved solutes under natural conditions (WHO 2003). The existence of suspended sediments ranging from nano scale particles, and colloids to excess suspended sand-sized particles is the most common cause of water quality deterioration in freshwater systems all over the world (Grove et al. 2015). It has now been established that suspended solids are an extremely important cause of water quality deterioration that may lead to higher costs of water treatment, a decline in the fisheries resources, and serious ecological degradation of aquatic environments (Bilotta and Brazier 2008).

2.7.4 Turbidity

Turbidity is a relative measure of the level of clarity of water (Zăbavă et al. 2019). It is an optical feature of water which measures the interference of water in the penetration of light. Excessive concentrations of particulate matter affect light penetration into the water which affect habitat and aquatic life (Gupta et al. 2017). High turbid water containing heavily suspended solids from raw sewage might shelter pathogens and lead to waterborne disease outbreaks (Manhokwe et al. 2013). The WHO (2008) guidelines have recommended a range limits of 2.5–5.0 ppm on turbidity for source drinking water, depending on the processes used for wastewater treatment.

Natural factors such as run-off and the geological composition of the riverbed affect the levels of the suspended solids and dissolved solutes in water (Katherin 2013). In most cases, anthropogenic factors such as industrial and agricultural activities severely influence the levels of dissolved and undissolved particles in river water (Mamba et al. 2008). These particles have a major influence on the biological, chemical and physical aspects of stream water.

2.7.5 Alkalinity

Alkalinity is a total measure of the acid neutralising capacity of water (Schroeder 2003; Sharma and Saxena 2016). It is usually measured by titration of water with a standardised acid such as sulphuric acid to the end point of the acid base titration. Alkalinity is a measure of the buffering capacity of the water (Gorde and Jadhav 2013). The buffering capacity of water is an important measure of water quality since pH has a direct effect on organisms as well as an indirect effect on the toxicity of certain other elements in the water. The buffering bases present in water are usually bicarbonates and carbonates and alkalinity can thus be generally expressed as the equivalence of calcium carbonate concentration (Sáez et al. 2013).

The alkalinity is also determined by the concentration of cations such as calcium and magnesium. Rivers and lakes with limestone bedrock are usually well buffered (Sáez et al. 2013).

2.7.6 Nitrogen and nitrates

Nitrogen makes up about 80% of the atmospheric gases (Gupta et al. 2017). Nitrogen and its derivatives can end up in water due to natural or anthropogenic activities (Xu et al. 2014). Nitrogen gas in water can be fixed by blue–green algae into ammonia. However, in most cases, nitrogen enters surface water and groundwater as nitrates from fertilisers that are used in agriculture (Mamba et al. 2008). An increase in the number of nitrates or nitrogen in surface water can result in the reduction of oxygen in surface water which negatively affects aquatic life (Mamba et al. 2008). High level of nitrates in drinking water have been shown to cause diseases such as the Blue Baby syndrome in babies (Fan 2014). The disease occurs because of the reaction between nitrates and iron within the haemoglobin of red blood cells creating a compound called methaemoglobin (Fan 2014; Knobeloch et al. 2000). Methaemoglobin has a poor binding capacity to oxygen and causes respiratory complications in children. The WHO (2006) guideline of 50 ppm for nitrate in drinking water has been established to protect infants from methemoglobinemia. Nitrate levels over the 50 ppm have been shown to have adverse health effects on reproduction in humans with possible links to carcinogenicity (Rojas-Rodriguez et al. 2020).

2.7.7 Microbiological organisms

The health of many people in the world is negatively affected by the microbial contamination of water that are used for drinking, cooking, and recreation (Papchepsky et al. 2018). The early detection of pathogenic microorganisms through use of indicator microorganisms in source water is crucial in the monitoring and management of water quality (Fan 2014). Indicator organisms such as Escherichia coli (E. coli), Enterococci, total coliforms, and faecal coliforms are mainly used as primary indicators for the contamination of water sources (Onyango et al. 2018). The presence of these microbial strains in water is usually an indication of the presence of possible pathogenic organisms which can be a danger to human health (Manhokwe et al. 2013). For instance, the presence of E. coli in water is an indication of faecal contamination (WHO 2004).

2.7.7.1 Limitations of using microbial organisms as indicators

Although indicator organisms have been traditionally used to indicate water contamination, they have their own limitations and must be used together with other methods of pollution detection. Several studies have shown that major etiological microorganisms such as Guardia, Vibrio Cholerae, Salmonella and Cryptosporidium, cannot be detected with other tests such as that of E. coli and Enterococci (Gorde and Jadhav 2013). It is also important to realise that rainfall can subsequently increase the levels of microbial contamination through surface run-off. This is an important aspect to consider when doing research on the seasonal effects on microbiological water quality (WHO 2004).

2.8 Application of the Water Quality Index in assessing water quality

Several water quality parameters have been used as indicators for measuring water quality. The major challenge of using different indicators for assessing water quality is that there is no single measure that can coherently give an overview description of the water quality for a water body (Adimalla 2020). The need for a composite index that identifies the need to which the water quality measurements deviates from the normal or expected concentrations is more appropriate for summarising water quality conditions across different water types in different periods of time. To address the challenges in standardising water quality measurements, the WQI was developed. The WQI combines several water quality property measurements to produce a single number that describes the water quality at a specific measuring point within a river, stream, or lake.

Currently, there is no method that has been accepted worldwide on measuring the composite index on water quality (Sarkar and Abbasi 2006). Some countries rely on the use of combined water quality data in the development of water indices. Several water quality indices depend on standardising data of each water quality parameter according to the expected concentrations which can be interpreted as acceptable or not acceptable. Water quality parameters are often weighed according to their perceived importance to the overall water quality and the index is calculated as the weighted mean of all the observations made (Hassan et al. 2008).

2.8.1 Development of the Water Quality Index

The development of a WQI that represents the water quality as a single value has been embraced by water managers around the world as it makes it easy to analyse different variables at a time. The first WQI that was developed for the analysis of surface water quality, was developed by Horton in 1965 (Malan et al. 2003: Wertz and Shank 2019). Horton was able to use 10 water quality parameters that included biological, chemical, and physical parameters (Lumb et al. 2011). Horton's approach was, however, criticised for excluding some crucial water quality parameters; therefore, several modifications have been done by assigning weights to individual water quality properties (Brown et al. 1970; Sarkar and Abbasi 2006).

The development of Horton's WQI paved the way for researchers to develop their own indexes. Several countries and researchers in countries such as Britain, Canada, Malaysia, and the United States of America developed their own water quality indexes that were more suited to their environmental contexts (Horton 1965; Sutadian et al. 2018). Some of the indexes that were developed included the Canadian Council of Ministers of the Environment WQI (CCME WQI), the Weighted Arithmetic Index Method, the Florida Stream WQI (FWQI) as well as the British Columbia WQI (BCWQI) (Gorde & Jadhav 2013; Sarkar & Abbasi 2006; Strategic Assessment of Florida Environment 1995).

2.8.2 World Health Organization guidelines on water quality parameters

The WHO guidelines have classified water quality parameters into two major areas, which are health guidelines and acceptable guidelines (United Nations Environment Programme 2007). The health guidelines consider the chemical and radiological constituents that have the capacity to negatively affect human health. On the other hand, the acceptability guidelines include water quality parameters that may not be harmful to human health, but negatively affect the taste and odour of the water. The WHO has also assigned microbial guidelines that stipulates the number of harmful microorganisms that can be detected by indicator organisms in water. Currently, the WHO guideline for faecal contamination is zero counts per 100 ml (Boyacioglu 2007). However, the guideline has been described as too stringent and other countries have developed their own guidelines for microbes, for instance, the guidelines for microbes in countries such as Swaziland for drinking water quality in rural areas have been set as 10 counts per 100 ml on coliform bacteria (Rickwood and Carr 2007).

2.9 Modder River catchment

2.9.1 Geography of the Modder River catchment

The Modder River catchment is situated in the Free State province in central South Africa. The Free State province is situated between latitudes 26.6° S and 30.7° S and between longitudes 24.3° E and 29.8° E (Moeletsi and Walker 2012). The Free State has an estimated area of 129 825 km^2, making it the third largest province in South Africa (Nape 2011). The whole Modder River catchment covers a total area of 17 366 km^2, which is approximately 13% of the area of the Free State province (Gwate et al. 2015). The Modder River catchment can be divided into three sub-basins, namely the Upper Modder, the Middle Modder, and the Lower Modder (Gwate et al. 2015).

2.9.2 Dams within the Modder River catchment

"Modder" is the Afrikaans name for mud (Rooseboom 1978). The Modder River originates in the eastern side of the Lesotho highlands and crosses the catchment downstream by dividing it approximately into two equal parts, the north and the south, which ends up at the western and flat lowlands (Gwate et al. 2015). It is estimated that the Modder River has a mean annual run-off of 184 × 106 m^3 (Bloemwater 2019). The water from the Modder River is stored in the Mockes, Rustfontein, Maselspoort and Krugersdrift dams (Koning and Roos 1999). The Modder River can be dry for long periods, particularly during the winter months, and the impoundments are the only permanent sources of water.

2.9.3 Settlements along the Modder River catchment

The Modder River catchment provides about 60% of the potable water supply of Bloemfontein (Welderufael et al. 2013). The Modder River catchment houses the Botshabelo settlement which was founded around the 1970s (Welderufael et al. 2013). The settlement releases treated and untreated effluent in tributaries flowing into the Modder River, thereby adding concentrations of contaminants into the streamflow (Griesel and Jagals 2002). The discharge of raw and treated effluent directly into the Modder River is a cause for concern for when it comes to the drinking water quality standards.

2.10 Research gap

The investigation of the effects of ET on water quantity and water quality at catchment scale is a well-known area that has been explored by numerous studies. Since the early 1970s, many studies have focused on deriving methods that can effectively measure crop ET in agriculture, but very little attention was paid to assessing terrestrial ET. Several methods which were used to measure ET in agriculture, such as the Penman–Monteith method, the SEBAL method, and the Blaney–Criddle method, have now been adopted for use in terrestrial environments. However, the major limitation posed by applying these methods in a terrestrial setting is the enormity of the scale required when assessing variables and catchment scale. The purpose of this study was to assess the effectiveness of employing remote sensing techniques in investigating the relationship between ET and water quantity and quality at catchment scale. The effectiveness of the remote sensing techniques will be validated by ground-based measurements on water quantity and quality. The possible use of remote sensing techniques involving remote sensing indices to give estimations of water quality and quantity, is a research area that has never been largely explored.

Chapter 3
Materials and Methods

3.1 Introduction

The remote sensing images used in the study were taken from the Mockes and Krugersdrift dams. The dams were chosen as they already have built-in gauges that can measure water levels and run-off flow along the catchments from the Department of Water and Sanitation (DWS). This made data access on water quantity convenient, thus saving time and resources. Another reason for choosing two representative study areas within the same river catchment was that it allowed room for validation and comparison of the results, which enhanced control on the accuracy of the study. The two sites that were chosen showed a whole representation of the Modder River catchment as one is in the Upper Modder River catchment (Krugersdrift Dam) and the other one in the Middle Modder River catchment (Mockes Dam).Furthermore, the Mockes and Krugerdrift dams are key water sources for agricultural and recreational activities with the Modder River basin and the study outcomes will benefit the development of the farming activities within the area.

For water quality measurements, more sampling sites along the Modder River were used; these included the Rustfontein and Groothoek dams. This ensured that the data from most areas along the catchment was adequately represented.

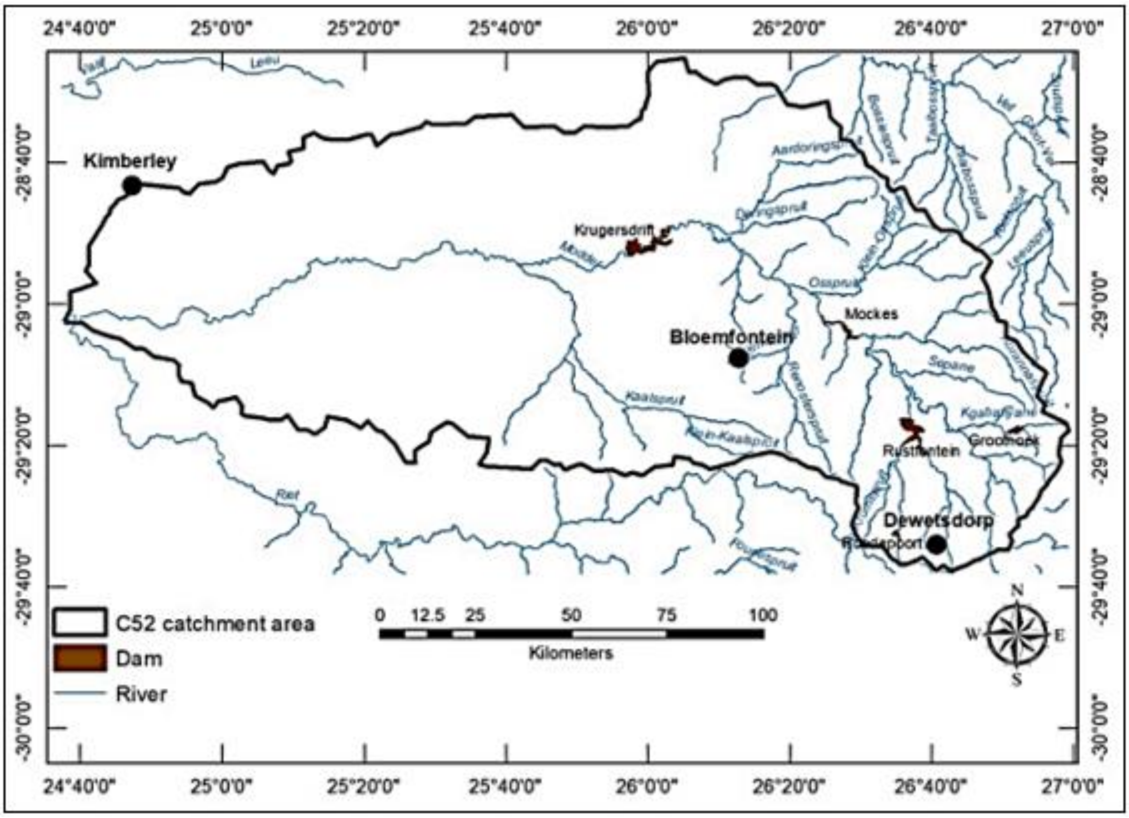
The workflow of this study included the selection of the study sites, data collection, including sampling, data processing, derivation of the seasonal water and vegetation indices, and the seasonal analysis of results for water quality and quantity. The remote sensing images from the two study sites along the Modder River catchment were analysed simultaneously, though independently. Each site was evaluated qualitatively and quantitatively based on the independent data collected. The results from the two study sites were compared to ascertain the accuracy of the results and methods used.

The South African climate is comprised of four seasons which are Summer, Autumn, Winter, and Spring. All the samples and datasets used in this study were collected at the peak month of each season. The peak months for Summer, Autumn, Winter, and Spring seasons were February, May, August, and November respectively.

3.2 Study area

The Modder River catchment has a total estimated area of 17 300 km^2 (Gwate et al. 2015). It is one of the catchments belonging to the Upper Orange River with a total area of 189 539 km^2 (South Africa DWA 2012). The Modder River is divided into three sub-catchments which are named the Upper Modder, the Middle Modder, and the Lower Modder (Gwate et al. 2015).

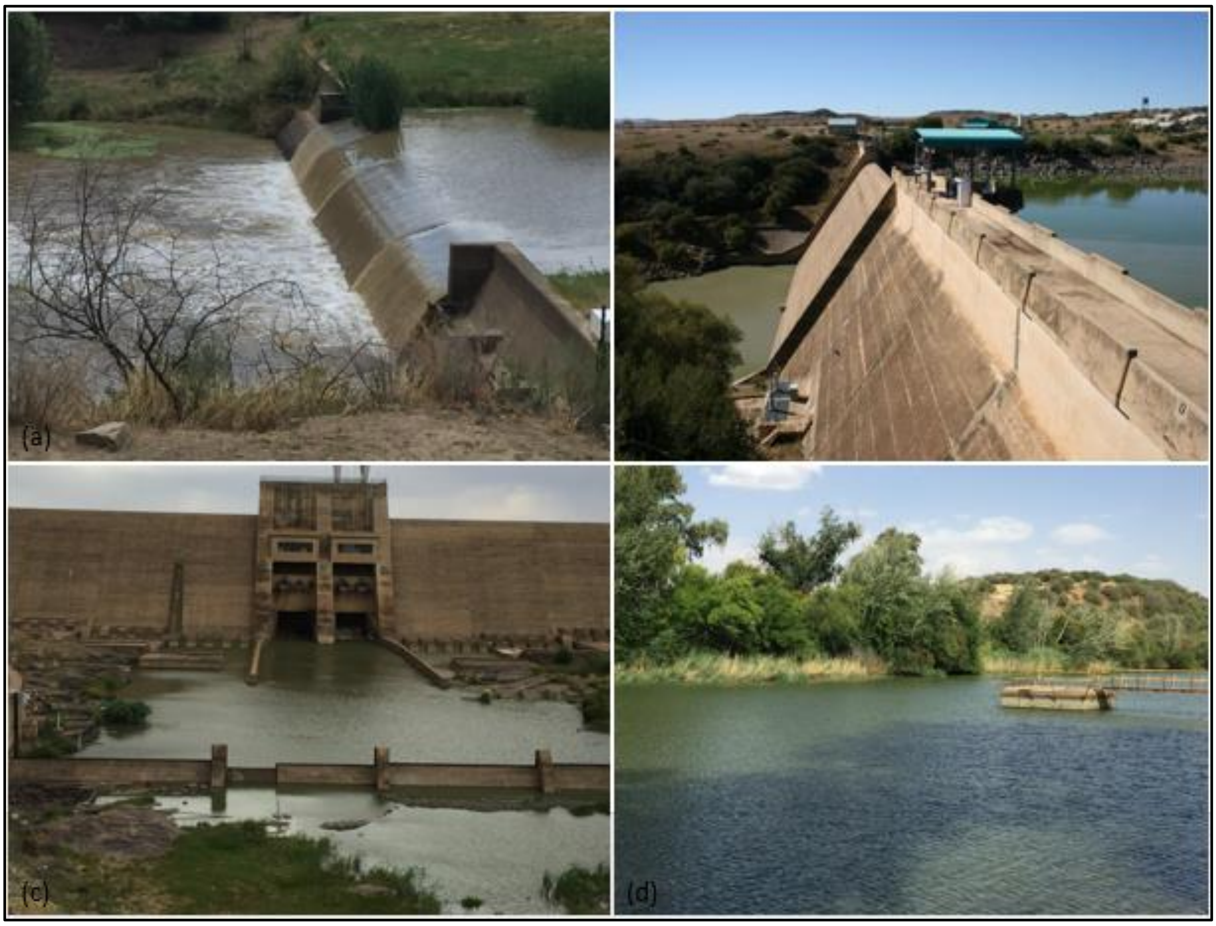
The Modder River catchment supplies water to the greater Mangaung Metropolitan Municipality which covers the areas of Bloemfontein, Botshabelo and Thaba 'Nchu (South Africa DWA 2012). Thaba 'Nchu receives raw water primarily from the Kgabanyane River where the water is stored in the Groothoek Dam with a capacity of 11 million cubic metre, and treated at the Groothoek water treatment plant (Ratikane 2013). The Rustfontein Dam receives water from the Knennespruit Dam and provides treated water to the Rustfontein water treatment works before it is released to the Mangaung Metropolitan Municipality to augment the Mockes Dam. The Rustfontein Dam has a capacity of 70 million cubic metre and a catchment area of approximately 940 km^2 (Bloemwater 2019). Figure 3.1 shows the map of the Modder River catchment with the Krugersdrift, Mockes, Rustfontein and Groothoek dams.



Source: Alowo and Oke (2020)

Figure 3.1: ***Map of the Modder River catchment showing the location of the Mockes and Krugersdrift dams***

In this study, samples collected form the Groothoek, Rustfontein, Maselspoort, Mockes and Krugersdrift dams were used for water quality analysis across the catchment. However, the Krugersdrift and Mockes dams were the only two dams from which remote sensing and surface water level data was acquired. This choice was made to improve the resolution of the remote sensing images by focusing on small areas within the catchment, rather than analysing the whole catchment. Figure 3.2 shows the dams from which the water quality samples were taken for analysis, and Figure 3.3 shows the map indicating the terrain of the Krugersdrift and Mockes dams with respect to the Southern African region.



Source: Author's own (2020)

Figure 3.2: ***Rivers and dams along the Modder River catchment (a) Likatlong, (b) Rustfontein, (c) Krugersdrift, (d) Maselspoort***

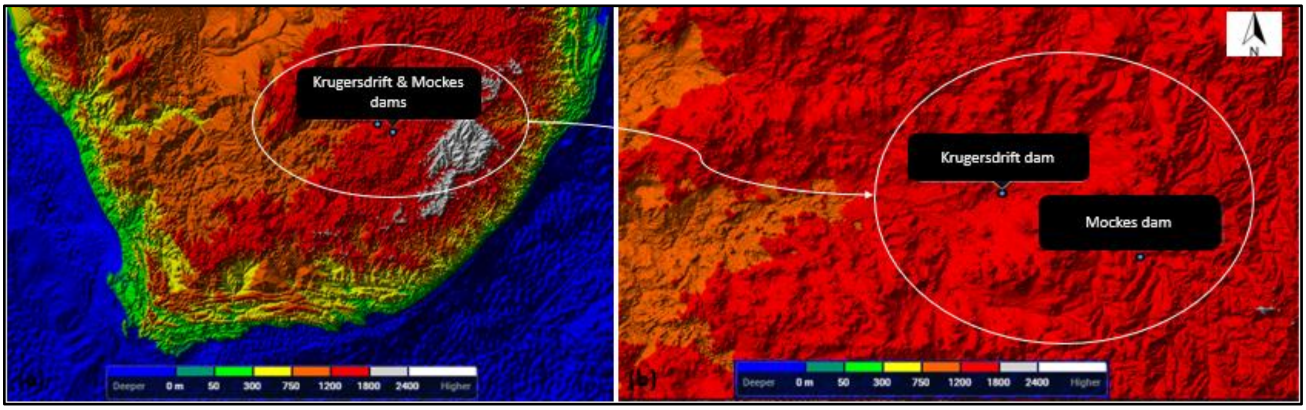


Figure 3.3: ***Map showing the terrain of the Southern African region (a) and an insert of the locations and terrain of the Krugersdrift and Mockes dams (b)***

3.3 Study design

A Time Series–Quasi Experimental Research design was used in analysing variables in this study. This study design was followed because it allowed the evaluation of the relationship between variables such as rainfall, temperature, humidity, ET, water quality and water quantity over time, under natural conditions (Patidar 2013). The objectives of the study were met through the collection and analyses of data without prior knowledge of the outcomes. The study design comprised of three distinct stages which are mapping of the study area, data gathering and data analysis. Figure 3.4 shows all the different stages of the study.

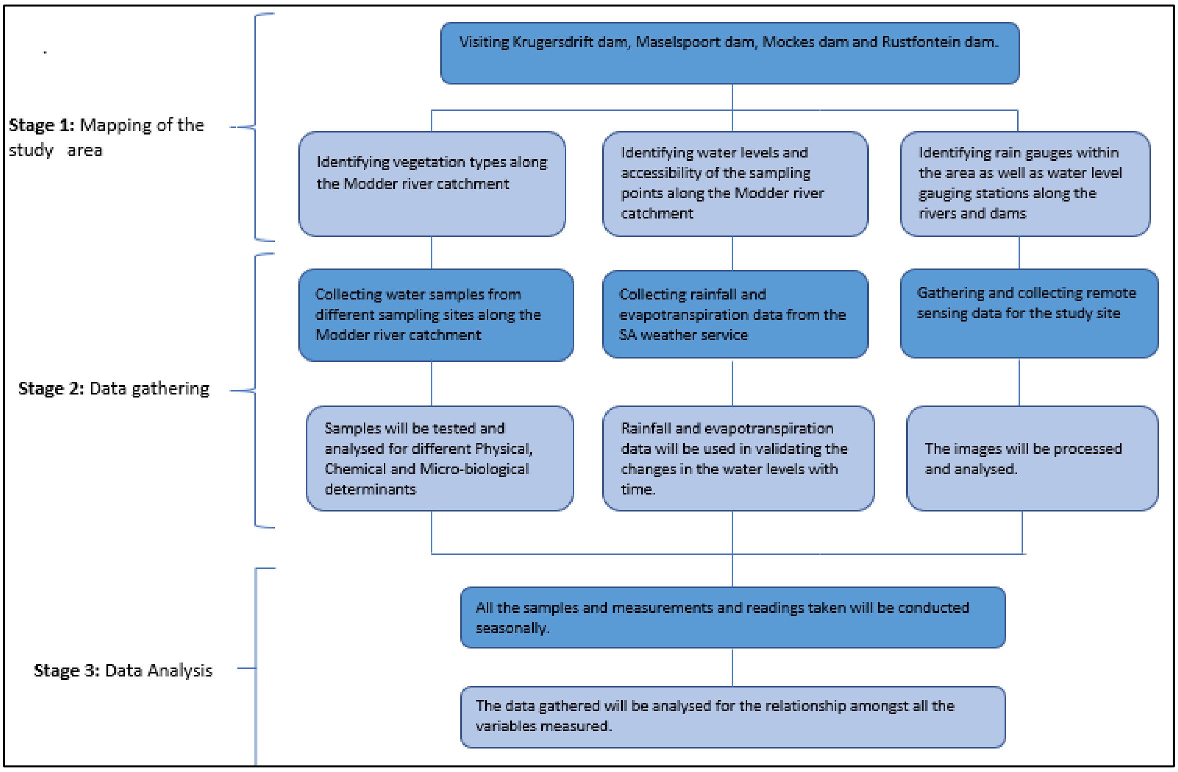


Figure 3.4: Different stages of the study

3.3.1 Mapping of the study area

The first stage involved the mapping of the Modder River catchment area from the Groothoek Dam area, Rustfontein Dam area, Mockes Dam area, Maselspoort Dam area to the Krugersdrift Dam area. The purpose of the mapping was to familiarise with the study sites, as well as to enable the planning and structuring of the study through the identification of the sampling points, the type of vegetation surrounding the catchments, water measuring points, and the instruments along the river catchment. The mapping stage also involved the identification and georeferencing of the study areas on the satellite images via the EOS.

3.3.2 Data gathering

Satellite data comprising of remote sensing indices and remotely sensed images of the study sites was continuously downloaded from the EOS Land Viewer website for each season between the years 2017 and 2019. To identify the seasonal effects of potential ET on water quality, water samples were collected seasonally from the six sampling points along the Modder River catchment. Some data on water quality and quantity was acquired from the National Water Management System provided by the DWS. The weather data used for the seasonal analysis and calculation of potential ET was obtained from the South African Weather Service (SAWS).

3.3.3 Data analysis

The satellite images acquired from the EOS, together with some analytical images of remote sensing indices were georeferenced and further analysed to provide information on the surface water area and the healthiness of vegetation along the Modder River catchment. The seasonal water samples collected from the study sites were tested for chemical, microbiological, and physical components at the Institute of Groundwater Studies at the University of the Free State in Bloemfontein. The results from the tests were used to calculate the WQI to help analyse the correlation patterns between the potential ET and water quality.

3.4 Description of the study method

3.4.1 Acquisition, processing, and analysis of remote sensing data

The remotely sensed Landsat 8 images of the Mockes and Krugersdrift dams, together with the surrounding vegetation, were acquired for a three-year period (2017–2019) from the EOS Land Viewer website. The three-year period was chosen because it followed the drought years of 2015 and 2016, and because the data was readily available.

This data does not suffice to be used on a study of climate change, which was however not the focus of this study. The Landsat 8 satellite images were used because of their comparatively improved radiometric resolution and precision in the characterisation of land cover states (U.S. Geological Survey 2020). For each year, two sets of images (one for the Mockes Dam area and the other for the Krugersdrift Dam area) were obtained for each of the four seasons, namely the summer, autumn, winter, and spring seasons. The images for the summer, autumn, winter, and spring seasons were acquired in the months of February, May, August, and November, respectively, according to the SAWS (2019). The image set for each season composed of the NDVI and the NDWI images to be used in the analysis of vegetation biomass distribution and surface water coverage along the Modder River sub-catchments, respectively. Although the satellite images acquired from the EOS website had already undergone preprocessing to correct some errors and remove distortions, the images were further processed by means of georeferencing to insert the geographical coordinates with respect to the location of the study area.

3.4.2 Use of the remote sensing indices

The NDVI and the NDWI were analysed for each year and season. The NDVI is a remote sensing method that displays the healthiness and greenness of vegetation relative to its biomass (EOS 2019). It does this by comparing the reflectivity of Near Infrared (NIR) and Red wavelength bands from plants with the formula:

$$\text{NDVI}=\frac{NIR-Red}{NIR+Red} \tag{6}$$

The NDVI value varies between -1 and +1. The NDVI value for healthy vegetation is closer to 1 as the healthy vegetation absorbs most of the visible light that hit it and reflects a large portion of the NIR (Chapungu and Nhamo 2016; Mather and Koch 2011).

The NDWI makes use of the reflected near-infrared radiation and visible green light was used to provide estimations on available surface water in the Mockes Dam area. The NDWI uses the formula:

$$\text{NDWI}=\frac{Green-NIR}{Green+NIR} \tag{7}$$

The NDWI values are dimensionless and vary between -1 and +1 (Mather and Koch 2011; Samborski et al. 2017). Values closer to +1 indicate higher water content and values closer to -1 indicate low water content (EOS 2020). Hydrological models on the EOS website were used together with the NDWI images in predicting the surface water available in the Mockes Dam area. The rainfall data and surface water level data obtained from the South African Department of Water Affairs (DWA) were used for validating the study data.

3.4.3 Image processing and classification

Image processing refers to the process of modifying an image from its original state to enhance landscape features and be able to conduct analysis of various parameters, while image classification refers to the interpretation of images using computer assisted techniques

(Zhong et al. 2018). In most cases, the image classification process is based on the detection of spectral signatures of land cover classes. There are two general types of image classification techniques: supervised and unsupervised (Mather and Koch 2011).

Both supervised and unsupervised classification methods were used in classifying images in this study. Recognisable vegetation features such as large trees and shrubs that were observed during sample data collections and site visits were used as markers in the land cover mapping. The spectral features of some regions of known land cover types, also known as training areas, were extracted from the image. The pixels in the whole image were then classified in relation to the proximity of their spectral features to the features of the training areas.

3.5 Surface water

The surface water used in this study was estimated using remote sensing techniques. EOS algorithms computed the estimations of the total surface water available within the catchment by using Landsat 8 images. The surface water was estimated for all four seasons between the years 2017 and 2019. To validate the remote sensing water data, the surface water level data from the DWS station gauges, located along various sub-catchments of the Modder River, were used to provide the measured data. The surface water area measured by remote sensing was used as the proxy of representing surface water quantity.

3.5.1 Estimating surface water using remote sensing

Estimations of surface water in the Modder River catchment were conducted using algorithms from the EOS on Landsat images. The EOS estimations were based on the surface area covered by water within the river catchment and was measured in square metres (m^2). In some instances, the units of surface water in this study were converted to square kilometres (km^2) to make them representable in graphs. Several steps were followed on the EOS website for the surface water estimations to be conducted. The steps are listed below.

Step 1: The login onto the EOS website platform was conducted using the URL https://platform.eos.com/

The EOS dashboard platform has four major focus options which are the Land Viewer, EOS Processing, EOS Storage, and EOS Vision. The Land Viewer option was selected from these four options by using the START NOW button as shown in Figure 3.5. The Land Viewer option provides users with information on Imagery search, on-the-fly indices calculation, custom band combinations, and save results in multiple formats.

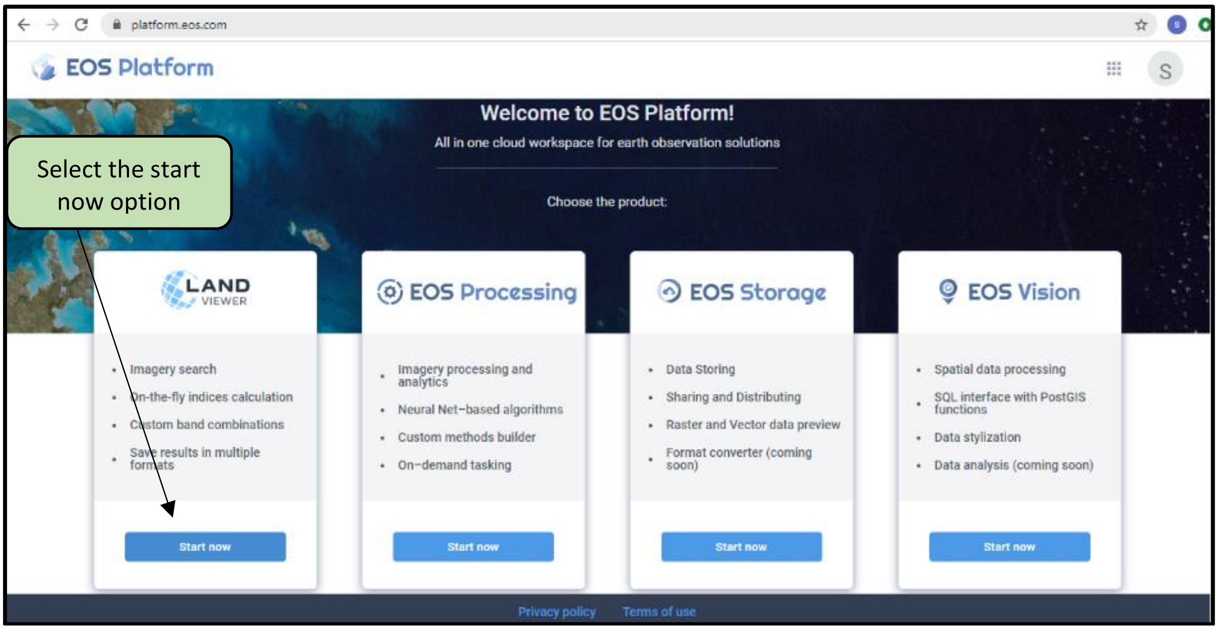


Figure 3.5: Dashboard platform on the EOS webpage

After clicking the START NOW button on the Land Viewer option, the page showing the world map showed up. The page offers various tools which can be used to select the area of interest (AOI) from the world map. The page is represented by Figure 3.6.

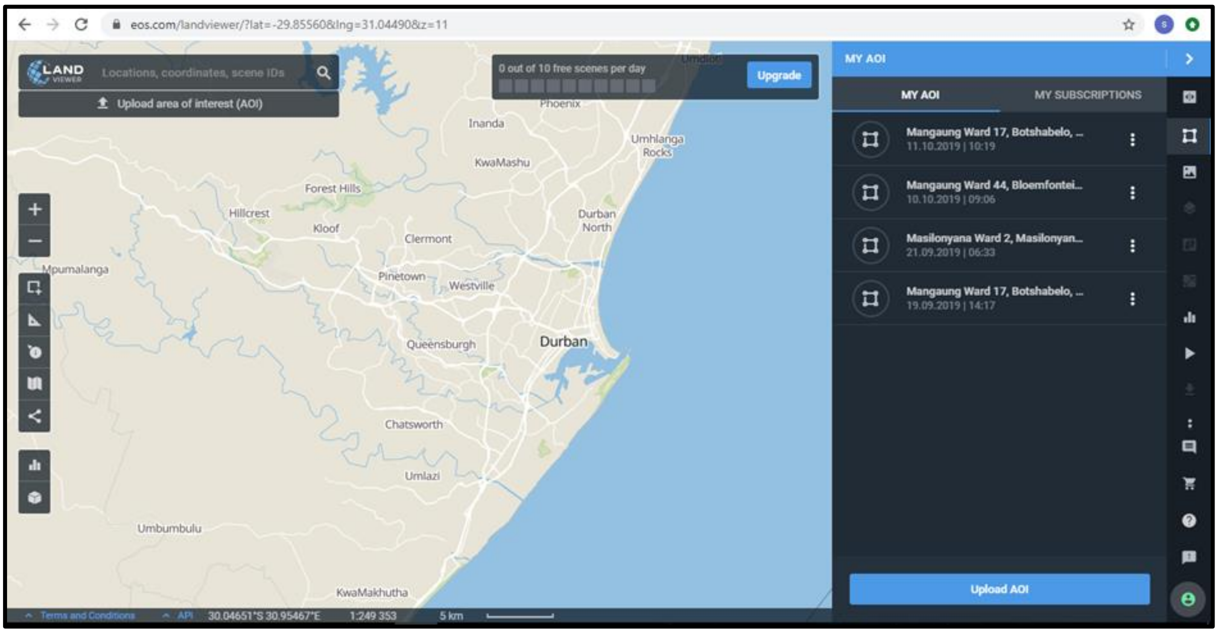


Figure 3.6: EOS page showing the world map

Step 2: Selecting the area of interest from the world map

Using the rectangular shaping tool on the far left, the AOI comprising of areas of the Modder River catchment was selected as shown in Figure 3.7. The sub-catchments selected for the study were the Mockes and the Krugersdrift dam areas.

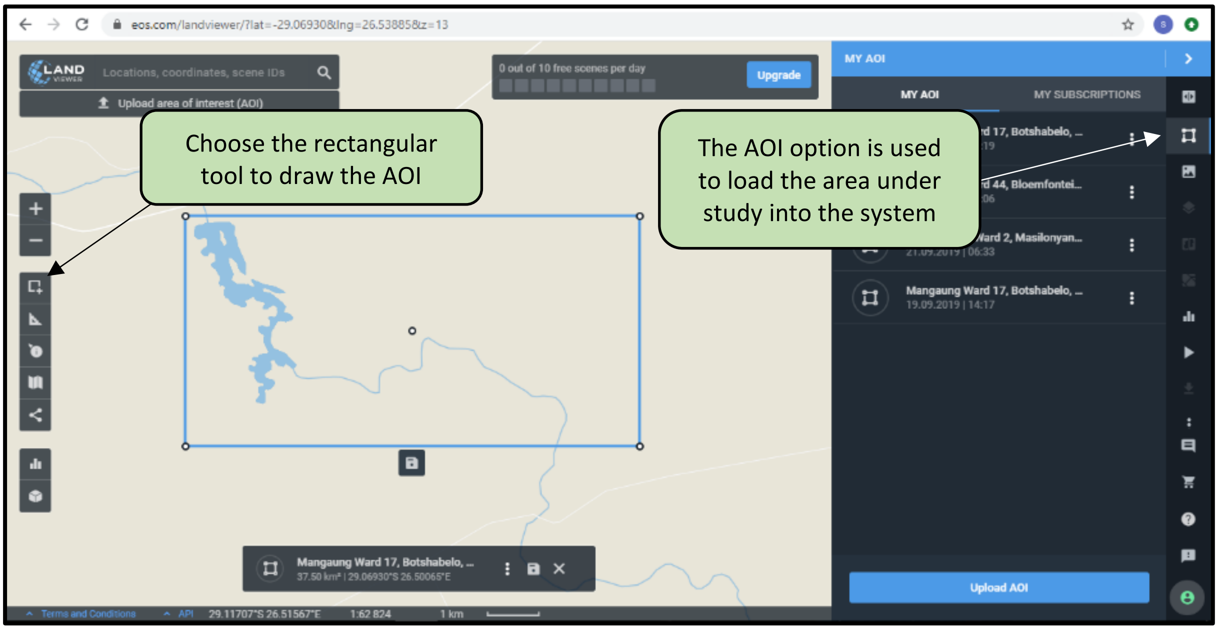


Figure 3.7: Area of interest map showing the selection of the Mockes Dam area

Step 3: Selection of satellite images

Using the scene settings option, the Landsat 8 satellite images were selected at various dates corresponding to the four weather seasons in South Africa as shown in Figure 3.9. The months from which the seasons were selected, included February, May, August, and November representing the summer, winter, autumn and spring seasons, respectively. The images were collected for all these months between the years 2017 and 2019.

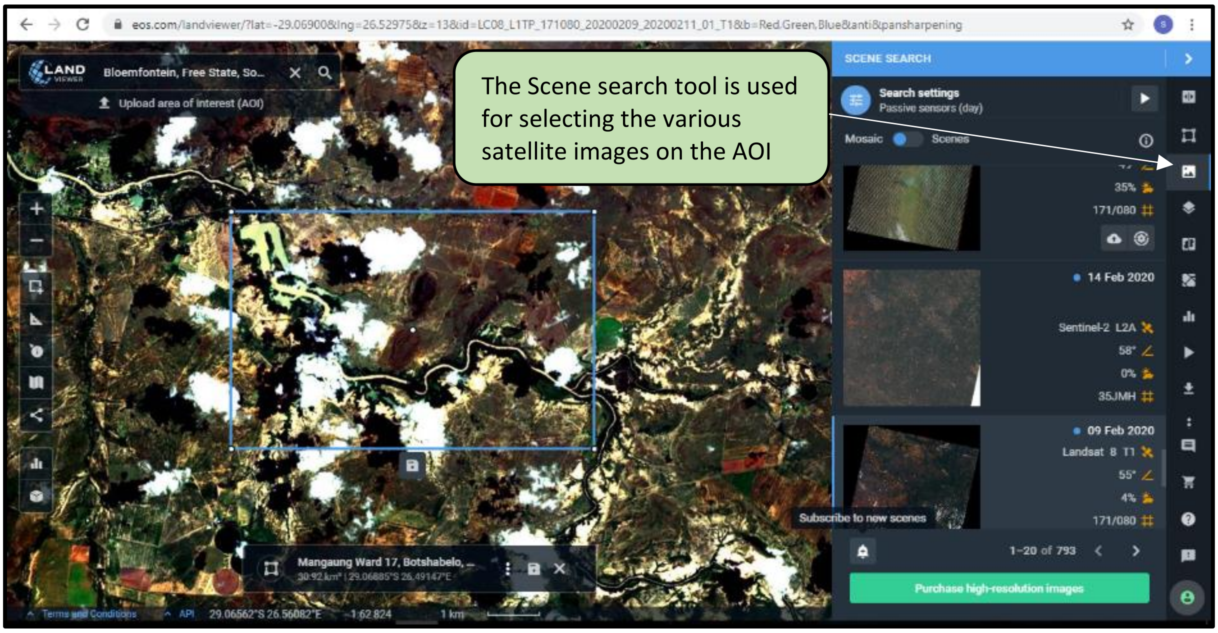


Figure 3.8: The extraction of the Landsat 8 Images for the Mockes Dam area

Step 4: Selection of band combinations

Various remote sensing indices with different band combinations are available on the EOS remote sensing tool. The NDWI band was selected to provide estimations of surface water for the AOI as shown in Figure 3.9. The NDWI makes use of reflected near-infrared radiation and visible green light to enhance the presence of such features, while eliminating the presence of soil and terrestrial vegetation features. The NDWI may also provide researchers with turbidity estimations of water bodies by using remotely sensed digital data (Masocha et al. 2017).

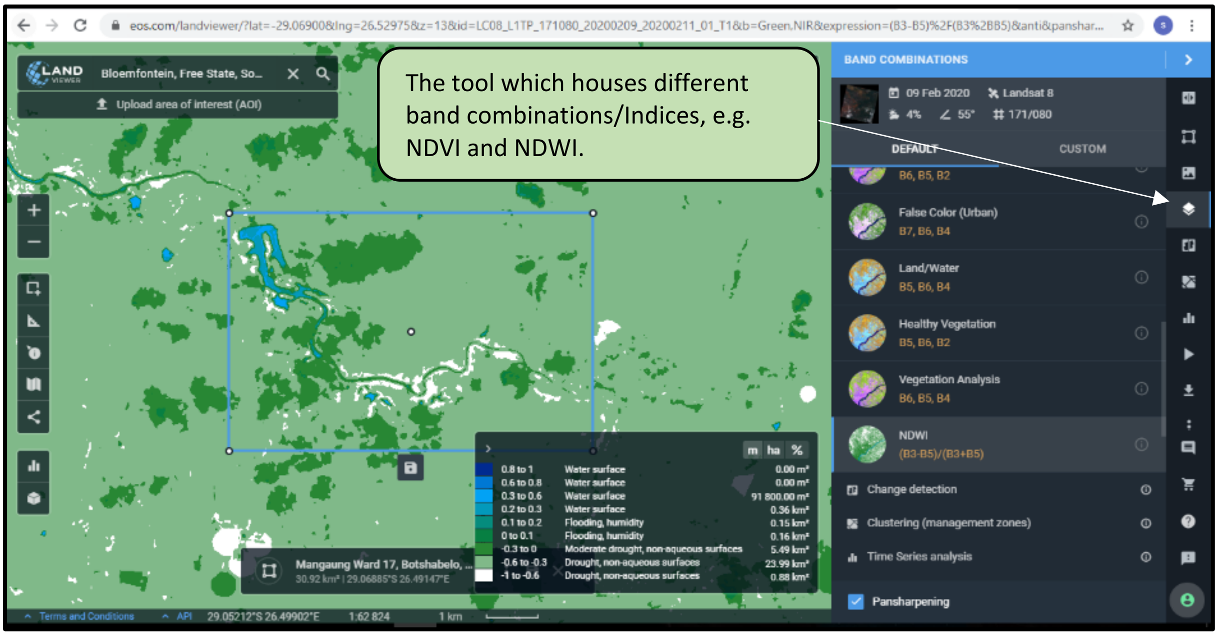


Figure 3.9: Selection of the Normalised Difference Water Index on the area of interest

Step 5: Calculation of surface water coverage from the area of interest

The surface water coverage estimations computed by the EOS tool on the AOI was extracted, recorded, processed, and analysed. Values indicating water surface, flooding and humidity were added together to represent surface water, while data for moderate drought and non-aqueous surfaces were added together to represent non-water surfaces.

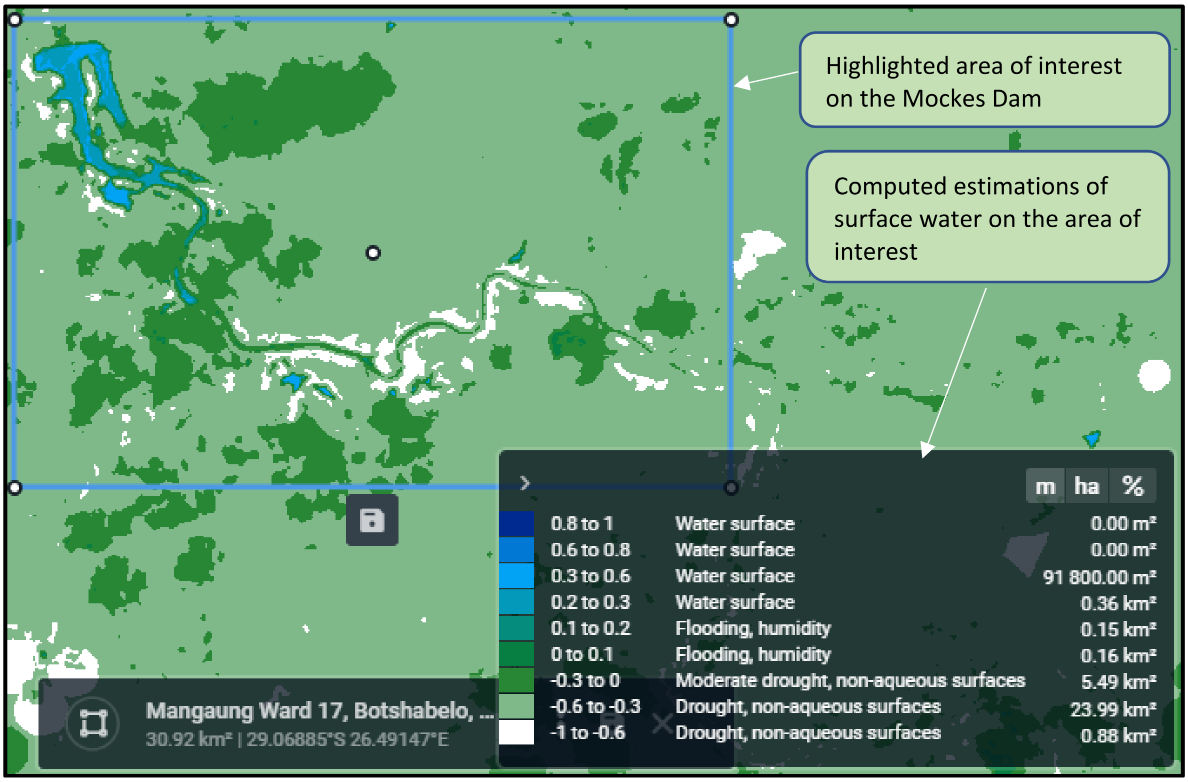


Figure 3.10: EOS computations of surface water levels from satellite data

3.5.2 Surface water data from the Department of Water and Sanitation

The surface water data used for validating the remote sensing data was obtained from the DWS. The DWS has gauge stations that measure surface water mounted on various points along the Modder River catchment. The readings from the various gauge stations are taken at various intervals and loaded on the DWS website. The procedure used for acquiring the data from the DWS website is shown as follows:

Step 1: Accessing the data from the website

The dashboard webpage of the DWS was accessed by using the DWS website URL http://www.dwa.gov.za/Hydrology/. The dashboard webpage has a continuum of water stations with various descriptors showing the locations from which the data was taken as shown in Figure 3.11.

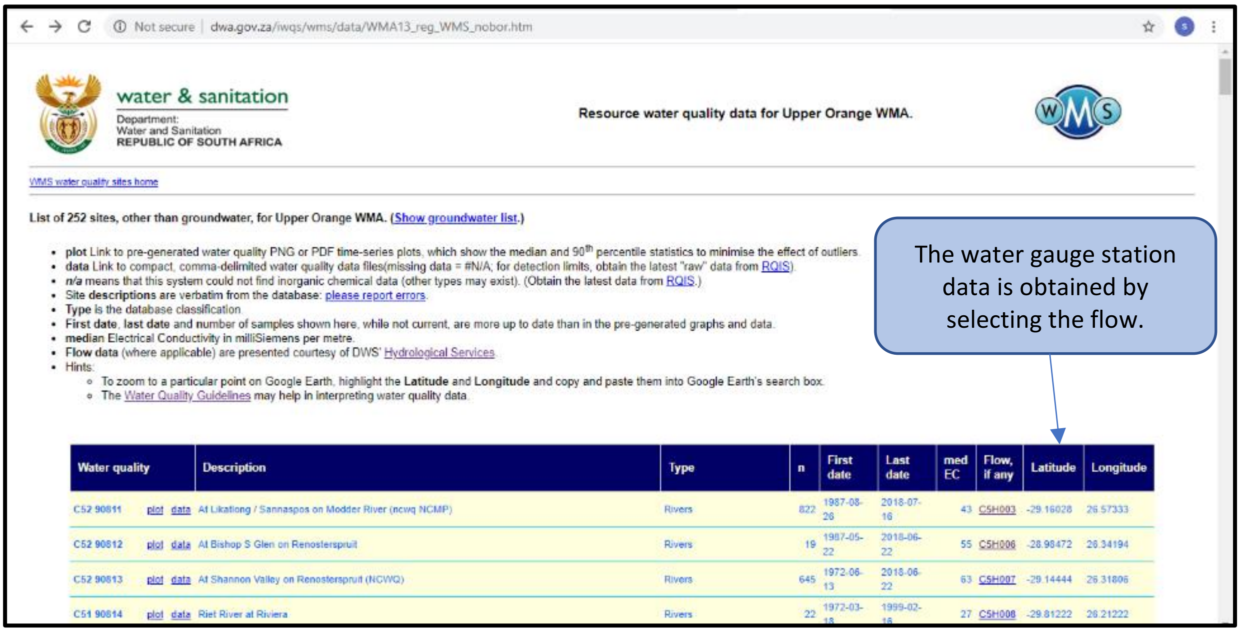


Figure 3.11: Department of Water and Sanitation dashboard webpage

Step 2: Selecting a station of interest

Different stations along the Modder River catchment were carefully selected to acquire the data on monthly surface water volume as shown in Figure 3.11.

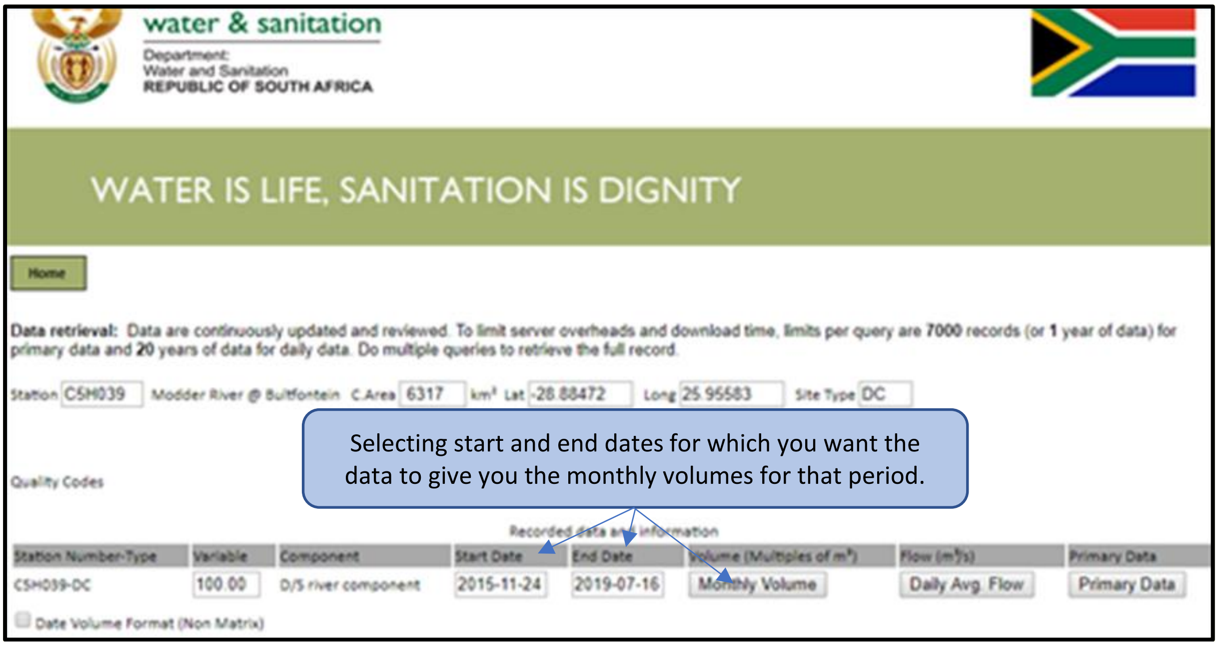


Figure 3.12: Selecting surface water volume for a gauge station

Step 3: Acquisition and recording of data

The data is acquired by year and month from the DWS after selecting the station inputs as shown in Figure 3.13.

```
Data are continuously updated and reviewed.
Format of the data is as follows :(I4,X,I4,13(X,A6,A1,A1) where:
    I4 = CCYY
     X = /
    I4 = CCYY
    13(X,A6,A1,A1) = 12 Monthly volumes in thousand cubic metres from Oct to Sep.
                     Value 13 is the yearly total.
                     X  = Space
                     A6 = 999999
                     A1 = &/+/E/*/m/M or space(& = Good monthly reading)
                                              (+ = Above rating)
                                              (E = Estimated Data)
                                              (* = Calculated estimate)
                                              (m = Greater than)
                                              (M = Less than)
                     A1 = # or space (# = record incomplete or does not exist)

MONTHLY VOLUMES C5H059
Variable 194.00 Pipeline Discharge
I4,X,I4,13(X,A6,A1,A1)
AAAAAAAAAAAAA
2014/2015         #         #         #         #         #         #         #         #         #   2696      2786      2665         #
2015/2016   2926      2840      2838      2815      2489      2594      2478      2381      2569      2131      2117      1598     29777
2016/2017   1621      1661      2107      2716      2454      2721      2573      2570      2700      2518      2500      2252     28391
2017/2018   2731      2786      2856      2839      2691      2854      2757      2279      2647      2561      2692      2769     32443
2018/2019   2762      2948      2964      2966      1991 #     324 #    2753      2906      2765      2565 #            #         #    #
ZZZZZZZZZZ
```

Figure 3.13: Surface water data by month and year

3.5.3 Images showing the surface water level gauge stations around different stations in the Modder River catchment

Some of the gauge stations from which the surface water level data was obtained are shown in Figures 3.14 to 3.16. The water sources within these station locations were used to collect samples that were used for qualitative water analysis.

(a)

(b)

Figure 3.14: (a) and (b): Gauge station C5H003 at Likatlong

(a)

(b)

Figure 3.15: (a) and (b): Gauge station C5H039 at Bishops Glen 1 Station

(a)

(b)

Figure 3.16: Gauge station at (a) Krugersdrift and (b) Bultfontein station

3.6 Estimation of vegetation density

The vegetation densities of the Modder River catchment were estimated using the EOS, NDVI generator function tool. The tool classifies the vegetation densities, depending on their spectral reflectance and area of coverage using the NDVI. The tool also detects the healthiness and biomass of vegetation through the NDVI. The procedure for obtaining the vegetation density is the same as the one shown under the three steps on estimating surface water, using remote sensing. To obtain the vegetation densities, the NDVI option was selected instead of the NDWI option, as shown in Figure 3.17 to give the NDVI images with the corresponding vegetation densities.

Step 1: Selection of Band Combination/Vegetative Index

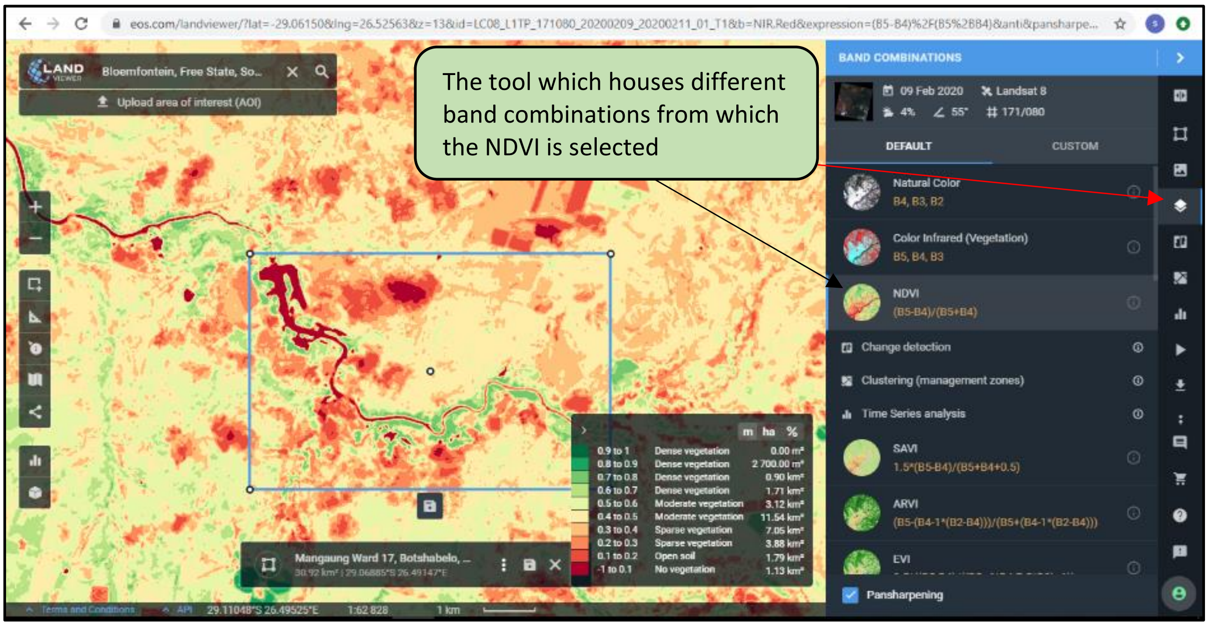


Figure 3.17: Selection of the NDVI band combination amongst other remote sensing indices

Step 2: Calculation of the extracted vegetation density

The NDVI index generates the estimated vegetation density once the AOI is highlighted, as shown in Figure 3.18.

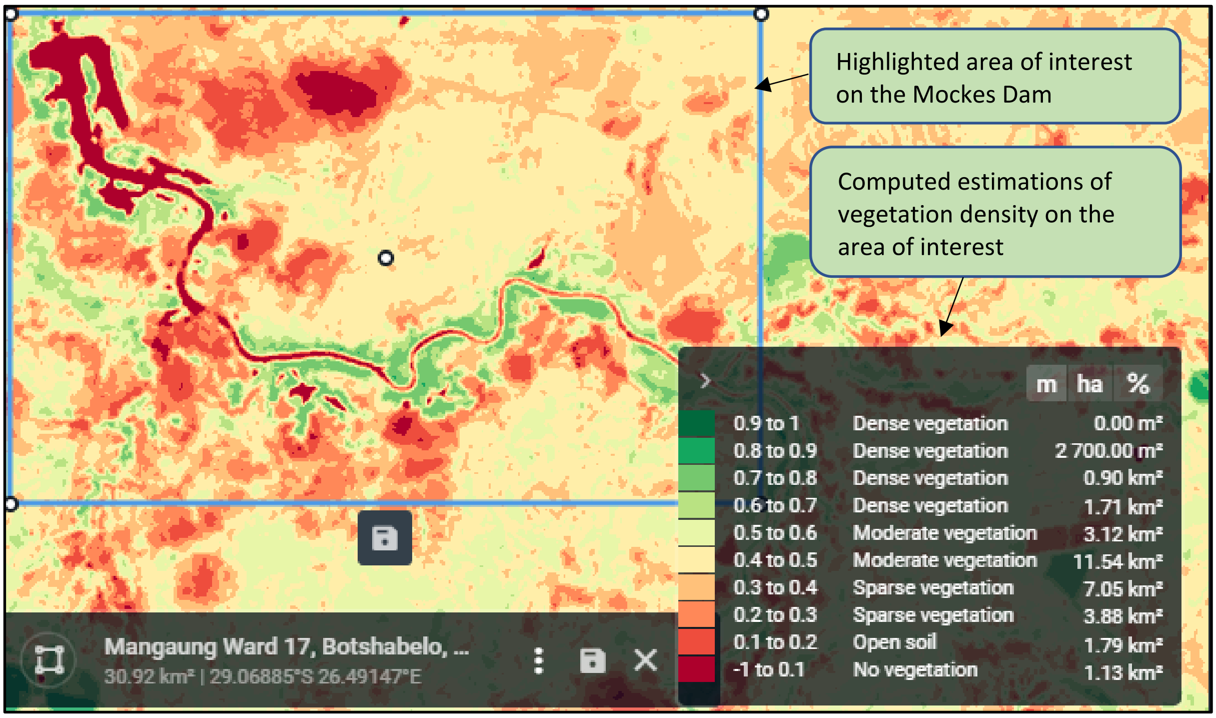


Figure 3.18: EOS computations of vegetation density from satellite data

3.7 Water quality sampling and analysis

The river water along various points in the Modder River catchment was sampled and analysed for chemical, physical, and microbiological water quality components. Water samples were taken in each of the four seasons (summer, autumn, winter and spring) along the Modder River. The samples collected were sent for analysis on the level of chemical, physical, and microbiological determinants at the Institute of Groundwater Studies, University of the Free State. However, due to the time available for the research, only two sets of samples could be collected and analysed for the year 2019. To fill in this gap, historical data was used to extrapolate and model some of the missing data. The water quality parameters collected in the study are represented in Table 3.1. However, not all the parameters where used for water quality analysis in this study.

Table 3.1: Water quality determinants analysed from water samples

Determinants	Parameters
Physical	Physical parameters: pH, EC, TDS, TSS, alkalinity, dissolved oxygen, turbidity
Chemical	Major anions (NO_3, PO_4, SO_4^{2-}, HCO_3^-) Major cations (Ca^{2+}, Na^+, K^+, Mg^{2+}) Major trace metals (Fe, Mn, Pb, Se, Ce, As, B, Be, Cd, Cr, Ti, Sn)
Microbiological	Bacteriological composition (Total coliforms, *E. coli*, faecal coliforms, total heterotrophic counts)

3.7.1 Water Quality Index

As indicated in the literature, several methods can be used to calculate the WQI, involving different physical, chemical, and biological parameters. In this study, the Weighted Arithmetic WQI was used to calculate the WQI for the water quality parameters that were measured during the study period. The Weighted Arithmetic WQI was chosen because it has relatively easy computations compared to the other WQI calculation methods and it can be used in analysing water quality parameters that are taken from more than one season.

Depending on the availability of the data, an average of 10–12 water quality parameters were used to determine the WQI for each season. These water quality parameters included the pH, EC, TDS, Cl, F, NO_3, SO_4, Ca, Mg, Na, K, faecal coliforms, and E. coli. Most of the water quality parameters were chosen based on the findings made from known literature about their impact on human health (Carr & Rickwood 2008; WHO 2008).

The WQI calculated was mainly used to compare the effects of ET on seasonal water quality. The WQI calculated were also analysed in relation to the WHO guidelines for drinking water quality considered for human consumption. The WQI was calculated by using the Weighted Arithmetic WQI method using the following steps:

Step 1: Calculation of the unit weight (W_i) for each water quality parameter to the recommended standard for the corresponding parameter

The unit weight values were calculated by using the following formula as recommended by Tiwari and Misha, (1985, cited in Gorde and Jadhav 2013):

$$W_i = K \sum_{n=1}^{n} \frac{1}{Si} \qquad (8)$$

Where, S_i is the recommended standard for the corresponding ith parameter, and the proportionality constant K is obtained by:

$$K = \frac{1}{\sum_1^\infty \frac{1}{Sn}} \quad (9)$$

Step 2: Calculation of the quality rating scale (Q_i) for each parameter was conducted by using the expression:

$$Q_i = 100 \left[\frac{Q\ actual - Q\ ideal}{Sstandard - Q\ ideal}\right] \quad (10)$$

Where, Q_{actual} = actual or estimated amount of the ith parameter; Q_{ideal} = the ideal value of the parameter, Q_{ideal} = 0 (except for pH = 7, and dissolved oxygen = 14.6 mg L^{-1}), $S_{Standard}$ = recommended WHO standard for the corresponding parameter.

Step 3: The overall WQI was calculated using the equation:

$$\text{Weighted Average WQI} = \frac{\sum_{i=1}^{i=n} QiWi}{\sum Wi}. \quad (11)$$

The proposed rating scale for the WQI was in the range of 0–100, where the grading was proposed as shown in table 3.2:

Table 3.2: Water Quality Indices and the states of water

Water Quality Index	State of water
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
Above 100	Not suitable for drinking purposes

Source: Gupta et al. (2017)

Sampling points: The following sampling points shown in Table 3.3 were used in collecting water that was used in analysing water quality data.

Table 3.3: Sampling points used in water quality analysis

Sample	Water quality code	Description	Coordinates	
S1	C5290833	Krugersdrift Dam on Modder River: Downstream weir (NCWQ NCMP*)	-28.88333	25.95028
S2	C5290836	Cypress 89 – at Glen on Modder River (NCWQ NCMP)	-28.94911	26.32099

Sample	Water quality code	Description	Coordinates	
S3	C52 90812	At Bishops Glen on Renosterspruit	-28.98472	26.34194
S4	C52 90837	At Bishops Glen on Renosterspruit (NCWQ)	-28.96667	26.33306
S5	C52 90811	At Likatlong / Sannaspos on Modder River (NCWQ NCMP)	-29.16028	26.57333
S6	C52 187233	Diepwater 227 on Modder River (NCWQ)	-29.37556	26.66556
S7	C52 90823	Kgabanyane River at Bedford Up Stream Groothoek D (NCWQ)	-29.28556	26.92194

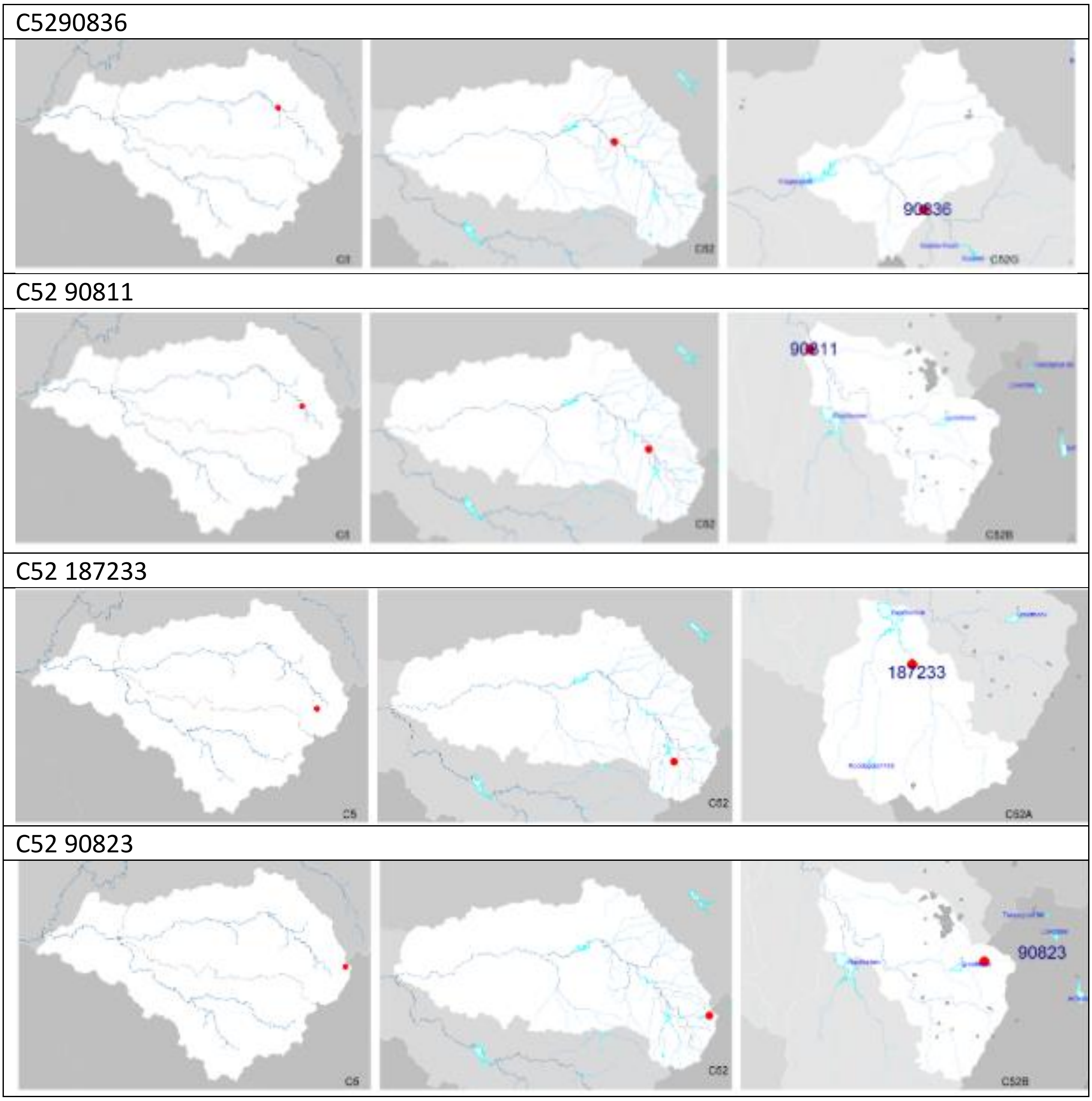
*NCWQ = National Commission on Water Quality; NCMP = National Chemical Monitoring Programme for Surface Water

The mapping of the sampling points along the Modder River Catchment are shown in Figure 3.19.The figure shows the location of each sampling point in three orientations of space within the Modder River basin starting from the C5 to C52 to C52X, where X can be A,B,G or F depending on the location of the sub-catchment.

C52 90812

C52 90837

C5290833



Source: DWA (2006)

Figure 3.19: Mapping of sampling points for water analysis along the Modder River

3.7.2 Images for water quality sampling at different sampling points along the Modder River catchment

Samples for water quality were collected along different points in the Modder River catchment (see Appendix A).The samples were collected along the Likatlong River, Rustfontein Dam, Krugersdrift Dam, and Maselspoort Dam.All the water quality samples were collected on the same day before they were sent for analysis at the University of Free State, Institute for Ground Water Studies.

3.8 Estimating potential evapotranspiration (ET_0)

The Hargreaves and Samani method was used to calculate the estimated ET_0 among several popular methods such as the Penman–Monteith equation which could have been possibly used to calculate ET_0. Although the Penman–Monteith method is the most widely used for calculating ET_0, its effectiveness in arid environments is severely limited due to its considerable data requirements (Moeletsi et al. 2013). To overcome this challenge, the Hargreaves and Samani model was utilised since it is an empirical radiation-based method which can be used in the conditions of limited weather data. The Hargreaves and Samani equation can be applied and relied upon when utilised in arid climate conditions (De Rooij 2018).

The Hargreaves and Samani equation can be represented as:

$$ET_0 = 0.0023Ra\ (T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5} \qquad (12)$$

Where, Ra = water equivalent of extraterrestrial radiation (mm day^{-1}); T_{mean} = mean air temperature; T_{max} = daily maximum air temperature (°C) and T_{min} = daily minimum air temperature (°C).

3.9 Statistical analysis of data

The Pearson's correlation coefficient was used in this study to analyse the relationship between variables (Frost 2020). Two variables were analysed at a time. The test utilised the null hypothesis H_0, meaning that there is no correlation between the two variables tested against the alternative hypothesis H_1, which implies that there is a correlation between the two variables.

H_0: $r = 0$
H_1: $r \neq 0$

The data taken from the variables was inserted into the Pearson's equation to find the value r, representing the test statistic (Frost 2020).

$$r = \frac{N\sum XY - (\sum X)(\sum Y)}{\sqrt{(N\sum X2 - (\sum X)2)(N\sum Y2 - (\sum Y)2)}} \qquad (13)$$

Where:

r = Pearson's correlation coefficient

N = number of pairs of scores

X = score of the first variable

Y = score of the second variable

XY = the product of the two paired scores

The Pearson's correlation coefficient is a single number that measures the direction as well as the strength of the relationship between two continuous variables (Hauke and Kossowski 2011). The values of r, which is often referred to as the sample statistic, ranged between -1 and +1 (Frost 2020). The greater the value of the correlation coefficient, the stronger the relationship between the two continuous variables. A coefficient of zero indicate that there is no relationship (Mukaka 2012).

Chapter 4
Results on the sensitivity of evapotranspiration to climate and weather trends, and the effects of evapotranspiration on surface water quantity, surface water quality, and vegetation healthiness

4.1 Introduction

This chapter shows the representation of the results obtained from the study. The results consisted of some historical and current data for the period 2017–2019. The section is divided into four main parts which are the sensitivity of ET to changing climate and weather elements, effects of ET on surface water, the effects of ET on water quality, and the effects of ET on vegetation healthiness.

Evapotranspiration depends on several climate and weather variables such as temperature, solar radiation, wind speed, humidity, and rainfall. The presence and combinable proportions of each of these weather variables at a time determine the extent and magnitude of ET. Despite having different climatic and weather elements affecting ET, this study relied only on two critical weather elements in solar radiation and temperature to calculate ET due to the availability of the weather data and ease of calculations. However, it will be of great value for this and future studies, to understand how other weather variables might have impacted ET. The effect of ET on surface water quantity was established through the surface water area. The effect of ET on surface water quality was mainly represented through the WQI.

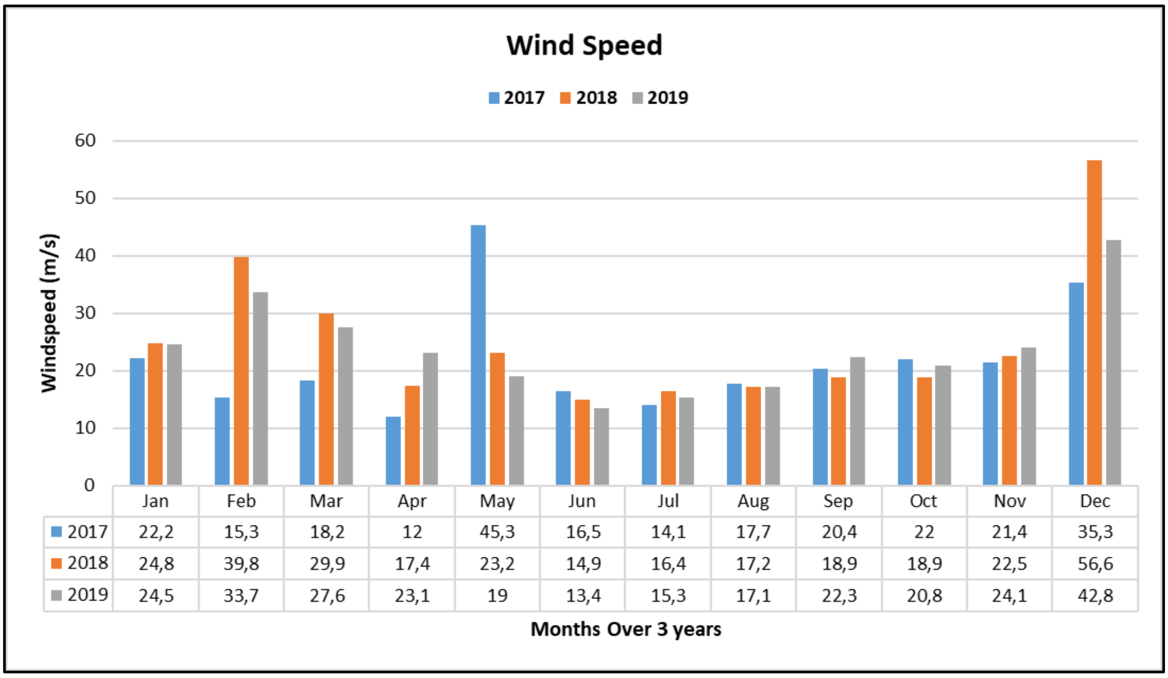
4.2 Sensitivity of evapotranspiration to changing climate and weather elements

In this study, the impact of weather and climate elements such as wind speed, rainfall, humidity, temperature and solar radiation on ET and surface water quantity were assessed over a three-year period from 2017 to 2019, using data obtained from the SAWS.

The sensitivity of ET to different weather variables can differ significantly among climates (Tabari and Talaee 2014). As most weather elements were not part of the Hargreaves and Samani equation that was used to calculate ET_0, it was crucial to see how these elements relate to the overall ET_0. From the comparison of the sensitivity of ET_0 to weather changes in different climates, it can be inferred that the sensitivity of ET to variables of wind speed and air temperature decreased from an arid to humid climate, whereas its sensitivity to sunshine hours increased from arid to humid environment.

4.2.1 Wind speed

Figure 4.1 shows that wind speeds within the river catchment were at their highest within the summer and spring seasons, with the highest wind speed recorded in December 2018. These high average wind speeds in the spring and summer seasons mean that the evaporation of water through wind occurred mainly in these seasons. On the other hand, these high wind speeds also caused a simultaneous reduction in transpiration in vegetation. Autumn and winter seasons experienced low wind speed, meaning that they may have experienced high transpiration rates but very low evaporation rates. However, the presence of other weather elements such as humidity, temperature and solar radiation plays a significant role in affecting the actual ET within the environment.



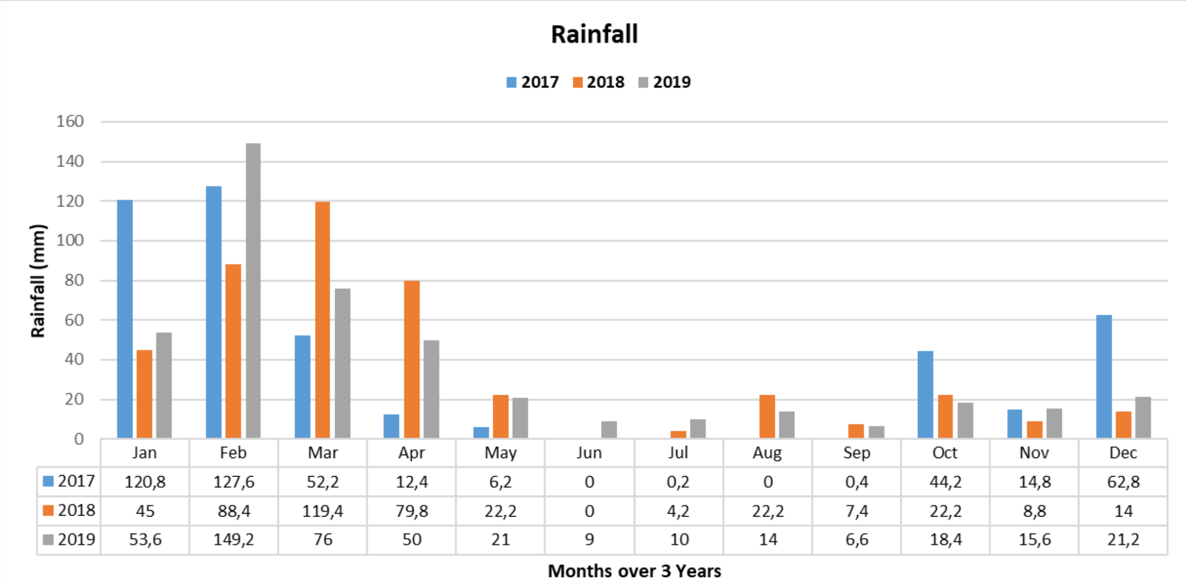
Source: SAWS (2019)

Figure 4.1: Graph of wind speed in the Modder River catchment over the three years

Although the effects of wind speed can be separately explained on evaporation and transpiration, the combined effects of wind speed on ET_0 in natural environments is a more complex process in nature. These results cannot exclusively tell us the exact effect of wind speed on ET. More studies need to be conducted on the effects of physical weather factors on ET under controlled laboratory conditions.

4.2.2 Rainfall

The results of the study showed an increase in rainfall between January and April months over the three-year period, as indicated in Figure 4.2. This shows that most parts of the summer and winter seasons where characterised by high streamflow within the Modder River catchment. The ET_0 results are, however, not consistent with the streamflow patterns as they show that ET decreased gradually between January and April where the rainfall was at its highest. Similarly, the months with the lowest rainfall had the highest ET rates. From the results, it is evident that more climatic factors other than rainfall were responsible for influencing the ET patterns.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2017	120,8	127,6	52,2	12,4	6,2	0	0,2	0	0,4	44,2	14,8	62,8
2018	45	88,4	119,4	79,8	22,2	0	4,2	22,2	7,4	22,2	8,8	14
2019	53,6	149,2	76	50	21	9	10	14	6,6	18,4	15,6	21,2

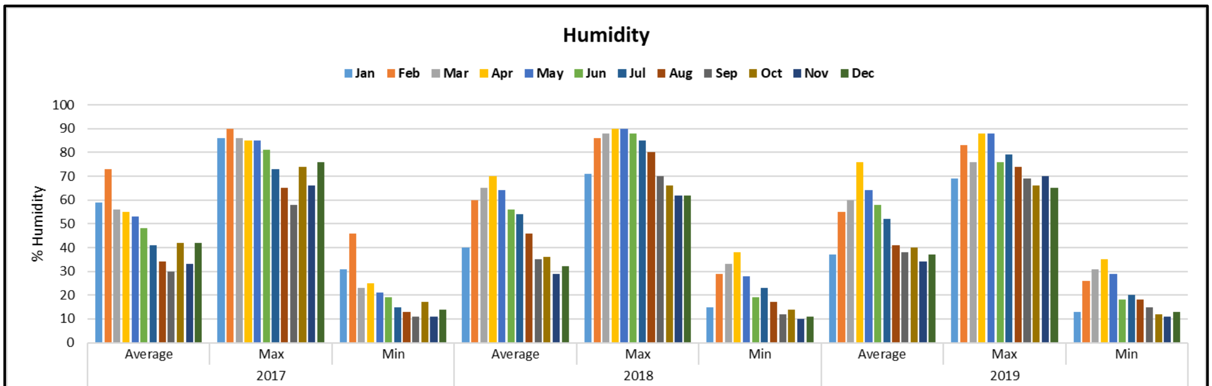
Source: SAWS (2019)

Figure 4.2: Graph of rainfall in the Modder River catchment over the three years

The strong rainfall and streamflow response indicated that planning and management of surface water storage and supply can be critically worked on bearing in mind that most rain is received in the summer and autumn months. The ET response to rainfall suggests that dryland farming and ecosystem vitality could benefit from the increased precipitation in summer and autumn months where the impacts of ET are more modest, and less water can be used for irrigation purposes.

4.2.3 Humidity

Humidity has an inverse correlation with ET (Farhat 2018). The results of the study indicated that the average humidity across the three-year period increased between January and April and decreased from May to December. This means that the rate of ET increased gradually between the summer and autumn months, but gradually decreased between the winter and spring seasons. The relationship between humidity and ET is important to study in catchment hydrology as it gives an indication of how weather data can be utilised to manage and maximise water use efficiency. However, just like other variables, the results of humidity against ET cannot be taken in isolation from other weather factors and more field and laboratory studies with better equipment need to be conducted.



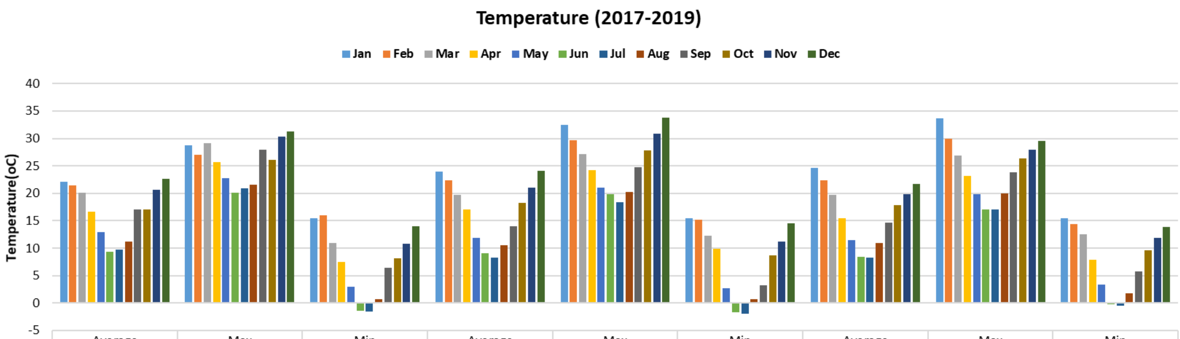
	2017 Average	2017 Max	2017 Min	2018 Average	2018 Max	2018 Min	2019 Average	2019 Max	2019 Min
Jan	59	86	31	40	71	15	37	69	13
Feb	73	90	46	60	86	29	55	83	26
Mar	56	86	23	65	88	33	60	76	31
Apr	55	85	25	70	90	38	76	88	35
May	53	85	21	64	90	28	64	88	29
Jun	48	81	19	56	88	19	58	76	18
Jul	41	73	15	54	85	23	52	79	20
Aug	34	65	13	46	80	17	41	74	18
Sep	30	58	11	35	70	12	38	69	15
Oct	42	74	17	36	66	14	40	66	12
Nov	33	66	11	29	62	10	34	70	11
Dec	42	76	14	32	62	11	37	65	13

Source: SAWS (2019)

Figure 4.3: Graph of humidity in the Modder River catchment over the three years

4.2.4 Temperature

Temperature is an important and major contributor to ET_0 (Allen et al. 1998; SAWS 2019). Measuring and assessing the impact of temperature outside other climatic and weather variables such as humidity and solar radiation within the ET_0 equation can help us determine the proportion in which it contributes to the evaporation and transpiration of water within the catchment. The summer and spring seasons generally had high temperatures, followed by the autumn and winter seasons over the three-year study period, as shown in Figure 4.4.



	Average	Max	Min	Average	Max	Min	Average	Max	Min
		2017			2018			2019	
Jan	22,1	28,8	15,5	23,9	32,4	15,4	24,6	33,6	15,5
Feb	21,5	27	16	22,4	29,7	15,2	22,3	30	14,4
Mar	20,1	29,1	11	19,7	27,1	12,3	19,7	26,9	12,5
Apr	16,6	25,7	7,5	17,1	24,2	9,9	15,5	23,2	7,9
May	12,9	22,7	3	11,9	21,1	2,7	11,5	19,8	3,3
Jun	9,3	20,1	-1,4	9,1	19,8	-1,7	8,4	17	-0,2
Jul	9,7	20,9	-1,6	8,3	18,4	-1,9	8,3	17,1	-0,5
Aug	11,2	21,6	0,7	10,5	20,3	0,7	10,9	20	1,8
Sep	17,1	27,9	6,4	14	24,8	3,2	14,7	23,8	5,7
Oct	17,1	26,1	8,2	18,3	27,8	8,7	17,9	26,3	9,6
Nov	20,6	30,3	10,8	21,1	30,9	11,2	19,9	27,9	11,9
Dec	22,6	31,3	14	24,1	33,8	14,5	21,7	29,6	13,9

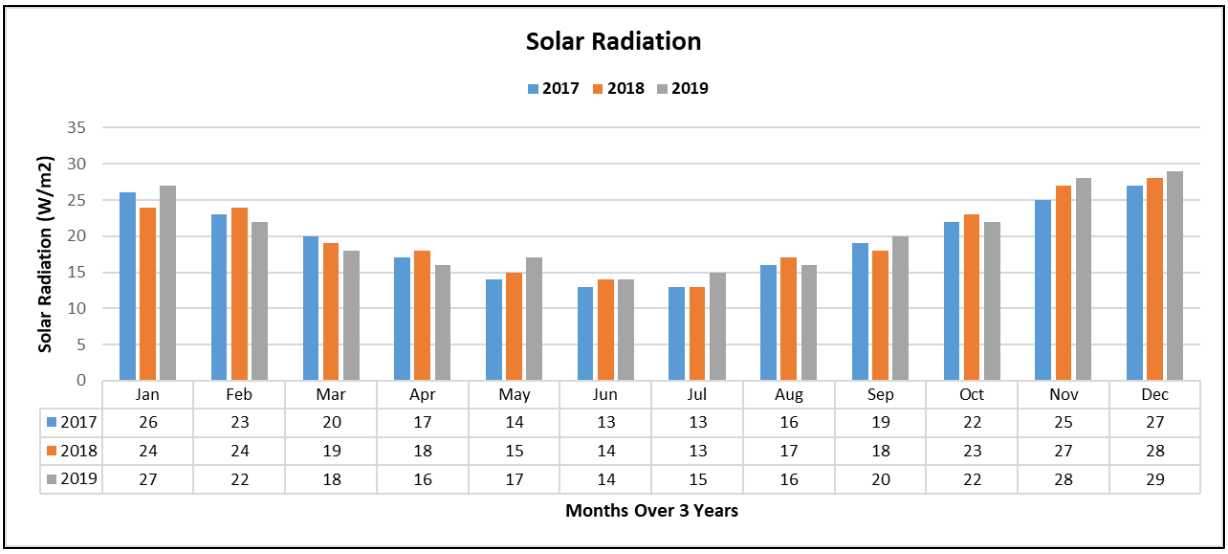
Source: SAWS (2019)

Figure 4.4: Graph of temperature in the Modder River catchment over the three years

Under normal circumstances, temperature has a direct effect on the evaporation of water from surfaces. An increase in temperature will lead to a direct increase in evaporation of water. Likewise, the remote sensing images taken during the study period showed that the surface water area in the Modder River catchment decreased in the summer and spring months, where the average temperatures were higher than the autumn and spring seasons, which experienced relatively cooler temperatures during the same period. These results mean that temperature plays a significant role in the evaporation and transpiration processes.

4.2.5 Solar radiation

The solar radiation detected across the catchment over the three-year period showed a steady decline between May and June and a steady rise between July and December as shown in Figure 4.5. Generally, the catchment received more sunshine in the summer and spring seasons compared to autumn and winter. Solar radiation resonates correspondingly with the ET patterns. This means that more ET could have occurred in summer and spring compared to autumn and winter.



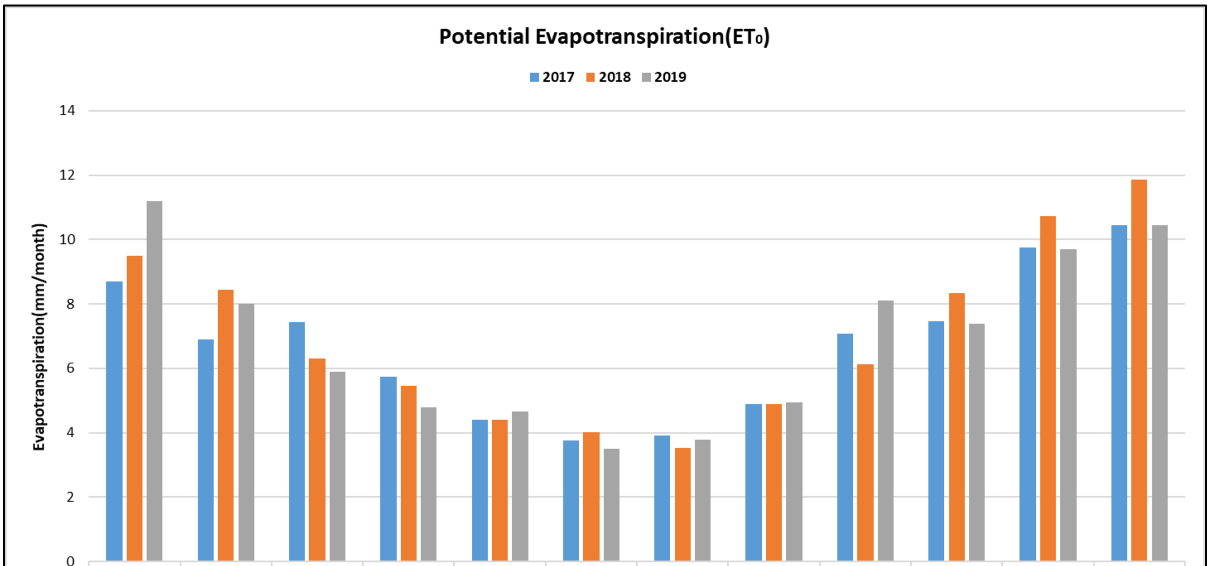
Source: SAWS (2019)

Figure 4.5: Graph of solar radiation in the Modder River catchment over the three years

Generally, the period between the summer and autumn months were characterised by healthier vegetation compared to the spring and winter months. This can be attributed to the combination of high rainfall and high solar radiation which contributed to higher photosynthetic activity. However, it is also notable that there is a direct relationship between solar radiation and ET_0.

4.2.6 Potential evapotranspiration

The ET_0 rates shown in Figure 4.6 were generated from solar radiation and temperature using the Hargreaves and Samani method. The ET_0 rates declined steadily from January and June across the three-year period, with the summer season having the highest ET_0 rates. The high temperatures associated with the high solar radiation characterised the larger part of the summer season leading to high ET_0 rates, while the winter and autumn seasons had relatively low ET_0 rates. The high ET_0 rates experienced during the summer season corresponded with the low surface water levels that were observed in the Modder River catchment during the summer seasons over the three years. This can be an indication of the impact of ET_0 on surface water. The ET_0 pattern changed drastically from July to December which saw the ET_0 rates steadily increasing from July up to December. Just like in the summer seasons, spring seasons also had the highest ET_0 rates which corresponded with relatively low surface water levels. The highest ET_0 rates were observed in 2018, compared to 2017 and 2019.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2017	8,7	6,9	7,43	5,74	4,39	3,76	3,9	4,88	7,07	7,47	9,75	10,44
2018	9,49	8,45	6,3	5,46	4,4	4,02	3,52	4,9	6,12	8,35	10,72	11,85
2019	11,2	8,01	5,89	4,79	4,65	3,5	3,78	4,93	8,11	7,38	9,71	10,44

Source: SAWS (2019)

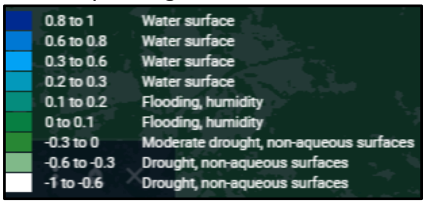
Figure 4.6: ***Graph showing the seasonal variation of potential ET_0 across the three years***

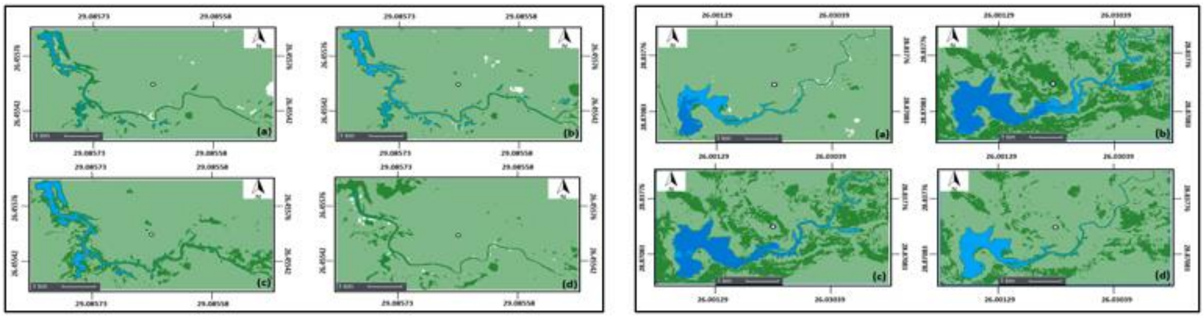
In general, the ET_0 results showed that summer and spring seasons over the three years experienced greater ET_0 values than the autumn and winter seasons. As ET_0 is one of the most significant aspects of the catchment water balance, its inverse correspondence with the surface water values might be an indication of its direct effect on surface water quantity. Similarly, it can be further inferred that low water volumes can be associated with high concentration of solutes which can negatively affect the water quality. This might indicate that the summer and spring seasons contained water of the lowest water quality, compared to the winter and spring seasons. However, these results need to be confirmed with water quality testing of the surface water at different points within the catchment.

The ET values used in this study were derived from the Hargreaves and Samani method which only utilises temperature and solar radiation climatic variables. Further validation needs to be conducted by using field methods, such as lysimeters, to directly measure ET_0. Directly measuring ET_0 will improve the accuracy of determining the exact magnitude of ET_0 and other climatic variables involved.

4.3 Effects of evapotranspiration on surface water quantity (2017–2019)

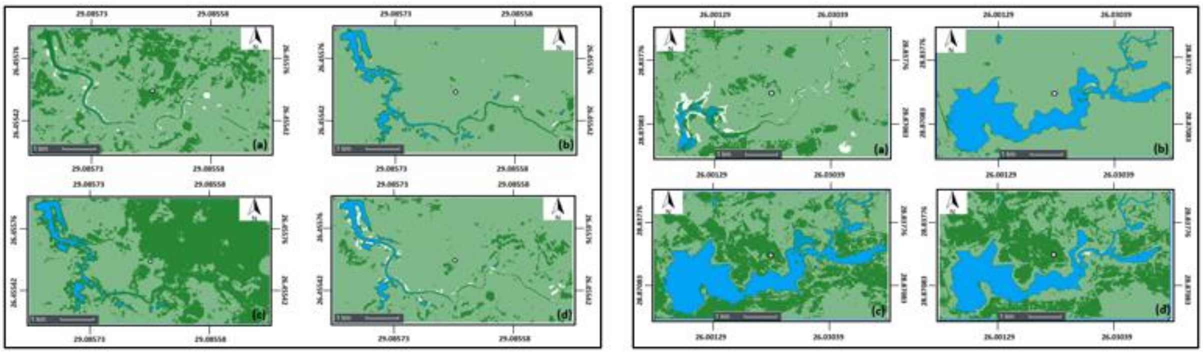
Key for Figures 4.7 to 4.9





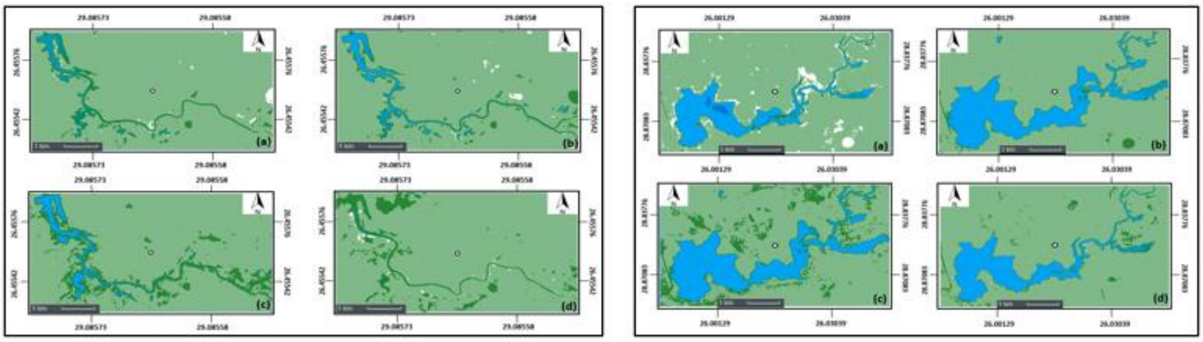
Note: Each of the two images is in the following order: (a) Summer, (b) Autumn, (c) Winter and (d) Spring.

Figure 4.7: ***2017 Images for the NDWI for Mockes Dam (left) and Krugersdrift Dam (right)***



Note: Each of the two images is in the following order: (a) Summer, (b) Autumn, (c) Winter and (d) Spring.

Figure 4.8: ***2018 Images for the NDWI in Mockes Dam (left) and Krugersdrift Dam (right)***



Note: Each of the two images is in the following order: (a) Summer, (b) Autumn, (c) Winter and (d) Spring.

Figure 4.9: ***2019 Images for the NDWI for Mockes Dam (left) and Krugersdrift Dam (right)***

Table 4.1: **Surface area covered by water within the Mockes Dam and Krugersdrift Dam areas**

Krugersdrift Dam												
Season	**Feb (Summer)**			**May (Autumn)**			**Aug (Winter)**			**Nov (Spring)**		
Year	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**
Surface water (km^2)	4,86	1,8	10,61	11,02	15,96	16,12	8,77	16,12	16,01	5,51	13,01	10,64
% Area covered by surface water	5,92	2,04	12,85	13,38	19,34	19,53	10,63	19,53	19,39	6,68	15,76	12,89
Rainfall	127,6	88,4	149,2	6,2	22,2	21,0	0,0	22,2	14,0	14,8	8,8	15,6
Evapotranspira-tion (ET)	6,9	8,45	8,01	4,39	4,40	4,65	4,88	4,90	4,93	9,75	10,72	9,71
Mockes Dam												
Season	**Feb (Summer)**			**May (Autumn)**			**Aug (Winter)**			**Nov (Spring)**		
Year	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**
Surface water (km^2)	1,169	0,233	1,058	1,431	1,347	1,400	1,444	1,300	1,434	0,768	0,985	0,178
% Area covered by surface water	4,014	0,8	3,97	4,508	4,623	5,25	4,957	4,463	5,38	2,636	3,380	0,67
Rainfall	127,6	88,4	149,2	6,2	22,2	21,0	0,0	22,2	14,0	14,8	8,8	15,6
Evapotranspira-tion (ET)	6,9	8,45	8,01	4,39	4,40	4,65	4,88	4,90	4,93	9,75	10,72	9,71

4.3.1 Surface water river catchment in 2017

The spring and summer seasons of 2017 had the least amount of areas covered by surface water as detected by the satellite data shown in Figure 4.7 and Table 4.1 for both the Mockes and Krugersdrift dams. This can be attributed to the high temperatures which can be linked to the high ET_0 rate of surface water in the atmosphere. The high rainfall experienced in the summer and spring seasons does not equate to the very little surface water that is observed from the data. This implies that rainfall alone was not the only determinant that affected the retention of water in the sub-catchment.

In 2017, surface water was greater in the autumn and winter seasons. The low rates of ET_0 for these two seasons might have contributed to the preservation of surface water, despite the months barely receiving any rainfall. The largest amount of rainfall in 2017 was received in the summer of 2017. However, despite receiving the highest amount of rainfall, the summer of 2017 had the lowest surface water. This might have been caused by other factors affecting surface water such as surface run-off. The weather and climate elements of air temperature, humidity, rainfall, and solar radiation had varied significantly in their influence on the retention capacity of surface water within the river catchment. These elements could have affected the vegetation cover and density of the catchment which has a great influence on streamflow and the water retention capacity of the soil.

4.3.2 Surface water river catchment in 2018

Like 2017, more surface water in 2018 was detected in the autumn and winter seasons for both the Mockes and Krugersdrift dams, respectively. The autumn and winter seasons had very low ET_0, compared to the spring and summer seasons which had the lowest surface water coverage within the Mockes Dam sub-catchment in the 2018 period. The high surface water depicted by the high-water volume had a significant dilution factor on solutes for the autumn and winter seasons. This dilution factor contributed immensely to the water quality of the river catchment. Despite receiving high rainfall in the summer season, the sub-catchment recorded its record low surface water area but the second highest ET_0 of the season. This evidence suggests that ET_0 had a significant impact on the surface water, regardless of the high rainfall received during the summer season. However, other factors such as the nature of the soil might be responsible for the unusual and disproportionate reduction of surface water during that season.

4.3.3 Surface water river catchment in 2019

The surface water area around the Mockes Dam area showed a significant decrease in the spring of 2019. As indicted by the lack of any blue traces representing surface water on the NDWI image of spring 2019, the Modder River and Mockes Dam appeared to have dried off during the 2019 spring season. The rainfall received during this season is within the same range as the rainfall that was received in the other three seasons within the same year. This indicates that factors other than rainfall were responsible for causing the low surface water area within the sub-catchment. The high ET rate experienced during the spring season could have been responsible for causing the low surface water. The autumn and winter seasons had the most percentage area covered by surface water. These seasons also recorded the lowest ET rates in 2019.

4.4 Effects of evapotranspiration on surface water quality (2017–2019)

4.4.1 Water quality parameters

The analysis of the physical and chemical determinants was conducted for all the seasons across the three-year period from the years 2017–2019. The microbiological determinants could only be sampled and analysed for the summer season of 2019 and the data acquired was not sufficient to conduct analyses and comparisons with other seasons. The data was acquired through a combination of six sampling points of Likatlong, Rustfontein, Groothoek, Maselspoort, Bishops Glen 1 Renosterspruit and Krugersdrift, as well as from the DWS records. Each season was analysed for each of the three years with a special focus on trying to establish the relationship between the water quality variables across all seasons, as well as the relationship between water quality and ET_0.

The analysis of physical variables focused on monitoring the EC, pH of the water and the TDS levels between seasons and years. It is important to monitor the TDS level and the pH of drinking water for several reasons. When a water source has a high level of TDS or a low pH, it is likely that there are other harmful contaminants in the water (WHO 2003). Both TDS and pH are also easy to measure and if something is happening to water, such as pollution, chances are that both TDS and pH levels will change, so keeping track of those changes can act as an early warning signal that something is happening to the water. For these reasons, it is important to monitor the TDS and pH levels so that if they change, action can be taken immediately.

The concentration of the physical determinants such as TDS and pH changed differently according to the different seasons. The summer seasons across the years had higher TDS concentrations compared to the autumn and spring seasons. This can be attributed to more run-off eroding debris into streams and rivers because of the relatively high rainfall recorded in summer compared to other seasons.

4.4.2 Water Quality Index

The average seasonal values for each of the water quality parameters were used in the WQI calculations as shown in Table 4.3. The WQI was calculated using the Weighted Arithmetic Index method. The WHO (2008) proposed limits for water quality guidelines for human consumption which were used as a benchmark for the water quality assessment (Meride and Ayenew 2016). However, the main goal of using the WQI was to find a common basis of integrating all the water quality parameters from which ET could be assessed. The WQI ranges were defined as shown in Table 4.2 (Gorde and Jadhav 2013):

Table 4.2: Classification of WQI values for human consumption

Water Quality Index	Water Quality Class
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
Above 100	Not suitable for drinking purposes

Table 4.3: Average seasonal water quality parameters and indices

Properties		pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K	Cl	NO_3	SO_4	WQI	Classification
Standard limits (WHO)		8.5	≤1000 µS/cm	≤600 mg/L	≤200 mg/L	≤50mg/L	≤200 mg/L	≤12 mg/L	≤250 mg/L	50 mg/L	≤250 mg/L		
Seasons	Summer	8.0	65.5	269	19	14	39.5	7.5	10	2.3	15	**53,5**	**Poor**
	Autumn	8.4	53.6	372	37	20	49	7.2	36	5.0	22	**66,3**	**Poor**
	Winter	8.4	53.4	372	37	20	41	7.2	35.8	5.0	21.6	**66,3**	**Poor**
	Spring	8.3	47.0	378	33	15	31	7.4	32.7	2.3	22.5	**62,6**	**Poor**

The average seasonal WQI showed that the water was of poor quality for all the four seasons as shown in Table 4.3.The autumn and the winter seasons shared the highest WQI value of 66.3 followed by the spring and summer seasons which had the WQI values of 62.6 and 53.5 respectively. The poor WQI of the autumn and winter seasons corresponded with very low ET values of 4.48 and 4.90 respectively whereas the high ET values of 10.06 and 7.79 corresponded with slightly better water quality as compared to that of the autumn and winter seasons.

4.4.3 Summer season

The summer seasons were generally defined by low surface water levels and high ET_0 rates. This resulted in poor water quality with a WQI of 53.5 due to high solute concentration. The results showed that the summer of 2019 had the highest EC and potassium concentrations, indicating that there was a very high concentration of solutes present in the water. The results also indicated that the concentration of the macrochemical variables such as nitrates, sulphates, and carbonates for the summer months, increased slightly between the years 2017 and 2019. These results further suggested that the chemical concentration of the water was high during this period and that ET_0 could have significantly contributed to the poor water quality during this season.

4.4.4 Autumn season

The autumn seasons were generally characterised by high surface water levels and low ET_0. The concentration of most ions such as calcium, magnesium, sodium, chlorides, and nitrates was higher compared to the other seasons, the WQI for the autumn season was poor with a value of 66.3.

4.4.5 Winter season

The WQI for the winter season was 66.3, indicating that the water quality was in the poor catergory. Despite the winter season having low ET_0 values and more surface water volume, the concentration of most macroelements such as calcium, magnesium, chlorides, and nitrates remained relatively high compared to other seasons. This might be an indicator that other factors involved in the hydrological system may have been responsible for controlling the movement of ions into the stream water.

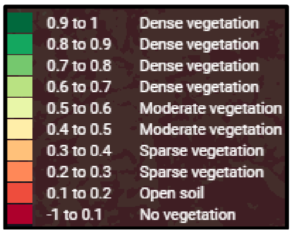
4.4.6 Spring season

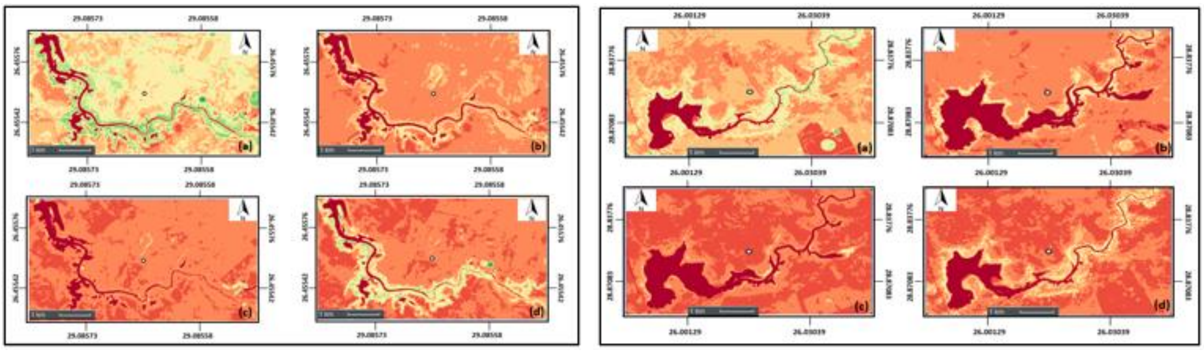
The spring season also had poor water quality as indicated by the very high WQI of 62.6. Just like the summer season, the spring season was characterised by very high ET_0 rates and very low surface water levels. The ET_0 rates for the spring season was double that of the autumn and winter seasons, resulting in the high TDS and sulphate concentrations. The correlation between the spring season's ET_0 against that of the WQI, indicated the impact that ET_0 can have on water quality.

4.5 Effects of evapotranspiration on vegetation density (2017–2019)

The Landsat images for the years 2017–2019 for the sub-catchment areas, covering the Mockes and Krugersdrift dams, were acquired for all the seasons through the EOS Land Viewer website. The NDVI images and vegetation density estimations obtained from the EOS software were analysed together to provide an overall indication of the state of vegetation healthiness across the catchment. Figures 4.10–4.12 shows the NDVI images for the Mockes Dam and Krugersdrift Dam catchment areas for the years 2017–2019.

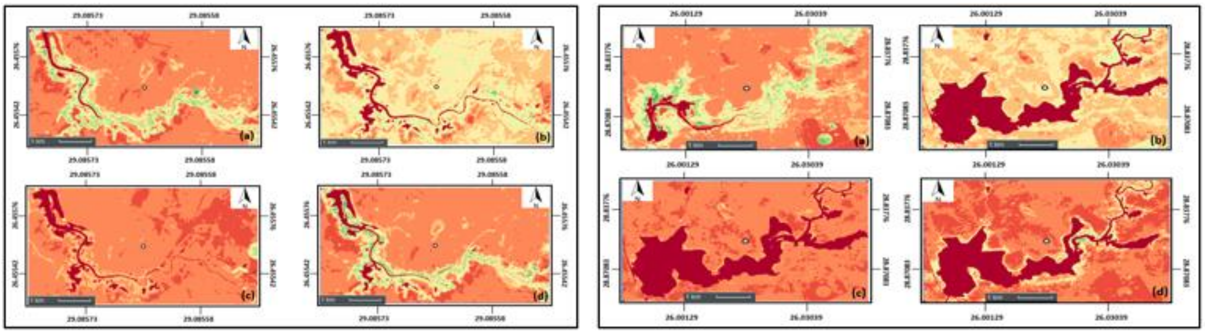
Key for Figures 4.10 to 4.12





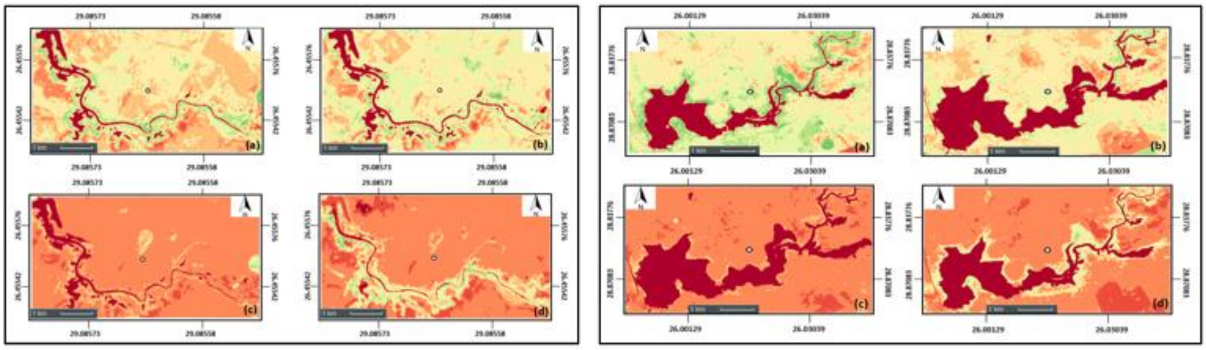
Note: Each of the two images is in the following order: (a) Summer, (b) Autumn, (c) Winter and (d) Spring

Figure 4.10: 2017 Images of the NDVI with Mockes Dam (left) and Krugersdrift Dam (right)



Note: Each of the two images is in the following order: (a) Summer, (b) Autumn, (c) Winter and (d) Spring

Figure 4.11: 2018 Images of the NDVI with Mockes Dam (left) and Krugersdrift Dam (right)



Note: Each of the two images is in the following order: (a) Summer, (b) Autumn, (c) Winter and (d) Spring

Figure 4.12: 2019 Images of the NDVI with Mockes Dam (left) and Krugersdrift Dam (right)

Table 4.4 shows the NDVI values for the Mockes and Krugersdrift dams for all the four seasons between the years 2017-2019.

Table 4.4: NDVI values for the Mockes and Krugersdrift dam areas

Year	Summer (February)		Autumn (May)		Winter (August)		Spring (November)	
	Mockes	Krugersdrift	Mockes	Krugersdrift	Mockes	Krugersdrift	Mockes	Krugersdrift
2017	0.41	0.30	0.31	0.21	0.20	0.13	0.24	#
2018	0.29	0.30	0.45	0.33	0.24	0.11	0.28	0.18
2019	0.31	0.28	0.44	0.30	0.24	0.12	0.28	0.16

4.5.1 Vegetation density across the Mockes Dam sub-catchment

The autumn and summer seasons had generally higher NDVI values ranging from 0.29 to 0.44 across the three-year period. This implies that most healthy and densely packed vegetations were found in these seasons, as shown in Table 4.4.

From the Landsat images taken between 2017 and 2019, the densely packed vegetation was mainly distributed along the banks of the river channel and became sparse with increasing distance from the riverbanks. Other parts of the catchment were relatively drier, and the vegetation appeared more stressed, compared to that on the riverbank. Shades of green, representing healthy photosynthesising vegetation, were more visible along the river channel compared to other parts of the catchment. Dense and healthy vegetation utilise a lot of water and carbon dioxide to continuously make food through the process of photosynthesis. The gaseous exchange process that occurs as plants open their stomata to release oxygen and absorb carbon dioxide, also results in them losing lots of water through transpiration. It can thus be inferred that the reason why higher ET_0 values were observed during the autumn and summer seasons, compared to the winter and spring seasons, could be attributed to higher photosynthetic activities in these seasons.

4.5.2 Vegetation density across the Krugersdrift Dam sub-catchment

In-order to have a fair representation of sub-catchments along the Modder River catchment, the Krugersdrift Dam sub-catchment was assessed for vegetation growth and healthiness as was done with the Mockes Dam sub-catchment. The Landsat images for the sub-catchment area covering the Krugersdrift Dam area were acquired for all the seasons through the EOS Land Viewer. The images were analysed together with the NDVI values and vegetation density estimations obtained from EOS. The NDVI images between the years 2017 and 2019 are shown in Figures 4.10–4.12.

The general outlook of the vegetation along the Krugersdrift dam sub-catchment area was very poor in all seasons over the three-year period. Like the Mockes Dam area, the summer and autumn periods had slightly higher NDVI values ranging between 0.21 and 0.30 which indicated very sparse vegetation with very little biomass.

Table 4.5 shows the seasonal vegetation cover densities for the Krugersdrift and Mockes Dam areas between the years 2017 and 2019.The low vegetation biomass was accompanied by very low water volumes in the sub-catchment area as detected by Landsat images, suggesting that the ET_0 rates might have been higher during this period. On the other hand, the spring and winter seasons had the lowest NDVI, indicating very low photosynthetic activity. This suggest that the vegetation was severely stressed during the winter and spring seasons due to the low water levels within the catchment.

Table 4.5: Surface area covered by vegetation cover (m^2) around the sub-catchments of the Mockes and Krugersdrift dams between the years 2017 and 2019

Season	Vegetation	2017		2018		2019	
		Mockes	Krugersdrift	Mockes	Krugersdrift	Mockes	Krugersdrift
Summer (February)	Dense	3 336 600	3 336 600	1 353 000	1 353 000	2 172 400	2 172 400
	Moderate	13 750 000	13 750 000	3 390 000	3 390 000	13 790 000	13 790 000
	Sparse	10 390 000	10 690 000	21 140 000	21 140 000	11 460 000	11 460 000
	Open soil	336 600	336 600	2 920 000	2 920 000	324 200	394 200
	None	1 300 000	1 300 000	324 000	324 000	1 300 000	1 300 000
Autumn (May)	Dense	4 500	4500	226 800	226 800	1 446 500	1 446 500
	Moderate	749 700	754 200	15 090 000	15 090 000	20 090 000	20 090 000
	Sparse	25 350 000	25 350 000	11 950 000	11 950 000	5 630 000	5 630 000
	Open soil	1 450 000	1 450 000	449 100	449 100	433 800	433 800
	None	1 570 000	1 570 000	1 410 000	1 410 000	1 530 000	1 530 000
Winter (August)	Dense	18 900	18 900	63 900	63 900	50 400	50 400
	Moderate	93 600	93 600	236 700	236 700	270 000	270 000
	Sparse	20 627 400	20 627 400	22 240 000	22 240 000	25 830 000	24 830 000
	Open soil	6 800 000	6 800 000	5 240 000	5 240 000	1 450 000	1 450 000
	None	1 580 000	1 580 000	1 340 000	1 340 000	1 510 000	1 510 000
Spring (November)	Dense	514 800	514 800	1 216 800	1 216 800	574 600	575 300
	Moderate	2 580 000	2 580 000	3 030 000	3 030 000	2 940 000	7 860 000
	Sparse	17 570 000	17 570 000	21 580 000	21 580 000	22 460 000	55 480 000
	Open soil	7 560 000	7 560 000	2 320 000	2 320 000	2 780 000	7 800 000
	None	895 500	895 500	982 800	982 800	370 000	10 850 000

Chapter 5

Discussion on the effects of evapotranspiration on surface water quantity, surface water quality and vegetation distribution and healthiness across the Modder River sub-catchments

5.1 Introduction

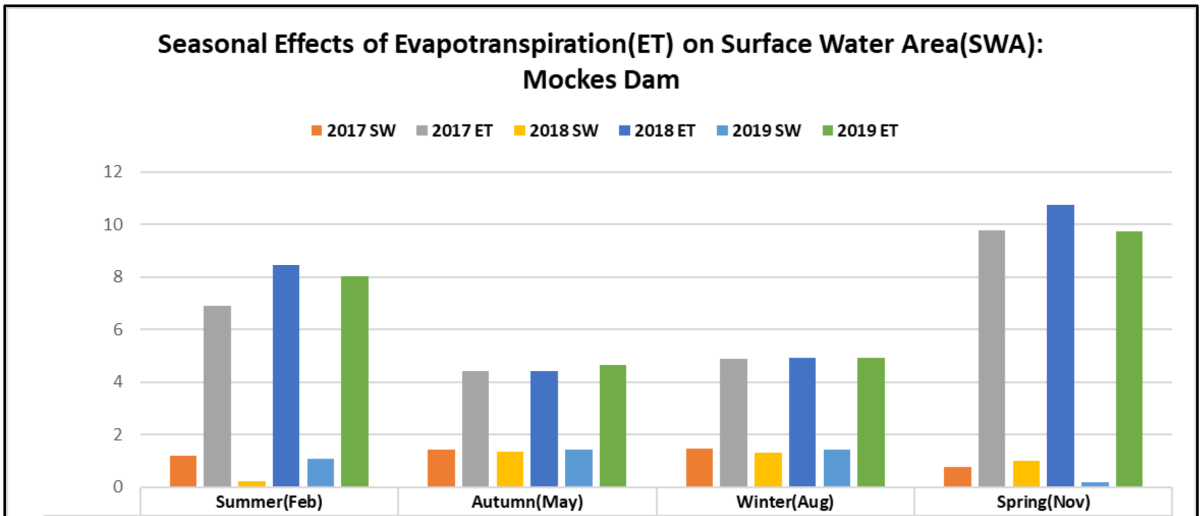
Water loss in catchments can have a negative effect on economic activities such as agriculture, fishing, forestry, and tourism (Botai et al. 2016). The continuous monitoring and management of water resources in the twenty-first century is one of the ultimate challenges facing the human global population. Previous research has pointed out some conflicting views on the effects of ET on water bodies. While some researchers believe that ET has a significant impact on water loss in river catchments, other researchers believe that ET does not play a significant role in catchment water loss compared to other parameters within the hydrological cycle, such as surface water run-off, discharge to groundwater or change in the soil water storage (Ali et al. 2016). This study aimed at using remote sensing techniques to investigate the effects of ET_0 on catchment water quantity and quality as well as to assess the effectiveness and reliability of using remote sensing techniques in estimating catchment water quantity and quality variables. The general outcome of this study showed an inversely weak correlation between ET and surface water quantity within the Modder River catchment.

The establishment of the very close relationship between remotely sensed data on surface water and physical water quality (TDS) is crucial in assisting water managers in routinely monitoring catchment water in relation to catchment activities. Further research could focus on validating this outcome as well as creating models that can be reliably applied to catchments in similar climatic conditions.

5.2 Effects of evapotranspiration on surface water quantity

The results of the study showed that ET_0 is inversely and weakly correlated to catchment surface water quantity. This outcome suggests that although ET_0 plays a role in determining catchment water quantity, that role does not supersede the individual or combined effects that other hydrological processes might have on catchment water quantity. This is contradiction to the findings of Ndou et al. (2017), who argued that evapotranspiration can contribute to more than 60% water loss within a river catchment.

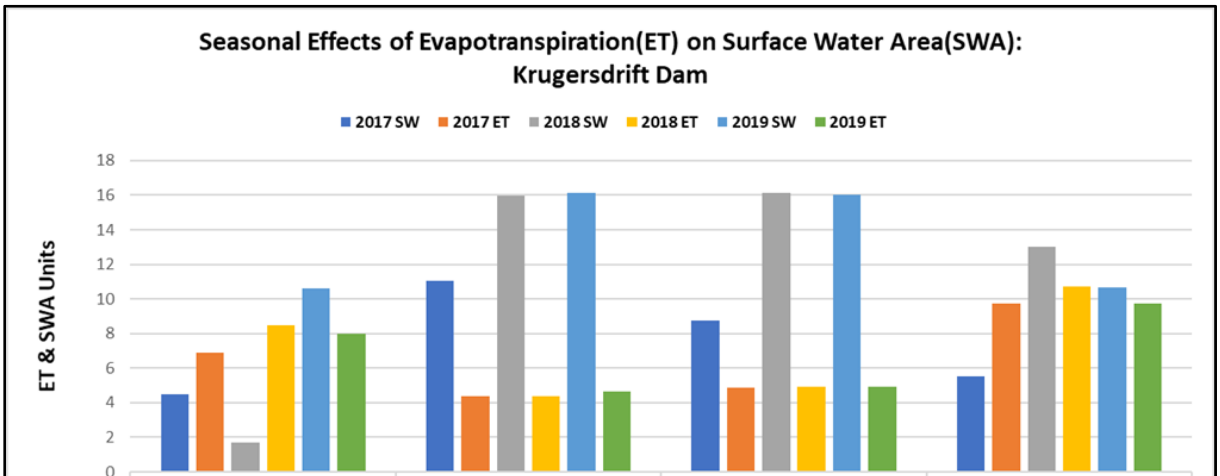
An analysis between ET_0 and surface water area in all the four seasons over the three-year period confirmed the inverse relationship between the two variables as shown in Figures 5.1 and 5.2. As the ET_0 rate increased, the surface water decreased proportionally and that was true for all the seasons in the Mockes Dam sub-catchment as well as for the summer and spring seasons in the Krugersdrift Dam sub-catchment.This finding can be compared to that of Zhang et al. (2001), who identified that ET_0 has a direct effect on reducing surface water within a river catchment.



	Summer(Feb)	Autumn(May)	Winter(Aug)	Spring(Nov)
2017 SW	1,17	1,43	1,44	0,77
2017 ET	6,9	4,39	4,88	9,75
2018 SW	0,23	1,35	1,3	0,99
2018 ET	8,45	4,4	4,9	10,72
2019 SW	1,06	1,4	1,43	0,18
2019 ET	8,01	4,65	4,93	9,71

Figure 5.1: ***Seasonal patterns of ET_0 and the surface water area in Mockes Dam***

In the Krugersdrift Dam area, only part of the summer and spring seasons followed the same pattern to that of the Mockes dam as the winter and autumn seasons showed a completely new and different relationship with the ET values not corresponding with surface water. This could have been attributed to ET_0 having a lesser impact on catchment water balance compared to other variables such as precipitation, recharge to groundwater and change in soil water storage. Interference from other weather elements such as wind, wind speed, and or humidity could also have impacted on the relationship between ET and surface water. It was noted that the relationship between ET_0 and surface water area is stronger than the relationship between surface water area and other independent climate variables such as rainfall, humidity, wind speed or temperature. From this evidence, it can be safely inferred that ET_0 has a relatively significant effect on water quantity in the Modder River catchment compared to other climate and weather variables, however, that impact can be compromised by other processes within the water balance equation such as surface run-off, seepage, and soil water storage capacity.



	Summer(Feb)	Autumn(May)	Winter(Aug)	Spring(Nov)
2017 SW	4,46	11,02	8,77	5,51
2017 ET	6,9	4,39	4,88	9,75
2018 SW	1,68	15,96	16,12	13,01
2018 ET	8,45	4,4	4,9	10,72
2019 SW	10,61	16,12	16,01	10,64
2019 ET	8,01	4,65	4,93	9,71

Seasons

Figure 5.2: ***Seasonal patterns of ET_0 and the surface water area in the Krugersdrift dam***

The ET_0 and surface water area values between 2017 and 2019 for all four seasons were plotted on a single graph for the Mockes and Krugersdrift areas as shown in Figure 5.3. The resultant plots showed some weak to moderate inverse relationships between ET and surface water area, with the latter decreasing with increasing ET.Although the relationship between ET and surface water varied across the two sites, the overall outcome of the study proved that ET has an effect of reducing surface water in the Modder river catchment. Furthermore, the study managed to prove that remote sensing techniques have the ability and potential to be used in estimating the amount of surface water present in large water bodies within catchments.

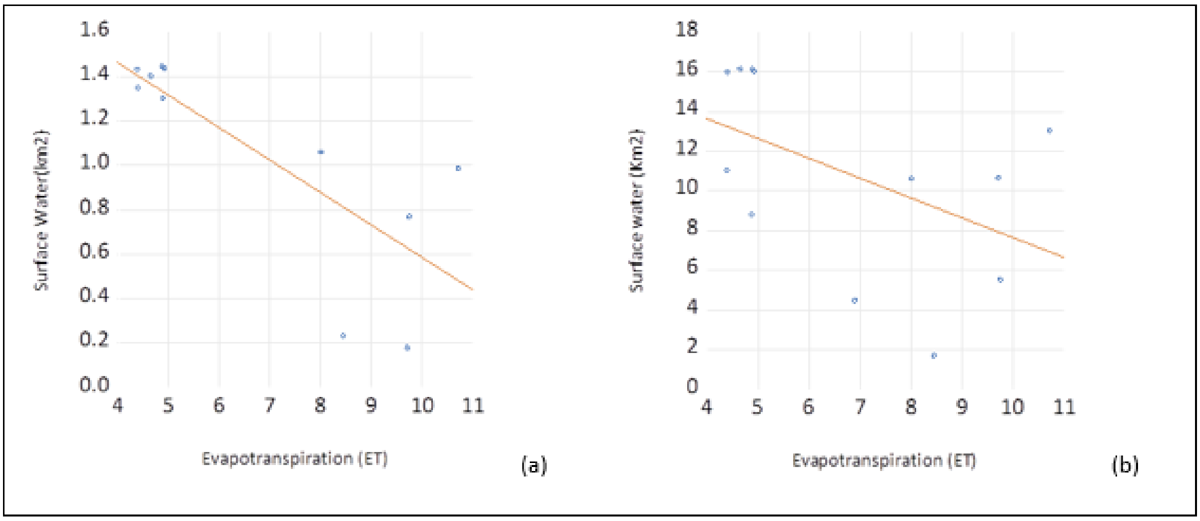


Figure 5.3: ***Scatter plot between evapotranspiration and surface water area values from 2017 to 2019: (a) Mockes area (b) Krugersdrift area***

The alignment of the ET_0 and surface water relationship with findings from other studies such as those of Xu and Singh 2002; Zhang et al. (2001), proved that remote sensing can be a useful and and reliable technique in assissing surface water quantity. However, although the nature of the relationship between ET and surface water area was established through use of remote sensing methods using Landsat 8 satellite images and data, other satellite images could also be employed to establish the effectiveness of the use of remote sensing technology.

5.3 Effects of evapotranspiration on surface water quality

Generally, there is a very close association between water quality and water quantity (Mamba et al. 2008). Since the study results showed that ET has a very weak inverse relationship to surface water quantity, it was generally expected that ET will also have a minimal impact on water quality. The results of the study however produced some unexpected outcomes in water quality conditions which do not correspond with the magnitude of ET in some of the study sites. These findings are crucial in investigating the nature and function of other contributory factors to water quality within a river catchment.However, establishing the detailed nature of these other factors might require further investigations through future studies.

5.3.1 Seasonal effects of evapotranspiration on water quality

The study outcome showed that the magnitude of ET in all the seasons across the study period was enough to influence the water quality condition to be poor as shown in Table 5.1.

Although this finding might not have been part of the objectives of this study, it is important in establishing the benchmark for investigating the ET levels necessary to cause water deterioration.

According to Collier (2016), Kool et al. (2014) and Pidwirny (2006), high ET rates are the largest contributory factors to poor water quality in river catchments.The study was able to show that high ET rates are characterised by high solute concentrations in catchment water, thus resulting in poor water quality. All the WQI values calculated for all the study sites lied within the range of 53.5 to 66.3 which falls under the poor water quality category as per the Weighted Arithmetic Index method scale. This is also another important finding as it depicts that the Modder river catchment water is not fit for human consumption before treatment and should be closely monitored when used for by animals and for recreational activities.

Previous studies have shown the relationship between ET and surface water to be very complex and unpredictable as it is affected by other natural processes and cycles involving soil, vegetation, and the atmosphere (Hellegers et al. 2010). The study also produced some unexpected findings which showed that the low ET rates of 4.48 mm and 4.90 mm in the autumn and winter seasons corresponded to the poorest WQI value of 66.3 as compared to the summer and spring seasons which had ET values of 7.79 mm and 10.06 mm with WQI values of 53.5 and 62.6 respectively. This study outcome suggests that other variables other than ET might have been responsible for influencing water quality especially in the autumn and winter seasons. It can be suggested that the low temperatures in the autumn and winter seasons might have caused the preservation and accumulation of contaminants which enter the river through different channels such as sewage waste. The low temperatures might have been responsible for increasing the residence time of the contaminats in the river water as they are degraded slowly by micro-organisms thus giving rise to poor water quality despite the high water volumes as compared to the summer and spring seasons.

Table 5.1: Seasonal values of the Water Quality Index against evapotranspiration

Season	Evapotranspiration	Water Quality Index	Water quality
Summer	7.79	53,5	Poor
Autumn	4.48	66,3	Poor
Winter	4.90	66,3	Poor
Spring	10.06	62,6	Poor

The poor water quality experienced for all the four sessions between the three year period might also be attributed to the drought period which corresponded with the years 2017-2019. Drought seasons are usually characterised by very high ET rates and poor water quality across all the seasons.

5.3.2 Effect of evapotranspiration on the Normalised Difference Vegetative Index

NDVI has been used as a proxy for assessing water quality in rivers. In most cases the NDVI relates to the physical water quality properties of water, such as the amount of TDS (Masocha et al. 2017). Since the NDVI is a parameter that was obtained through remote sensing, its relationship with ET can be used to infer the impact of ET on TDS, a physical water quality parameter.

One of the fundamental objectives of the study was to establish whether remote sensing can be applied in determining water quality in river catchments. If a relationship between ET_0 and NDVI is comparably validated against the ET–WQI relationship, then we can safely infer that remote sensing can be applied in determining water quality in river catchments, with similar conditions to that of the Modder River catchment.

A regression test was conducted on ET_0 against NDVI, using the values acquired over the three-year period as shown in Table 5.2. The test gave a result of $r = -0.2$, indicating a very weak inverse correlation between ET_0 and NDVI.

Table 5.2: Seasonal effect of evapotranspiration on the Normalised Difference Vegetative Index

	2017				2018				2019			
Seasons	S	A	W	S	S	A	W	S	S	A	W	S
Evapotranspiration (X)	6,9	4,39	4,88	9,75	8,45	4,40	4,90	10,72	8,01	4,65	4,93	9,71
NDVI (Y)	0,41	0,31	0,20	0,24	0,29	0,45	0,24	0,28	0,31	-	-	-

Key: S=Summer; A=Autumn; W=Winter; S=Spring

The significance of this result gives an indication that ET_0 has an overall negative effect on NDVI. This similar weak inverse relationship is synonymous with the results obtained between ET and surface water quantity as well as the results between ET and the WQI.Studies by Nouri et al. (2013) also highlighted that remote sensing indices such as the NDVI can be related to evapotranspiration. It can thus be inferred that the NDVI can be used as a remote sensing proxy for assessing water quality in river catchments synonymous to the Modder River catchment. However, further research in other catchments need to be conducted for validating this finding.

5.4 Seasonal effects of evapotranspiration on vegetation density and healthiness

The NDVI can be used to measure and assess vegetation healthiness and density. Vegetation healthiness in a river catchment can be affected by various factors, including weather, soil type, soil nutrients and, most importantly, the availability of water. An analysis of the average NDVI values for all four seasons across the Mockes and Krugersdrift dams showed that the autumn and summer seasons had the healthiest and most dense vegetation compared to the spring and winter seasons as indicated in Table 5.3.

Table 5.3: Seasonal Normalised Difference Vegetative Index values between 2017 and 2019

Year	Summer	Autumn	Winter	Spring
2017	0,41	0,31	0,20	0,24
2018	0,29	0,45	0,24	0,28
2019	0,31	-	-	-
Average	0,34	0,38	0,22	0,26

The NDVI values ranged from 0 to 1, with values close to 1 indicating very healthy vegetation, and values close to 0 indicating very unhealthy vegetation. Values closer to 0,5 indicated moderate to average vegetation healthiness. Although ET has been related to reducing surface water that is crucial for plant growth, ET has also been shown to positively contribute to plant health. The process of transpiration allows plants to draw water and nutrients from the soil. It also has a cooling effect on the plant from the solar radiation and high temperatures.

An analysis of the relationship between ET and NDVI in Table 5.2 showed that high ET values are characterised by very low NDVI values, and the same holds true for low ET values. These results imply that ET has an overall negative impact on vegetation healthiness within the Modder River catchment. These results are consistent with the findings of Gulcan and Mehmet (2016), who discovered that high ET levels around lake Burdur in Turkey,were resulting in low NDVI values for terrestrial vegetation. Further analysis must be conducted to ascertain the extent to how other variables such as soil type and nutrients might have an impact on plant growth in the catchment. The effect of ET_0 on vegetation growth is only positively correlated up to a certain optimum level beyond which ET_0 will negatively affect the photosynthetic processes which negatively contribute to the health of plants.

Chapter 6
Validation of Results

6.1 Introduction

This chapter seeks to validate the results and outcomes that were discussed in the results and discussion chapters of this study. Tables, graphical analyses, and statistical tests were used to further elaborate on the relationships between the variables that were analysed in this study.

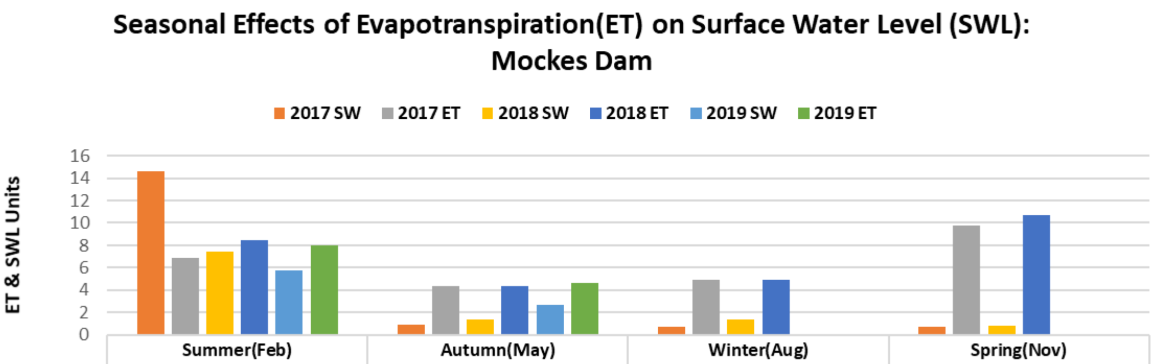
6.2 Validation of the evapotranspiration and surface water area relationship using the Department of Water and Sanitation surface water level data

The surface water level obtained from the DWS was used to validate the results and findings of the study. The surface water area obtained through remote sensing was replaced with the surface water level which was measured at stations along the Modder River. The surface water levels from the DWS are shown in Table 6.1.

Table 6.1: Surface water level for the Krugersdrift and Mockes dam area catchments

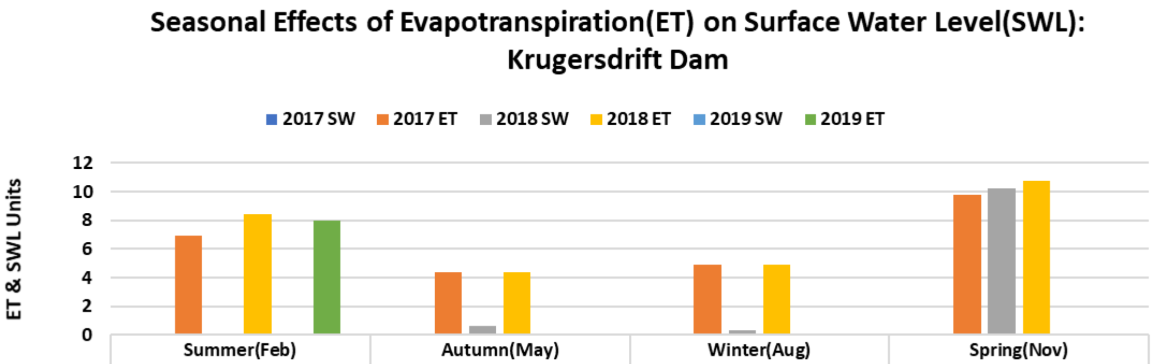
Month	2016		2017		2018		2019	
	Krugersdrift	Mockes	Krugersdrift	Mockes	Krugersdrift	Mockes	Krugersdrift	Mockes
October	8.88	-	11.9	#	1.59	1.29		1.16
November	0.008	-	0.005	#	10.2	0.710		0.819
December	11.9	-	12.0	#	9.34	1.47		0.906
January	0.02	5.93+	0.002	4.63+#	0.001	0.831	2.46	2.26
February	0.009	0.701	0.003	14.6+	0.009	7.41+	0.002	5.74+
March	0.004	1.38	0.010	2.78	0.035	20.0+	10.8	1.63
April	0.012	3.19	0.017	0.937	39.2	11.5+	73.0	13.8+
May	13.0	7.27+	0.019	0.879	0.632	1.39		2.68
June	0.036	0.612	10.3	0.882	0.093	1.23		1.14
July	0.029	2.08#	0.021	0.755	0.130	1.35		#
August	0.025	0.954	0.015	0.763	0.303	1.42		#
September	1.89	0.299#	0.015	0.982	9.05	1.13		#

The surface water level was plotted in a graph against ET for each of the four seasons between 2017 and 2019 for each of the two sub-catchments. The graphs plotted are shown in Figures 6.1 and 6.2.



	Summer(Feb)	Autumn(May)	Winter(Aug)	Spring(Nov)
2017 SW	14,6	0,879	0,763	0,71
2017 ET	6,9	4,39	4,88	9,75
2018 SW	7,41	1,39	1,42	0,819
2018 ET	8,45	4,4	4,9	10,72
2019 SW	5,74	2,68		
2019 ET	8,01	4,65		

Figure 6.1: Seasonal effects of evapotranspiration on surface water level in the Mockes Dam area



	Summer(Feb)	Autumn(May)	Winter(Aug)	Spring(Nov)
2017 SW	0,003	0,019	0,015	0,005
2017 ET	6,9	4,39	4,88	9,75
2018 SW	0,009	0,632	0,303	10,2
2018 ET	8,45	4,4	4,9	10,72
2019 SW	0,002			
2019 ET	8,01			

Figure 6.2: Seasonal effects of evapotranspiration on surface water level in the Krugersdrift Dam area

The surface water level measured from gauge stations along the Krugersdrift dam was used to draw a comparison with ET_0. The graphs of surface water level with ET_0 were plotted to determine the relationship between the two variables for each season between the years 2017 and 2019. A comparison between the rate of surface water level and ET_0 showed that the rate at which the surface water level reduced, was in proportion to the extent of the ET_0

magnitude in both sub-catchments. This observation was also proved true by the relationship between the surface water area and ET_0, across all the seasons in the three-year period. The surface water level within the Mockes and Krugersdrift dam sub-catchments decreased with increasing ET_0 for each year and season. This evidence further proved that ET_0 is one of the major contributors of water loss in a catchment as it has a direct impact on water quantity within dams and sub-catchments as indicated in this study.

The results shown in Figures 6.1 and 6.2 further proved that ET_0 has a negative effect on catchment water across all seasons over the three-year period. The summer seasons experienced the greatest ET_0 with respect to the highest water loss within the catchment. Because of the very high ET_0 within the summer season, very little water was available within the catchments. This data concurred with the findings from remote sensing and is crucial to inform decisions on planning economic activities such as farming operations within the catchment.

6.3 Validation of the evapotranspiration and surface water area relationship using statistical analysis

The Pearson Correlation Coefficient test was conducted to evaluate the relationship between ET and the surface water quantity represented by the surface water area. The average seasonal values of ET and surface water area for each year between 2017 and 2019 were used in calculations to establish the test statistic r (see Table 6.2).

Table 6.2: Evapotranspiration and surface water area from the Mockes and Krugersdrift dams

	2017				2018				2019			
Evapotranspiration (X)	6,9	4,39	4,88	9,75	8,45	4,40	4,90	10,72	8,01	4,65	4,93	9,71
Surface water – Mockes (Y)	1.17	1.43	1.44	0.77	0,233	1,347	1,300	0,985	1,058	1,400	1,434	0,178
Surface water – Krugersdrift (Y)	4.86	11.02	8.77	5.51	1.68	15.96	16.12	13.01	10.61	16.12	16.01	10.64

Example:

In this test, the null hypothesis, H_0, that there is no correlation between ET and surface water area, was tested against the alternative hypothesis, H_1, that there is a correlation between these two variables. The data taken from the Mockes and Krugersdrift areas for all four seasons in three years was used to investigate which of these opposing hypotheses was most likely to be true.

H_0: $r = 0$

H_1: $r \neq 0$

The variables were inserted into Pearson's equation:

$$r = \frac{N\sum XY - (\sum X)(\sum Y)}{\sqrt{(N\sum X2 - (\sum X)2)(N\sum Y2 - (\sum Y)2)}} \quad (14)$$

$$r = \frac{-72.864}{\sqrt{\sum 127.434 + 844.062}} \quad (15)$$

$$r = -0.22 \quad (16)$$

where:

r = Pearson's correlation coefficient

N = number of pairs of scores

X = score of the first variable

Y = score of the second variable

XY = the product of the two paired scores

The result of r= -0.22 rejects the null hypothesis and indicates a weak relationship between ET and surface water area. This test result shows that ET and surface water area have a negative linear correlation. However, the value of 0.22 is closer to 0 than 1, further indicating that the correlation between ET and surface water area is weak. This implies that ET might not be the strongest contributor to surface water loss compared to other hydrological processes in the water balance equation, such as soil water storage, run-off flow and water seepage. However, study periods of more than three years might need to be carried out to validate this outcome. Some remote sensing methods with modified water indices and satellite data obtained from more high-resolution satellites, such as SENTINEL, can be used to reproduce the study and compare the outcomes.

6.4 Validation of the relationship between evapotranspiration, Water Quality Index, and the Normalised Difference Vegetative Index using statistical analysis

The Pearson's correlation coefficient test was conducted to assess the relationship between the seasonal WQI, seasonal ET_0, and NDVI. The test results between the WQI and ET_0 gave an r value of -0.5, which indicated a very moderate inverse relationship between ET_0 and the WQI. The results imply that ET_0 has an average contribution to catchment water quality. This validation is significant as it point out similarities between the effects of ET on surface water and water quality.The regular monitoring and possible control of ET_0 is thus important in preserving water quality in the catchment.

The relationship between the WQI and the NDVI (represented in Table 3) was also assessed using the Pearson's correlation coefficient yielding an r-value of -0.2. This indicates a negative poor correlation between the two variables. The NDVI has been used as a reliable tool for estimating physical water quality using the TDS parameter (Masocha et al. 2017). However, this result is significant as it shows that the NDVI cannot be relied upon in predicting water quality in all contexts. Further studies need to look into suitable environments for which the NDVI can be applied in assessing water quality.

Table 6.3: Seasonal effect of Normalised Difference Vegetative Index on total dissolved solids

Year	Parameter	Summer (February)	Autumn (May)	Winter (August)	Spring (November)
2017	NDVI (x)	0.41	0.31	0.20	0.24
	TDS (y)	240.75	442.3	409.67	641.8
2018	NDVI (x)	0.29	0.45	0.24	0.28
	TDS (y)	257	-	-	-
2019	NDVI (x)	0.31	0.44	0.24	0.28

The results of this study indicated that although the remotely sensed NDVI have been used to estimate water quality in other catchments, it must be used in conjunction with other supportive ground-based methods to correctly determine the water quality in catchments.

6.5 Validation of the relationship between total dissolved solids, Normalised Difference Vegetative Index and vegetation growth

The Pearson correlation coefficient test between TDS and NDVI showed r = -0.6. This implied that a very strong inverse correlation exists between TDS and NDVI. The higher NDVI values corresponding with healthy vegetation gave rise to low TDS values, while the lower NDVI values corresponding to unhealthy vegetation corresponded to high TDS values. It can be implied that the healthy vegetation in catchments had some effect on reducing the discharge of dissolved solids into the water. On the other hand, it can also be implied that unhealthy vegetation also has the opposite effect. The results imply that remote sensing can be reliably used in combination with other groundwater quality monitoring methods to estimate catchment water quality with respect to TDS. More studies should be carried out in other catchments besides the Modder River to validate this study.

Chapter 7
Conclusion and Recommendations

7.1 Introduction

The aim of this research was to investigate the effects of potential ET on the surface water quantity and water quality along the Modder River catchment using remote sensing technology. By investigating the impact of ET on water quality and quantity, the study also paved way in constructing new knowledge on the suitability of applying remote sensing methods in environmental monitoring.Despite several questions being asked about certain outcomes, all the study aims, and objectives were met, and the conclusions are presented under the sub-aims as follows:

7.2 Assessing the effects of ET on surface water in the Modder River catchment

- The study clearly demonstrated that ET has a negative effect on surface water as demonstrated in all the study sites. This finding was further confirmed through validation by using data from the Department of Water Affairs. The study also demonstrated that although ET does affect surface water volumes in river catchments, other natural factors and processes also play a crucial role in determining the surface water quantities.

7.3 Assessment of the effect of evapotranspiration on water quality in the Modder River catchment

- The study was able to prove that ET has an adverse effect on water quality to a certain extent. The correlation coefficient of -0.5 between the WQI and ET showed the significance of ET in the hydrological cycle and water balance equation as demonstrated in many other studies. The study also demonstrated that for other seasons such as autumn and spring, ET is not always directly impacting on surface water quality.This outcome however further raises questions on the possibility of other processes being involved in effecting water quality in the river catchment.
- The seasonal analysis of the water quality data highlighted that all the four seasons have poor water quality irregardless of the ET values. The significance of this outcome is that it

opens up areas for further research in tracing out the minimum ET values that are required to effect poor water quality within the catchment.

7.4 Assessment on the effect of ET on vegetation density and healthiness

- The NDVI values suggested that the vegetation density within the Modder River catchment ranged from moderate to sparse for all the seasons in the period 2017–2019. These findings are typical of sub-Saharan Africa vegetation for arid to semi-arid regions. Overall, the study findings showed that ET has mixed effects on vegetation density and healthiness.

7.5 Use of Remote Sensing techniques in water monitoring

- The study demonstrated that remote sensing methods can be used to detect water quality and quality within river catchments. The remote sensing indexes NDWI and NDVI can be used to give an approximation of the area covered by surface water as well as the healthiness and density of vegetation. The surface water area can be used to infer and give rough estimates of the total loss or gain of water within a river catchment. The significance of this finding is that remote sensing can be used as a technique for estimating surface water in areas that are not well equipped with instruments for measuring water quantity in river catchments or in instances when rapid water quantity assessments need to be conducted.

7.6 Recommendations

The use of remote sensing technology in monitoring and assessing water resources can be one of the most efficient, sustainable, and cost-effective ways of managing our water resources. The following recommendations are crucial for further studies and investigations on assessing the effectiveness of this technique so that it can be uniformly applied and refined for use in all arid and semi-arid regions in water quantity and quality monitoring.

7.6.1 Recommendations for future studies

Although the findings of this study indicated that remote sensing has the potential to be used in assessing the effect of weather elements such as ET on river catchments, further studies need to be conducted in other catchments to validate these outcomes. The promising relationship between the NDVI and WQI, is a significant outcome that might need to be further explored for validation of larger water parameter sample sizes. The weak correlation found between ET and surface water area obtained through remote sensing might need to be further investigated using data from other satellites, such as SENTINEL, SPOT, MODIS or IKONOS. The outcomes from this study were based on data observed in a three-year period; it is therefore recommended that the study period be extended to ensure the consistency and validity of these findings.

7.6.2 Recommendations to the local government, farmers, and communities along the Modder River catchment

As some of the water measuring instruments along the Modder River were not functioning properly and some were not available due to vandalism and theft, it is recommended that the local water authorities begin to invest in remote sensing technology to aid them to monitor the water quality and quantity quickly and conveniently across the catchment. The water within the Modder River catchment should be closely monitored in the summer and autumn seasons as its quality is poor due to the presence of heavy solutes. It is important for both subsistence and commercial farmers using the catchment water for their livestock to properly test the water during the summer and spring seasons.

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Appendix A

Appendices A1 to A4 shows images for water quality sampling at different sampling points along the Modder River catchment

Appendix A1: Water sampling at Likatlong River

Appendix A2: Water sampling at Rustfontein Dam

Appendix A3: Water sampling at Krugersdrift Dam

Appendix A4: Water sampling at Maselspoort

Appendix B

Chemical determinants for the four seasons

Appendices B1 to B4 shows the chemical determinants for each season between 2016 and 2019.

Appendix B1: Determinants measured in the summer season (2016–2019)

Determinant	Units	Samples																							
		Likatlong				Rustfontein (Diepwater on Modder River)				Groothoek				Maselspoort (Glen on Modder)				Bishops Glen 1 Renosterspruit				Krugersdrift			
		2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Physical																									
pH	pH units	8.2	8.1	8.0	7.11	8.3	8.3	8.3	7.50	7.07	11.7	6.9	6.76	8.1	8.1	8.6	7.74	7.65	8.2	8.2	7.83	8.4	8.9	7.7	7.45
Electrical conductivity	mS/m	20.7	19.6	67.2	26.7	27.2	18.3	17.4	25.5	32.1	21.4	22.1	46.0	33.3	15.0	44.2	58.1	63.8	24.9	38.9	104.3	65.4	86	45	25.4
Total hardness as $CaCO_3$	mg/L	95	58	148	93	112	70	68.8	90	161.8	90.1	#	188	197.5	49	139	162	211.17	71.4	90.4	308	199.9	319	131.8	84
TDS	mg/L	186	134	331	195	213	141	124.6	183	270	168	166	342	390.7	104.9	344.4	403	507	178	270	701	485.5	718.6	307.4	190
Chemical (Macro)																									
Calcium (Ca)	mg/L	24	14	31.1	23.9	21.2	17.4	15.9	22.64	27.0	19.1	19.4	48.12	39.1	12.2	32.3	36.33	44.6	20.6	26.9	65.76	29.4	53.6	24.9	22.54
Magnesium (Mg)	mg/L	7.65	5.7	11.4	8.12	14.7	8.0	6.6	8.11	14.84	10.7	10.4	16.53	20.2	4.6	14	17.45	25.3	6.2	9.8	34.97	20.1	52.1	14.3	6.77
Sodium (Na)	mg/L	11.97	13.9	29.2	16.34	0.05	0.05	0.05	14.21	0.05	0.05	0.05	20.07	27.3	8	42.2	53.73	60.84	14.1	33.1	100.67	75.5	71	39.9	17.02
Potassium (K)	mg/L	5.37	4.4	7.7	5.21	4.53	5.5	4.6	4.73	5.75	5.7	4.6	14.67	6.1	3.2	9.6	10.47	10.5	2.2	9.2	15.42	12.6	8.5	10.4	9.24
Fluoride (F)	mg/L	0.195	0.095	0.156	0.24	0.206	0.76	0.3	0.22	0.32	0.83	0.31	0.57	0.45	0.025	0.249	0.34	0.22	0.21	0.57	0.43	0.695	0.244	0.284	0.17
Chloride (Cl)	mg/L	10.6	13.2	29.9	10.86	12.1	10	5.3	7.31	8.0	6.8	5.9	18.89	25.8	7.4	42.7	57.79	52.7	17.7	33.2	106.65	78.4	81.6	41.3	17.01
Nitrate (N)	mg/L	0.257	1.10	0.846	0.4	#	#		0.21	8.1	8.3	8.5	0.25	1.825	0.653	3.1	0.35	2.129	2.011	3.61	0.31	0.755	6.189	0.1	0.69
Sulphate (SO_4)	mg/L	10.49	7.7	26.3	14.54	15.2	6.2	2.2	13.65	3.63	5.9		6.64	22.6	6.4	19.1	21.28	42.16	19.2	28.1	53.32	21.5	32.8	14.6	11.97

Appendix B2: Determinants measured in the autumn season (2016–2019)

Determinant	Units	Samples: Likatlong				Rustfontein (Diepwater on Modder River)				Groothoek				Maselspoort (Glen on Modder)				Bishops Glen 1 Renosterspruit				Krugersdrift			
		2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Physical																									
pH	pH units	8.0	7.8	8.4		8.4	8.5	8.7		6.6	8.5	8.4		8.4	8.2	7.6		7.4	8.0	7.7		7.8	8.5	8.3	
Electrical conductivity	mS/m	19.7	53.4	48.6		24.2	50	42.5		26.6	59	49.4		49.3	63.9	24.9		56.8	63.5	60.7		53.5	52.5	26.6	
Total hardness as $CaCO_3$	mg/L	69.9	168.3	135.7		93.5	217.5	208.4		120.4	309.9	248.2		134.8	175	77.6		159	205.4	137.2		147.1	161.8	88.8	
TDS	mg/L	152	399	#		189.8	400	#		220	516	#		365	454.7	#		424	515	#		382	369.1	#	
Chemical (Macro)																									
Calcium (Ca)	mg/L	18.5	48.9	#		24.1	34.6	#		23.9	41	#		29.9	36.5	19.7		36.3	42.2	#		26.1	28.0	#	
Magnesium (Mg)	mg/L	6.4	15.2	#		12.7	42.9	26.5		15.1	35.2	27.9		13.7	17.3	7.3		15.2	17.4			16.4	18.6	#	
Sodium (Na)	mg/L	11.2	41.2	32.7		0.05	0.05	0.05		0.05	0.05	0.05		43.6	57.5	13.5		54.7	60.7	49		53.7	41.8	17.5	
Potassium (K)	mg/L	3.2	7.7	6.6		3.6	4.4	5.1		4	5.4	4		8.7	10.2	4.6		9.8	10	9.4		8.9	10.4	5.9	
Fluoride (F)	mg/L	0.203	0.282	0.203		0.762	0.368	0.23		0.879	0.544	0.254		0.796	0.277	0.121		0.619	0.391	0.264		0.649	0.437	0.025	
Chloride (Cl)	mg/L	12.6	41.3	37.3		9.6	16.4	9		8.2	13.6	8.1		46.4	55.6	#		48.2	53.7	53.7		57.3	41.4	20.0	
Nitrate (N)	mg/L	0.783	2.18	12.6						8.1	#			3.87	3.96	0.67									
Sulphate (SO_4)	mg/L	10.8	29.8	26.7		14.8	15.2	9.5		10.4	13.3	11.9		37.7	44.3	#									

Appendix B3: Determinants measured in the Winter season (2016–2019)

Determinant	Units	Samples																							
		Likatlong				Rustfontein (Diepwater on Modder River)				Groothoek				Maselspoort (Glen on Modder River)				Bishops Glen 1 Renosterspruit				Krugersdrift			
		2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Physical																									
pH	pH units	8.3	8.6	8.4		8.5	8.4	8.6		8.4	8.7	8.4		8.3	8.8	8.5		8.4	8.7	7.1		8.4	8.6	8.5	
E. Conductivity	mS/m	33.1	63.1	61.8		31	27.5	59.7		41.5	65.9	49.4		58.1	75.9	62.5		64.9	76	68.8		49.1	42.5	33	
Total hardness as $CaCO_3$	mg/L	102.1		138.9		149.2	82.9	282.9		202.9	335.7	248.2		143.3	#	187.2		171.7	251.3	164.5		165.8	163.2	120.8	
TDS	mg/L	245.4		#		268.8	175.4	#		349.0	584.0	#		425.6	#	#		496.2	552.7	#		371.9	327.0	#	
Chemical (Macro)																									
Calcium (Ca)	mg/L	26.7	44.9	#		32.4	21.2	#		33.3	47.2	#		38.5	53.3	#		43.7	39.2	#		32.6	29.5	#	
Magnesium (Mg)	mg/L	9.3	16.5	#		#	7.4			22.3	54	27.9		16.8	25.7	#		22.8	22.6	#		17.8	15.8	20.5	
Sodium (Na)	mg/L	23.4	60	48.2		17.8		55.8		0.174	0.05	0.05		55.8	69.1	56.7		61.9	76.5	59.9		39.8	31.9	#	
Potassium (K)	mg/L	4.9	9.4	#		3.8	0.025			4.3	4.3	4		8.8	9.3	10.1		9.9	12.4	10.7		8.0	8.2	6.5	
Fluoride (F)	mg/L	0.565	0.3	9.5		0.37		0.361		0.303	0.397	0.254		0.025	0.339	0.121		0.313	0.27	0.203		0.847	0.361	0.139	
Chloride (Cl)	mg/L	25.6	52.7	48.3		11.5	9.0	#		11.6	17.5	#		47.3	65.3	57		54.3	66.1	56.6		42.4	33.3	18	
Nitrate (N)	mg/L	2.17	1.81	15.7		#	0.161	0.03		8.4	#	8.4		7.54	3.84	6.184		8.30	4.28	12.7		0.426	0.05	2.24	
Sulphate (SO_4)	mg/L	19.9	32.3	25.6		9.4	18	#		12.6	12	11.9		6.46	#	47.1		51.5	0.6	52.5		26.3	8.6	13.7	

Appendix B4: Determinants measured in the Spring season (2016–2019)

Determinant	Units	Samples																							
		Likatlong				Rustfontein				Groothoek				Maselspoort				Bishops Glen 1 Renosterspruit				Krugersdrift			
		2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Physical																									
pH	pH units	8.1	8.2	#		8.4	8.0	#		8.4	9.6	#		7.8	8.3	#		8.0	8.3	#		8.4	8.4		
E. Conductivity	mS/m	28.9	69	#		31.1	47.6	#		26.0	59.4	#		31.9	75.1	#		35.8	69.9	#		45.8	43.0		
Total hardness as $CaCO_3$	mg/L	110.9	170.8	#		149.4	230.1	#		146.8	310.4	#		103.9	247.2	#		107.9	238.7	#		148.4	133.7		
TDS	mg/L	229	524	#		277.03	398.3	#		241.38	543.3	#		241.1	596.8	#		273.6	552.03	#		341.3	314.3		
Chemical (Macro)																									
Calcium (Ca)	mg/L	25.2	45.9	#		35.3	49.7	#		26.3	14	#		20.9	51.3	#		26.8	50	#		24.9	29.1		
Magnesium (Mg)	mg/L	9.6	18	#		17.4	27.8	#		9.3	8.0	#		9.5	22.6	#		10.2	22.6	#		14.9	15.1		
Sodium (Na)	mg/L	17.1	64.4	#		0.05	0.05	#		15.7		#		26.5	70.1	#		31.6	61.6	#		40.5	38.4		
Potassium (K)	mg/L	5.6	12.3	#		4.0	3.9	#		4.1	1.8	#		6.7	12.6	#		7.7	10.5	#		10.7	8.6		
Fluoride (F)	mg/L	0.383	0.211	#		0.554	0.458	#		0.936	0.727	#		0.816	0.3	#		0.577	0.299	#		0.797	0.255		
Chloride (Cl)	mg/L	16.3	57.4	#		11.5	14.9	#		4.8	30.4	#		23.6	69.3	#		28.7	58.2	#		42.9	34.1		
Nitrate (N)	mg/L	1.64	16.95	#		#	#	#		0.101		#		1.442	1.913	#		1.987	0.189	#		0.05	0.447		
Sulphate (SO_4)	mg/L	11.5	42.6	#		14.8	3.2	#		0.6	0.6	#		18.2	55.5	#		23.4	51.6	#		23.9	23.7		

Appendix C

Calculations of the Water Quality indexes

Parameter	Standard	1/Sn	Sum(1/Sn)	K=1/Sum(1/Sn)	Wi=K/Sn	Ideal Value(V0)	Mean Conc Val (Vn)	Vn/Sn	Vn/Sn*100=Qn	WnQn
pH	8,5	0,117647	0,261647059	3,821942446	0,44964	7	8	0,67	67	30,1259
EC	1000	0,001	0,261647059	3,821942446	0,003822	0	65,5	0,0655	6,55	0,025034
TDS	600	0,001667	0,261647059	3,821942446	0,00637	0	269	0,44833333	44,83333333	0,285584
Ca^{2+}	200	0,005	0,261647059	3,821942446	0,01911	0	19	0,095	9,5	0,181542
Mg^{2+}	50	0,02	0,261647059	3,821942446	0,076439	0	14	0,28	28	2,140288
Na^{+}	200	0,005	0,261647059	3,821942446	0,01911	0	39,5	0,1975	19,75	0,377417
K	12	0,083333	0,261647059	3,821942446	0,318495	0	7,5	0,625	62,5	19,90595
Cl	250	0,004	0,261647059	3,821942446	0,015288	0	10	0,04	4	0,061151
NO_3	50	0,02	0,261647059	3,821942446	0,076439	0	2,3	0,046	4,6	0,351619
SO_4	250	0,004	0,261647059	3,821942446	0,015288	0	15	0,06	6	0,091727
		0,261647			1					53,54621

Autumn

Parameter	Standard	1/Sn	Sum(1/Sn)	K=1/Sum(1/Sn)	Wi=K/Sn	Ideal Value(V0)	Mean Conc Val (Vn)	Vn/Sn	Vn/Sn*100=Qn	WnQn
pH	8,5	0,117647	0,2616471	3,821942446	0,44964029	7	8,4	0,93	93	41,81655
EC	1000	0,001	0,2616471	3,821942446	0,00382194	0	53,6	0,0536	5,36	0,020486
TDS	600	0,001667	0,2616471	3,821942446	0,0063699	0	372	0,62	62	0,394934
Ca^{2+}	200	0,005	0,2616471	3,821942446	0,01910971	0	37	0,185	18,5	0,35353
Mg^{2+}	50	0,02	0,2616471	3,821942446	0,07643885	0	20	0,4	40	3,057554
Na^{+}	200	0,005	0,2616471	3,821942446	0,01910971	0	49	0,245	24,5	0,468188
K	12	0,083333	0,2616471	3,821942446	0,3184952	0	7,2	0,6	60	19,10971
Cl	250	0,004	0,2616471	3,821942446	0,01528777	0	36	0,144	14,4	0,220144
NO_3	50	0,02	0,2616471	3,821942446	0,07643885	0	5	0,1	10	0,764388
SO_4	250	0,004	0,2616471	3,821942446	0,01528777	0	22	0,088	8,8	0,134532
		0,261647			1					66,34001

Winter

Parameter	Standard	1/Sn	Sum(1/Sn)	K=1/Sum(1/Sn)	Wi=K/Sn	Ideal Value(V0)	Mean Conc Val (Vn)	Vn/Sn	Vn/Sn*100=Qn	WnQn
pH	8,5	0,117647	0,26164706	3,821942446	0,4496403	7	8,4	0,93	93	41,81655
EC	1000	0,001	0,26164706	3,821942446	0,0038219	0	53,4	0,0534	5,34	0,020409
TDS	600	0,001667	0,26164706	3,821942446	0,0063699	0	372	0,62	62	0,394934
Ca^{2+}	200	0,005	0,26164706	3,821942446	0,0191097	0	37	0,185	18,5	0,35353
Mg^{2+}	50	0,02	0,26164706	3,821942446	0,0764388	0	20	0,4	40	3,057554
Na^{+}	200	0,005	0,26164706	3,821942446	0,0191097	0	41	0,205	20,5	0,391749
K	12	0,083333	0,26164706	3,821942446	0,3184952	0	7,2	0,6	60	19,10971
Cl	250	0,004	0,26164706	3,821942446	0,0152878	0	35,8	0,1432	14,32	0,218921
NO_3	50	0,02	0,26164706	3,821942446	0,0764388	0	5	0,1	10	0,764388
SO_4	250	0,004	0,26164706	3,821942446	0,0152878	0	21,6	0,0864	8,64	0,132086
		0,261647			1					66,25983

Spring

Parameter	Standard	1/Sn	Sum(1/Sn)	K=1/Sum(1/Sn)	Wi=K/Sn	Ideal Value(V0)	Mean Conc Val (Vn)	Vn/Sn	Vn/Sn*100=Qn	WnQn
pH	8,5	0,117647	0,26164706	3,821942446	0,4496403	7	8,3	0,867	86,7	38,98381
EC	1000	0,001	0,26164706	3,821942446	0,0038219	0	47	0,047	4,7	0,017963
TDS	600	0,001667	0,26164706	3,821942446	0,0063699	0	378	0,63	63	0,401304
Ca^{2+}	200	0,005	0,26164706	3,821942446	0,0191097	0	33	0,165	16,5	0,31531
Mg^{2+}	50	0,02	0,26164706	3,821942446	0,0764388	0	15	0,3	30	2,293165
Na^{+}	200	0,005	0,26164706	3,821942446	0,0191097	0	31	0,155	15,5	0,296201
K	12	0,083333	0,26164706	3,821942446	0,3184952	0	7,4	0,61666667	61,66666667	19,64054
Cl	250	0,004	0,26164706	3,821942446	0,0152878	0	32,7	0,1308	13,08	0,199964
NO_3	50	0,02	0,26164706	3,821942446	0,0764388	0	2,3	0,046	4,6	0,351619
SO_4	250	0,004	0,26164706	3,821942446	0,0152878	0	22,5	0,09	9	0,13759
		0,261647			1					62,63747