MONITORING EUTROPHICATION IN THE VAAL DAM USING SATELLITE REMOTE SENSING

Keneilwe Hlahane

Student No: HLHKEN001

Dissertation for Master of Science

MSc Ocean and Atmosphere Science

University of Cape Town

Faculty of Science

Department of Oceanography

Supervisor: Professor Chris Reason

Co-Supervisor: Dr. Mark Matthews

DECLARATION

I, **Keneilwe Motlalepula Hlahane**, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

I empower the university to reproduce for the purpose of research either the whole or any portion of the contents in any manner whatsoever.

Signature: Signed by candidate

Date: 14 September 2018

TABLE OF CONTENTS

Contents

I. ACKNOWLEDGEMENTS

I would like to thank God for providing me with strength, breakthroughs and guidance and he provided for me to complete this dissertation.

I am thankful to my supervisor Dr. Mark Willian Matthews for giving me the opportunity to be part of his research team on the EONEMP project. For his support, teaching, constructive input on my work and advices. From him I have learned a lot about remote sensing and water quality, and to be positive in seeking solutions to water problems.

I extend a grateful thanks to Professor Chris Reason for supervising my work and providing valuable input to the dissertation.

I am thankful to the following individuals and institutions for providing me with data for the research: from Rand Water Board Dr. Annelie Swanepoel for her assistance in obtaining water quality data. From the Department of Water and Sanitation, Mike Silberbauer, Erica Erasmus, Nhlapo Elias, Louw Triana for providing in-situ water quality datasets and the South African Weather Services for their climate data.

I would like to thank Malukhanye Mbopha from the South African National Biodiversity Institute for helping me edit this thesis.I would like to thank my entire family for their endless love, encouragement and support through my studies. I am blessed to have them in my life.

For funding: The South African Space Agency (SANSA) and National Research Foundation (NRF).

II. ABSTRACT

The Vaal Dam is one of South Africa's important inland water resources, however it is experiencing ecological problems related to eutrophication. The dam supplies water for domestic, industrial, mining and agricultural usage. This research aims to assess and monitor the threats of eutrophication and cyanobacterial blooms within the Vaal Dam. A 10-year archive of remotely sensed satellite data was collected from the medium resolution imaging spectrometer full resolution (MERIS FR) satellite from 2002 to 2012. Data products on chlorophyll-a, cyanobacteria concentration, cyanobacteria and surface scum percentage coverage data were derived from MERIS satellite imagery, using the maximum peak height (MPH) algorithm. The derived data products were used as indicator measures of the trophic status. This research presents a time series analysis of chlorophyll-a (a proxy for eutrophication) and cyanobacteria to establish the status, seasonality and trends for the Vaal Dam. Statistical analysis methods were applied to determine the drivers of eutrophication. In addition, the effects of climate variables on eutrophication were analyzed. Geographic Information Systems methods were applied to determine the spatial distribution and variations of chlorophyll- a. The results indicate the trophic status of the Vaal Dam ranged from being eutrophic and hypertrophic over the 10-year period. Seasonality analysis indicated that cyanobacteria blooms increased in production during the summer period and decreased in winter. Statistical analysis of the results indicated that the correlation between Chl-a and nutrients is not statistically significant. Therefore, nutrients themselves are not driving eutrophication in the Vaal Dam. The produced maps from satellite images showed the spatial distribution of Chl-a within dam. The maps indicated the eastern areas of the Vaal Dam as areas where algal and cyanobacteria blooms occur in high concentrations. The correlation between Chl-a and climate variables indicates that there is a correlation with temperature and wind speed, and an indistinct relationship with rainfall. The study concludes that both nutrient and climatic variables contribute as drivers of eutrophication within the Vaal Dam. The methods applied in this research will help to transform the satellite data into useful knowledge products, which can be used to supplement current monitoring of inland freshwater resources.

III. LIST OF FIGURES

IV. LIST OF TABLES

V. LIST OF ABBREVIATIONS

- Chl-a: Chlorophyll –a
- CDOM: Coloured Dissolved Organic Matter
- DO: Dissolved oxygen
- DWAF: Department of Water Affairs and Forestry
- EONEMP: Earth observation National Eutrophication Monitoring programme.
- ESA: European Space Agency
- FR: Full Resolution
- GIS: Geographic Information Systems
- IR: Infra-Red
- MERIS: Medium Resolution Imaging Spectrometer
- MPH: Maximum Peak height algorithm
- NEMP: National Eutrophication Monitoring Programme
- OECD: Organization for Economic Co-operation
- RR: Reduced Resolution
- RS: Remote Sensing
- SD: Secchi Disk
- SIOP: Specific Inherent Optical Property
- TN: Total Nitrogen
- TP: Total phosphorus
- TSS: Suspended Solids
- VD: Vaal Dam
- WMA: Water Management Areas

1. CHAPTER ONE: INTRODUCTION

South Africa is a water scarce country faced with the challenges of having polluted freshwater water systems. Eutrophication is one of the water pollution problems the country is facing. Eutrophication is defined as the process of enrichment by nutrients, particularly phosphorus and nitrogen, and toxin producing cyanobacteria in waterbodies (Rast & Thornton, 1996). An increase in harmful algal species deteriorates water quality, reduces biodiversity and increases waterborne diseases causing negative human health impacts. Eutrophication also has negative economic impacts by increasing the cost of water treatment and management.

Eutrophication is linked to the growth of cyanobacteria and algal blooms species, which can be detected using satellite remote sensing. Common methods used for monitoring eutrophication are by collecting in-situ biological and chemical data. These methods usually don't provide sufficient monitoring data as they lack spatial coverage and temporal consistency.

Satellite remote sensing is an alternative method which can be used to supplement current eutrophication monitoring efforts. Eutrophication in waterbodies can be quantified in using phytoplankton which can be detected by satellite sensors. Water variables that are obtainable using remote sensing comprise of phytoplankton measured by the concentration of Chl-a, the dominant phytoplankton group and water clarity measured by Secchi disk or turbidity. These variables are fundamental for water quality assessment. Various studies have demonstrated the medium resolution imaging spectrometer (MERIS) as the suitable sensor used for obtaining data on water quality products due to its spectral, temporal and spatial resolution (Matthews, et al., 2010).

The study area is the Vaal Dam. The Vaal Dam forms part of the Vaal river system, which is one of the most important river systems in South Africa. The river system supplies water to the country major industries such as agriculture, industry and mining. All these industries produce polluted water which flows into the Vaal system resulting in eutrophication and water quality problems. Excess phosphorus gets into water systems from sewage, industrial discharges, and runoff from agriculture. Several studies have indicated high eutrophication levels & constant algal bloom appearance (Walmsley, 1984; van Ginkel, et al., 2000). Eutrophication is currently being monitored using in-situ sampling methods, whereby biogeochemical water parameters data are being collected. The used sampling methods are labour intensive, have high costs and lack to provide consistent spatial and temporal data. Ten years of MERIS archive data (2002- 2012) was utilised to retrieve water quality parameters used to monitor eutrophication in the Vaal Dam.

1.1. AIM AND OBJECTIVES

This research aims to assess and monitor the threats of eutrophication and cyanobacterial blooms within the Vaal Dam. A time series analysis was conducted using ten years of MERIS archive data. The study focuses on two main aims:

1) The assessment of eutrophication in the Vaal Dam through the analysis of water quality parameters derived from MERIS data.

2) Monitoring eutrophication by obtaining quantitative information on chlorophyll-a concentrations, phytoplankton and algal blooms.

The specific objectives of the research are:

1. To determine the trophic status, seasonality and trends of Chl-a, an indicator of eutrophication and cyanobacteria blooms, of the Vaal Dam.

2. To determine what are the drivers of eutrophication within the Vaal Dam by determining the relationship/correlation between chlorophyll-a concentrations and nutrients i.e. Total Nitrogen and Phosphorus and cyanobacteria occurrence.

3. To determine the spatial distribution of Chl-a within the Vaal Dam using Geographic Information systems (GIS) and remote sensing methods.

4. To determine the relationship between climatic variables such as temperature, rainfall and wind, and eutrophication in the Vaal Dam.

The methods applied in this research will help to transform the satellite data into useful knowledge products, which can be used to supplement current monitoring of inland freshwater resources.

2. CHAPTER TWO: LITERATURE REVIEW

2.1. Eutrophication of Freshwater Resources

There are many definitions of the word eutrophication in literature. The term ‘eutrophic’ comes from the Greek word “*eutrophos”* meaning well-sustained. Eutrophication is defined as an enrichment of the natural process of biological production in water resources resulting from increased concentrations of nutrients, usually phosphorus and nitrogen compounds (Vollenweider, 1968). Eutrophication is also defined as the natural ageing process of lakes (Rast & Thornton, 1996). The difference between the two definitions is that one only defines it as the process of nutrient enrichment, while the other include problems associated with nutrient enrichment. Eutrophication can occur as a “natural” process, as defined by (Rast & Thornton, 1996) and it depends on the local geology and natural features of the catchment. Eutrophication can also occur as a “cultural” process, meaning it was caused by anthropogenic activities that increase the rate of process beyond the natural process, i.e. the increase of nutrient load into the water system. Nutrient enrichment can come from point or non-point sources. Point sources are the points can be detected and as a result can be controlled, for example wastewater treatment pipes and storm water pipes. Non-point sources flow from large open areas and cannot be easily controlled, such as agricultural runoff into aquatic systems (Carpenter, et al., 1998).

The process of eutrophication can be categorized according to different stages. The trophic status of the waterbody is used as a description for this purpose. Thus, the waterbody may be classified as the following (Walmsley, 2000) :

- **Oligotrophic** - low nutrient concentration, low aquatic and plant life productivity
- **Mesotrophic** – fair nutrient concentration, fair aquatic and plant life productivity
- **Eutrophic** - high nutrient concentration, high aquatic and plant life productivity
- **Hypertrophic** - very high nutrient concentrations where plant growth is controlled by physical features. Water quality problems almost on going and serious.

The trophic status in waterbodies can be related to indicators such as phosphorus and nitrogen nutrient concentration, water clarity measured using Secchi Disk depth, and phytoplankton biomass measured using Chl-a concentrations. The Organization for Economic Co-operation and Development (OECD) classification *Table 1* is used to describe the relationship between indicators and trophic status (OECD, 2002). The classification is also applicable to South Africa freshwater systems.

Table 1 : The relationships between trophic status and indicators

Variable	**Unit**	**Oligotrophic**	**Mesotrophic**	**Eutrophic**	**Hypertrophic**
Mean annual chlorophyll a	µg/ℓ	$0 < x \leq 10$	$10 < x \leq 20$	$20 < x \leq 30$	>30
% of time chlorophyll a > 30 µg/ℓ	%	0			>50
Mean annual Total Phosphorus	mg/ℓ	$x \leq 0.015$	$0.015 < x \leq 0.047$	$0.047 < x \leq 0.130$	>0.130

The increase of nutrients into aquatic systems promotes the growth of cyanobacteria and algal blooms. The excessive growth of cyanobacteria decreases biodiversity and impacts the ecosystem negatively. The negative impacts can be ecological, social and economic (DWAF, 2002). The ecological impacts are caused by the excessive growth of cyanobacteria blooms which sometimes dominates over other aquatic plants. Cyanobacteria also forms floating scums on the water, when their cells decay they release toxic organic compounds, cyanotoxins into the water. Cyanotoxins are harmful to humans and can cause animal deaths (Holdsworth, 1991).

The social impacts are those impacts which affect human health and recreational usage through contact exposure and drinking water. Human health impacts are caused by the invasion of cyanobacteria in waterbodies, which can provide a breeding habitat for mosquito larvae, which leads to the development of water diseases such as bilharzia (Scott, 1979). Long term consumption of the water for drinking purposes, and the exposure to bad smell from water channels polluted with decomposing algae may also result to bad health effects. Negative recreational impacts of eutrophication occur when there is excessive growth of water hyacinth and cyanobacteria. They decrease the fitness of water use for recreational sports such as canoeing and fishing. The economic impacts of eutrophication are related to the increase of the costs of water treatment for potable water. Algal blooms also block water filters which increases maintenance costs. The cost of treating eutrophic water systems and managing eutrophication monitoring initiatives also impacts the economy. The economic cost of eutrophication was estimated in 2008 to be approximately $2.2 billion annually in the US freshwaters (Dodds, et al., 2009). The potential annual value losses are calculated based on waterfront real estate, real estate, spending on the recovery of threatened and endangered species and treating water to portable usage. In England and Wales, the destruction costs of eutrophication in freshwater systems are assessed to be $105-160 million per year (Pretty, et al., 2003). The costs are measured based on how much it is spending to address this damage.

2.2. Eutrophication in South Africa, Vaal Dam

Many dams in South Africa are facing the pollution problem of eutrophication. Cultural eutrophication is a major threat caused by fertilizers and sewage inputs into the freshwater systems. The Vaal Dam, situated in the Gauteng province of the country is one of the dams faced by the challenge of eutrophication. The Dam is the largest sources of water for the Gauteng region, the economic centre of South Africa. It supplies the region with water which is used for portable and industrial uses. Therefore, the water quality of the dam is very important for the country. However, the dam is faced with challenges of eutrophication. Studies by (Harding, 2008) classified the Vaal Dam reservoir as eutrophic founded on the total in-lake phosphorus and Chl-a content. Other studies by (Van Ginkel, 2004) have shown the existence of cyanobacteria in the dam. The Vaal

Dam has high nutrient enrichment and eutrophication-related problems. Eutrophication is of major concern for the Vaal Dam.

2.3. Eutrophication management in South Africa

Eutrophication is of major concern because it has many negative impacts and affects water quality. It is therefore important to monitor and assess the overall state of South Africa ‘s freshwater resources. It is mandatory for the national monitoring systems to provide information on the quantity, quality and health of aquatic ecosystems, and to assess fulfilment with quality objectives and measures taken for rehabilitation (Republic of South Africa National Water Act., 1998). It is compulsory that national monitoring systems must give information on the quantity, quality and health of aquatic ecosystems, and to assess compliance with quality objectives and measures taken for rehabilitation (Republic of South Africa National Water Act., 1998) . It is the task of the Department of water and sanitation to monitor and assess the overall state of South Africa’s water resources at a national level.

The National Eutrophication Monitoring Program was put into operation particularly to monitor the impact of eutrophication. The primary function of the NEMP is to gather, assess and report on eutrophication and its related problems on a National level in South Africa. The NEMP collects and investigates surface water samples from around 160 dams, lakes and rivers nationally. The dams are sampled once a month. Point samples are analysed for Chl- a concentration, phytoplankton type, chemical parameters nitrogen and phosphorus and Secchi disk depth (Republic of South Africa National Water Act., 1998). Water quality monitoring has the aim of obtaining quantitative information on the chemical, physical and biological characteristics of water. The sampling methods which are currently being used are expensive. It is therefore a challenge to have frequent monitoring due to the rising costs of sampling. The sampling methods also have a challenge of providing data for more widespread locations. This creates large information gaps regarding the trophic status and presence of cyanobacterial blooms in freshwater resources. Frequent monitoring and new monitoring methods are required to provide more reliable data regarding the water quality of freshwater resources. There remains a need for regular monitoring of inland waters.

Satellite remote sensing offers an alternative method of monitoring water quality of our resources. Satellite remote sensing can also contribute to solving some of the challenges faced by the NEMP. Past programs, such as the increased space science and earth observation grand challenges were formed by DWAF and the Department of Science and Technology (DWAF, 2002) to make opportunities available for incorporating remote sensing technology into present initiatives, so that monitoring of water resources may be improved (DWAF, 2004). This leads to the discussion in the next chapter, which outlines how satellite remote sensing is used to monitor eutrophication of inland waters.

2.4. Satellite remote sensing of Chl-a, Chl-a retrieval Algorithms and Phytoplankton in inland waters

It is essential to explain the remote sensing process prior to explaining how Chl-a values can be retrieved from satellite images used to monitor eutrophication. Remote sensing is the science of obtaining information about objects or areas using light. This can be done using satellites or aircrafts mounted with sensor equipment. Remote sensors gather data by detecting the light energy that is reflected from the earth's surface. Remote sensors can be passive or active. Active remote sensing is when a signal is emitted by satellite and its reflection from the object is detected by a sensor. Passive remote sensing is when the instruments sense only the radiation reflected by the object from a source other than the instrument. Electromagnetic radiation is a form of energy that is described in terms of wavelength, frequency and amplitude. It includes radio waves, infrared, microwave, visible light, x-rays and gamma rays. Sunlight is also a form of electromagnetic energy, but visible light is only a small part of the electromagnetic spectrum, which contain a broad range of electromagnetic wavelength between 400 and 700 nm. Satellite remote sensing for water related applications uses the electromagnetic spectrum to measure the light in the visible and near-infrared part of the electromagnetic wavelengths (400 to 750 nm). Continuous research on the remote sensing of waterbodies and developments on space technology has made monitoring of eutrophication and cyanobacterial blooms in inland water from space possible.

This study will make use of remote sensing data collected from a passive sensor of Medium Resolution Imaging Spectrometer (MERIS) satellite. The selection of a suitable satellite is determined by the spectral, spatial and temporal resolutions, suitable for water applications. MERIS satellite operated from 2002 until April 2012. The spatial resolution of MERIS is 260 m by 290 m, a temporal resolution of two to three days, and a spectral resolution of 15 bands. These specifications make MERIS ideal for water-related applications. These specifications are combined with the recent development of algorithms for detecting Chl-a and cyanobacteria have allowed MERIS data to be exploited for near real-time monitoring. MERIS onboard of ENVISAT satellite launched by the European Space Agency (ESA) has spectral bands that can be used to record the maximum absorption of phytoplankton. The data collected was for the period between 2002 and April 2012 after which MERIS ceased collecting data. MERIS data is provided in two levels; level 1B data, which is not atmospherically corrected and level 2 data which is geometrically and atmospherically corrected. Below table gives a summary of MERIS specifications (European Space Agency, 2000).

Table 2: MERIS satellite specifications from *(European Space Agency, 2000)*

Geometric Specifications	
Field of view	68.5° centred at nadir
Swath width	1150 km
Localisation accuracy	< 2 km
Spatial resolution	RR:1040 m × 1200 (nadir) FR: 260m 300m (nadir)
Band to band registration	< 0.1 FR pixel
Spectrometric Image quality	
Spectral Range	390 nm -1040 nm
Spectral sampling interval	1.25m

Spectral resolution	1.8 nm

Another satellite mission which is suitable for water related applications is SENTINEL 3. However, this study is using MERIS satellite for its data because it is studying a long time-series that is from 20002-2012.It is an ocean and land mission composed of three versatile satellites (SENTINEL-3A, SENTINEL-3B and SENTINEL-3C). The mission provides data continuity for the ERS, ENVISAT and SPOT satellites. SENTINEL-3 uses various sensing instruments to deliver the following objectives:

- SLSTR (Sea and Land Surface Temperature Radiometer)
- OLCI (Ocean and Land Colour Instrument)
- SRAL (SAR Altimeter)
- DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellite)
- MWR (Microwave Radiometer)

SLSTR and OLCI are optical instruments that are used to provide data continuity for ENVISAT's AATSR and MERIS instruments and the swaths of the two instruments overlap, allowing for new combined applications. The OLCI instrument baseline is the successor to ENVISAT MERIS with additional spectral channels, different camera arrangements and simplified on-board processing. OLCI has a spatial resolution of 300m, a temporal resolution of three days with one satellite, and a spectral resolution of 21 bands. These specifications make MERIS ideal for water-related applications. OLCI is a medium-resolution imaging spectrometer, using five cameras to provide a wide field of view. Below table gives a summary of OLCI specifications (Europopean Space Agency, Sentinel 3 team, 2013).

Table 3:OLCI satellite specifications

Geometric Specifications	
Field of view	The field of view of the five cameras is positioned in a fan-shaped design in the vertical plane, perpendicular to the platform velocity. Each camera has an individual field of view of 14.2° and a 0.6° overlap with its neighbours.
Swath width	1 270 km
Spatial resolution	FR: 300 m resolution, RR:1 km
Spectrometric Image quality	
Spectral Range	400 nm to 1 040 nm
Spectral sampling interval	1.25 nm (MERIS heritage)
Radiometric resolution	<0.03W m-2 sr-1 mm-1 (MERIS baseline)

Chlorophyll is the green pigment found in plants and found mostly in all types of algae. Chlorophyll allows plants and algae to use sunlight for growth during photosynthesis. In limnology, scientists often use chlorophyll a (Chl-a), which is one type of chlorophyll. Measurements of the chlorophyll concentrations are used to estimate algal biomass in a waterbody and to assess productivity (Lakewatch, 2000). Chl-a concentration is one of the most frequently used parameters to determine the trophic status of freshwater systems. Therefore, it is often used as a proxy for algal biomass and primary production in waterbodies.

Chl-a concentrations can be measured from water samples collected using ground in-situ methods, or they can be detected using satellite imagery. This study will make use of Chl-a concentration measures derived from satellite imagery. Scientists make use of different algorithms to retrieve the

Chl- a concentrations, using different bands in the satellite image. This study made use of The Maximum Peak Height (MPH) algorithm, which is suitable to be used on images collected from MERIS. The algorithm MPH is useful for computing the concentration of surface Chl-a and to identify cyanobacteria dominated waters and surface scum conditions in inland freshwater systems (Matthews, et al., 2012; Matthews, et al., 2010).The MPH algorithm can function over a widespread trophic status range from oligotrophic to hypertrophic circumstances. The MPH algorithm was derived using matchup data of MERIS satellite imagery and Chl-a measurements collected from South African inland waters using in-situ methods. The algorithm is based on the MERIS red/near infra-red bands between 664 and 850 nm, using the sun generated Chl-a fluorescence produced by algae near 685 nm and the backscatter induced peak near 710 nm visible in Chl-a levels greater than approximately 20 mg^{-3}. The algorithm is used to characterize the trophic status of the waterbodies through Chl-a estimates, to identify cyanobacterial blooms, and to identify cyanobacterial surface scum conditions (Matthews, et al., 2012).

The use of satellite images for monitoring water quality provides a large quantity of data products, due to the frequent temporal resolution of satellites. It is important to turn that data into useful information. The information can be used to inform water scientist on the water quality on the status of Eutrophication in the Vaal Dam. The information can also be used to warn the public about the safety use of the water from the dam, it brings focus to places within the dam that require immediate remediation action. The information can also be used to inform policy makers who make decisions regarding the monitoring of South Africa’s freshwater resources.

2.5. Drivers of Eutrophication in inland waters

There are various factors that affect the dominance of cyanobacteria in waterbodies. Eutrophication can be driven by the input of nutrients into the waterbody, or it can be driven by climate variables such as temperature, precipitation and wind. Cyanobacteria are predicted to increase due to climate change and increasing temperatures. The increasing temperature and nutrients concentration levels are believed to be the main factors driving the increase in cyanobacteria in freshwater systems (Conley, et al., 2009). In temperate climates such as South

Africa, the dominant phytoplankton genera commonly found in eutrophic and hypertrophic freshwater are from the cyanobacterial group (Rae, et al., 1999).

2.5.1. Nutrients: Phosphorus and Nitrogen

All waterbodies have nutrients in them. Water plants and algae use the nutrients for their growth. Algae are a wide variety of tiny and often microscopic organisms that live both in water and on land. Water living algae can be categorized based on where it lives. The three types of algae are typically described as follows: phytoplankton which float freely in the water; periphyton which are attached to aquatic vegetation and benthic algae that grow on the bottom sediments. Algae can also be defined as single-celled, colonial grouped together in colonies or filamentous (Lakewatch, 2000). Free floating algae are called phytoplankton. Phytoplankton can be classified into three main classes: green algae, diatoms, and blue-green algae which is bacteria and not algae.

The quantity of algae found in a waterbody is called biomass, and it is an indication of the amount of algae found in the waterbody. Algal biomass is measured using methods such as counting individual algal organisms in a water sample and measuring chlorophyll concentrations. Most algae contain chlorophyll in them. Therefore, the concentration of chlorophyll in a water sample is used as a measure of algal biomass. The algae collected from water samples does not furnish quantities for all the types of algae, only phytoplankton. Phytoplankton are very important in waterbodies and it plays a vital role in the food web by providing food and oxygen to the aquatic animal life.

Waterbodies contain nutrients that originate from natural or anthropogenic sources. Natural sources are from plants or animal remains. A limiting nutrient is a chemical that is required for plant growth, but it is available in smaller quantities that required for algae to grow (Lakewatch, 2000). The algae population will stop growing once the limiting nutrient in the waterbody is no longer available. When more of the limiting nutrient is added, it results in an algal population increase. Therefore, it is useful to know what the limiting nutrient is in water bodies. Phosphorus and nitrogen are the commonly assessed limiting nutrients for inland waters. Phosphorus compounds are found in many rock and soil types, which are often washed into inland water.

Phosphorus is an element that promotes the growth of algae in waterbodies. Total Phosphorus (TP) includes both dissolved and particulate phosphorus is used to approximate the amount of phosphorus in a system. There are various ways in which phosphorus enter waterbodies such as through erosion of phosphate rich soils and rocks. Phosphorus also enters waterbodies by getting washed away from the crop fertilizers used for agriculture into the waters. Phosphorus becomes a limiting nutrient in waterbodies in the following manner; waterbodies with higher concentration of phosphorus will have higher concentrations of algae, and waterbodies with low concentration of phosphorus will have lower concentrations of algae.

However, phosphorus is not always the limiting nutrient in waterbodies. Nitrogen is also a nutrient that is essential for the growth of algae in waterbodies. Total nitrogen (TN) is a measure of the different forms of nitrogen found in a water sample. It consists of both organic and inorganic form of nitrogen. Algae use the inorganic form of nitrogen such as nitrates, nitrites and ammonia for growth. Nitrogen enters the water systems from fertilizers, animal and human wastes from effluent. It also enters the system in a natural way from the air: for example, some cyanobacteria have the ability to synthesize nitrogen from air. The concentration of TN and TP can vary seasonally for different waterbodies. Nitrogen can also become a limiting nutrient. This happens when the waterbody has a limited supply of TN, it occurs when the ratio TN to TP is less than 10 (TN/TP <10).

Determining the limiting nutrient

Total Nitrogen: Total Phosphorus ratios is a method used in limnology to determine which nutrient is the limiting agent within the water system. A limiting nutrient is a chemical that is needed for plant/algae growth in freshwater systems. When the limiting nutrient in a waterbody is used up, the population of algae will stop increasing. When the limiting agent is added, it will result in the increase of the algae growth, which in return will affect the trophic status of the waterbody. It is therefore important to know if there is a limiting nutrient (or some other limiting factor) in the waterbody (Lakewatch, 2000).

A waterbody can have many other factors besides nutrients as limiting factors. The ratio of nitrogen to phosphorus was calculated to determine which one is the limiting nutrient within the Vaal Dam.

Freshwater systems are considered as being phosphorus limited when the total nitrogen (TN) to total phosphorus (TP), TN/TP ratios is above the value of 15. The system will classify as nitrogen limited when the TN/TP ratios is below the value of 7. For ratios of TN/TP between 15 and 7, either phosphorus or nitrogen, or both could be a limiting agent. A TN/TP ratio greater than 10:1 indicates a phosphorus limitation, meaning the available supply of phosphorus will be consumed before the supply of nitrogen (Guildford and Hecky, 2000).

$$\text{TN:TP ratio} = \frac{\text{Total Nitrogen}}{\text{Total phosphorus}}$$

2.5.2. Climate Variables as drivers of eutrophication in inland waters

Effect of Temperature on Eutrophication

Temperature is an important environmental factor that influences water ecosystems, growth and survival of living organisms (Mooij, et al., 2007). Climate change increases temperature, therefore influencing eutrophication in water systems. The temperature of water is in close equilibrium with air temperature, this causes the freshwater to rise as the air temperature increases (Mooij, et al., 2007). Increasing air temperatures will influence the water temperature, physical and chemical properties of that water. Increasing temperatures has direct effects on cyanobacterial growth rates. The growth rates of freshwater eukaryotic phytoplankton usually stabilize or decrease with changing temperature. However, the growth rates of many cyanobacteria increase when the temperature is around 20°C (Houghton, et al., 2001). At this temperature cyanobacteria have a driven advantage over other types of algae.

Temperature above 25° C can directly endorse an increasing growth of cyanobacteria compared to other phytoplankton groups in waterbodies (Mooij, et al., 2007). For example, higher temperatures will decrease surface viscosity and increase nutrient diffusion towards cell surface. This process is important when species compete for nutrients (O'Neil, et al., 2011). Cyanobacteria can regulate buoyancy to offset their sedimentation, when viscosity decreases it will promote the sinking of larger phytoplankton with weak buoyancy such as diatoms. This will give cyanobacteria a further advantage in the system (Paerl & Huisman, 2009).

An added aspect related to temperature is the stability of the water column. When temperature rises it causes the surface of the water to heat up while the deeper waters remain cool. This temperature difference creates a density stratification known as thermal stratification. Thermal stratification creates stability to the water column and reduces turbulent mixing. This creates conditions that are favorable for the growth of cyanobacteria: a combination of warm waters and stable water column with absence of mixing (Paerl, 1988). Increasing temperatures also have indirect effects on the water system which promote eutrophication. The indirect effects are changes in the physical and chemical characteristics of water systems, and the nutrient loading from soil.

Therefore, it is generally concluded by studies that increasing global temperatures will cause cyanobacterial blooms to increase in intensity and distribution (Paerl & Huisman, 2009).

Rainfall effect on Eutrophication

Freshwater systems react to changes in inflow volumes resulting from low and high rainfall periods. Changes in rainfall could disturb river flows, therefore affecting mobility and dilution of nutrients phosphorus and nitrogen, which have an impact on eutrophication. Low rainfall result into low flow rates, in that way increasing the residence time of nutrients inland waters. Increased residence time increases intensification possibility of algae, increasing the settling rate of sediments and decreasing water column sediment concentrations. Turbidity is also reduced, and the light penetration increases which promotes favorable conditions for algae growth (Whitehead, et al., 2009). High rainfall can result into flooding from rivers and dams. Eutrophication becomes affected by high rainfall because floods can increase concentrations of sediments from agricultural and urban runoff (Hickey & Salas, 1995). Conversely, floods could also decrease the eutrophication levels by increasing the volume of water in the rivers and dams, thereby diluting contaminants and pollutants.

During the study period of 2002-2012 period of your data, the Vaal Dam region was affected by several El Nino and La Nina events occurred and there were periods of drought and flood. The high and low level of rainfall in the region influences the level of eutrophication in the Dam. During the year 2009-2010 South Africa experienced an El Niño rainfall event. The event of 2009-2010 is considered to have been a Central Pacific El Niño event due to anomalous rainfall. During the summer of 2010, the Vaal Dam was more than 100 percent full for the first time in 13 years. Rainfall over South Africa during the months of December, January and February 2009-2010 was anomalously high (Driver, 2014).

Wind effect on Eutrophication

Wind influences the chemical and physical forcing in freshwater systems. Wind energy is responsible for the mixing of nutrients stratigraphy. Wind energy brings nutrients from deeper waters to upper columns, and transports nutrients and particulate material both vertical and horizontal in the water system. Wind also affects the concentrations of TN, TP and Chl-a because of drifting and mixing of bed sediments. The flowing effect is often a result of the wind-induced shear stress on the water surface, whereas the resuspension likely occurs once the shear stress shifted downward to the water bed is larger than the critical shear strength of the bed sediments. (Cyr, et al., 2009). The mixing effect is due to the shear stress transported into the water column. Because of mixing, when the TN, TP and Chl-a concentrations are measured using water samples that are collected close to the water surface, the results will have greater concentrations than the related concentrations at a deeper depth of the water column (Cyr, et al., 2009). Wind direction is also responsible for the spatiotemporal distribution of TN, TP and Chl-a across the dam. The primary wind direction plays an important role as it pushes the nutrients in a certain direction, causing the nutrients to concentrate often closer to the shore of the waterbody. The concentrations of nutrients when measured at these places will be higher than the rest of the waterbody (Zhang, et al., 2017).The wind speed is another factor which affects TN, TP and Chl-a concentrations in inland waters. Slow winds endorse water stability and gathering of cyanobacteria at the surface to form blooms (Cao, et al., 2006). Higher wind speeds have a greater mixing effect, therefore decreasing the nutrient concentrations in the surface water and increasing them at deeper depths. This lowers the nutrient concentrations for the higher wind speeds as matched to the concentrations measured at more calm wind speeds. Greater wind speed conditions are less beneficial for the development of algae because there is mixing of nutrients conditions. Wind mixing in water can sink cyanobacteria downward below the euphotic zone, therefore restraining their expansion due to the sub-optimal light conditions and reducing the algal biomass existing in the surface water (George & Edwards, 1976). Strong winds may also limit the growth of cyanobacteria by damaging the cyanobacteria cells therefore reducing the algal blooms (Moreno-Ostos, et al., 2009). All the above points show how wind influences the measured concentrations of TN, TP and Chl-a.

3. CHAPTER THREE: STUDY AREA AND DATA SETS

STUDY AREA

3.1. Vaal Dam South Africa

The study area for this research is the Vaal Dam, South Africa (Figure 1). The Vaal Dam is situated in Gauteng Province with the following co-ordinates 26.8947° S, 28.1455° E. The Vaal Dam forms part of the Vaal River System, which is one of the most important river systems in the country (DWAF, 2004).The river system is valued as an important because it supplies water to Gauteng, the central economic place of South Africa. The Vaal Dam also supplies water to the nearby provinces of the Free State and Mpumalanga (McCkenzie & Wegelin, 2009). The Vaal Dam is in the Upper Vaal WMA. This WMA is characterised by urban and industrial areas in the northern and western parts, and it has big coal and gold mining activities (Braune & Roger, 1987).

Figure 1: Satellite image of the Vaal Dam, South Africa (Google Earth).

The Vaal Dam was completed in 1938, and at full supply capacity can store up to 2575 million cubic metres of water, which have a hydraulic retention time of 2 years. The Vaal Dam has a catchment area that covers 38 505 square kilometres (Braune & Roger, 1987). Eighty percent of the water that is stored in the Vaal Dam is treated at Zuikerbosh Water Treatment Plant for potable use (Rand Water, 2011). Water extracted from the Vaal Dam undergoes purification following the conventional processes of coagulation, flocculation, sedimentation, rapid sand filtration and chlorination (Ewerts, et al., 2013).

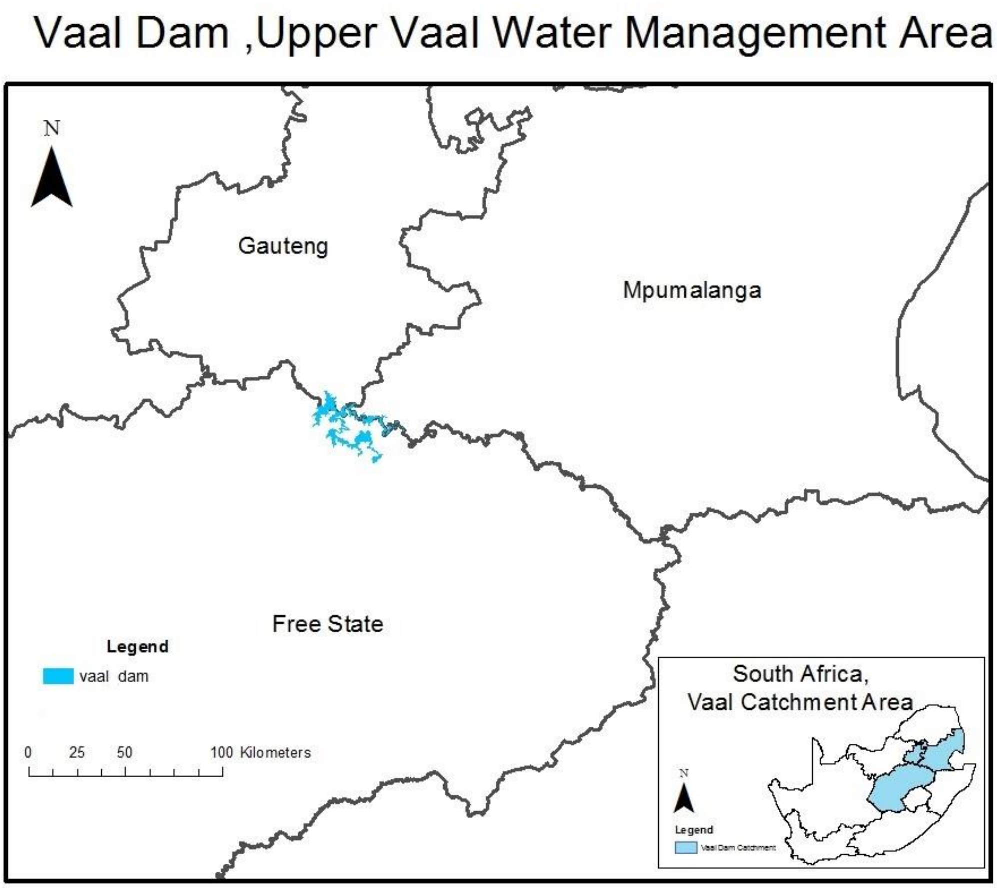


Figure 2: Map showing the area of the Vaal Dam. The dam is in the Gauteng Province, South Africa.

3.2. Climate of the Vaal region and its Variability

The Vaal region is situated in the central part of South Africa. Southern Africa is a semi-arid region situated south of 15^0S of the equator. Southern Africa has a strong seasonal cycle with most of the region experiencing summer rainfall due to convective thunderstorms (Tyson, 1986). The average annual rainfall is 659 mm. The driest months are the winter months (May-July) and the most rainfall is received in January as shown in Figure 3.

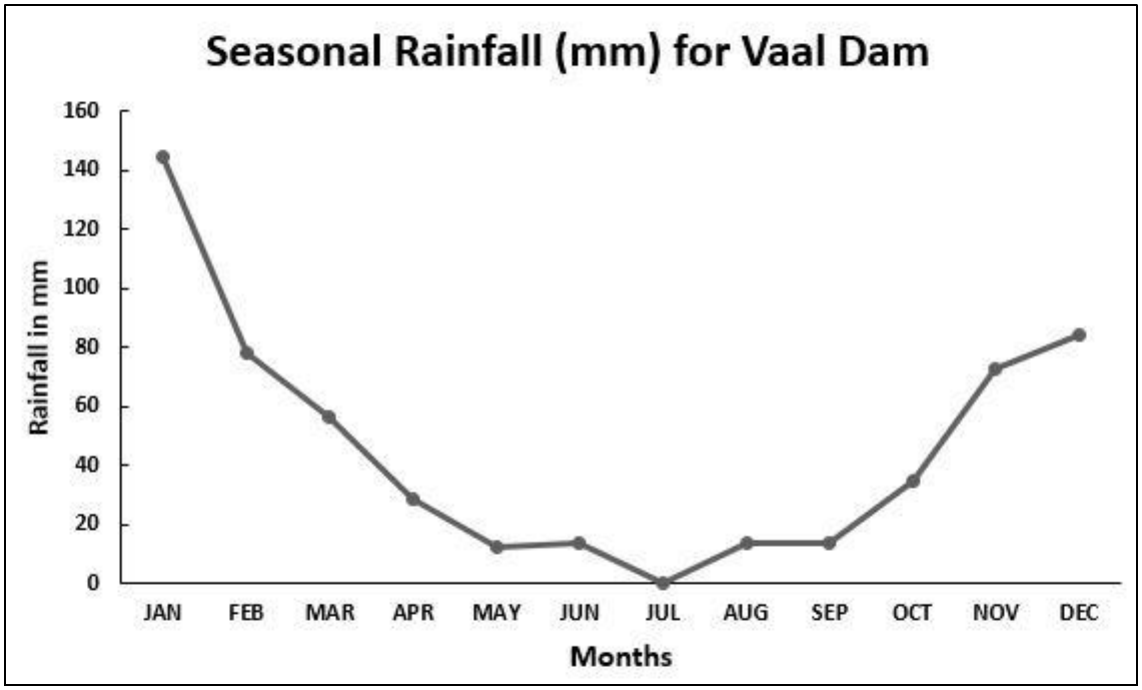


Figure 3:Vaal Dam monthly average rainfall measured at Deneysville weather station. Information obtained from *(South Africa Weather Services, 2018)*.

Annual rainfall for the Vaal region

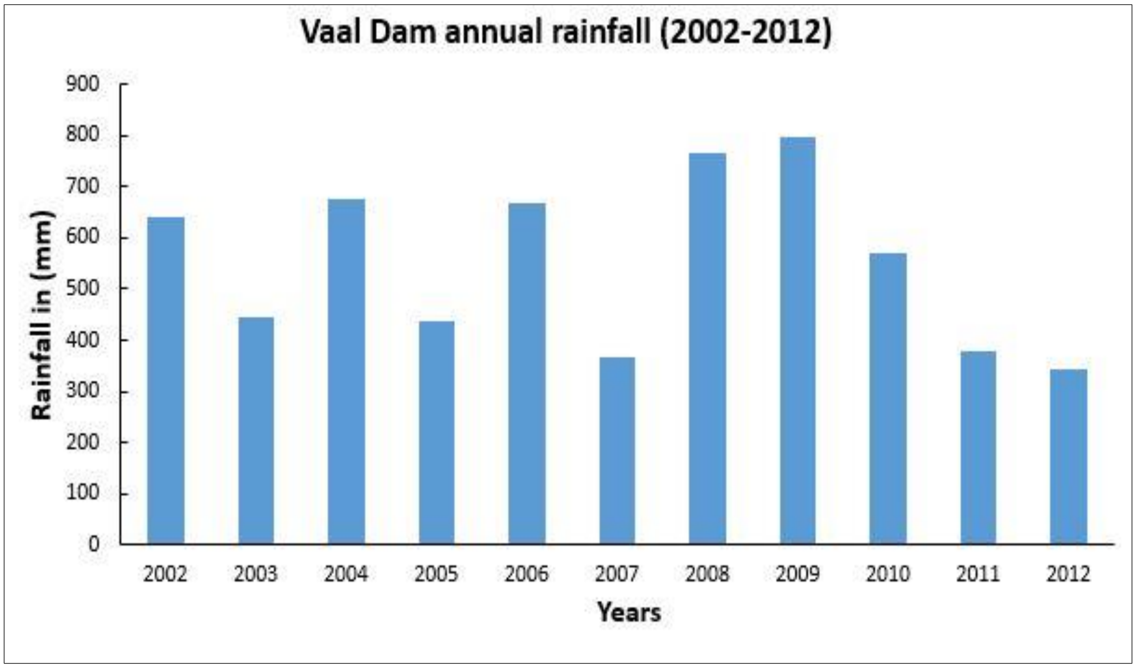


Figure 4:Annual rainfall for the Vaal Region, data from *(South Africa Weather Services, 2018)*

The annual rainfall 2002-2012 is shown in *Figure 4*. This study period is too short to derive a proper climatology, and data was not collected for the month of July due to technicalities. To derive proper climatology a minimum 30-year data series is needed. The trend analysis applying a data series shorter than 30 years is less relevant because normal climate is usually defined for three decades. The highest annual average rainfall occurred in 2008, with rainfall amounting to 765.3 mm and 2009 with 798.6 mm. The lowest amount of rainfall was received in 2012 with an amount of 345 mm.

One of the study objectives is to determine the relationship between climate variables and eutrophication in the Vaal Dam. Therefore, it is important to explain the climate systems influencing South Africa and the study region. Southern African rainfall is influenced by The Angola low, the Intertropical Convergence Zone and the South Atlantic and South Indian anticyclones.

Inter-Tropical Convergence Zone (ITCZ)

ITCZ is a low-pressure zone along the tropics whereby the north eastly trade winds and south eastly trade winds converge. The wet summers in South Africa are associated with an irregular southward movement and strengthening of the ITCZ over tropical southeastern Africa (Cook, et al., 2004). A clear seasonal cycle is shown by the movement of the ITCZ over Africa (Tyson, 1986). Southern Africa region experiences a high precipitation in summer, making it the rainy season due mainly to the development of the Angola low and cloud bands (tropical temperate troughs).

The Angola low is a partially constant shallow heat low, positioned over southern Angola and northern Namibia. Its development begins in October during each year and intensifies during the months of January and February. The Angola low operates at south of 15^0S of the equator as the tropical supply region for the tropical-extratropical cloud bands that that produce most of the summer rainfall over Southern Africa (Reason, et al., 2006). The Angola Low is known as the main driver of tropical moisture that helps the occurrence of the cloud bands by continuous moisture transport (Mulenga, 1999). The summer rainfall over southern Africa south 15° S of the equator is often due to tropical temperate troughs (TTTs).

Tropical Temperate Troughs TTTs are defined as synoptic rain-bearing system during summer and changes in their occurrence or location lead to large rainfall variability over southern Africa (Hart, et al., 2010). TTTs are evident as rainfall-producing convective and NW-SE stretched cloud bands which join the upper tropospheric frontal system embedded in the mid-latitude westerly circulation with a tropical disturbance over the subcontinent (Fauchereau, et al., 2009). The existence of an intense Angola low usually lead to increased levels of rainfall, hence the Angola Low is a tropical supply area for the TTTs and their related cloud bands (Reason, et al., 2006).

South Atlantic Anticyclones

The Southern African region experiences dry winters due to the continental anticyclone. The South Atlantic anticyclone (SAA) is found in the southern part of the Atlantic Ocean and it is described as a partially -permanent high-pressure system. The SAA has a zonal shift of approximately 13^{o} and it moves 6^{o} latitudinally between seasons (Reason, et al., 2006) . The SAA is linked to moist environments over certain places in southern Africa (Tyson, 1986). During austral summer, the west coast of southern Africa, Namibia and South Africa experience an intense upwelling. The upwelling is linked to colder SSTs induced by the southerly winds surrounding the SAA. SSTs particularly in the upwelling zones along the western coast of southern Africa are impacted by the changes in surface winds, which drive seasonal variations (Reason, et al., 2006).

Inter-annual variability

The main interannual mode of climate variability over the tropical southern hemisphere is the El Niño Southern Oscillation (ENSO) (Reason, et al., 2006). ENSO is a naturally occurring phenomenon that consist of ocean-atmosphere exchanges which happens almost every two to seven years in the central and equatorial Pacific Ocean. ENSO also leads to fluctuations in ocean temperatures. The term “El Niño” was created by fishermen from Ecuador and Peru, signifying the yearly heating of water in Christmas time at the coast. The phrase is used in climatology to refer anomalous heating of the central and eastern Pacific Ocean. The Southern Oscillation (SO) is the atmospheric part of ENSO, it represents the variability of atmospheric mass between the eastern and western Pacific Ocean (Cane, 2005). Inter-annual rainfall variability in southern Africa is driven by ENSO (Dufois & Rouault, 2012). ENSO has its highest impact around Southern Africa during the summer months of December to March (Mason & Jury, 1997). Dry conditions over Southern Africa are commonly connected with El Niño events. The opposite of El Niño is La Nina and it relates to wet conditions over Southern Africa (Reason, et al., 2000).

Temperature for the Vaal Dam

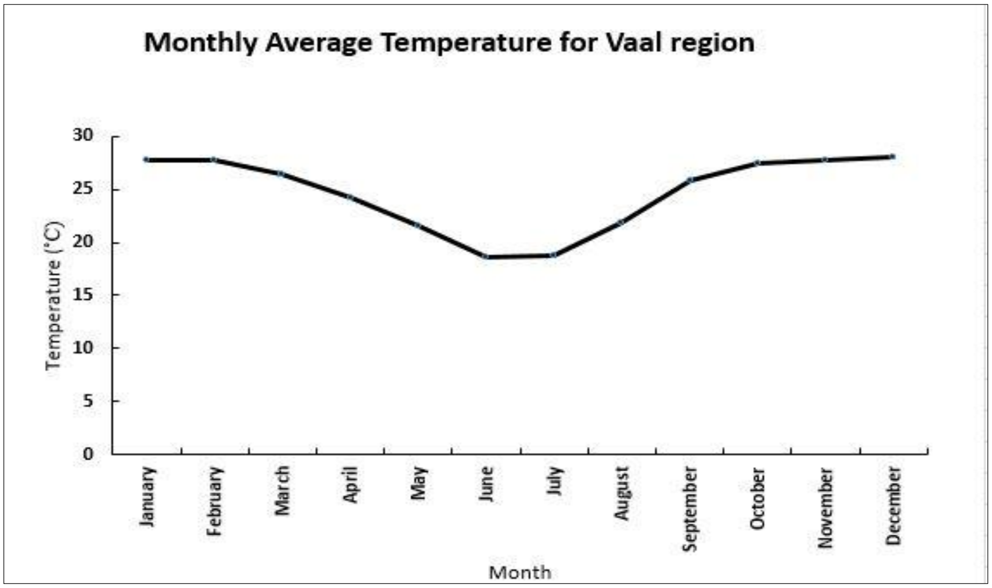


Figure 5: Monthly Temperature Vaal region (C) Data for station [0438784 3] - VEREENIGING Measured at 08:00, data obtained from *(South Africa Weather Services, 2018)*

The climate data obtained for this study is from 2003-2012 data for Vereeniging from SAWS. This study period is too short to derive a proper climatology. To derive proper climatology a minimum 30-year data series is needed. The trend analysis applying a data series shorter than 30 years is less relevant because normal climate is usually defined for three decades. Vereeniging average daily maximum temperature during the summer months (December to March) is 21.7°C. The month with the lowest temperature is June with the average maximum temperature being 19 °C as shown in *Figure 5*.

Wind speed timeseries Vaal Dam Vereeniging

The monthly average wind speed data for the Vaal Dam from 2002 to 2012 is presented in Figure 6 below. The study period is too short to derive a proper climatology for the area. The data shows that high wind speeds are experienced in the area from August to November with ab average speed of 4.2 m/s. lower wind speeds occurs in January measuring 2.7 m/s.

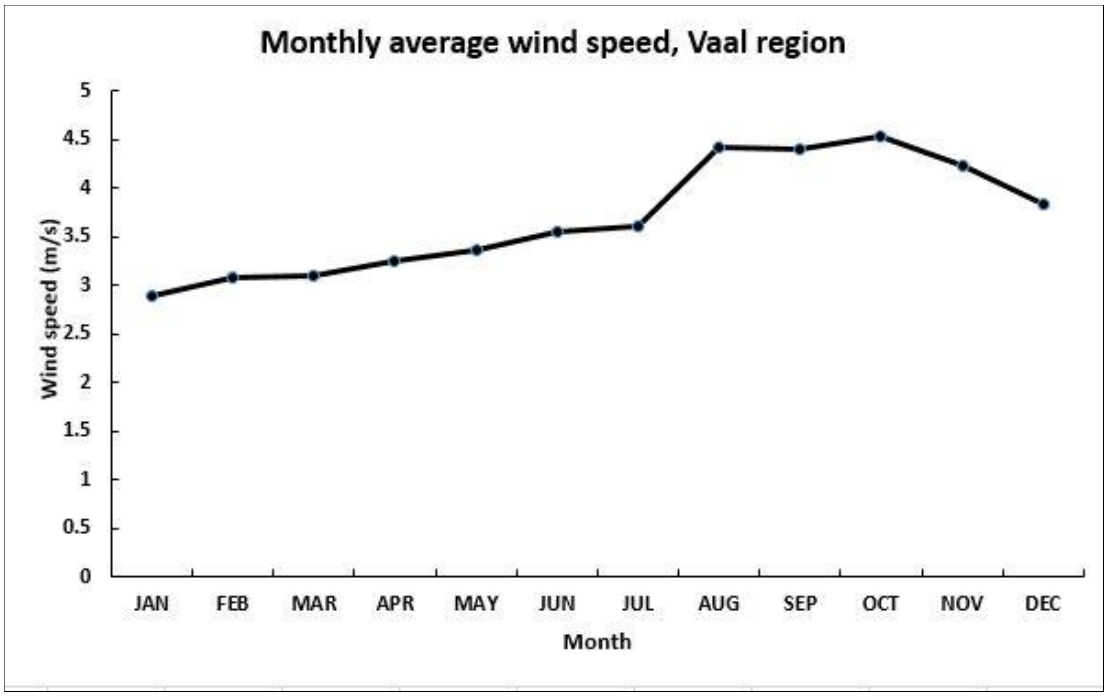


Figure 6:Average Wind speed (m/s) Data for station [0438784 3] – VEREENIGING Measured at 14:00 data from *(South Africa Weather Services, 2018)*.

3.3. The Geology and Soil types of the Vaal Area

It is important to know the soil types in the Vaal Dam area because they form part the sediments and minerals that becomes deposited into the Vaal Dam. Presented in *Figure 7* is the map of soil types found in the Vaal area. The major soil types found in the region are calcic vertisols in light brown colour, paraplinthic acrisols represented in grey colour, lithic leptosols in dark brown colour which are rocks or rocky area, and rhodic lixisols (Dijkshoom, 2003). An acrisol and lixisols are the type of soils that are classified as clay rich by soil classification a taxonomic system for south Africa (Macvicar & DE Villers, 1991).

The geology of the rocks in this region belong to the Karoo Supergroup, which forms about 90% of the rocks (Truswell, 1970). The other 10% of the rocks is formed by Rocks of the Transvaal, Ventersdorp and Witwatersrand Supergroups. There is a high presence of clay minerals within the drainage basin coming from the rocks. Studies by (Birch, 1983) show that the Vaal Dam and Vaal River downstream contain sediments which are enriched in smectite and kaolinite clays. The study further shows that upstream of the Vaal Dam on the Klip, Vaal and Wilge Rivers illite clay is dominant with almost 95 % of the mineral composition. The Vaal Dam has similarly high concentrations of illite clay microparticles which greatly increase the turbidiy of the water and reduce water transparency. In fact, the word “Vaal” means pale in Afrikaans / Dutch and is derived from the light pale grey of illite clays which dominate the water colour.

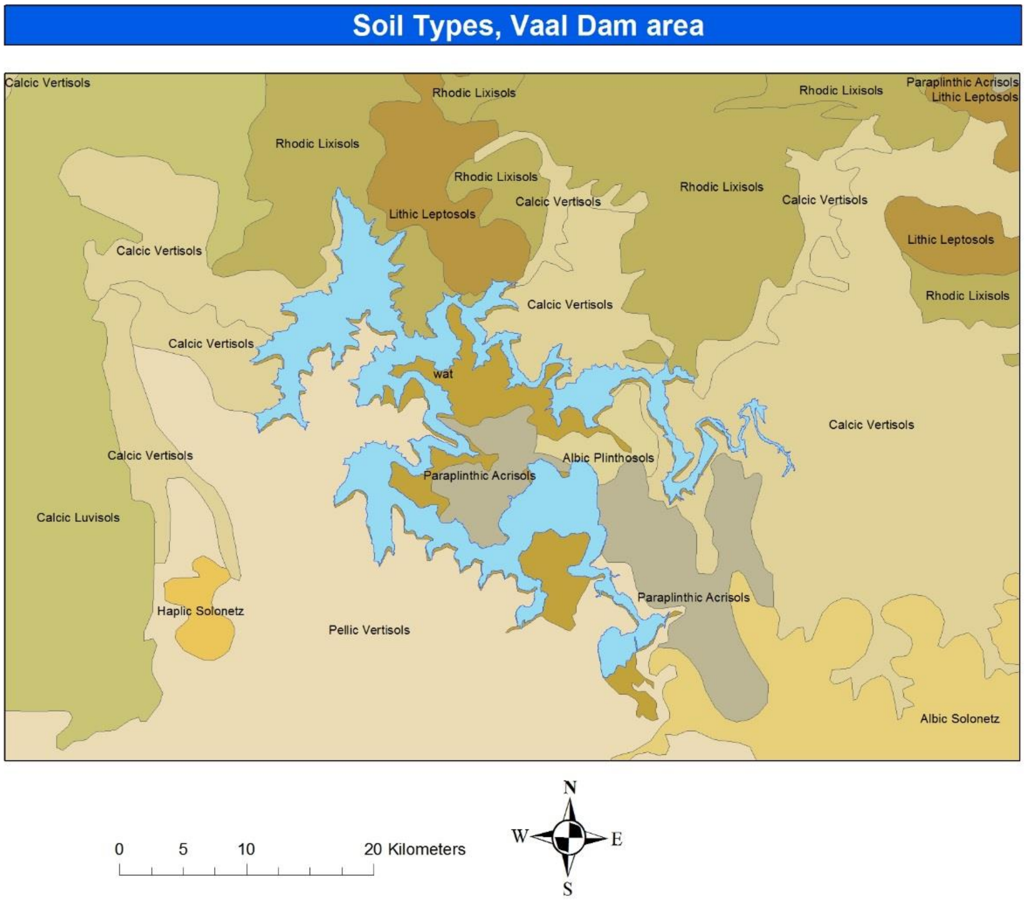


Figure 7:Map of the different soil types in the Vaal Dam area. Information to create the map was obtained from *(Dijkshoom, 2003)*.

Land Use and Land Cover of the Vaal area

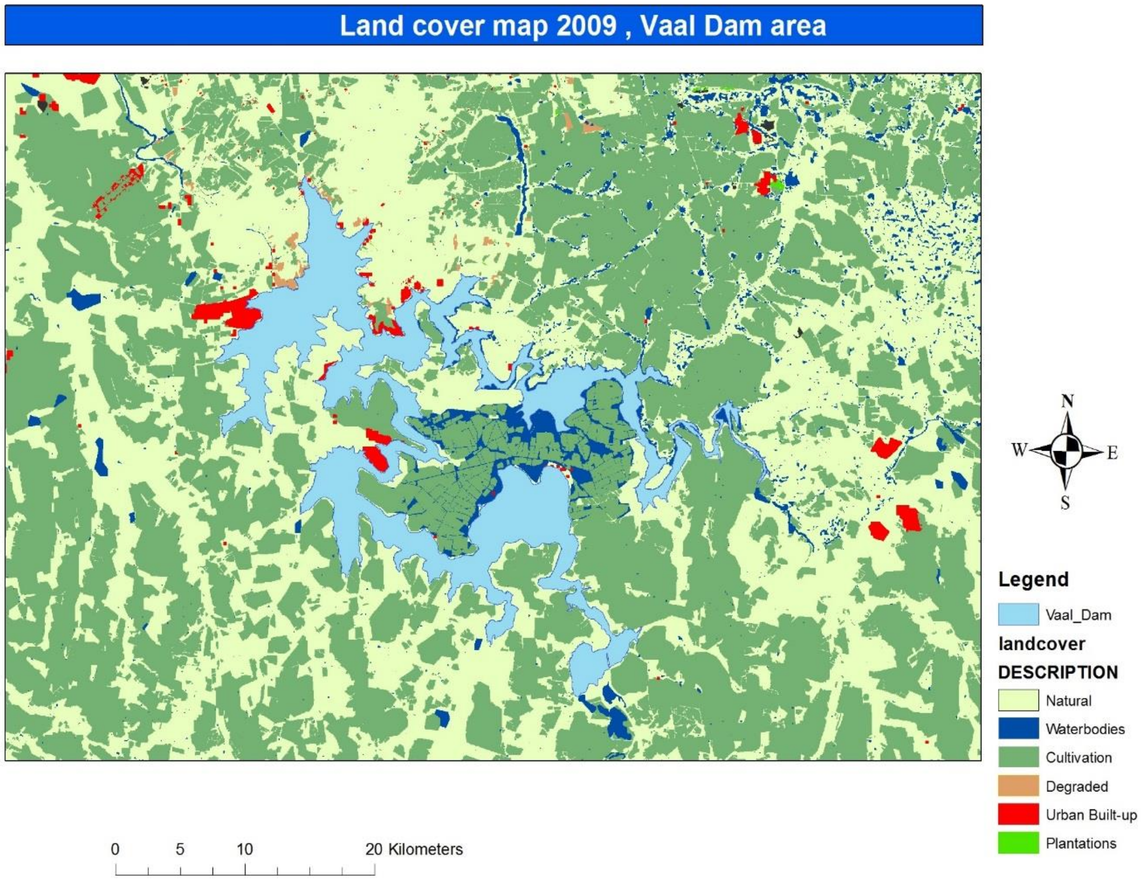


Figure 8:Map of land cover in the Vaal Dam area. Adapted from 2008-2009 South African National Land Cover Dataset by *(Department of Environmental Affairs, 2009)*

Presented in Figure 8:Map of land cover in the Vaal Dam *area. Adapted from 2008-2009* South African National Land Cover Dataset by Land use and cover influences the quality of the water in the Dam through the runoff of nutrients and sediments. The presence of cultivated land can result in an increase in phosphorus from fertilizers. The area is mainly surrounded by cultivated/agricultural land (represented in dark green color), which results in fertilizers being washed into the dam through runoff. The map shows the presence of urban build up areas (represented in yellow color) which also contributes to the pollution through sewage discharges.

3.4. Vaal Dam water quality

Pollution in the Vaal Dam has been increasing in alarming rate. Some sources of pollutants are sewage works that come from the Deneysville waste water plant, which has its final discharge point within 400m of where Rand Water extract their water for treatment (Steward, 2015). Many problems have been identified regarding the water quality in the Vaal River System (Rand Water, 2008). The water quality problems are localized to certain dams within the system, while others form part of the entire river system. One of the main problems identified is the increase in salinity and related macro ions; there is also an increase in total dissolved solids and chloride and sulphate (Rand Water, 2008).

The following factors affect the water quality of the Vaal Dam: The pollutants generated by gold mining activities in the Vaal area (mining areas are in red color on **Error! Reference source not found.**) .The most significant pollutant is the oxidation of pyrite in gold bearing reef, which results in acid mine drainage water entering the Vaal Dam. Another factor is the fuel production and power generation from the SASOL power station (**Error! Reference source not found.** Sasolburg area in yellow color). The power station discharges its effluents into the Vaal Dam.Water pollution sources from power generating plants are oil spills. The oil spill can have severe environmental impacts on the dam water system. The urban and industrial developments also affect the water quality in the Vaal River. The industrial and municipal effluents and solid waste disposal are major contributors of pollution in the Dam such as the Deneysville local municipality opening pipes to spew raw sewage into the Vaal Dam (Steward, 2015).

In addition to the above threats, the Vaal Dam has also been experiencing problems because of eutrophication. A trophic status classification study in some of South African impoundments conducted by the South African Water Research Commission (WRC) indicated that the Vaal Dam is eutrophic (Toerien, et al., 1975). One of the key results of eutrophication is the cyanobacteria blooms that frequently cover the surface of the Dam. These toxic blooms are a hazard to the life in the water system and to the supply of drinking water from the dam A study conducted by (Chinyama, et al., 2016) on the "*Occurrence of cyanobacteria genera in the Vaal Dam: implications for potable water production*" identified five genera of cyanobacteria occurring in the

Vaal Dam. The cyanobacteria genera found were *Anabaena*, *Merismopedia*, *Microcystis*, *Nodularia and Oscillatoria*.

Cyanobacteria such as *Microcystis* and *Anabaena* species were found to be most dominant in the Vaal Dam (Chinyama, et al., 2016). The dominance of cyanobacteria genera appears during the hot months of the year, to be precise February and March. These months are indicated by reasonably high air temperatures which convert to high water temperatures. Cyanobacteria genera were dominant in the months of February and March, their average count was 50% and above. However, in the month of January and April their average count was below 50%, but *Microcystis* and *Anabaena* still showed a significant control of one taxon versus all the other taxa found in the reservoir (Chinyama, et al., 2016).

This study further discovered that Cyanobacteria dominance was extensively positively correlated to air and water temperatures and negatively correlated to NO2-N and NO3-N concentrations. Total phosphorus was not meaningfully related to cyanobacteria dominance. A study by (Toerien, et al., 1975) found that the primary phytoplankton growth-limiting nutrient for Vaal Dam was nitrogen (Chinyama, et al., 2016) .

3.5. Data Sets

3.5.1 Satellite Remote Sensing data

The study uses a 10-year archive of MERIS satellite imagery for the Vaal Dam. The data archive was collected from the period of 2002 until 2012. The following water quality parameters were derived from MERIS imagery, using the maximum peak height (MPH) algorithm, to monitor eutrophication:

- Chl-a concentration
- cyanobacteria area coverage calculated by the area covered by cyanobacteria in m^2 and percent of the total water surface area
- surface scum area coverage, defined as cyanobacteria with chlorophyll-a values greater than 350 mg m^{-3}

3.5.2 In-situ data

To supplement satellite data the study makes use of ground in-situ data. The In-situ water quality datasets were obtained from two sources:

1. ***<u>National Eutrophication Monitoring Program (NEMP) data</u>***

NEMP is a program initiated by the Water Research Commission under the Department of Water Affairs for collecting eutrophication data. The project makes use chemical and biological data to access the state of eutrophication within the dam. The trophic status is determined using Chl-*a* and total phosphorus concentrations. These are the primary variables that are monitored. Additional variables such as Secchi Depth, total nitrogen, total suspended solids and pH were also sampled. The overall dataset used comprised of Chl-a total nitrogen and total phosphorus data. Water samples were taken usually once every two weeks, but often less frequently. The samples were taken near the dam wall located at Latitude: -26.8834, Longitude: 28.1167 of the Vaal Dam. The sampling procedure followed is to make use of a 5m hosepipe if the water is deep enough, if the water is not deep enough and if it fitting to access the water , a subsurface grab sample was used (DWAF, 2002).

The following steps are the procedure that is followed by NEMP to collect water samples using 5m hosepipe method.

1. Sink the weighted end of the hosepipe into the water so that it falls vertically until the unweighted end is below the surface. Make certain that the hosepipe is suspended vertically.
2. Pull up the weighted end of the hosepipe using the attached rope. Pull it up in a U shape until the end reaches the surface. Raise the hosepipe out of the water keeping the u shape.
3. Fill the collected water into the sample bottle, ensuring the correctly marked bottle is used.
4. Pour out an amount of 2 cm from the top of the bottle to allow the water sample to be properly mixed before analysis.
5. Close the water bottle sample tightly with a cap.

Below is the procedure of how the subsurface water samples are collected:

1. Dip the bottle in the water, fill with it with the water and throw away to rinse. Rinse the bottle twice.
2. Fill the bottle with water again by holding the bottle 15 cm below the surface.
3. Pour out 2 cm from the top of the bottle to allow the sample to be well mixed before assessment.
4. Close the water bottle sample tightly with a cap.

This method is also used by Rand Water Board to collect their water samples. After collection of the water samples, they are then taken to the laboratory, whereby water quality parameters get extracted and preserved *Table 4*. (DWAF, 2002).

Below is the method used to filter the water samples for Chl-a**:**

- Put the clean glass fibre filter paper between the top and bottom sections of the filter unit.
- Carefully fill the top section of the filter unit up to the 250ml mark with the sampled water.
- Slowly create a vacuum, measuring up to 15 cm on the pressure gauge, so that water is slowly sucked through the filter paper.
- Remove the receiver flask (bottom part of filter unit) and discard the water.

- Replace the receiver flask. If the water is not very turbid, again fill the top section to the 250m mark, remove the receiver flask and discard the water so that a total of 500 m has been filtered. Carefully remove the top section of the filter unit and carefully remove the filter paper.
- Roll this paper with the rough side (with the filtered substances) on the inside.
- Place the rolled filter paper in the bottle containing the (colourless) ethanol.
- Screw the bottle top tightly into place.
- Write the time of sampling, the date, the sampling site (*e.g.* the dam name) (DWAF, 2002).

Table 4: A list of preservatives used by NEMP to preserve extracted variables

Variable	**Recommended Variable**
Chl-a	Ethanol (extractant and preservative)
Phytoplankton count	Lugol' solution
Phytoplankton identification	Lugol's solution
Total Phosphorus	$HgCl_2$ to give 6 mg/ℓ Hg(ll)
Total nitrogen	$HgCl_2$ to give 6 mg/ℓ Hg(ll)
Kjeldahl nitrogen	$HgCl_2$ to give 6 mg/ℓ Hg(ll)
Nitrate	$HgCl_2$ to give 6 mg/ℓ Hg(ll)
Nitrate	$HgCl_2$ to give 6 mg/ℓ Hg(ll)
pH	Not necessary
Electrical conductivity	Not necessary
Total suspended solids	Not necessary

In the laboratory the samples are analyzed following the recommended analytical procedures in the below table.

Table 5: A table of analytical procedures used by NEMP

Variable	**Recommended procedure**	**Reporting units**
Chlorophyll a	Spectrophotometry	µg/ℓ
Phytoplankton counts	Sedimentation and enumeration using an inverted microscope	Cells/mℓ
Phytoplankton identification	As at Rand Water (using an inverted microscope)	
Total Phosphorus	Phosphomolybdate colorimetry	mg/ℓ
Total Nitrogen	Kjeldah nitrogen + nitrate + nitrite	mg/ℓ
Kjeldahl nitrogen	Digestion and colorimetry	mg/ℓ
Nitrate	Cadmium reduction	mg/ℓ
Nitrite	Colorimetry	mg/ℓ
pH	pH electrode	pH
Electrical conductivity	Conductivity meter	mS/m
Total Suspended solids	Filtration	mg/ℓ

2. ***<u>Rand Water data</u>***

The Rand Water conducts intensive water quality monitoring in the Vaal River catchment and its tributaries. Most of their monitoring is confined to the Upper Vaal water management area, which is their area of supply. The monitoring is focused on the Vaal Dam and Vaal Barrage catchments. The datasets obtained comprises of data from the 2000 to 2012 period. The water quality parameters measured includes Chl-a, toxic algae, total algae and cyanobacteria species. The data was collected from four different sampling points located within the Vaal Dam. The sampling frequency used by Rand Water is once a month. The sampling methods used are subsurface grab samples, similar to the one described for the NEMP program.

3.5.3. Climate Data

South African Weather Service Data (SAWS)

Climate Variables data was obtained from SAWS. The data comprised of Temperature (Monthly averages from January to December), for the period 2002 to 2012. The monthly average was obtained from calculating the Average Daily Maximum Temperature Data, for station [0438784 3] - VEREENIGING Measured at 08:00 am. Vereeniging is town that is situated in the Vaal Dam area, about 34 km away. Rainfall monthly average datasets were also obtained, the rainfall was calculated monthly using daily rain (mm) data, for station [0439203 9] - DENEYSVILLE, measured at 08:00 am. Wind datasets which comprised of Average Wind Speed (m/s) data for station [0438784 3] - VEREENIGING, measured at 20:00 were also obtained.

3.5.4. Limitations of the dataset

The ground in-situ NEMP provided data from 2002-2013. NEMP collected data once or twice a month for the following variables: sample coordinates, date, time, sample depth, preservatives, Chl-a suspended in water and Chl-a detection limit. The datasets had incomplete data because of months during which sampling/ data collection was not done. NEMP also took samples at one location which is near the bridge.

The MERIS satellite data also comprised of data from November 2002 to April 2012. This means that only complete data exist for years between 2003 and 2011.

Rand water data was collected at four different sample which provided some spatial variability of the Chl-a in the dam. The variables sampled by Rand water are more than those of NEMP, however the dataset is from the year 2000-2010.

4. CHAPTER FOUR: METHODOLOGY

4.1. Remote Sensing and GIS Analysis

4.1.1. MERIS Imagery Processing Vaal Dam

Archived MERIS full resolution (FR) level 1P data were obtained for the Vaal Dam for the study period 2002 to 2012. Cloud free images were selected for each month; the date on which the images were captured had to correspond with the collection date of ground in-situ data. Shown in *Figure 9:Schematic processing method for MERIS data*. The files were initially processed using BEAM V4.9.0.1 open source software tools (Brockmann Consult). Images were masked for land and cloud. The MPH algorithm was used to retrieve the concentrations of chlorophyll-a, cyanobacteria and surface scum, following the method described in (Matthews, et al., 2012) The BEAM files were subset for the Vaal Dam. The scenes were then further rectified for radiometric effects using radiometry processor V.1.0.1 and rectified for gaseous absorption using bottom of Rayleigh (BRR) processor V.2.3. The final output products are subset BRR images of the Vaal Dam.

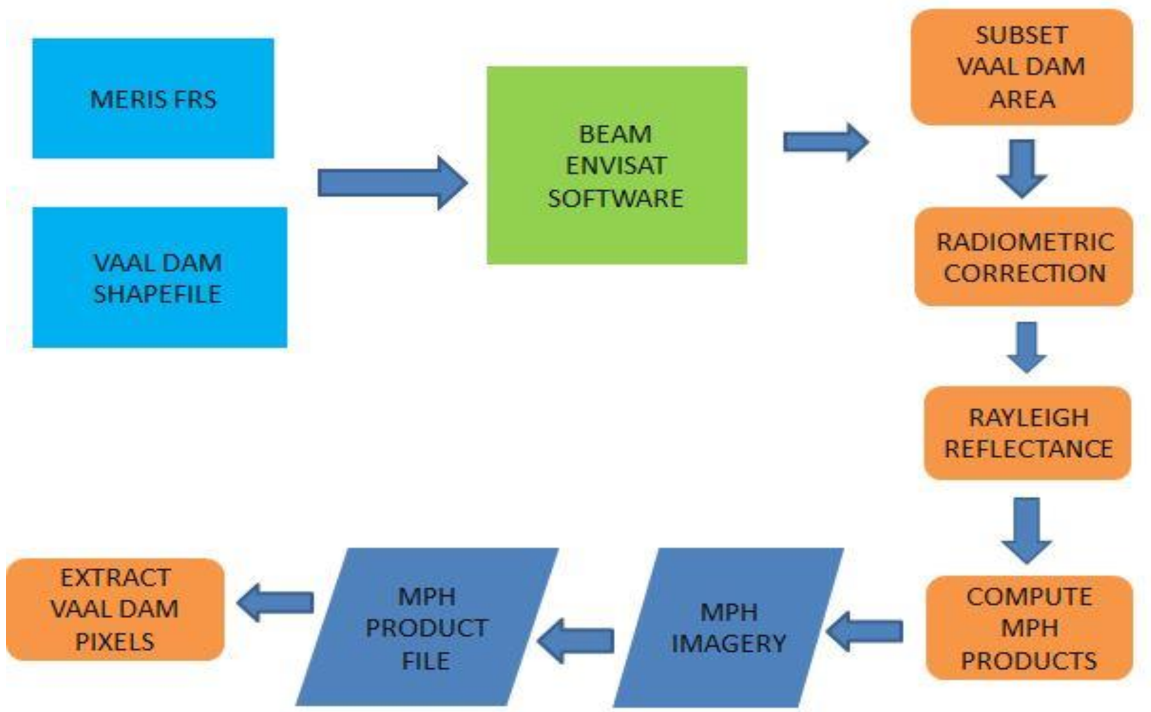


Figure 9:Schematic processing method for MERIS data. Definitions of acronyms in figure; **FRS** = full resolution (FR) level 1P, **MPH =** maximum peak height (MPH) algorithm.

The images were further processed in Python programming language to calculate the Chl-a products. MERIS satellite data products on Chl-a, cyanobacteria and surface scum area coverage, acquired using procedures described by (Matthews, 2014) were used for computing time series data for the period 2002-2012.

4.1.2. GIS Analysis

A shapefile of the Vaal Dam was created using Google Earth mapping application. The shape file was exported into ArcMap 10.4 to be used as base map. The Chl-a pixels values which were extracted in BEAM through computing MPH products and were saved in an Excel spreadsheet. To display the spatial Chl-a pixel values in ArcMap 10.4, the Excel spreadsheet was added into the software programme as a table. X and Y fields were chosen as the longitude and latitude data, respectively. Chl-a pixel values were chosen as the Z field. Chl-a concentrations were displayed as point data in ArcMap.

The resulting base map of the Vaal Dam with Chl-a concentrations was projected using WGS84 datum. Chl-a concentrations were further mapped as a layer file in ArcMap. The maps can show the spatial distribution of Chl-a, especially at places which are difficult to sample using in-situ methods. The main advantage having of the Chl-a maps produced using GIS methods, is that they can be saved as layer files. The layer will have attribute data to describe each point saved. These files can further be analyzed using methods such as interpolation, they can be used together with layers of other variables such as nutrients data collected in-situ and spatial analysis and statistics can be calculated and displayed in map form using the layer.

Interpolation of in-situ Chl-a

ArcGIS has various tools for generating a projected surface from sample data points. Chl-a pixel were interpolated to make a map showing the spatial distribution of Chl-a within the Vaal Dam. The Chl-a values are stored as points in ArcMap using the x and y coordinates. The Spline interpolation method was the method applied on the data to create a surface only for mapping purposes in this study, so that the final maps can be visually appealing. Spline calculates each grid cell values by fitting a minimum-curvature surface to the sample data. Similar to a flexible sheet of plastic that passes through each data point but otherwise bends as little as possible. The distinction between regularized and tension splines are one of flexibility: a regularized spline has more "give" in it and creates smooth surfaces with projected values that may fall outside the sample data range. Tension splines are less smooth but follow more closely to the range of the sample (ESRI, 2007).

4.2. Time series Analysis: Trophic Status, seasonality and trends of Chl-a and cyanobacteria

Trophic Status

Time series data for chlorophyll-a was calculated for each dam using Python 2.7 software programme. The mean and average Chl-a values were calculated for the Vaal Dam. The MERIS satellite images were processed in BEAM following the method described in *Figure 9*. BEAM software was used for radiometric corrections, rectification of gaseous absorption using bottom of Rayleigh (BRR), and to compute MPH products. The computed MPH products were processed in Python programming language to calculate the Chl-a values. The average Chl-a value was determined as the median Chl-a value of valid water pixels of each image.

The median value of the Chl-a observations was chosen to represent the trophic status because it is less sensitive to outliers than the mean. The mean and median Chl-a values used were based on observations of the entire time series. Guidelines from the Organization for Economic Co-operation and Development (OECD) were followed to define and classify the trophic status of the Vaal Dam.

Trends

The Chl-a trend of was calculated using the anomalies and linear regression analysis. Chl-a anomalies were calculated by subtracting the monthly Chl-a averages from the Chl-a value of that month. Linear regression is defined according to (t) = at + b, where a is the regression coefficient and the linear trend with respect to time (t). The statistical significance of the trend was calculated using the student t-test statistic.

Seasonality

The seasonal change of Chl-a in the Vaal Dam was calculated using the monthly mean value from the entire time series of observations. The seasonal cycle phase was calculated using the month with the highest Chl-a value. The amplitude was calculated by subtracting the highest and the lowest Chl-values. The area coverage of cyanobacteria and surface scum area coverage were calculated in percentage using the number of pixels identified as cyanobacteria or surface scum visible in each image. Pixels which are identified as cyanobacteria and have Chl-a concentration more than 350 $mg.m^{-3}$ are identified as surface scum. The trends of cyanobacteria and surface scum were calculated based on the percentage coverage between 2002-2012, in a similar method to Chl-a trends. The seasonality of cyanobacteria and surface scum was calculated using the monthly mean values.

4.3. Correlation Analysis

This study applied statistical analysis methods to determine the drivers of eutrophication within the Vaal Dam. The study investigated the possibility of nutrients, namely Nitrogen and Phosphorus being the possible drivers of eutrophication. Linear regression statistical analysis was performed using the ground in-situ data collected from NEMP and MERIS satellite data for Chl- a. A relationship/correlation was determined between Chl-a and Nitrogen, and Chl-a and Phosphorus measurements taken from the Vaal Dam. The monthly mean values of nitrogen and phosphorus were calculated for each year, from 2003 to 2012. The year 2012 was excluded from the correlation calculations because the year was incomplete. A liner regression model was used for the correlation analysis using Microsoft excel software.

A linear regression was calculated using the Nutrients data using the following method. Total phosphorus, total nitrogen ad Chl-a was recorded in excel spread sheets. The data was plotted using scatterplots diagrams, the dependent variable was Chl-a and the independent variables were Total phosphorus and Total Nitrogen. The monthly mean values of nitrogen were correlated to the Chl-a monthly mean and presented using scatterplot diagrams. The diagrams are useful for visualizing the data and analyzing how it is distributed. From the scatterplots diagrams the correlation coefficient (R value) and the Person values (P value) were calculated to determine the significance of the correlation. The results of the correlation coefficient were interpreted in the following manner: Correlation coefficients have a value of between -1 and 1. 0. The value indicates the strength and direction of a linear relationship between two variables, while -1 or +1 means that there is a perfect negative or positive correlation. A value of zero indicates that there is no linear relationship between the variables. A value greater than zero indicates a positive relationship, that is, as the value of one variable increases, so does the value of the other variable. A value less than zero indicates a negative relationship. As the value of the other variable decreases, the value of the other variable decreases

The P values were computed in Excel to calculate the statistical significance of the linear regression. P values evaluate how well the sample data support the null hypothesis to be true. The P value is number between 0 and 1. A low P value such values less than 0.05 shows that the null hypothesis can be rejected. High P values which are above 0.05 shows that the null hypothesis is true, and the correlation is statistically significant.

4.3.1. Total Nitrogen: Total Phosphorus ratios analysis

The study uses the TN:TP ratio method to determine which of the nutrients is the limiting agent in the system. For this method the study made use of nutrient data from NEMP ground in-situ dataset to calculate the limiting agent ratios. Monthly total phosphorus and total nitrogen measurements were averaged to calculate the annual mean for each. To calculate the TN: TP ratio take the TN value and divide it by the TP value.

$$\text{Ratio Formula} = \frac{\text{Total Nitrogen}}{\text{Total phosphorus}}$$

The results of the numbers obtained were interpreted using the following explanation by (Lakewatch, 2000):

- When the TN/TP ratio is less than 10, the system is nitrogen-limited.
- When the TN/TP ratio is between 10 and 17, nitrogen or phosphorus could be limiting agent in the system.
- When the TN/TP ratio is greater than 17, the system is phosphorus-limited

.

4.3.2. Climate Variables Analysis

A linear regression analysis was used to determine the correlation between Chl-a and air temperature, rainfall and wind data. The constant variable is Chl-a and it was correlated against temperature, rainfall and wind. The air temperature of average daily maximum temperature (°C) data for Vereeniging, obtained from South African Weather Services and the Chl-a obtained from MERIS satellite imagery were there two variables used for the analysis. The first step was to produce a scatter plot of the two variables against each other. The plot is fitted with the best fit linear line, that will help to determine the trend between the two variables. From the scatter plot, the equation of the best fit line was used to determine the slope. The slope could either be positive or negative value. The value of the slope would indicate the relationship between the two variables.

The correlation coefficient (r) value was computed in excel to determine the strength of the relationship between the two variables. The P value was also computed to measure the statistical significance between the two variables. The next step was to plot the climate variables together with Chl-a on the same timeseries. It is important that the period is the same for the variables to be plotted. To measure the degree of correspondence between variables that have different units we first must normalize the data. This was done according to the below formula: where $\overline{x}$ is the mean and σ_x is the standard deviation.

$$X_{norm} = \frac{x - \overline{x}}{\sigma_x}$$

The normalized data must then be used to plot Chl-a and rainfall, or Chl-a and temperature or Chl-a and wind speed on the same linear graph. This step, together with scatterplots are a useful method of visualizing data, to draw informed conclusions. The last step was to plot all the correlations on the time series to see how the variables change against each other. This was done by taking the normalized data of each variable and plotting it on the same time series using Microsoft Excel.

4.4. In-situ validation method

The Validation of satellite Chl-a estimates was done using in-situ Chl-a data collected by the Rand Water. Four sample points distributed across the Vaal Dam were selected for the analysis presented in *Table 6*.

Table 6:Points within the Vaal Dam that were selected for the matchup analysis with MERIS satellite points

Point	Latitude	Longitude
Vaal Dam 1	26.53.26°S	28.14.35°E
Vaal Dam 2	26.91.68°S	28.20.38°E
Vaal Dam 3	26.93.69°S	28.21.42°E
Vaal Dam 4	26.92.94°S	28.29.12°E

Satellite and in-situ data collected on the same day were used, and Chl-a was measured following the methods of using subsurface grab sampling as done by Rand Water. A matchup analysis between the satellite and in-situ data was done. A comparison of the Chl-a mean, median and standard deviation of the in-situ versus satellite was done. Pixels covered in a small area (10 pixels ≈ 1 km^2) matching to the probable location of the in-situ sample point were extracted from the time series of satellite data and the mean and standard deviation was computed. The correlation between satellite and in-situ measurements were determined using linear regression analysis. The results of the matchup were presented by using scatter plots graphs and statistical results were computed to produce the correlation coefficient and the p-value. The results were also presents in a time series graph, plotting both satellite and in-situ results on the same graph. A matchup was determined to be good or bad based on the results of the linear regression analysis. Adequately good matchups were obtained from the correlation coefficient results. The complete algorithm performance was assessed for the joined matchup dataset.

5. CHAPTER FIVE: RESULTS

5.1. Remote Sensing and GIS Analysis Results

5.1.1 MERIS Imagery Processing Vaal Dam

MERIS satellite images were analyzed using remote sensing methods to produce maps of Chl-a for the period 2003-2007The below map Figure 10 show the distribution of Chl-a within the Vaal Dam for 2003. The map images for the other years can be found in the APPENDIX. The maps show the Chl-a variation over the different years. A single image was obtained during the month of June for each year. June was a preferred month because it is during winter and mostly cloud-free for good images to be obtained. A total of 3 images were analyzed for each year, however, only images that had a good scene and cloud free were used for this section. The MERIS distribution maps can show areas that have a high Chl-a concentration within the Vaal Dam. Lower Chl-a concentration values are represented by blue color and high concentration values are in red on a log scale of values between 1 and 1000 mg m^{-3}. The high concentration values occur at places where the sources of pollutants enter the dam. They are also areas which should be prioritized for remediation of water quality.

2003

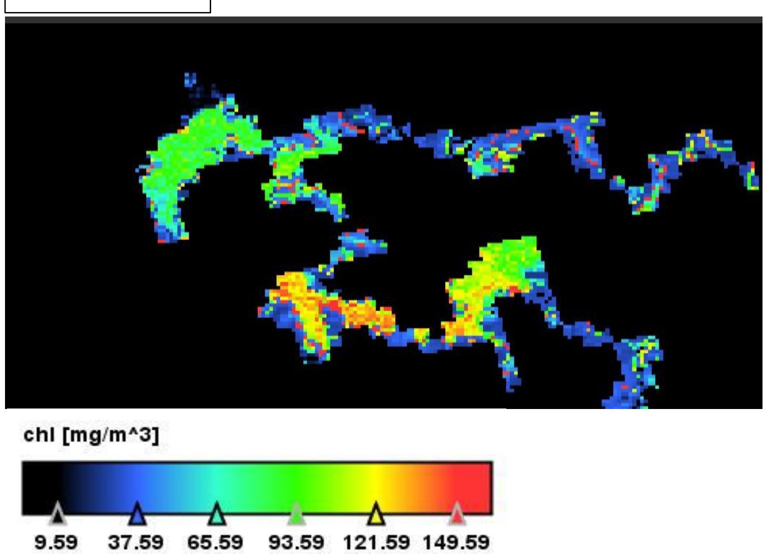


Figure 10: Maps from MERIS satellite images, showing the spatial distribution of Chl-a within the Vaal Dam.

5.1.2 GIS Analysis Results

Chl-a spatial variation

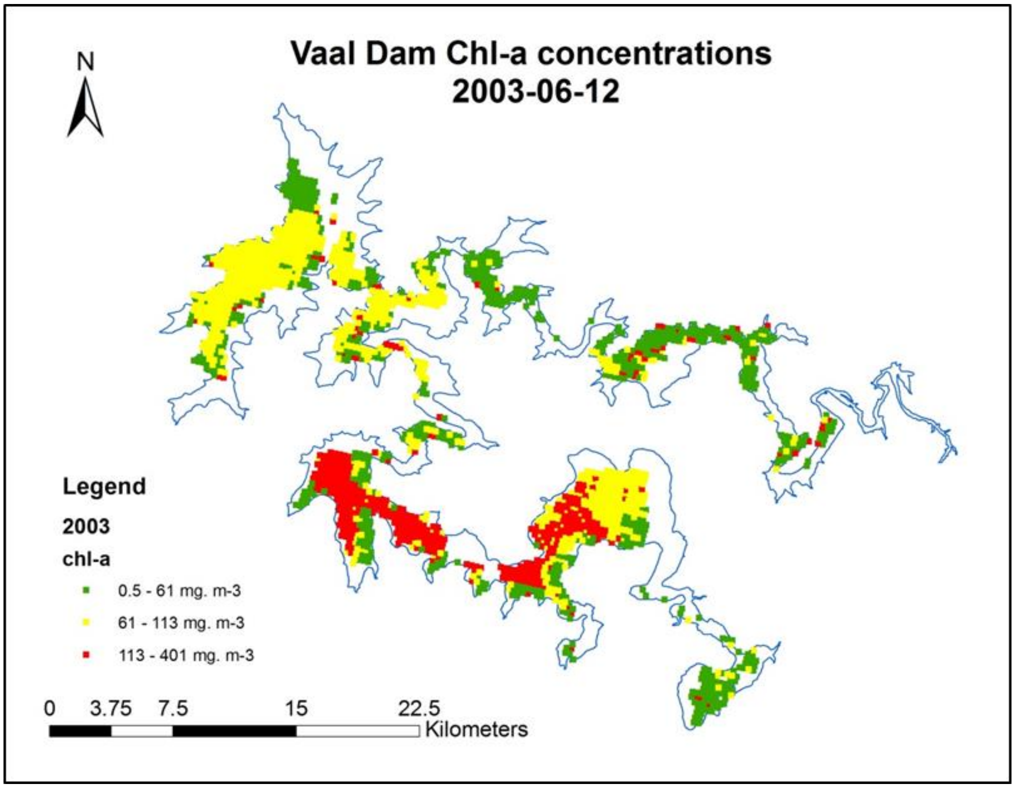
Maps of the Vaal Dam were created using ArcGIS 10.1 software to show the spatial distribution of Chl-a and the areas that are the worst affected (high Chl-a values) over the 5-year period shown in *Figure 11*. The GIS maps show a spatial variability like the Chl-a maps produced using MERIS satellite images. These map images show the distribution of Chl-a within the Vaal Dam over a period of five years from the year 2003 to 2007. Low Chl-a concentration values are represented in green color, yellow is medium range, and the red color represents high concentration values. The GIS Chl-maps are similar to MERIS Chl-a maps because they were created using the pixel values extracted from the MERIS satellite images. The advantage having of the Chl-a maps produced using GIS methods, is that they can be saved as layer files. The layer will have attribute data to describe each point saved. These files can further be analyzed using methods such as interpolation, they can be used together with layers of other variables such as nutrients data collected in-situ, and spatial analysis, spatial statistics can be calculated and displayed in map format using the layer.

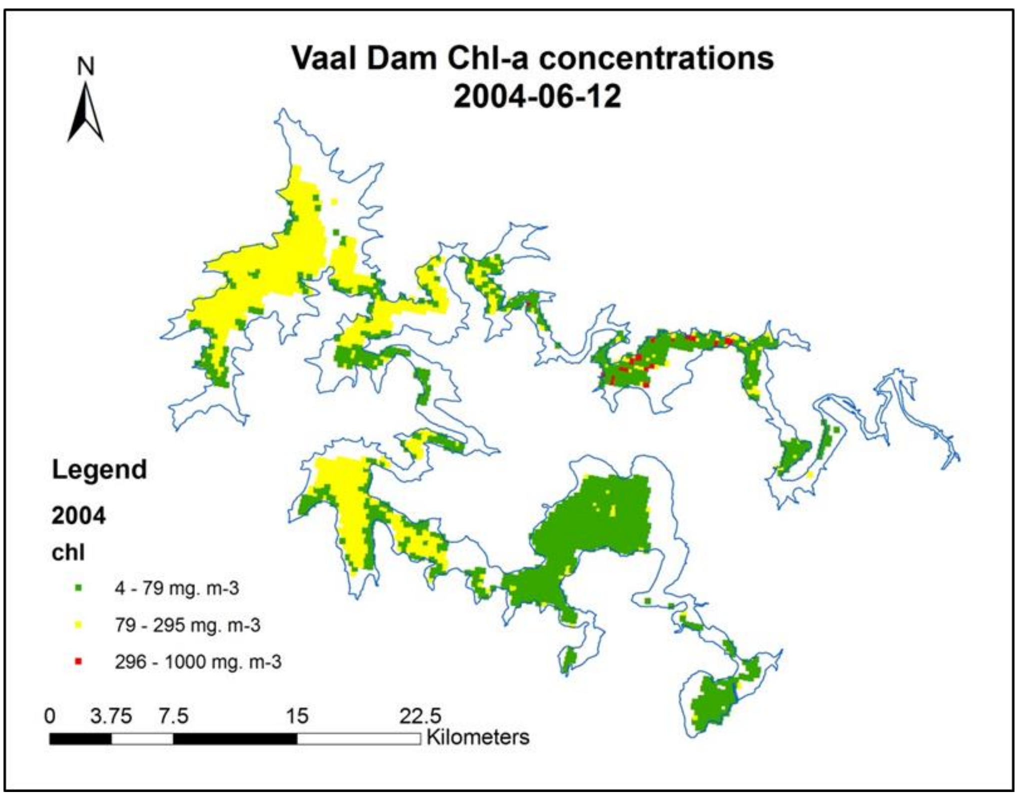
2003 Chl-a map

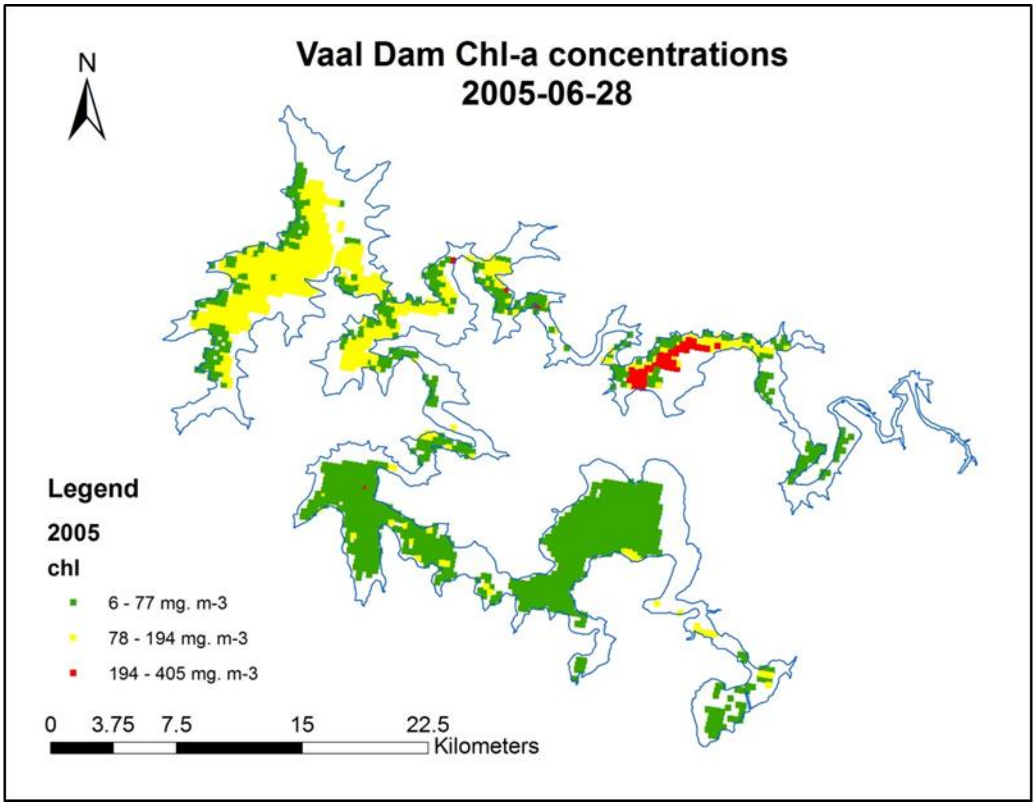
The areas in the red color are the worst affected with values ranging between 113 to 401 $mg.m^3$, the areas lie in the southern parts of the Vaal Dam. They are followed by the areas represented in yellow with values that range between from 61 to 112 $mg.m^3$. The areas with the lowest values are in the green color with values that range between 0.5 to 61 $mg.m^3$. All these values represent a hypertrophic system.

2004 Chl-a map

The worst affected areas in the year 2004 lie in the eastern side of the Vaal Dam and are marked in the red shade, the Chl-a values range from 296-1000 $mg.m^3$. The system is still hypertrophic. The western side of the dam marked in yellow with Chl-a that range 79-295 $mg.m^3$. The green shade is seen at the southern parts of the dam and represents Chl-a values between 4-79 $mg.m^3$.


Vaal Dam Chl-a concentrations
2003-06-12
N
Legend
2003
chl-a
0.5 - 61 mg. m-3
61 - 113 mg. m-3
113 - 401 mg. m-3
0 3.75 7.5 15 22.5
Kilometers


Vaal Dam Chl-a concentrations
2004-06-12
N
Legend
2004
chl
4 - 79 mg. m-3
79 - 295 mg. m-3
296 - 1000 mg. m-3
0 3.75 7.5 15 22.5
Kilometers



2005 Chl-a map

The Vaal Dam Chl-a are high in the eastern part of the dam, at a small area in the red color. The Chl-a values range from 194-405 mg.m^3. The southern parts are shaded in green with lower values ranging from 6-77 mg.m^3. The western parts have values ranging from 78-194 mg.m^3. The values still classify the dam as a hypertrophic system.

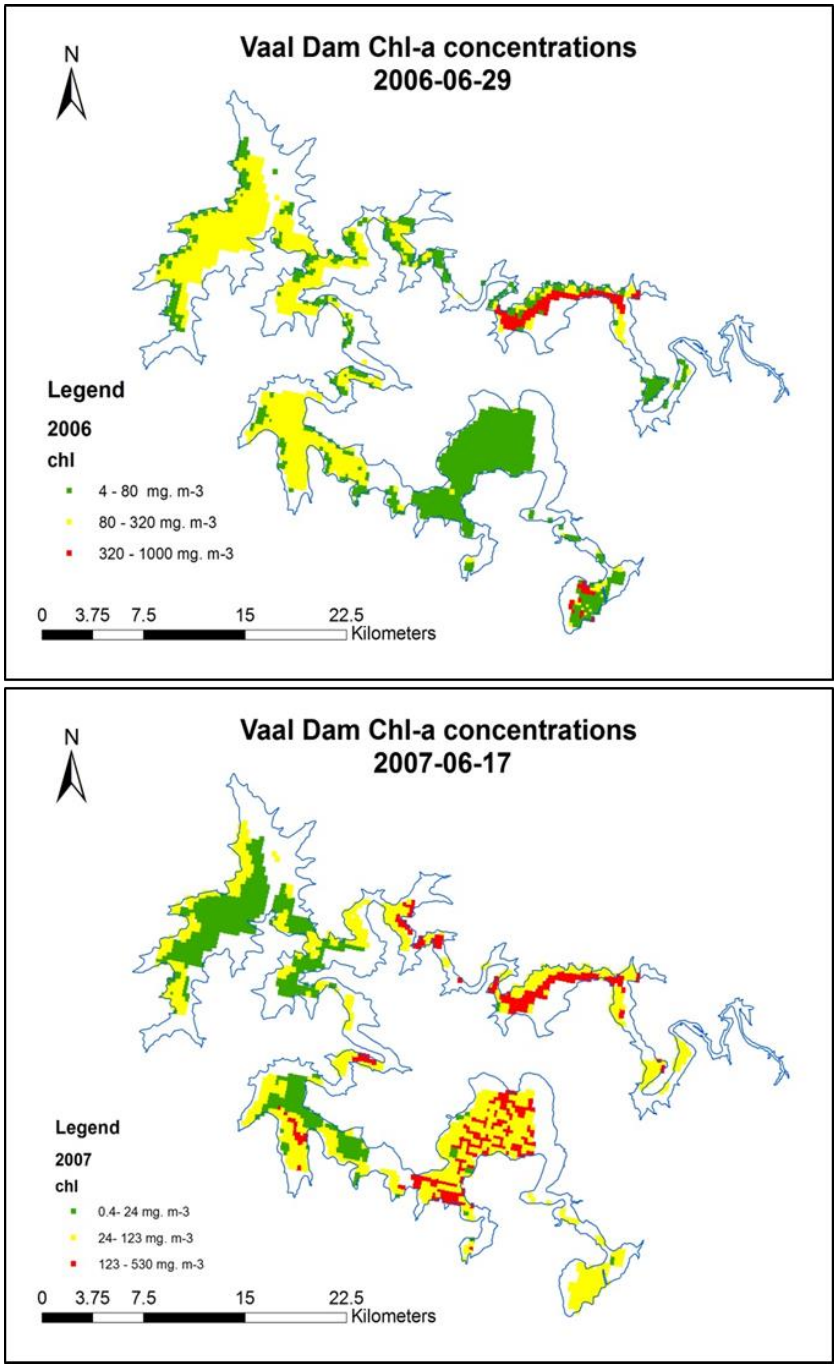


Figure 11 : Chl-a spatial variability maps of the Vaal Dam.

2006 Chl-a map

The high Chl-a values are presented in red appear on the eastern part of the dam, with values that range between 320-1000 mg.m^3. The yellow represents Chl-a that range between 80-320 mg.m^3, and they appear on the western part of the dam. The southern part is dominated by green, which are the lower range between 4-80 mg.m^3 of Chl-a values.

2007 Chl-a map

In the year 2007 the Vaal Dam had high values represented by red, in north eastern part and in the south-eastern part of the dam. The values range from 123-530 mg.m^3. The area is also occupied by yellow color which represent values between 24-123 mg.m^3. The low values are represented in a green color, they range from 0.4-24 mg.m^3. They appear in the western part of the dam and the area classify as eutrophic.

The overall observation is that high Chl-a values which are represented in red color, appear frequently on the eastern part of the dam for all the years. They appear as a small area for the year 2003 and 2004, but the area increases for the other years 2005,2006 and 2007.

5.2. Time series Analysis Results: Trophic Status, seasonality and trends of Chl-a and cyanobacteria

5.2.1 Trophic Status

MERIS satellite time series products of Chl-a, cyanobacteria and surface scum coverage are represented in *Figure 12* for the Vaal Dam. The results represented in *Figure 13* show the median and standard deviation of Chl-a concentration of the Vaal Dam, derived using the MPH algorithm. The results indicate the dam as a representative of a eutrophic system that is dominated by the presence of cyanobacteria blooms.

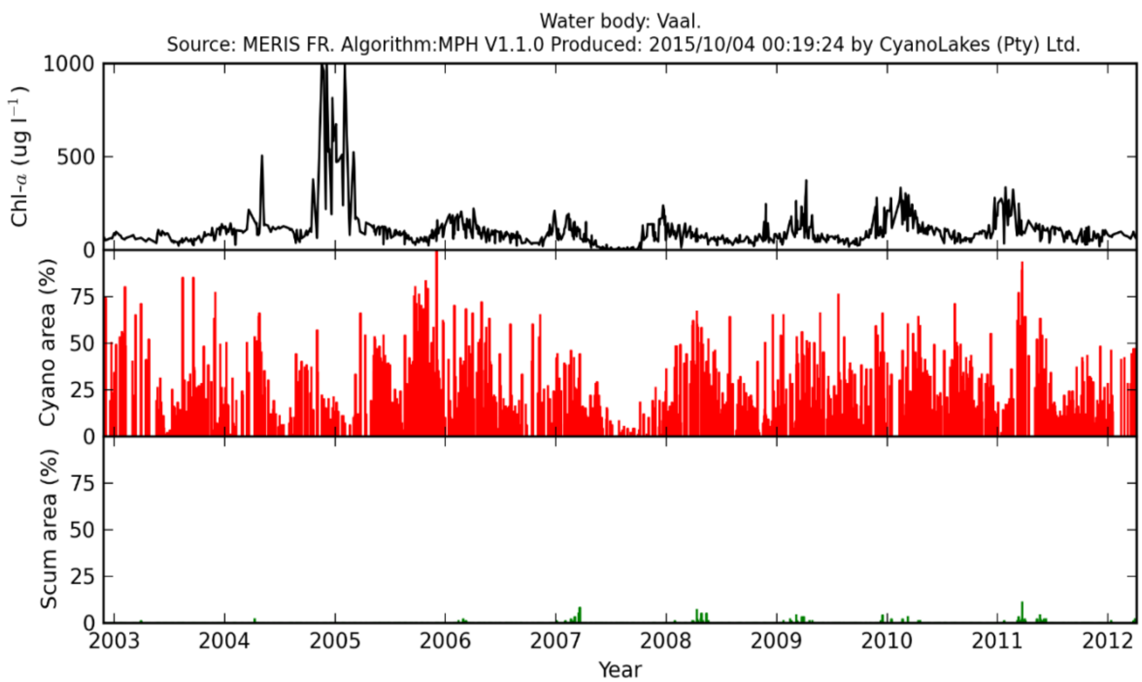


Figure 12: Time series of Chl-a and area coverage for cyanobacteria and surface scum derived using the MPH algorithm for the Vaal Dam.

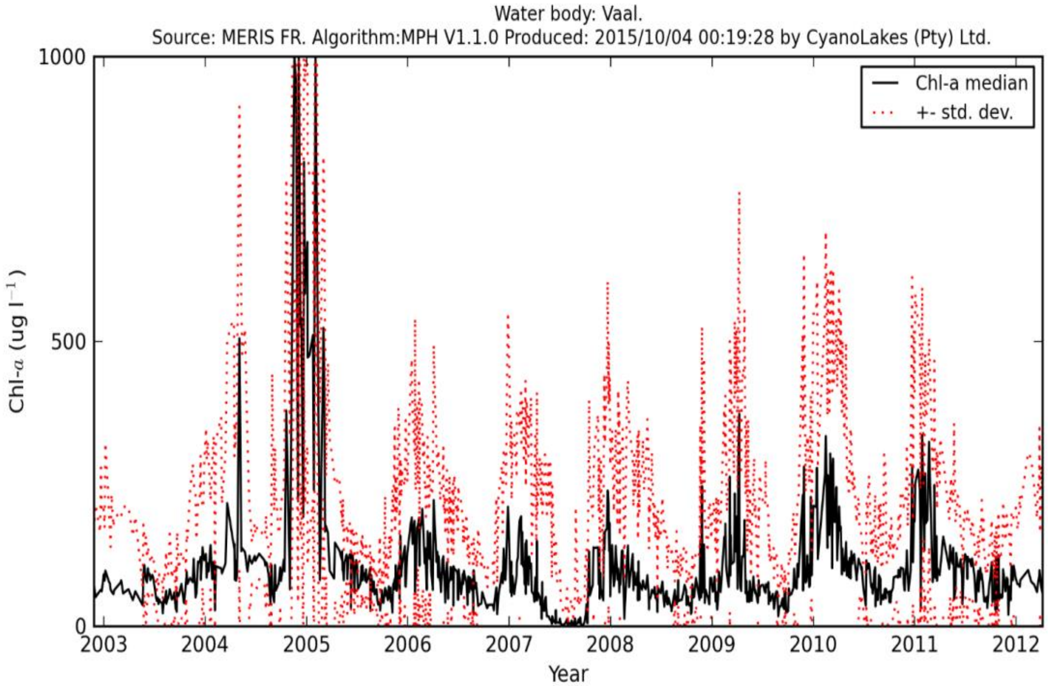


Figure 13: A time series of Chl-a products derived using MPH algorithm. Chl-a median is represented by black lines and standard deviation in dotted red lines.

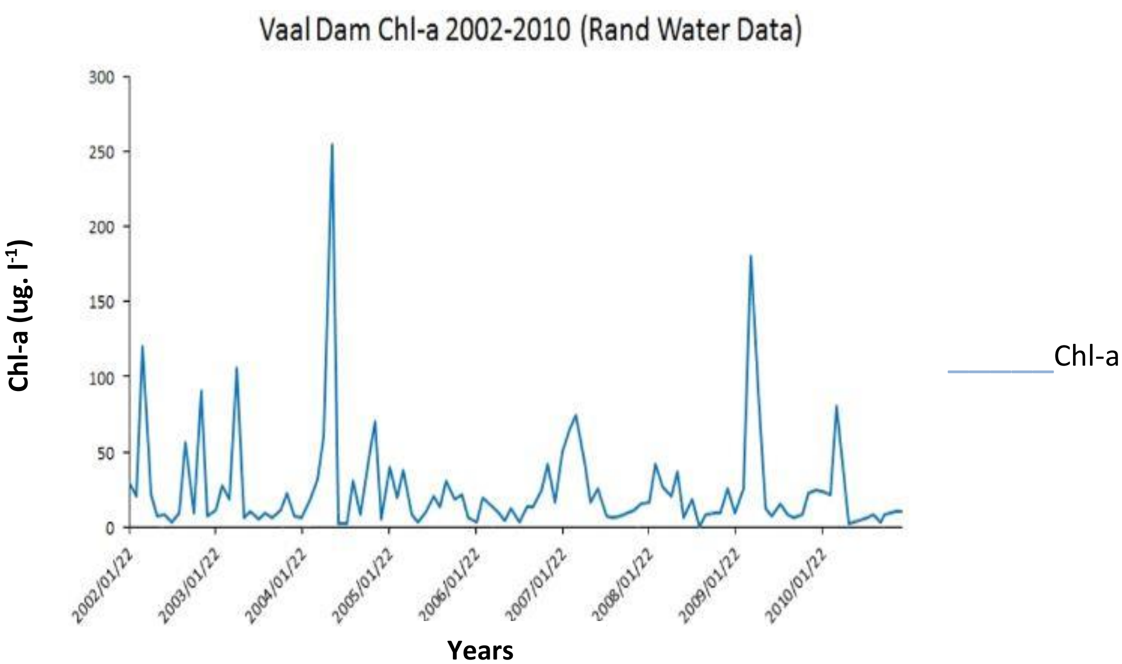


Figure 14: A time series of Chl-a monthly mean from in-situ data collected by Rand Water

5.2.2 Seasonality

Chl-a values and Cyanobacteria cover percentage values derived from MERIS satellite images were both normalized and plotted in *Figure 15* below. The values are from the period of 2002-2012 and they are monthly averages of all the years combined. The plot of the graph shows that Chl-a (marked in red) increases from the month of January to March, which are the summer months. The percentage cover of cyanobacteria is also observed to increase during the summer months. The Chl-a concentration shows a decrease in values from Autumn to the winter months (April to August) while the cyanobacteria percentage cover starts to decrease from (May to August). September marks the beginning of Spring and temperatures begin to rise, the Chl-a concentration values also begin to increase, together with the cyanobacteria percentage cover,

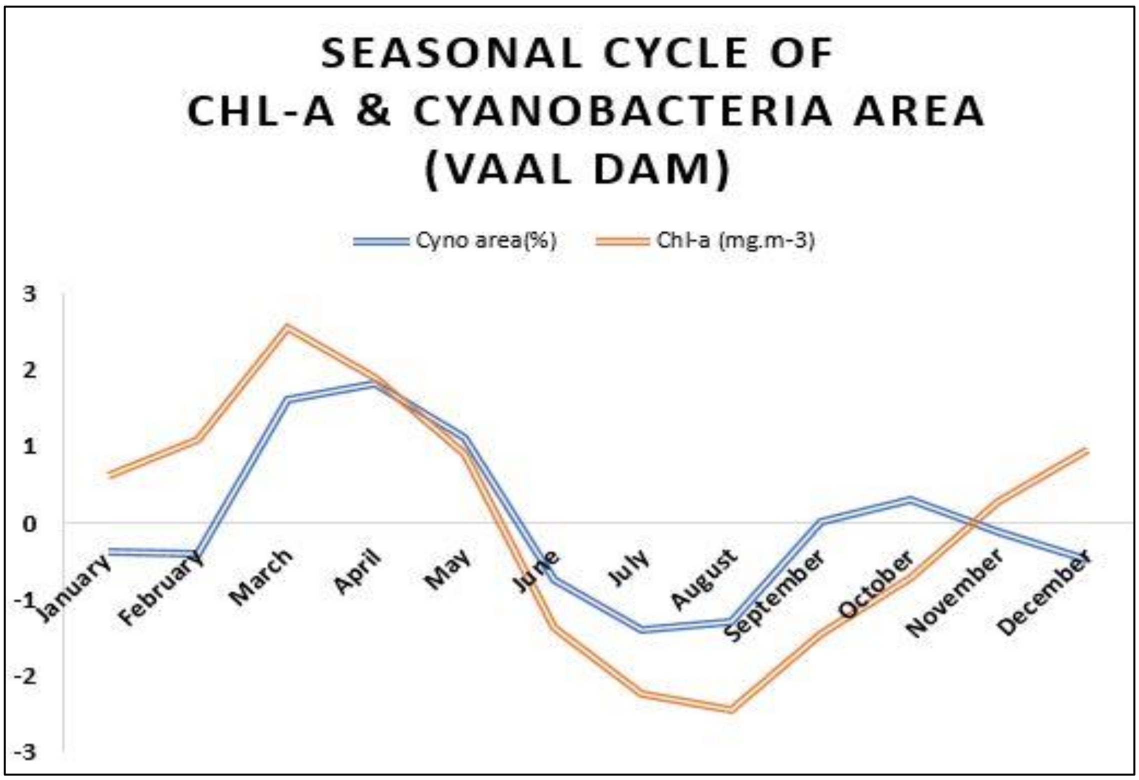


Figure 15:Seasonal Cycle of Chl-a and Cyanobacteria area in percentage.

The observation of the seasonal cycle graph of Chl-a concentration and Cyanobacteria area percentage, show that as the Chl-a concentration increases with the Vaal Dam, the Cyanobacteria area percentage also increases.

5.2.3 Trends

A summary of the trend statistical results is shown in *Table 7*. The significant trend is for the Chl-a anomalies, whereby the absolute t-value is greater than the t-significant value. The rest of the calculated results are not significant at the 95 %. Confidence interval (C.I).

Table 7: Summary statistics of trends for Chl-a and Cyanobacteria area cover in the Vaal Dam. r is the regression coefficient of the linear trend with respect to time. To test for the trend significance Student t-test values were used and compared at the 95% confidence interval. N is the number of observations in the trend calculations.

	Chl-a yearly average trend	**Chl-a anomalies trend**	**Cyanobacteria area yearly trend**	**Cyanobacteria area anomalies trend**
r	-0.28354	***-0.10049***	-0.14648	-0.06045
Trend in mg m^{-3} y^{-1}	-4.08309	***-3.61717***	-0.27459	-0.41539
t	-0.81576	***-3.03009***	-0.39603	-1.81113
t sig. (95% C.I.)	2.364624	***1.96263***	2.364624	1.96263
n	893	***893***	893	893

5.3. Correlation Analysis Results

5.3.1. Nutrients analysis results

Total Nitrogen versus Chl-a

The monthly mean values of nitrogen were correlated to the Chl-a monthly mean and presented using scatterplots graphs in Figure *16* and Figure *17*. The results calculating the correlation coefficient (r) and p-value (statistical significance) calculated from the monthly mean (N=12) are presented in Table *8*. From analyzing the correlation coefficient (r value), the calculated values ranged from r⁼0.01 to 0.594, showing a weak positive relationship amongst nitrogen and Chl-a. The statistical significance was calculated at 95% confidence level. Many of the p-value results was calculated ranged close to 0 but more than 0.05, resulting in the correlation not being statistically significant. The relationships were not significant for most years, the null hypothesis is accepted for those years. The only statistically significant results for the correlation is in the year 2000 where the p value is less than 0.05. The nitrogen values were measured from the dam wall, while the Chl-a values were derived from MERIS satellite and represented the whole dam. The above-mentioned factor could be the reason why the two variables are not statistically significant.

Table 8: Linear regression statistics for Nutrient Nitrogen from in-situ data and satellite Chl-a estimates. Count=N, correlation coefficient = r, p-value= statistical significance.

Total Nitrogen versus Chl-a				
YEAR	**R^2**	**r**	**p-value**	**N**
2003	**0.353**	**0.594**	**0.0416**	**12**
2004	0.0001	0.01	0.975	12
2005	0.0649	0.255	0.4240	12
2006	0.0842	0.290	0.3602	12
2007	0.0085	0.0922	0.3563	12
2008	0.0074	0.086	0.3922	12
2009	0.0362	0.1902	0.5537	12
2010	0.2366	0.4864	0.1087	12
2011	0.0026	0.0509	0.8746	12
2012	0.027	0.1643	0.4129	12

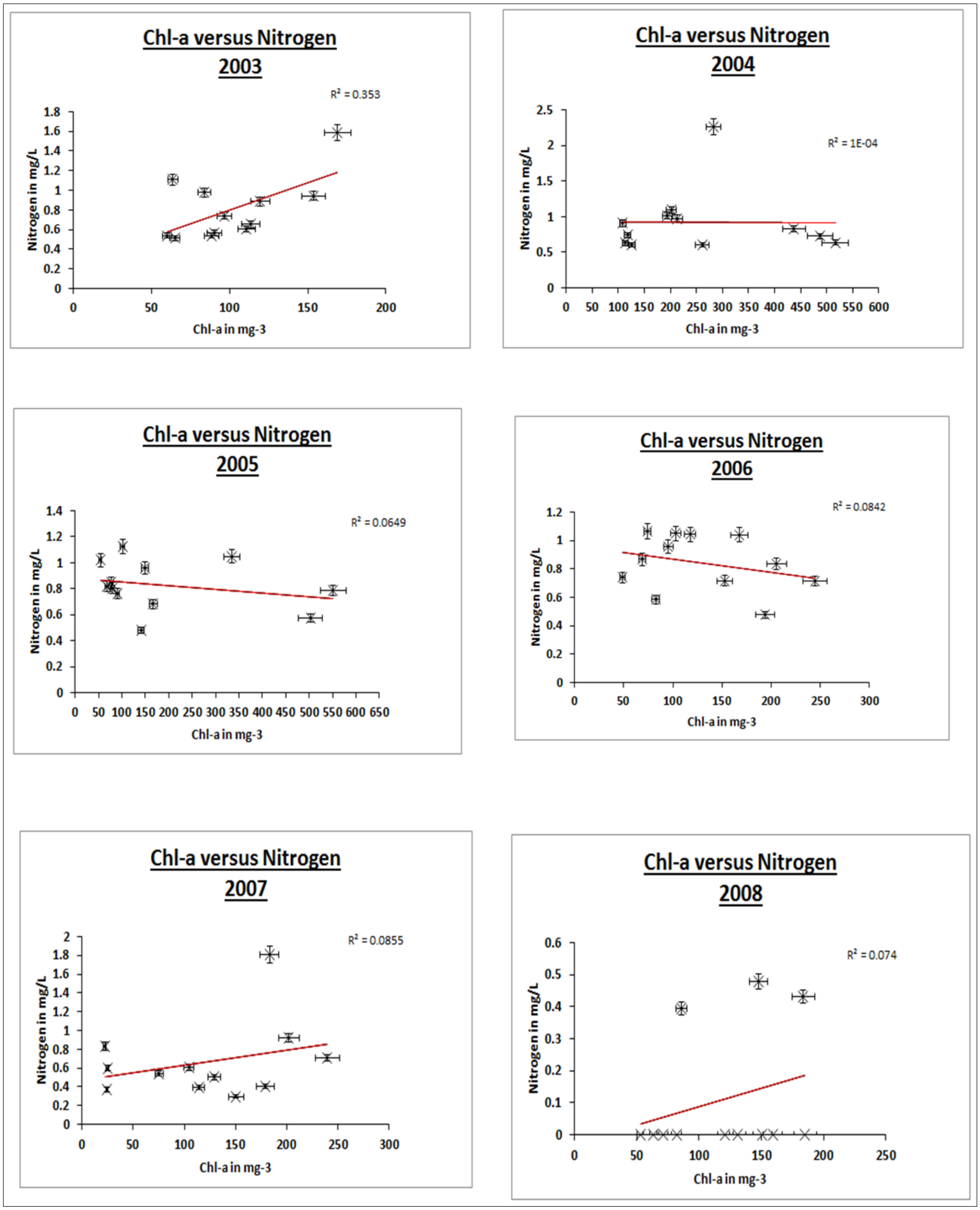


Figure 16: Scatterplots graphs of linear regression between Chl-a and Nitrogen. The graphs indicate the relationship between Chl-a and Nitrogen.

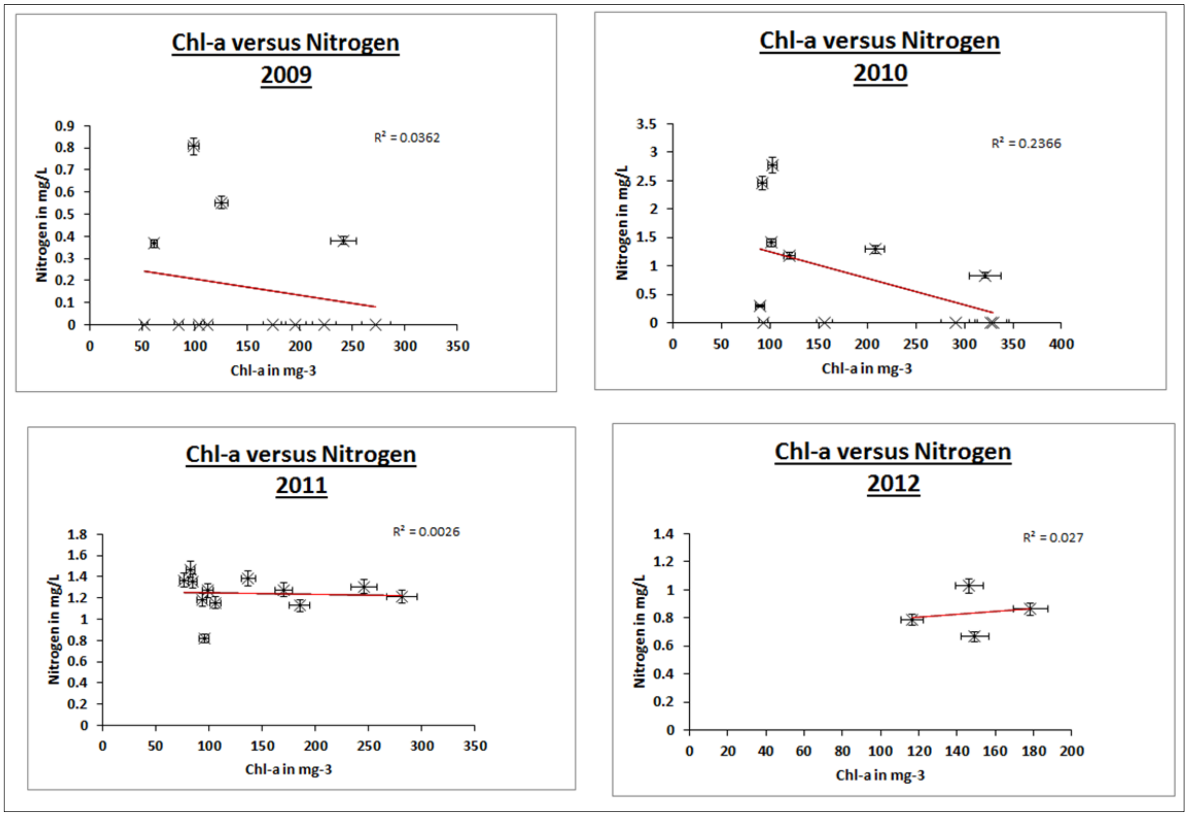


Figure 17: Scatterplots graphs of linear regression between Chl-a and Nitrogen. The graphs indicate the relationship between Chl-a and Nitrogen.

Total Phosphorus versus Chl-a

The correlation between Phosphorus and Chl-a was calculated using a linear regression model. The results calculating the correlation coefficient (r) and p-value (statistical significance) calculated from the monthly mean (N=12) are presented in Table *9*. From analyzing the r value, the calculated values ranged from r = 0.7598 down to r = 0.0663. Most of the years r value was less than 0.30indicating a weak positive relationship between phosphorus and Chl-a. The monthly means of phosphorus were correlated to the monthly mean values of Chl-a and presented using scatterplots graphs in *Figure 19*. The statistical significance was calculated at 95% confidence level. Most of the p values calculated ranged close to 0 but more than 0.05. Therefore, indicating that there is no significant relationship between phosphorus and Chl-a. The relationships were not significant for most years, the null hypothesis is accepted for those years. The only statistically significant relationship was in the year 2003 where p value was less than 0.05. Therefore, in-situ phosphorus nutrients cannot reliably be estimated/ calculated using Chl-a data collected from satellite images. The phosphorous values were measured from the dam wall, while the Chl-a values were derived from MERIS satellite and represented the whole dam. This could be the reason why the two variables are not statistically significant.

Table 9: Linear regression statistics for Total Phosphorus from in-situ data and satellite Chl-a estimates. Count=N, correlation coefficient = r, p-value=p.

Total Phosphorus versus Chl-a				
YEAR	**R^2**	**r**	**p-value**	**N**
2003	**0.5773**	**0.7598**	**0.0041**	**12**
2004	0.0044	0.0663	0.833	12
2005	0.0625	0.250	0.433	12
2006	0.0056	0.0748	0.8179	12
2007	0.0944	0.3072	0.3313	12
2008	0.0178	0.1334	0.6789	12
2009	0.1564	0.3955	0.2032	12
2010	0.1114	0.3337	0.2898	12
2011	0.1331	0.3648	0.2431	12
2012	0.0075	0.0866	0.5287	12

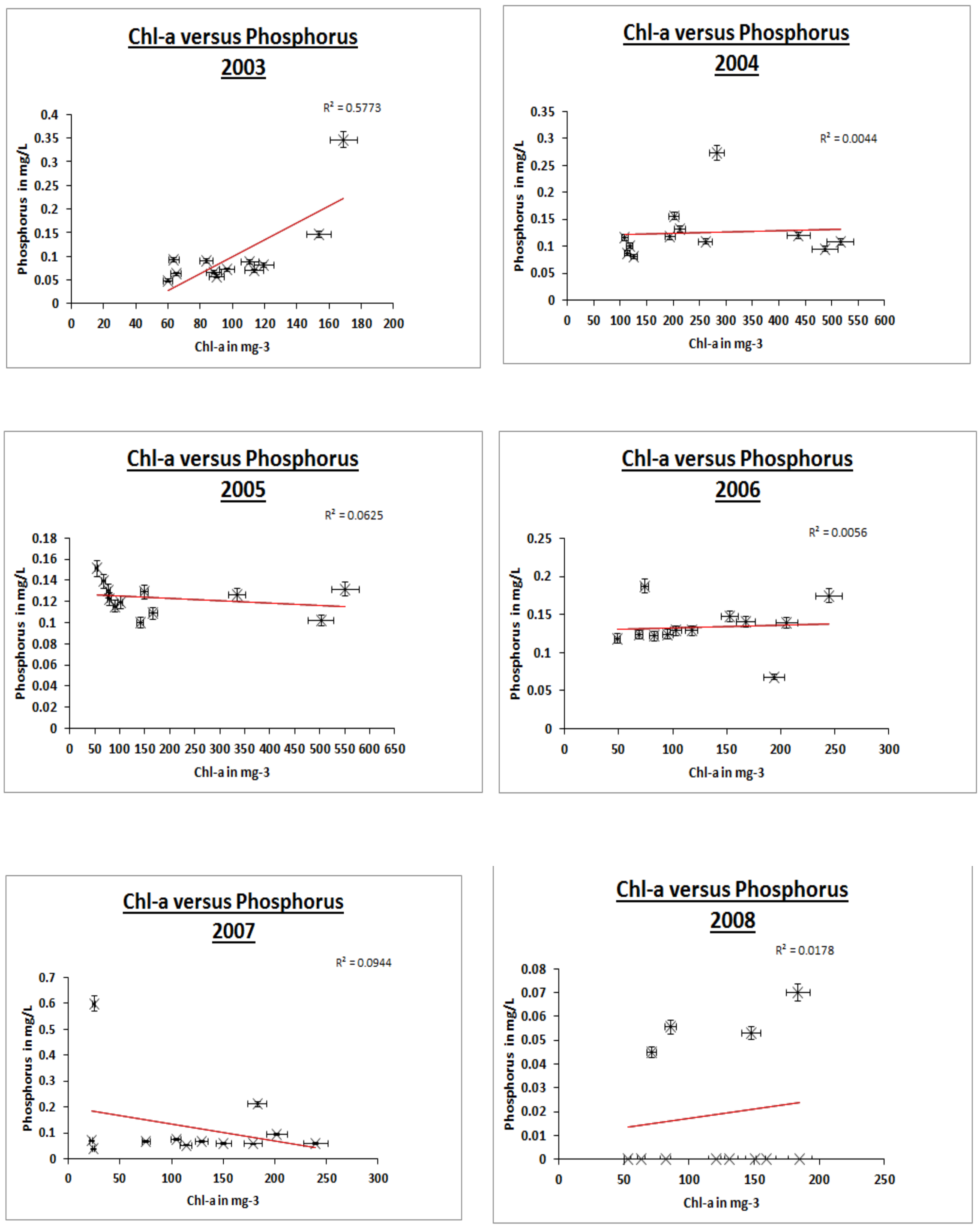


Figure 18:Scatterplots graphs of linear regression between Chl-a and Phosphorus

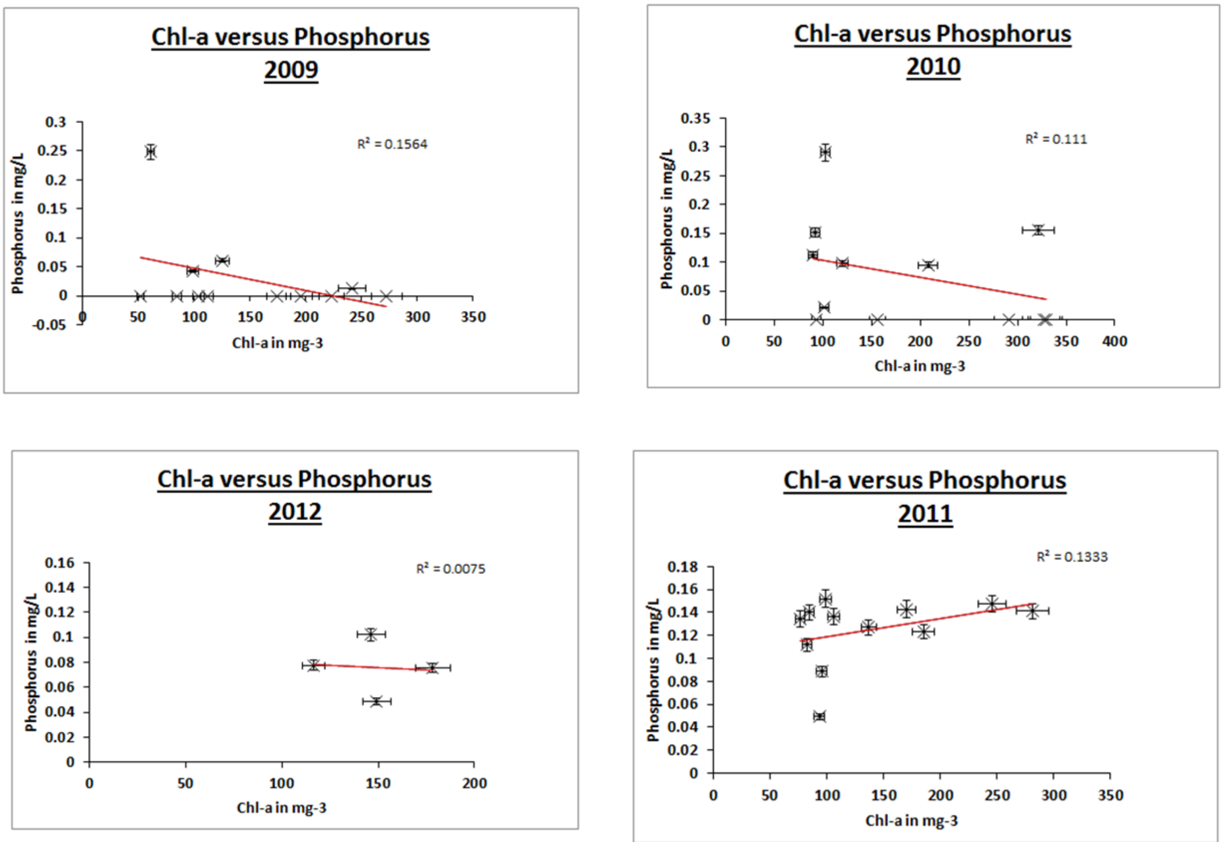


Figure 19: Scatterplots graphs of linear regression between Chl-a and Phosphorus.

5.3.2. Total Nitrogen: Total phosphorus ratio analysis results

The ratio of nitrogen to phosphorus was calculated to determine which one is the limiting nutrient within the Vaal Dam. Freshwater systems are considered as being phosphorus limited when the total nitrogen (TN) to total phosphorus (TP), TN/TP ratios is above the value of 15. The system will classify as nitrogen limited when the TN/TP ratios is below the value of 7. For ratios of TN/TP between 15 and 7, either phosphorus or nitrogen, or both could be a limiting agent. A TN/TP ratio greater than 10:1 indicates a phosphorus limitation, meaning the available supply of phosphorus will be consumed before the supply of nitrogen (Smith, 1983; Guildford and Hecky, 2000). The results of the TN/TP ratio analysis are presented in *Table 10*. The results indicate ratio values were less than 7 from the year 2002 to 2006, and again in 2009. This indicates nitrogen as the limiting nutrient during those years. This means that the Vaal Dam has lots of phosphorus, which also means that cyanobacteria can dominate because they can fix nitrogen, unlike most algae. Reservoirs that have low nutrient concentration are normally phosphorus limited. When the eutrophication increases, nitrogen limitation become evident and the reservoirs that have hyper eutrophication are all limited by nitrogen (Toerien, et al., 1975) . The Vaal Dam system changed in 2007 to 2012 where it was not limited by N or P.

Table 10: The ratio of TN: TP of the Vaal Dam (2002-2012)

Year	**Total Nitrogen (mg/L)**	**Total Phosphorus**	**TN:TP**	**Limiting nutrient**
2002	0.54	0.088	6.09	N
2003	0.68	0.097	6.95	N
2004	0.78	0.129	6.10	N
2005	0.61	0.122	4.97	N
2006	0.55	0.140	3.96	N
2007	0.59	0.077	7.69	None
2008	0.53	0.056	9.41	None
2009	0.45	0.085	5.36	N
2010	1.11	0.132	8.38	None
2011	0.93	0.124	7.51	None
2012	0.83	0.069	12.00	None

5.3.3. Climate Variables Analysis Results

Presented in *Figure 20* is the graph of monthly median Chl-a concentration values obtained from MERIS satellite imagery using the MPH algorithm. The graph indicates a high peak in values for the year 2005, indicating the Vaal Dam as being hypertrophic.

Presented in *Figure 21* is the graph of showing daily maximum air temperature in the Vaal region. Increasing air temperatures will influence the water temperature including physical and chemical properties of that water (Houghton, et al., 2001). Therefore, the study correlates temperature and Chl-a to determine if temperature is a possible driver of eutrophication in the Vaal Dam.

Vaal Dam Meris Satellite Chl-a Concentration

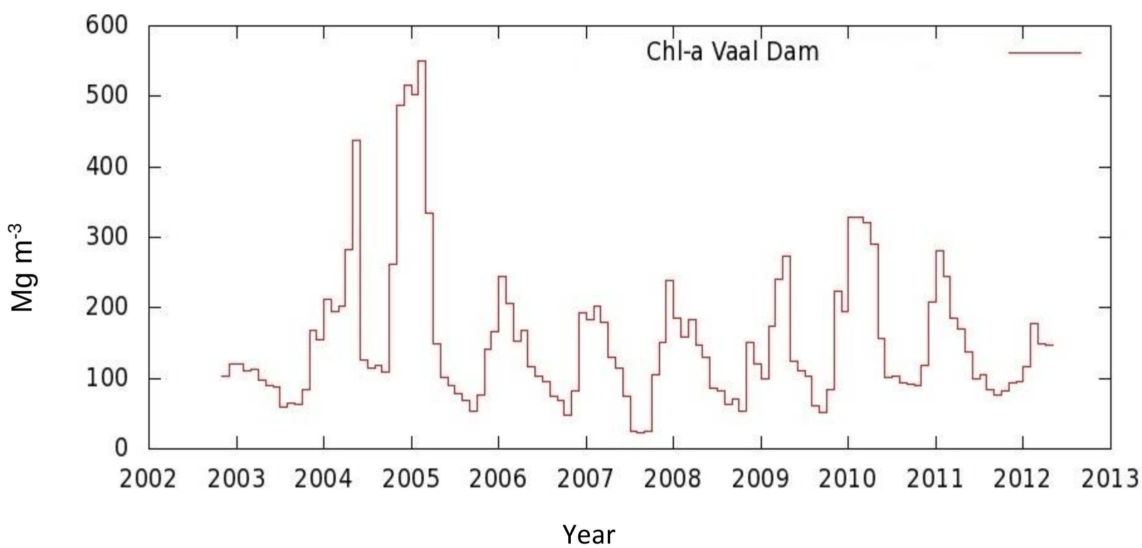


Figure 20: A graph showing Chl-a concentration values derived from MERIS satellite images using the MPH algorithm.

Vaal Dam maximum daily Temperature

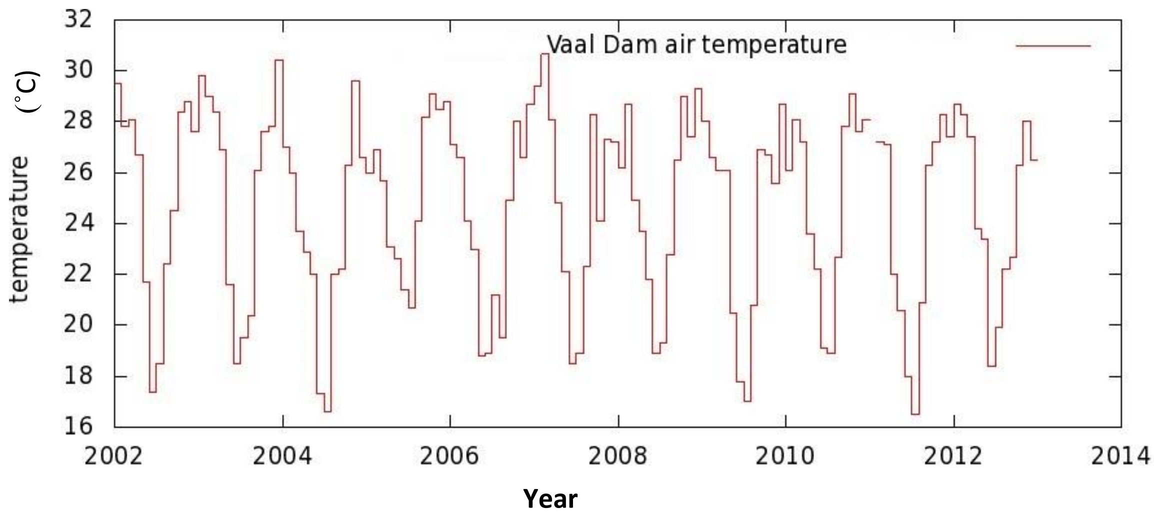


Figure 21:A graph showing monthly average daily maximum temperature for the Vereeniging station in the Vaal region.

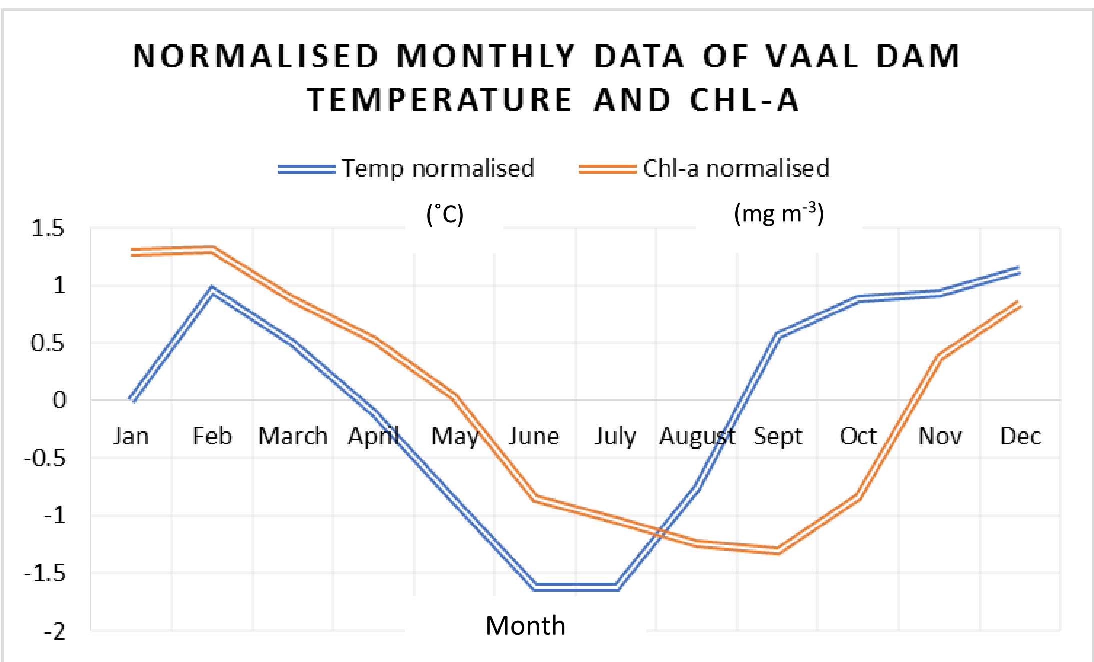


Figure 22:Graph of normalised monthly averages of Temperature and Chl-a, measuring the degree of correspondence between the two variables.

The Chl-a and Temperature data was normalized and plotted on the same graph presented in *Figure 22*. This was done to calculate the degree of correspondence amongst the two variables. The graph is showing temperatures values are decreasing from the month of January to May. The Chl-a values also seen to decrease as the temperature decreases. The temperature values then remain low and start to increase in August. The Chl-a values remain low and only start to increase in September.

Chl-a and Temperature correlation results:

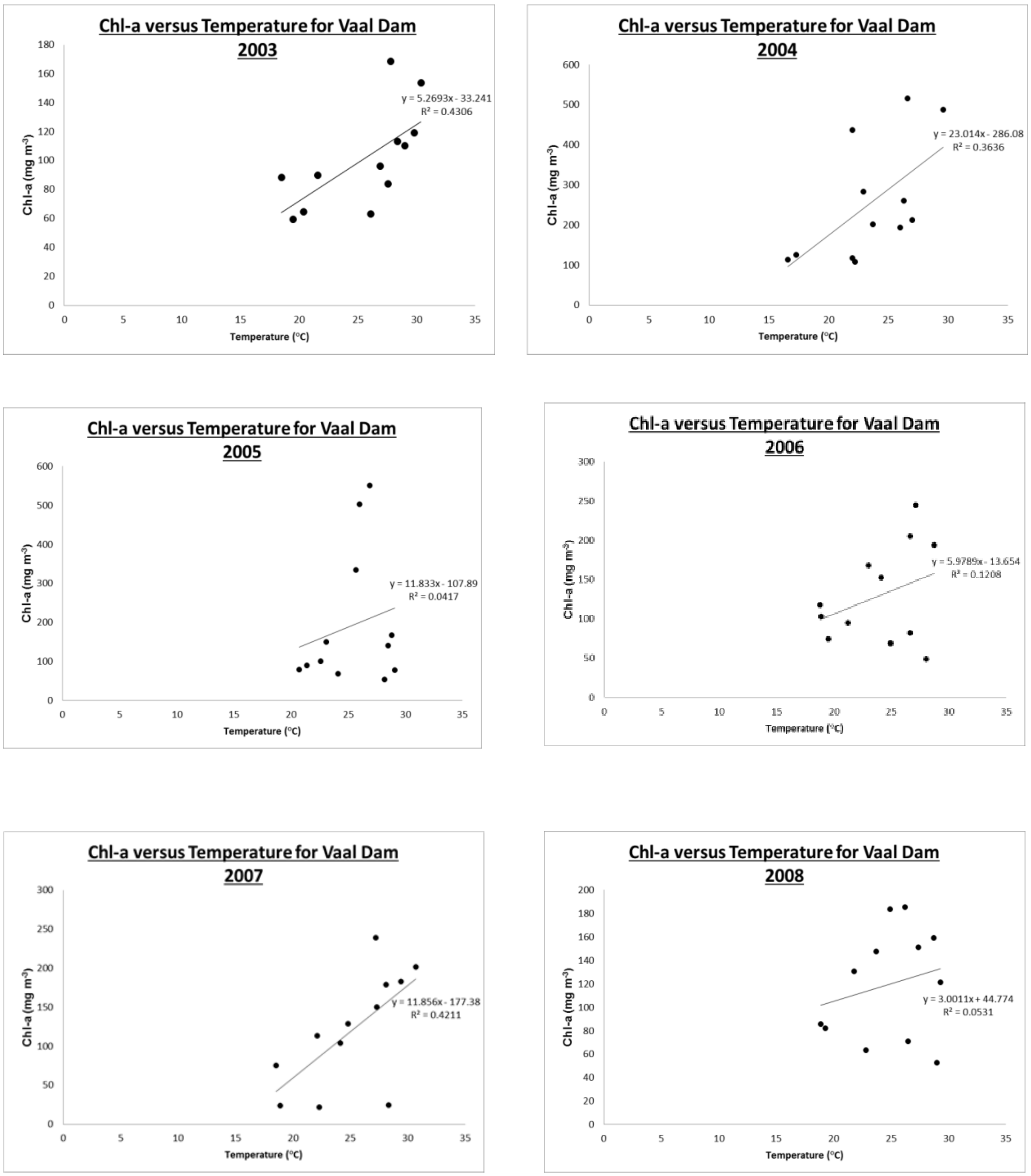


Figure 23: Scatter plot graphs of linear regression, showing the relationship between Chl-a and Temperature.

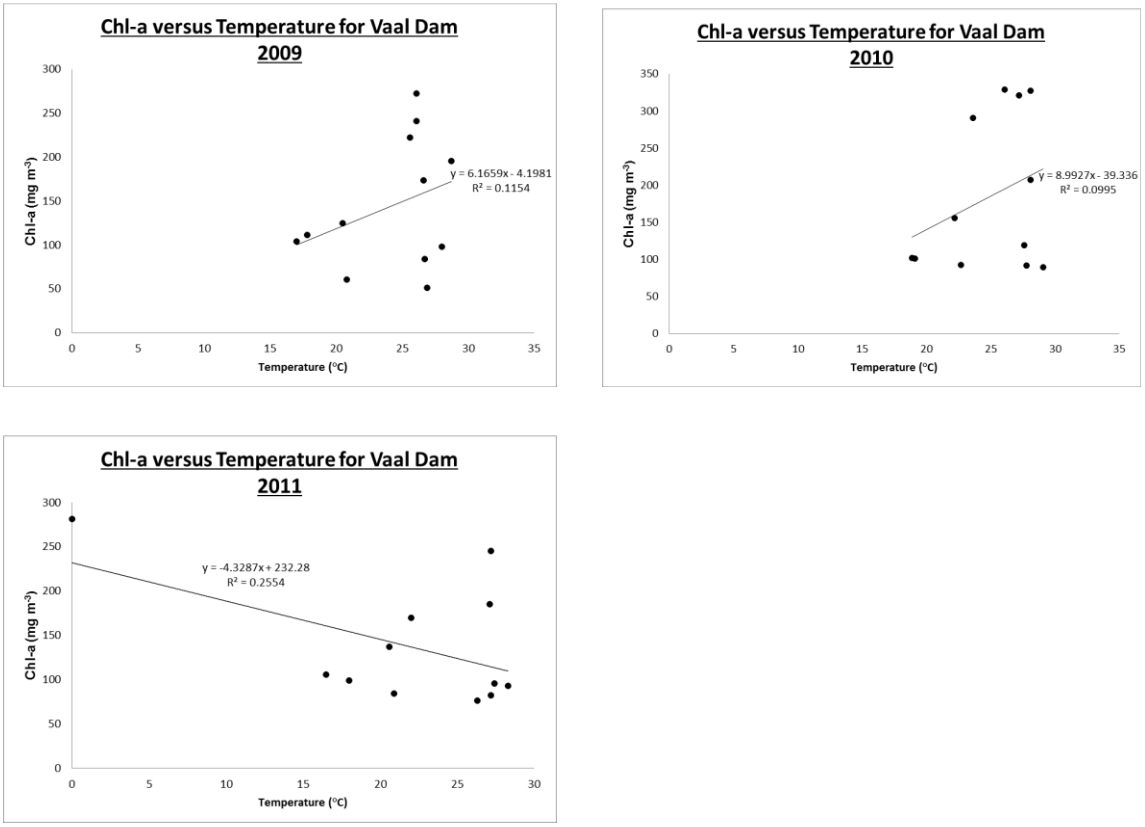


Figure 24: Scatter plot graphs of linear regression, showing the relationship between Chl-a and Temperature.

Table 11: Correlation results of Chl-a and maximum annual Temperatures for the Vaal region. Bold p-values indicate significant correlations at the 95% C.I.

YEAR	**r^2**	r	**P-value**	**N**
2003	0.4306	0.6562	**0.0205**	12
2004	0.3636	0.6030	**0.0379**	12
2005	0.0417	0.2043	0.5242	12
2006	0.1208	0.3476	0.2682	12
2007	0.4211	0.6489	**0.0224**	12
2008	0.0531	0.2304	0.4714	12
2009	0.1154	0.3397	0.2800	12
2010	0.0995	0.3154	0.3180	12
2011	0.2554	0.5054	0.0937	12

Presented in *Figure 24* the scatter plot graphs of linear regression, showing the relationship between temperature and Chl-a. The r correlation coefficient values from the scatter plots show a positive linear relationship between Chl-a and Temperature values. The graph also indicates higher temperature values also tend to have high Chl-a values.

Table 11 shows the correlation results of Chl-a and Temperature in the Vaal Dam. The N value represent the count, which is the number of months calculated in a year, which is 12. The r^2 value, which is the coefficient of determination, the r value which is the correlation coefficient and the p-value which represents statistical significance were calculated. The correlation that is statistically significant for the two variables is seen for the years 2003,2004 and 2007. The p values are less than 0.05 showing a statistically significant relationship. The rest of the years in the table do not show a statistically significant relationship between Chl-a and Temperature. The relationships were not significant for most years, the null hypothesis is accepted for those years.

Rainfall

Rainfall data was measures by the SAWS at the Deneysville station, which is situated close to the Vaal Dam. The graph of the rainfall data is presented in **Error! Reference source not found.**. The gaps in the data are a result of no rainfall occurring during the months of July and August. The Vaal area is a summer rainfall region. It experienced high rainfall that measured 250 mm in the year 2006 and 390 mm in the year 2010.

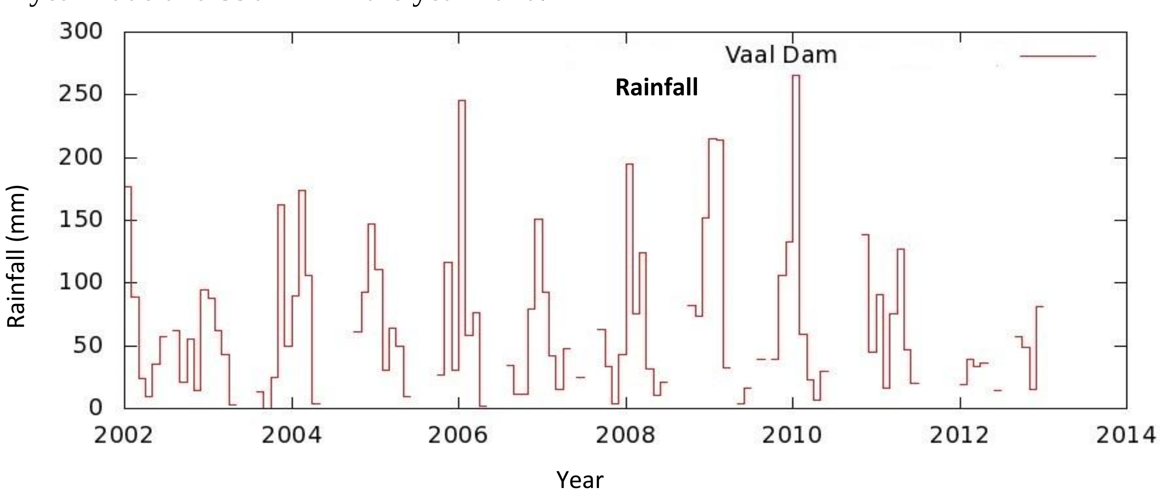


Figure 25: A graph of monthly averages daily rain in mm for Deneysville in the Vaal area.

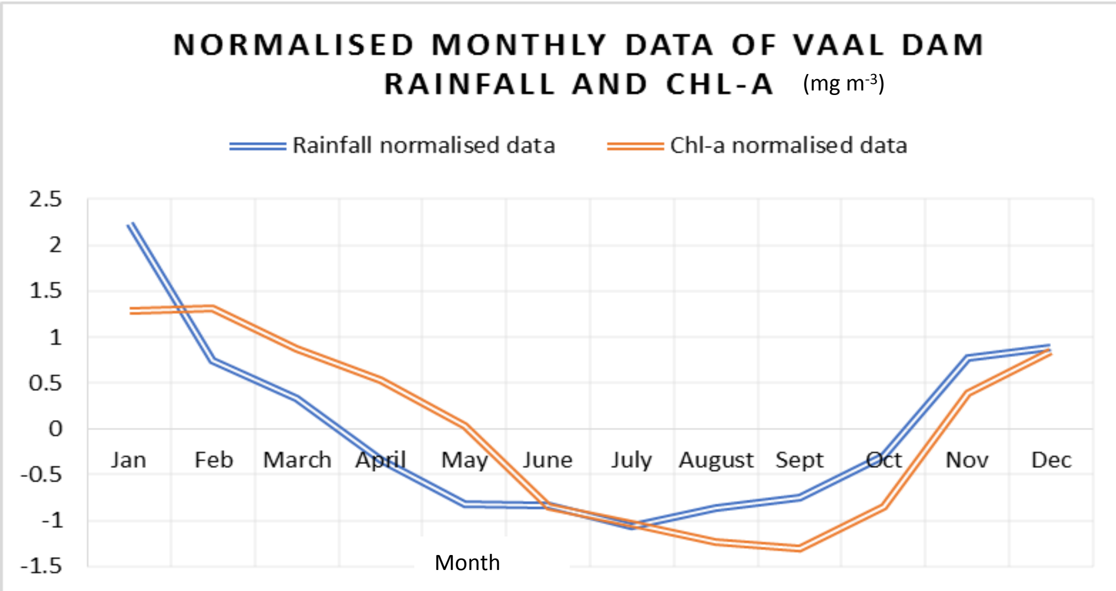


Figure 26: A graph of normalised Chl-a (mg m^{-3}) and rainfall (mm) monthly averages over the ten-year period.

To measure the degree of correspondence between rainfall and Chl-a, the normalized values of the monthly average were calculated and plotted on the same graph presented in *Figure 26*. The rainfall values decrease from January to June and the Chl-a values also decrease from January to June. The graph shows low rainfall values from the month of June to October. Both Chl-a values and rainfall begin to increase in the month of October to December. This indicates that low rainfall means low Chl-a values for the Vaal Dam.

Chl-a and Rainfall correlation results

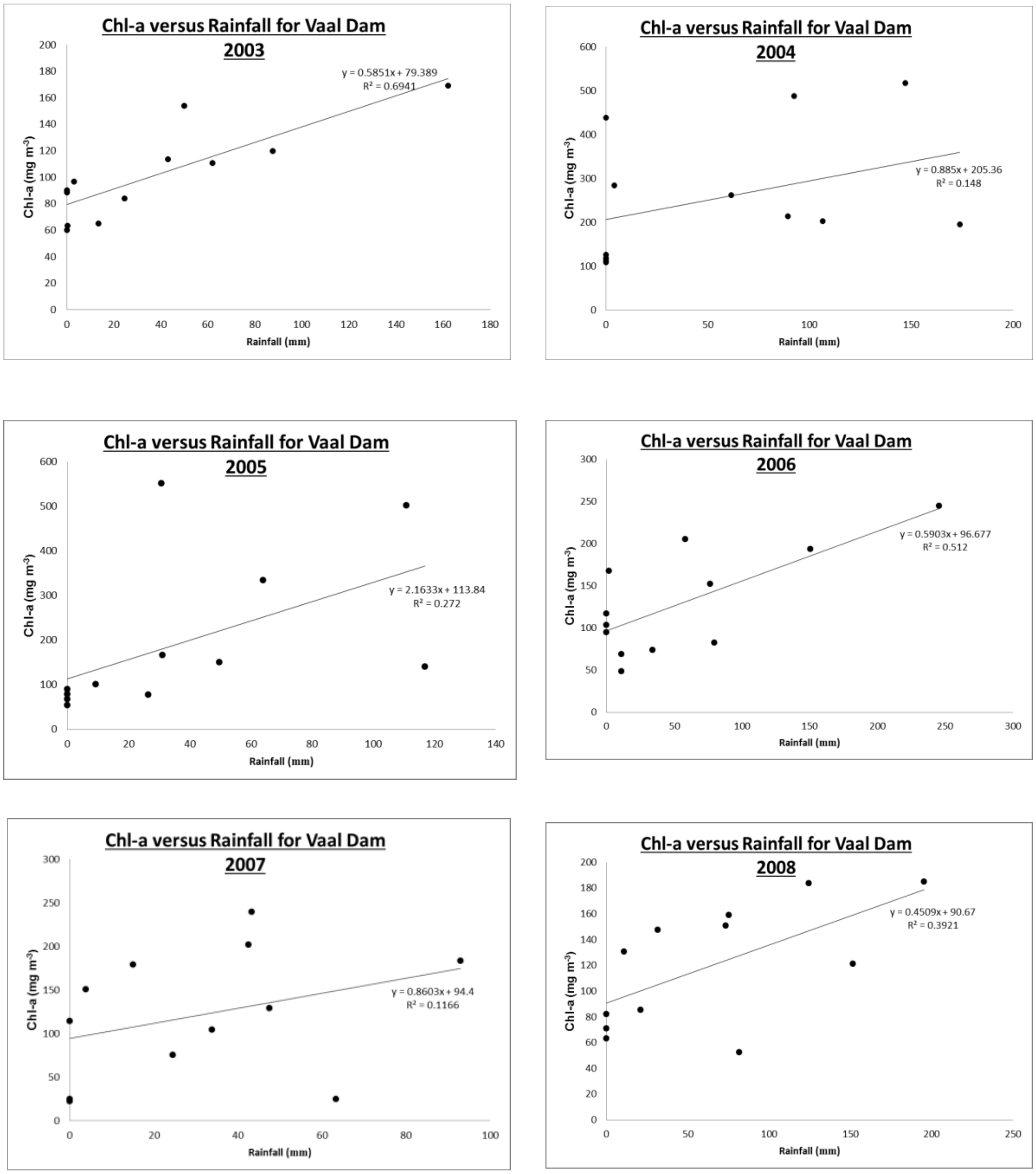


Figure 27: Scatter plots graphs of linear regression, showing the relationship between Chl-a and Rainfall for the Vaal Dam.

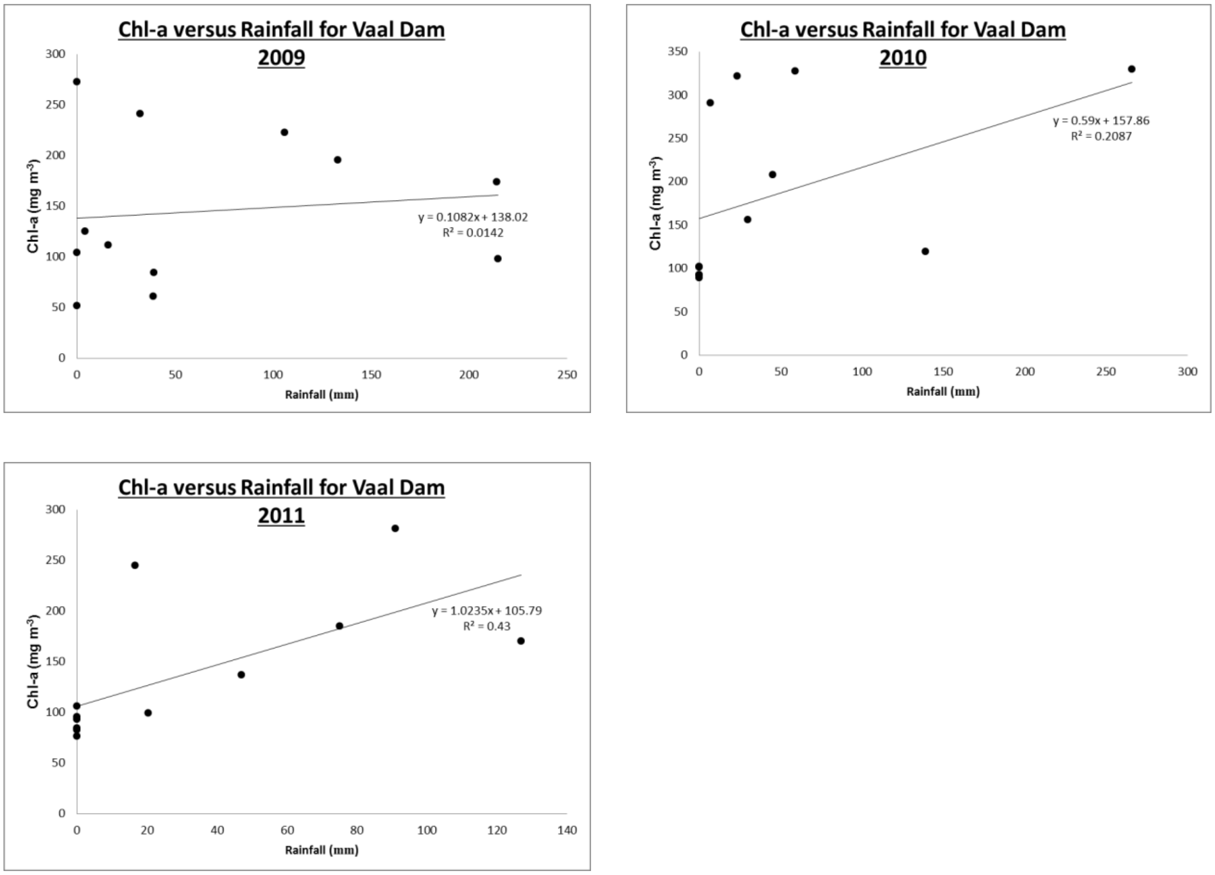


Figure 28: Scatter plots graphs of linear regression, showing the relationship between Chl-a and Rainfall for the Vaal Dam.

Presented in *Figure 28* are the scatter plots graphs showing the relationship between Chl-a and rainfall. The r values show a positive correlation between the two variables. Presented in Table *12* are the results of the correlation between rainfall and Chl-a. The p value represents the statistical significance of the relationship between the two variables. The relationship between rainfall and Chl-a is statistically significant for the year 2003, 2006,2008 and 2011, with the p values less than 0.05. The rest of the year show a relationship that is not statistically significant. The relationships were not significant for most years, the null hypothesis is accepted for those years.

Table 12: The results of the correlation between rainfall and Chl-a. The statistically significant relationships are shown in bold.

Year	**r^2**	**r**	**p-value**	**N**
2003	**0.6941**	**0.8331**	**0.000765**	**12**
2004	0.1480	0.3847	0.216951	12
2005	0.2720	0.5215	0.082035	12
2006	**0.5120**	**0.7155**	**0.008878**	**12**
2007	0.1166	0.3414	0.277283	12
2008	**0.3921**	**0.6262**	**0.02938**	**12**
2009	0.0142	0.1192	0.712558	12
2010	0.2087	0.4568	0.13543	12
2011	**0.4300**	**0.6557**	**0.020592**	**12**

Wind Speed

Presented in *Figure 29* is the graph showing the average wind speed for Vereeniging in the Vaal region. The results show that the area experienced strong winds in the year 2006 with average speeds up to 5.4 m/s. The weakest winds were experienced in the year 2003 and 2010 with average monthly windspeed less than 2.5 m/s. *Figure 30* is the graph showing the correspondence between wind speed and Chl-a using the normalized monthly average data of the two variables. The graph indicates that from the month of January to June low average wind speeds are experienced. The Chl-a values on are increasing from the month of January to June. This indicates that Chl-a measures higher during periods of lower wind speeds. The wind speed values start to increase in the month of August to November while the Chl-a values decrease because of mixing of nutrients and sediments in the water caused by higher wind speeds.

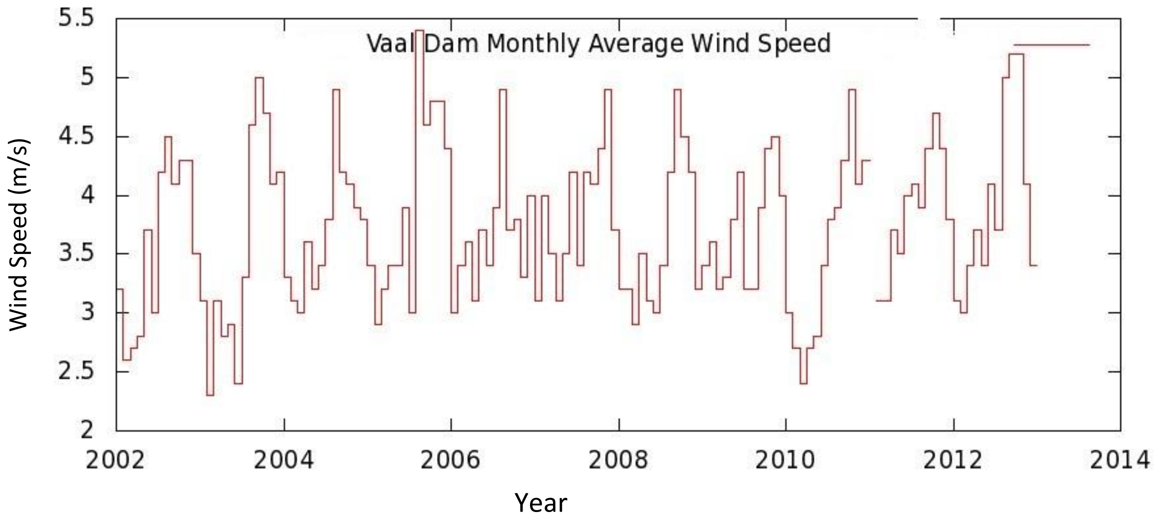


Figure 29:Graph showing average wind speed (m/s) for Vereeniging

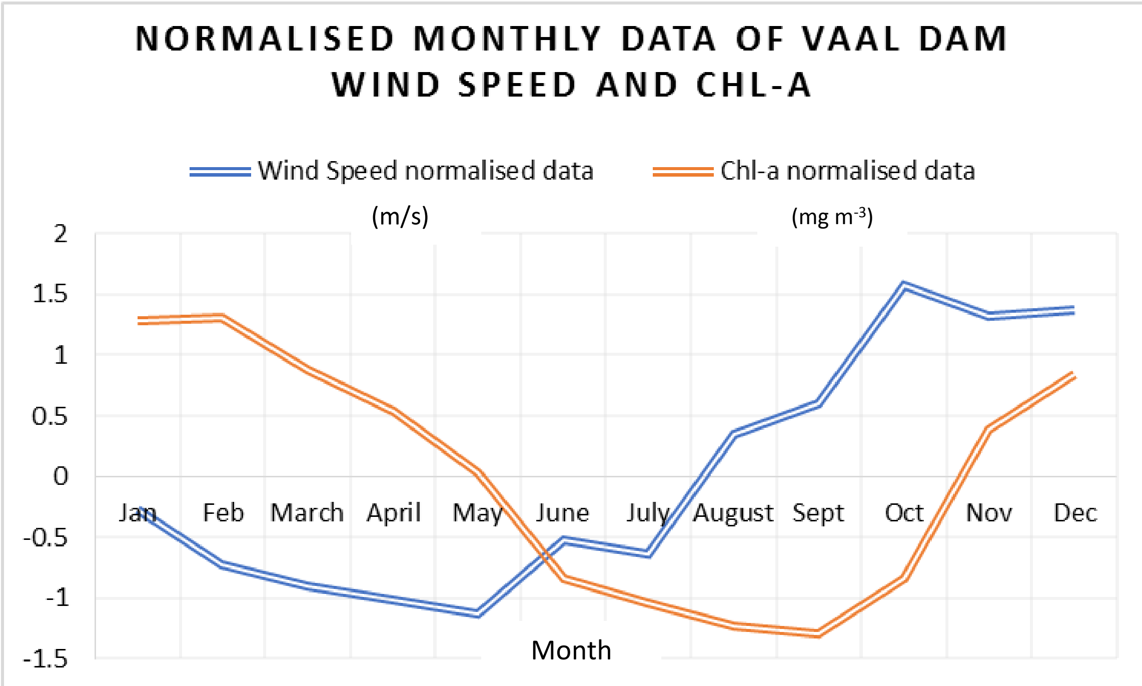


Figure 30: A graph showing normalised monthly averages of wind speed and Chl-a

Chl-a and Wind Speed correlation results:

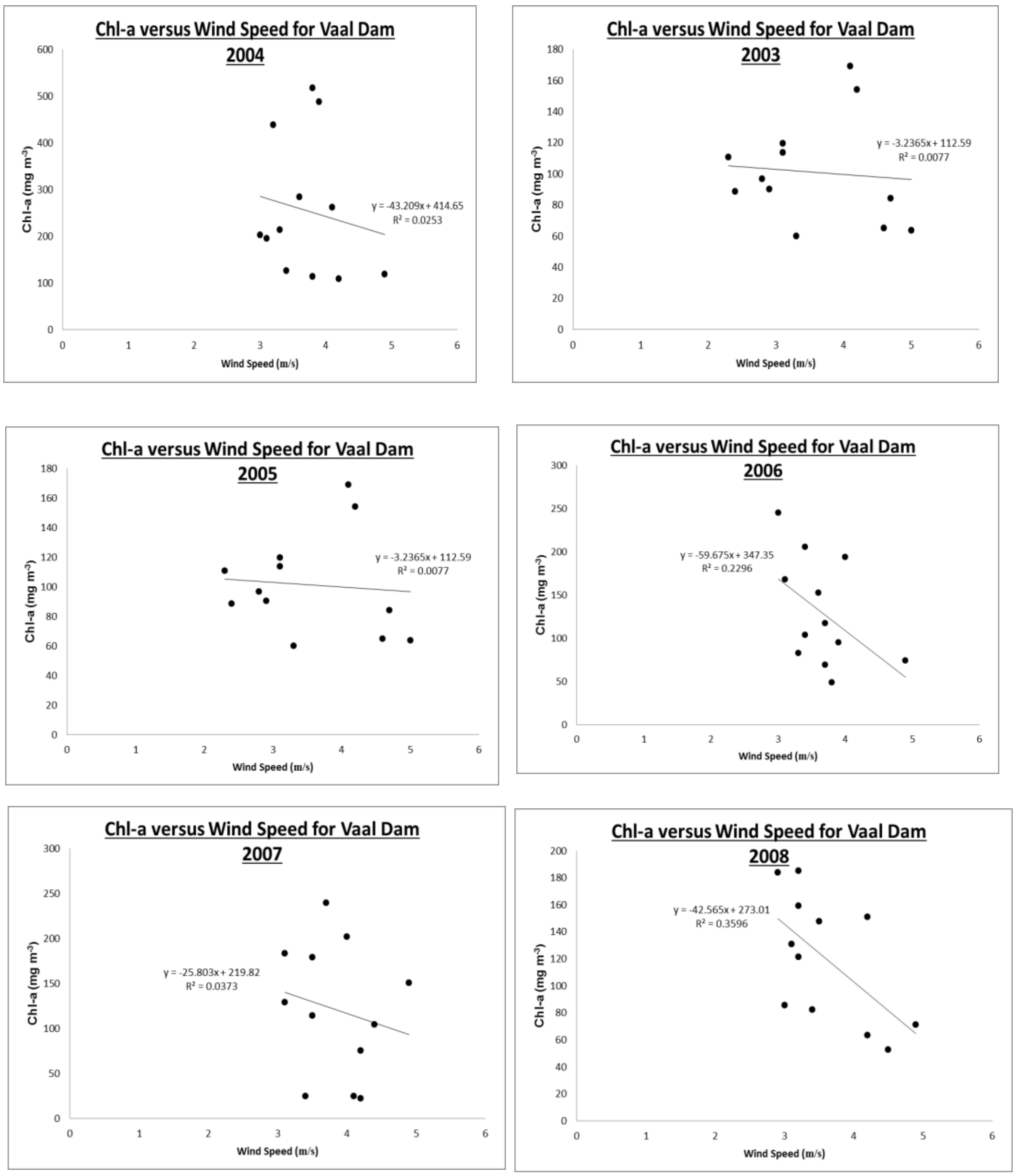


Figure 31: Scatter plots graphs of linear regression, showing the relationship between Chl-a and Wind speed for the Vaal Dam.

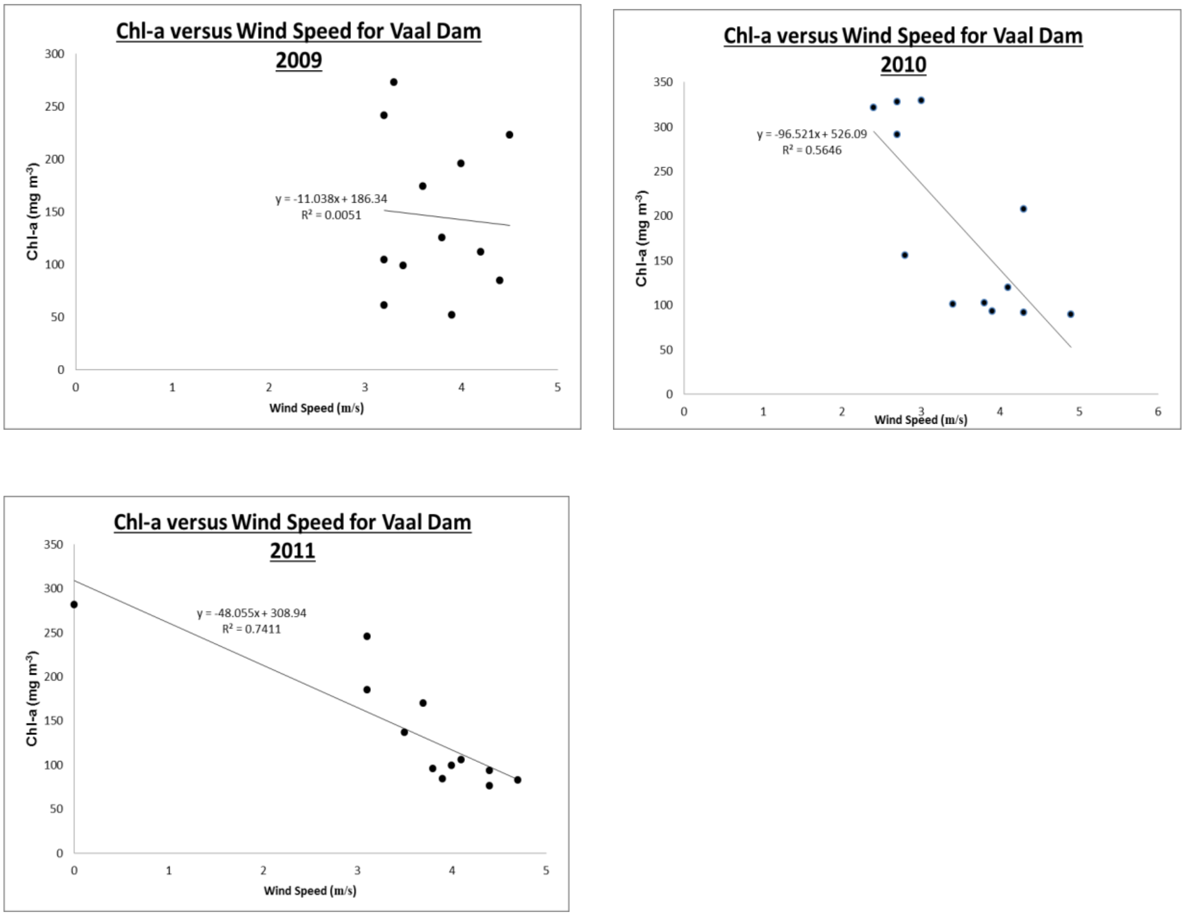


Figure 32: Scatter plots graphs of linear regression, showing the relationship between Chl-a and Wind speed for the Vaal Dam.

Plotted in *Figure 31* are the scatterplots graphs showing the correlation between Wind speed and Chl-a. The graphs show that low wind speed values have high Chl-a values. Presented in Table *13* are the results of the correlation analysis between Wind speed and Chl-a. The results of the correlation coefficient (r value) show a positive correlation between Wind Speed and Chl-a. The correlation is statistically significant for the year 2010 and 2011 where the p-value is less than 0.05. The relationships were not significant for most years, the null hypothesis is accepted for those years.

Table 13: The results of the correlation between Wind Speed and Chl-a

Year	r^2	r	p-value	N
2003	0.0077	0.0877	0.785779	12
2004	0.0253	0.1591	0.621654	12
2005	0.3145	0.5608	0.057835	12
2006	0.2296	0.4792	0.114968	12
2007	0.0373	0.1931	0.547821	12
2008	0.3596	0.5997	0.785779	12
2009	0.0051	0.0714	0.824666	12
2010	**0.5646**	**0.7514**	**0.004839**	**12**
2011	**0.7411**	**0.8609**	**0.000324**	**12**

A Comparison between the climate variables (temperature, rainfall and wind speed) with Chl-a.

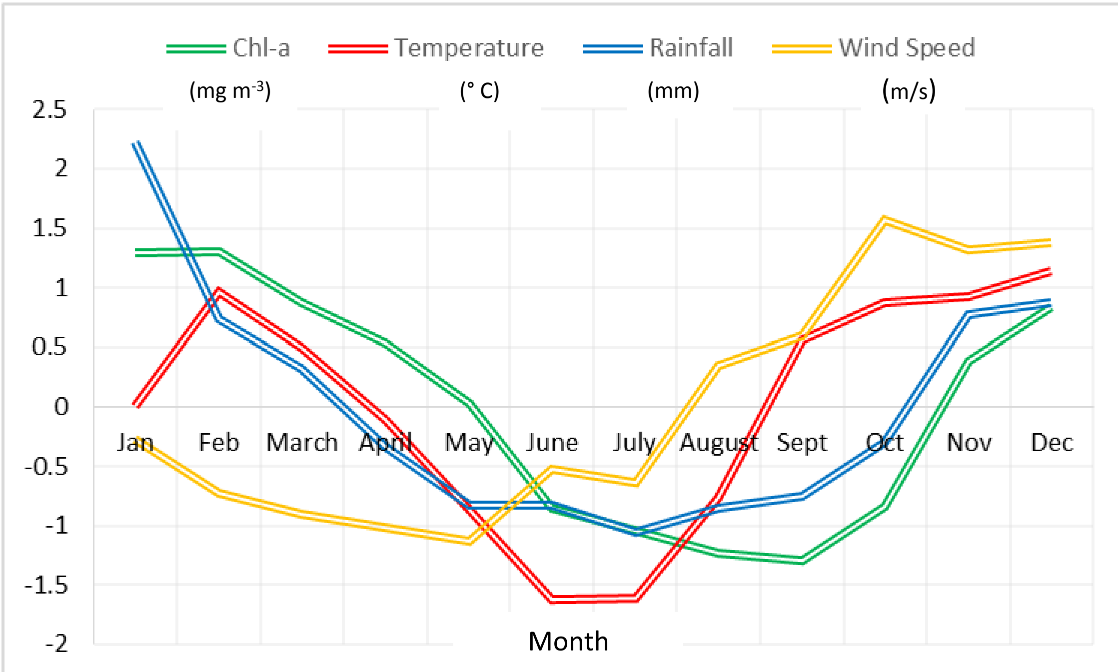


Figure 33: A graph showing a comparison of normalised Chl-a, Temperature, Wind Speed and rainfall monthly data

To determine the correspondence between Chl-a and climate variables, normalized monthly values of temperature, rainfall and wind speed were plotted against normalized values of Chl-a and presented in *Figure 33*. The Chl-a values (marked in a green marker) are showing to decrease as the rainfall and temperature are also decreasing, and at low wind speed. The temperature, wind speed and rainfall values seem to increase from the month of August, while the Chl-a continues to decrease and only increases in the month of September. This could indicate that the Chl-a does not react immediately to the change of the climate variables but there exists a lag between climate and the response of phytoplankton within the Dam.

5.4. In-situ validation results

Table 14 : The mean, median and standard deviation of satellite and in-situ Chl-a estimates measured in mg.m^{-3}. The in-situ measurements are presented in brackets.

	Mean	**Median**	**Standard deviation**
Vaal Dam 1	124.89 (13.95)	102.05 (7.95)	129.55 (16.94)
Vaal Dam 2	139.24 (18.04)	76.60 (11.50)	193.52 (22.33)
Vaal Dam 3	183.76 (37.93)	118.75 (12.50)	166.71 (3.60)
Vaal Dam 4	262.59 (90.34)	123.30 (33.00)	293.08 (130.80)

Table 15: Linear regression statistics for matchups of in-situ and satellite Chl-a estimates. Count=n, coefficient of determination = r^2, correlation coefficient= r, slope=m, intercept=c, p-value=p. RMSE values are represented in mg m-3, MAPE is represented in %.

Sampling Point	n	r^2	r	m	c	p	RMSE	MAPE
Vaal Dam 1	*14*	*0.5*	*0.707*	*5.41*	*49.33*	0.0045	1.28	22.35
Vaal Dam 2	14	0.01	0.1	-0.75	152.87	0.76	1.26	19.61
Vaal Dam 3	*14*	*0.46*	*0.678*	*2.07*	*105.22*	*0.008*	1.13	13.60
Vaal Dam 4	*13*	*0.42*	*0.648*	*1.44*	*132.00*	*0.017*	1.02	11.79

Presented in Table *14* and Table *15* and plotted in *Figure 34* and *Figure 35* are the results for the matchups between satellite and in-situ data. Four sample points located within the Vaal Dam were selected for the analysis. The relationship between in-situ data and satellite was shown to be statistically significant by the linear regression analysis performed. Three out of the four sample points that were measured showed a positive linear correlation. Table *15* shows the linear regression statistics between in-situ and MERIS satellite data. The correlation coefficient (r) at Vaal Dam point 1 is r = 0.707, Vaal Dam point 3 is r= 0.678 and Vaal dam point 4is r= 0.648 shows a positive strong relationship. Vaal Dam point 2 shows a positive weak relationship with values of r= 0.1. Sample point Vaal Dam 2 has a p-value of 0.76 which shows the relationship to not be statically significant. This could be a result of various factors, such as the satellite image and in-situ data were collected on the same day, but different times, or human error when collecting the in-situ results. The p-values for the correlation were statistically significant at Vaal Dam point 1, 3 and 4 with the values being 0.0045; 0.008 and 0.017 respectively. Therefore, the relationship between in-situ data and satellite is statistically significant.

The comparison of the Chl-a mean, median and standard deviation of the in-situ versus satellite is presented in Table *14*. Sample point Vaal Dam 1 the mean satellite estimate is 124.89 mg m^{-3} versus for 13.95 mg m^{-3} for in-situ. At sample point Vaal Dam 2 the satellite estimate is 139 mg m^{-3} while the in-situ estimate is 18.04 mg m^{-3}. The overall observation as shown in Figure *35* is that satellite estimates are higher than the in-situ results. This could be a result of various factors such as the how the in-situ data grab samples were collected and at what depth the sample was collected. Mixed waters because of wind or other factors also affects the output results of both in-situ and satellite measured. Because of mixing, the in-situ water samples measured from near the water surface will have higher concentration than the equivalent concentrations at a deeper depth of the water column. The satellite results have a higher Chl-a measurement most likely because of high concentrations of suspended illite clay. The highly scattering clay particles produce enlarged reflectance values that are detected by the satellite in a similar way to phytoplankton scattering signals. Therefore, this affects the output measurements being taken by the satellite for Chl-a. All these factors that affect the output of the results will be further explained in the following discussion chapter.

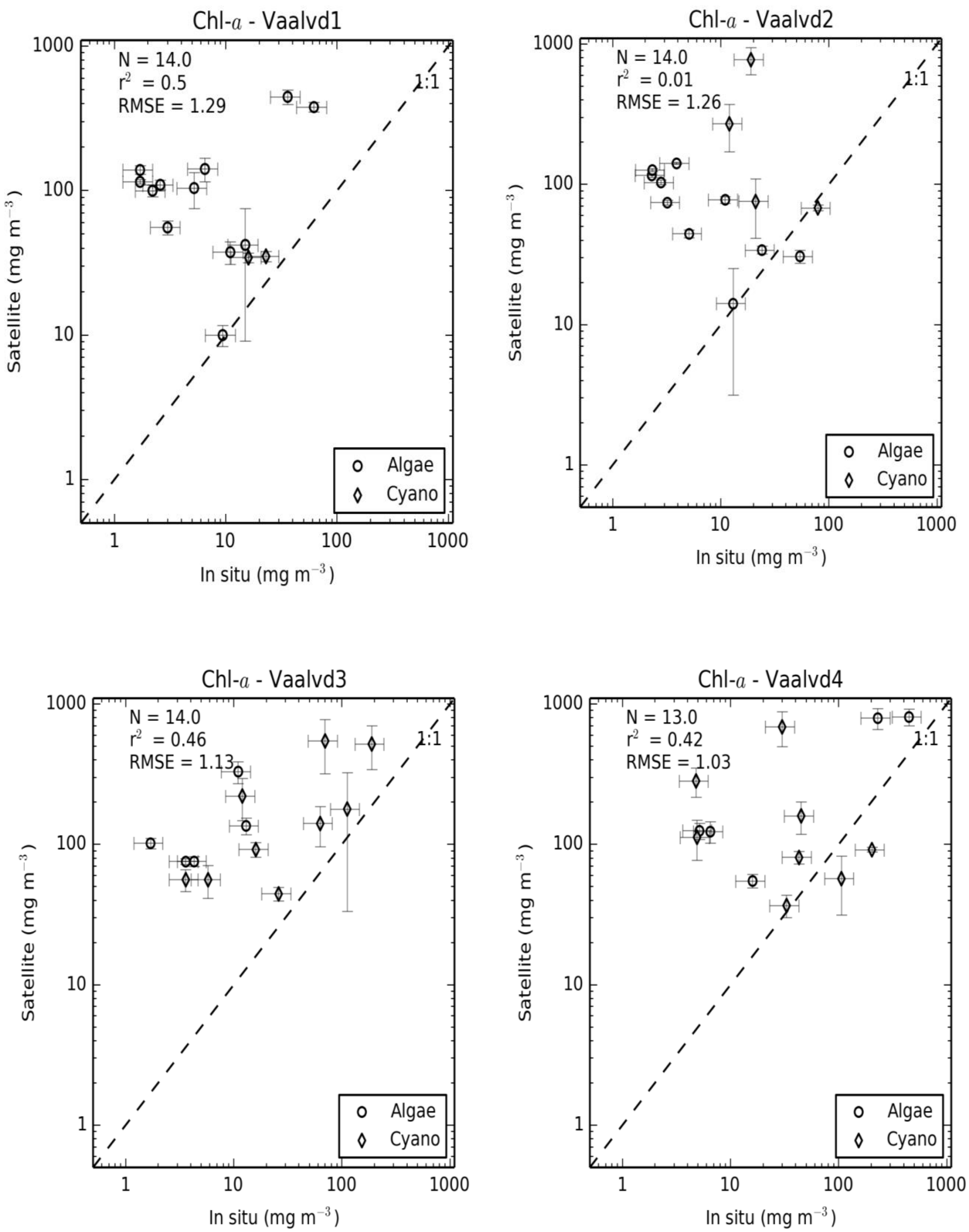


Figure 34: Scatter plots of in-situ versus satellite estimated for the four sampling points located within the Vaal Dam. The Algae is represented in circles and cyanobacteria in hexagon shape. The dotted line represents the 1:1 fit.

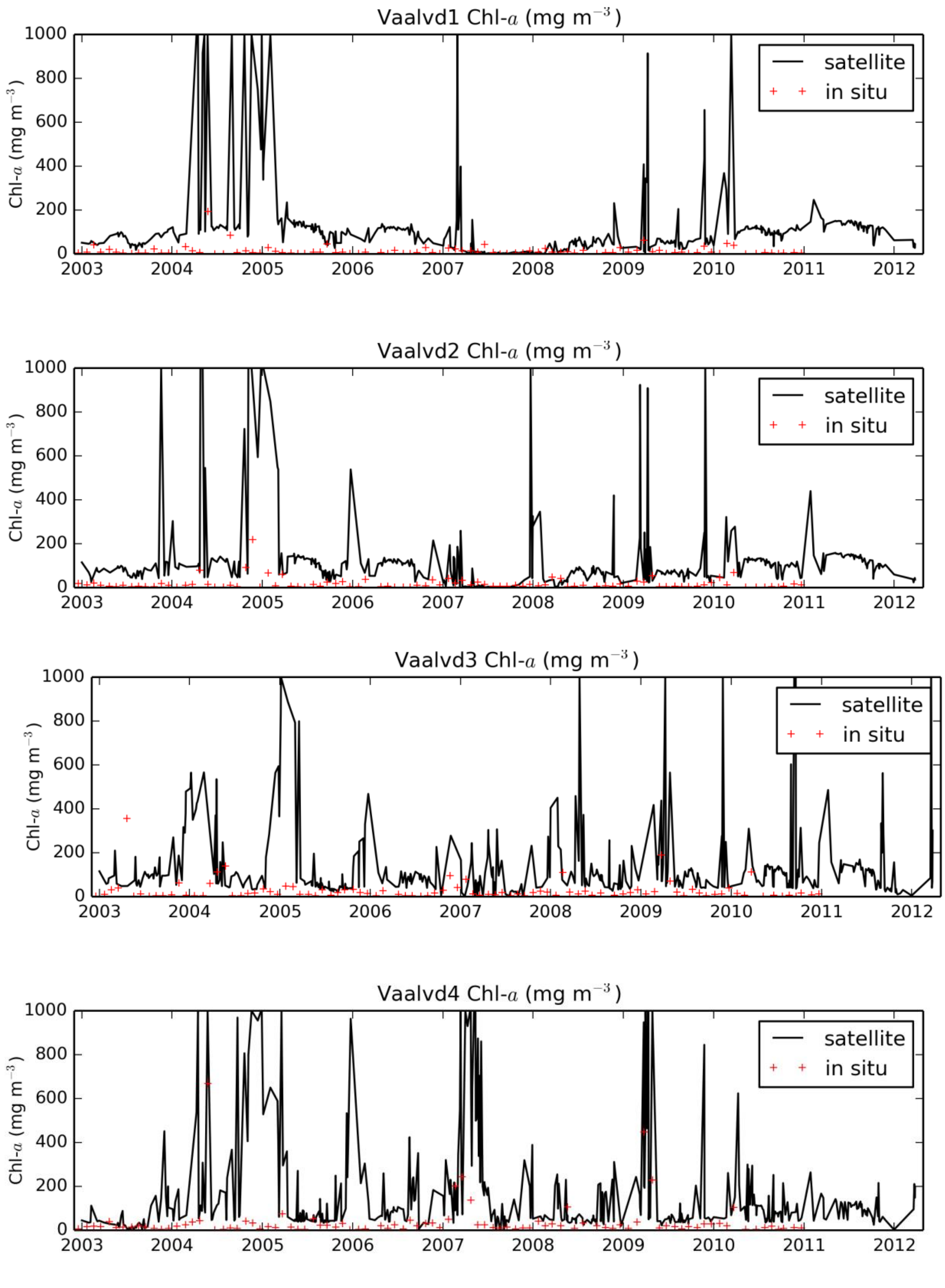


Figure 35: A time series of in-situ versus satellite Chl-a estimates over a ten-year period (2002-2012). The satellite values are represented by a solid line and in-situ values in red stars. The satellite values were acquired from images of similar day to in-situ.

6. CHAPTER SIX: DISCUSSION

6.1. Time series discussion

Trophic status and cyanobacteria blooms

The minimum Chl-a values during the 10 years occur in the year 2007 during the months of July, August and September, having the following values 24 mg^{-3}, 22 mg^{-3} and 25 mg $^{-3}$ respectively However trophic status of the dam still classified as eutrophic, according to trophic indicators discussed in *Table 1*. A high peak in Chl-a values is observed for the year 2005. High Chl-a values were observed during the months of January, February and March with the following values respectively 503 mg^{-3}, 551 mg^{-3} and 334 mg^{-}3. The high peak in Chl-a values are similar to the observations of the data collected by the Rand Water. These results classify the Vaal Dam as a hypertrophic system. The results of previous research studies, (Chinyama, et al., 2016; Harding, 2008) based on the total lake phosphorus and nitrogen concentrations, classified the Vaal Dam as being eutrophic system.

The seasonality of Chl-a concentration and Cyanobacteria cover percentage values derived from MERIS satellite images were both normalized and plotted in Figure 15. Chl-a increases from the month of January to March, which are the summer months. The percentage cover of cyanobacteria is also observed to increase during the summer months. The Chl-a concentration shows a decrease in values from Autumn to the winter months, while the cyanobacteria percentage cover starts to decrease from (May to August). September marks the beginning of Spring and temperatures begin to rise, the Chl-a concentration values also begin to increase, together with the cyanobacteria percentage cover.

The trend for Chl-a yearly averages are summarized in *Table 7*. The Chl-a correlation is r = 0.28, which shows a negative weak correlation. The Chl-a anomalies r value is -0.1 which is also a negative weak correlation. The Chl-a yearly average trend and Chl-a anomalies trend are both negative trends with Chl-a at 4.1 mg m-^{3}.y-^{1} and Chl-a anomalies at -3.6 mg m-^{3}.y-^{1}. A summary of the trend statistical results is shown in Table 7. The significant trend is for the Chl-a anomalies, whereby the absolute t-value is greater than the t-significant value. The rest of the calculated results are not significant at the 95 %. confidence interval.

The satellite images results show Cyanobacteria blooms were present within the dam, with percentage coverage ranging from minimum of 12 % experienced in year 2007, and maximum of 34 % cover in 2005. The dam is usually covered by *Microcystis* and *Anabaena* cyanobacterial blooms and surface scum conditions on a regular basis with medium coverage (Chinyama, et al., 2016). This is verified by the satellite images. Scum conditions covered a small surface percentage area of the dam. The percentage area for scum appeared as less than 25 % over the study period.

6.2. Correlation Analysis discussion

6.2.1 Nutrients

The study investigated whether the nutrients phosphorus and nitrogen are the limiting nutrient for algal growth and therefore controls the primary productivity in the dam. The monthly mean values of Nitrogen were correlated to the monthly mean of Chl-a. The linear regression analysis results showed a weak positive correlation between the two variables and the p-value results was calculated ranged close to 0, resulting in the correlation that is statistically significant. The same method of linear regression was applied to determine the correlation between phosphorus and Chl-a. The results indicate a weak positive relationship between phosphorus and Chl-a, the p-values also indicate there is typically no statistically significant relationship between phosphorus and Chl-a. Therefore, there is a statistically weak positive relationship between Chl-a and P and N nutrients. It would appear that the concentrations of nutrients are high enough to be non-limiting and are therefore not the primary factors regulating the phenology and occurrence of the blooms. However, 2003 was the only year which showed significant correlation between Chl-a and the nutrients. The hypothesis is that when you look at the climatic variables in 2003, the Vaal Dam area experienced a low rainfall for the year with an average of 150mm. Low rainfall result into low flow rates, in that way increasing the residence time of nutrients inland waters. Increased residence time increases intensification possibility of algae, increasing the settling rate of sediments and decreasing water column sediment concentrations. Turbidity is also reduced, and the light penetration increases which creates good conditions for algae growth.

TN: TP ratios analysis

The study further applied another method of using ratios to analyze the relationship between nutrients and Chl-a. The ratio of nitrogen to phosphorus was calculated to determine which one is the limiting nutrient within the Vaal Dam. TN and TP concentrations are indicative of available N and P to support algal growth. The results indicate ratio values were less than 7 from the year 2002-2006. This indicates nitrogen as the limiting nutrient during those years. This implies that in the Vaal Dam system all nitrogen nutrients get depleted first, subsequently leaving phosphorus as a surplus in the system Phosphorus dominance directly translate to cyanobacteria abundance which denotes that cyanobacteria productivity succeeds through nitrogen fixation, contrary to other algae. Water systems that have low nutrient concentration are normally phosphorus limited. When the eutrophication increases, nitrogen limitation become evident and the reservoirs that have hyper eutrophication are all limited by nitrogen (Toerien, et al., 1975). The Vaal Dam system changed in 2007 to 2012 where it was not limited by either N or P. This implies that either of the nutrients P or N can dominate in the system

.

6.2.2 Climate Variables

To understand what the drivers of Eutrophication in the Vaal Dam the study conducted a correlation analysis between Chl-a and the following climate variables: temperature, rainfall and wind speed.

Chl-a and temperature

Various studies have shown that there is a relationship between the growth of phytoplankton and water temperature (Paerl & Fulton, 2006). Increasing air temperatures influence water temperature, physical and chemical properties of the water (Paerl & Huisman, 2009). Using the temperature data collected from SAWS and Chl-a from MERIS satellite for the 10-year period, the study normalized both the datasets values so that they can be directly compared against each another (*Figure 22*). During the summer months the temperature increases and so does the Chl-a values. When the temperature decreases, the Chl-a values also decreases. Increasing temperatures also has direct effects on cyanobacterial growth rates. Cyanobacteria can take advantage of warming, while the growth rates of other phytoplankton taxa decrease over 20°C (Reynolds, 2006).

The study further demonstrates this by conducting a linear regression analysis to determine the value of the correlation coefficient r, with scatter plot diagrams presented in *Figure 24*. The r shows a positive linear relationship between Chl-a and Temperature values. The graph also indicates higher temperature values also tend to have high Chl-a values. Thus, temperature is identified as one of the drivers increasing eutrophication in the Vaal Dam.

Chl-a and Rainfall

The study investigated the effect of rainfall on eutrophication in the Vaal Dam. The results from the linear regression analysis between Chl-a and rainfall data *Table 12* show that r value of show a positive correlation between the Chl-a and rainfall. The normalized data graph *Figure 26* of rainfall and Chl-a show that the rainfall values are high in January and decrease towards the month of June. On the other hand, the Chl-a values are also high in January and decrease towards June. The graph shows low rainfall values from the month of June to October. Both Chl-a values and rainfall begin to increase in the month of October to December. This indicates that low rainfall in the Vaal area means the Chl-a values for the Vaal Dam also become lower. Therefore, it appears that rainfall does significantly affect the blooms in the dam. A possible explanation to this is that when there is low rainfall, there are less nutrients entering the dam from water runoff. Less contaminants result into less P and N nutrients entering the dam, the eutrophication would decrease and there will be low Chl-a values. The study conducted by (Hickey & Salas, 1995) explain this phenomenon better by explaining that eutrophication becomes affected by high rainfall, because floods can increase contamination and introduce sediments from agricultural and urban runoff into the dam.

Chl-a and wind

The study investigated the possibility of wind being one of the drivers of eutrophication in the Vaal Dam. Wind energy plays a very important role in freshwater systems as it can influence the chemical and physical forces of freshwater. The wind speed measurements were plotted on a graph to indicate the periods of high and low winds *Figure 29*. The graph indicates that from the month of January to June low wind speed is experienced while the Chl-a values are increasing from the month of January to June. Low wind speeds promote water stability and enables cyanobacteria to gather at the water surface to form blooms (Cao, et al., 2006). This is the reason why the Chl-a values are higher during periods of low speeds. Low wind speed of approximately 3-4 m/s are best for *Microcystis* to gather at the water surface (Cao, et al., 2006). Low wind speeds are therefore advantageous for buoyant *Microcystis* to gather on the water surface. Hence decreasing vertical turbulent mixing may move the competitive balance in support of the buoyant cyanobacteria, increasing the formation of cyanobacterial blooms (Jo¨hnk, et al., 2008).

The collected data also supports the statement which is being observed on the scatterplot graphs in *Figure 31*. The scatterplots showed that as the wind speed is inversely related to Chl-a. The results of the correlation coefficient and the scatter plots graphs show a statistically significant negative relationship between wind speed and Chl-a. The wind speed begins to increase in the month of August to November while the Chl-a values seem decrease during those months. High wind speed promotes mixing of nutrients and sediments within water. When the water is mixed at the surface the measurements taken will be lower than those taken in still water environment where there are low winds. High wind speed also pushes the cyanobacteria in the direction of the wind and causing them to accumulate at the shore, promoting the development of scum. When the Chl-a value is measured at that specific spot where the cyanobacteria has gathered, the values will be high. This indicates that wind speed also plays a role in the spatial distribution of Chl-a across the dam.

A summary table of the correlation of climate variables and eutrophication in the Vaal Dam is presented in the table below:

Table 16:Sumary of correlation between climate variables and Chl-a.

Chl-a and Temperature	Chl-a and rainfall	Chl-a and wind speed
High Temperatures = High Chl-a	High rainfall = High Chl-a	High wind speed = Low Chl-a
Low Temperatures = Low Chl-a	Low rainfall = Low Chl-a	Low wind speed = High Chl-a

6.3. In-situ validation

The study conducted a matchup analysis between Chl-a MERIS satellite data and the Chl-a data measured in-situ. The matchup results show that there is a weak but significant positive correlation between in-situ and MERIS satellite measurements. The relationship between in-situ data and satellite was proved to be statistically significant by the linear regression analysis. Three out of the four sample points that were measured showed a positive linear correlation. The matchup results show that that MERIS satellite estimates are higher than the in-situ results. There are several factors that can contribute to this outcome such as the method and the sample depth used to collect in-situ data.

The water clarity in the Vaal Dam is turbid and was dominated by cyanobacteria species *Anabaena* and *Microcystis* for the period 1990 to 2000 (Downing & Van Ginkel, 2004). Studies by (Birch, 1983) also show that the Vaal Dam also has a high component of illitic clay minerals which increases the turbidity of the water. The satellite results tend to overestimate Chl-a because of the high concentrations of illite. The Vaal Dam has high percentage highly scattering illitic clay minerals (Birch, 1983). The high reflectance properties are detected by the satellite in a similar manner to scattering from cyanobacteria at the surface.

It is important to know what the inherent optical properties (IOPs) of the water constituents in the Vaal Dam are that affect the remote sensing signal. Many of the inland freshwater (case 2 waters) systems are optically complex systems. The IOPs normally refer to the absorption coefficient and the volume scattering function, which when combined over the backward hemisphere gives the backscattering coefficient, and when integrated over both hemispheres gives the scattering coefficient. The total absorption and backscattering coefficients of the water can be calculated as the sum of the respective coefficients of each of the optically significant elements. These are subdivided into living phytoplankton, dissolved organic matter described to as *gelbstoff*, and non-phytoplankton particles described to *tripton*, which includes minerals and debris. In this case, the illite clay component is the dominant optical contributor, followed by the cyanobacteria.

The dam is also affected by moderate to strong winds, that were measured up to 5.4 m/s which means that the water is generally well-mixed. The above mention factors affect the measurements taken using the satellite or in-situ methods and can lead to either over- or under-estimating the Chl-a concentrations. During windy conditions, in-situ measurements from water samples taken near the water surface are likely to have lower concentration than the matching concentrations at depth, and that measured from satellite will be lower. Conversely, during still conditions (senescence) cyanobacteria collect at the surface leading to a tendency to overestimate the Chl-a concentration with satellite, while surface grab samples can often underestimate Chl-a during scum conditions due to sampling procedures that disturb the surface blooms. This can explain at least partially some of the disagreement between the in-situ and satellite observations.

6.4. Summary of the correlation analysis results

Table 17:Summary of Correlation analysis between Chl-a and different variables

Summary of Correlation analysis between Chl-a and different variables				
Variable	**Average correlation coefficient (r)**	**Direction of influence**	**Average p value**	**Significance**
Total Nitrogen	0.22	Positive weak correlation	0.45	Statistically not significant
Total Phosphorus	0.28	Positive weak correlation	0.44	Statistically not significant
Temperature	0.43	Positive moderate correlation	0.23	Statistically not significant
Rainfall	0.52	Positive moderate correlation	0.16	Statistically not significant
Wind	0.42	Positive moderate correlation	0.42	Statistically not significant

The statistical significance was calculated at 95% confidence level. The only statistically significant results for the correlation is when the p value is less than 0.05.

7. CHAPTER SEVEN: CONCLUSION AND RECCOMENDATIONS

The Vaal Dam has proved to be an ideal study area for monitoring eutrophication using the applications of remote sensing and geographic information systems. The findings of these study present alternative methods for improving monitoring eutrophication in other dams with similar water quality problems. This can be done by following the application of techniques similar to the ones used in this study.

Satellite remote sensing data must be use together with ground in-situ methods to fully monitor the state of eutrophication in the Vaal Dam. Satellite remote sensing produces a lot of data depending on the temporal resolution of the satellite over the dam. For the data to be meaningful it must be transformed into information. This research presented three useful methods of changing data into useful information by applying time series analysis methods, statistical analysis methods and GIS and remote sensing methods.

The aim of the research is to monitor eutrophication within the Vaal Dam using satellite remote sensing methods, and it has been successfully achieved. MERIS is well-suited for monitoring eutrophication and cyanobacterial algal blooms in inland waters. Monitoring eutrophication using remote sensing satellite methods produces a large amount of data. Satellite remote sensing helps us to obtain data on the current eutrophication status in the dam using current sensors such as OLCI on board Sentinel-3A and 3B satellites, but because of the frequent monitoring period, it generates large amount of data. This results into being data rich but information poor. Therefore, the data must be further processed and analysed for it to be converted into useful information. Analysing data derived from satellite images using the above-mentioned methods, will help alleviate the situation of being data rich but information poor.

The following conclusions may be made concerning the four project objectives:

1. **To determine the trophic status, seasonality and trends of Chl-a, an indicator of eutrophication and cyanobacteria blooms in the Vaal Dam.**

   The average values and trends for Chl-a, cyanobacteria area coverage and surface scum, were presented for the ten-year period, between 2002 and 2012. The overall trend showed a decreasing Chl-a over the entire time series.

   Analysis of the averages between the years showed that the Vaal Dam trophic status classifies as eutrophic and at other years hypertrophic. The study was able to show the event that led to an increase in Chl-a values, which was observed in the year 2005. The event was detected from using MERIS satellite imagery and by the in-situ data that was collected by Rand Water. This was observed in a timeseries of Chl-a presented in Figure 13 and *Figure 14* seasonal cycle of the Vaal Dam has shown the maximum values of Chl-a are experienced during the summer months.

   This study has therefore demonstrated that time series of satellite-based Chl- a estimates are a useful tool for monitoring eutrophication over a period of years.

2. **The second objective of the study was to determine the main drivers of eutrophication within the Vaal Dam. This was done by determining a relationship/correlation between Chl-concentrations and nutrients i.e. total Nitrogen, total Phosphorus and cyanobacteria in the Vaal Dam**.

   Statistical methods were applied on the Chl-a data derived from MERIS satellite. Linear regression methods were applied to determine the correlations between Chl-a and Total phosphorus, and Chl-a and Total nitrogen. The p-values results were not statistically significant for Chl-a against phosphorus, and Chl-a against nitrogen. Therefore, the results indicated that neither Total phosphorus and Total nitrogen are correlated to Chl-a in the water system.

The study also applied another method of analysing nutrients data in the Vaal Dam. Total phosphorus and Total nitrogen ratios were advantageous for determining which nutrient is the limiting agent in the Vaal Dam, and to inform which is nutrient is driving eutrophication within the dam. The study has determined the limiting nutrient from the year 2003 to 2007 to be nitrogen. The system changed in 2007 to 2012 where it was not limited by N or P. When the the limiting agent is known in a system, the results are used to inform on the remediation processes that must be put in place to decrease eutrophication. Based on the findings of this study eutrophication remediation programs should be a combination of treating the basic causes or the symptoms such as reducing nutrient inputs phosphorus and/or nitrogen from the water system or having control programs such as harvesting of aquatic plants e.g water hyacinth caused by eutrophication.

Furthermore, nutrient control programs can be directed primarily toward controlling point such as limiting nutrient inputs from wastewater-treatment plants such as the sewage from Deneysville municipality which enters the dam at a point close to where Rand Water abstract water (Steward, 2015). Nonpoint sources come from crop fields shown in landcover map in **Error! Reference source not found.** ,control programs can be directed at controlling nutrient runoff from farmland and/or urban areas of nutrients. For the long-term management of eutrophication and improvement of water quality, it is better to treat the causes of eutrophication, rather than the symptoms.

3. **The third objective of the study was to determine the spatial distribution of Chl-a within the Vaal Dam using Geographic Information systems (GIS) and remote sensing methods.**

MERIS satellite data was processed using the remote sensing software application ENVISAT BEAM and custom python computer code to derive the Chl-a products. The results were presented in a form of maps showing areas of high concentration values. The results of the distribution maps produced show that high Chl-a values are often high in the eastern part of the Vaal Dam this trend is seen from the year 2004-2007.These are the areas located near Deneysville and Orangeville which are residential areas as seen on the map

Error! Reference source not found.. Often the sewage discharges from these areas enter the dam resulting into these areas being worst impacted within the Dam. However, the southern areas of the Vaal are shown to have lower values of Chl-a. When we look at the land-use map of the Vaal **Error! Reference source not found.**, these areas are surrounded by croplands and cultivation fields, there are no residential areas. The nutrients from fertilisers that are used in these fields can enter the Dam when it is raining as runoff.

The maps will be useful in informing eutrophication monitoring programmes of which areas are highly affected by eutrophication. The Chl-a value pixels were successfully extracted from MERIS satellite images and further analysed using GIS applications. The pixels were plotted as a map shapefile using GIS software application ArcGIS to show the variations and distribution of Chl-a within the Vaal Dam. Plotting the Chl-a data in GIS also provide a platform to apply spatial analysis methods, therefore deriving more useful information. Both these methods applied by the study can show the Chl- a at locations that are difficult to sample using ground in-situ methods. The maps have successfully shown the spatial variation of Chl-a within the Vaal Dam through the application of GIS and remote sensing methods.

4. **The fourth objective was to determine the impacts climatic variables such as temperature, rainfall and wind on eutrophication in the Vaal Dam.**

This study used MERIS satellite images as a data source to obtain Chl-a and cyanobacteria information in the Vaal Dam. The correlation between climatic variables and Chl-a were analyzed using linear regression. The study found that climatic variables play a role in in the increasing levels of eutrophication, together with high nutrient loadings. The results of the study show that there is a correlation between temperature and Chl-a. The r values from show a positive linea[r] relationship between Chl-a and Temperature The p -value also show a statistically significant relationship for some of the years. The scatter plot graphs indicate higher Chl-a correspond to high temperatures. Increased temperature directly affects eutrophication by advancing its onset time extending its duration. Increasing temperatures has direct effects on cyanobacterial growth rates. The growth rates of freshwater eukaryotic phytoplankton usually stabilize or decrease as temperatures increase. However, the growth rates of many cyanobacteria continue to increase when the temperature is around ^{2}0°C (Houghton, et al., 2001).

The study showed a positive correlation between the Chl-a and rainfall observed from the results of correlation coefficient r value. The normalized data graph of rainfall and Chl-a show that the rainfall values are high in January and decrease towards the month of June. On the other hand, the Chl-a values are also high in January and decrease towards June. Furthermore, wind speed is another variable that plays a role in the how the levels of Ch-a are distributed across the dam. The study results show that Chl-a values are high during periods of low wind speed. The wind speed values begin to increase in the month of August to November. The Chl-a values decrease as a result of mixing of nutrients and sediments in the water caused by high wind speeds.

The overall correlation between Chl-a and climate variables where the normalized monthly values of temperature, rainfall and wind speed were plotted together with normalized values of Chl-a. The Chl-a values decrease as the rainfall and temperature are also decreasing, and at low wind speed. The temperature, wind speed and rainfall values seem to increase from the month of August, while the Chl-a continues to decrease and only increase in the month of September. This could indicate that the Chl-a does not react immediately to the change of the climate variables but is lagged. Therefore, our study offers evidence that nutrients and climatic variables both play a role in increasing the levels of eutrophication within the Vaal Dam.

In-situ validation

MERIS satellite estimates were compared to the time series of in-situ data using same-day matchups. Four sample points located within the Vaal Dam were selected for the analysis. The resulting matchups of the same date were compared using linear regression analysis. The relationship between in-situ data and satellite was proved to be statistically significant, but overall was weak with a tendency of the satellite to significantly overestimate Chl-a relative to in-situ measurements. However, three out of the four sample points that were measured showed a positive linear correlation.

The recommendations for future work from this study are as follows:

- The methods applied in this study can be used to analyse data collected by eutrophication monitoring programmes, to understand the trends and changes of eutrophication in further dams.
- The time series methods used in this study can also contribute in understanding the seasonal factors that drive eutrophication. Future eutrophication prediction methods can also be determined by studying eutrophication over a certain period of years.
- There should be an assessment of how the changes in land use and land cover affect eutrophication in the dam, analysing eutrophication drivers such as nutrients.
- Eutrophication remains an issue of concern for water security in South Africa and it needs effective management attention. Satellite remote sensing data can be used to supplement current eutrophication monitoring efforts.

8. REFERENCES

References

Birch, G., 1983. The clay mineralogy of sediments in the Vaal Dam and in the rivers supplying and draining the dam upsteam of the barrage.. *Water SA,* Vol. 9.(No.3.).

Braune, E. & Roger, K., 1987. *The Vaal River Catchment: Problems and research needs. National Scientific Programmes Unit: CSIR, SANSP Report 143. 44 pp.,* Pretoria: URL: http://researchspace. csir.co.za/dspace/handle/10204/2373.

Cane, M., 2005. The evolution of El Niño, past and future. *Earth and Planetary Science.*

Cao, H. et al., 2006. Effects of windand wind induced waves on vertical phytoplankton distribution and surface blooms of Microcystis in lake Taihu. *Journal of Freshwater Ecology,* Volume 21, pp. 231-238.

Carpenter, S. et al., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications,* pp. 559-568.

Chinyama, A., Ochieng, G., Snyman, J. & Nhapi, I., 2016. Occurance of cyanobacteria genera in the Vaal dam: Implication son portable water production. *Water SA Vol 42 No3.*

Conley, D. et al., 2009. Controlling Eutrophication: Nitrogen and Phosphorus. *Science,* 323(5917), pp. 1014-1015.

Cook, C., Reason, C. & Hewitson, 2004. Wet and dry spells within particularly wet and dry summers in the South African summer rainfall region. *Climate Research,* 26(1), pp. 17-31.

Cyr, H., MaCabe, S. & Nürnberg, G., 2009. Phosphorus sorption experiments and potential for internal phosphorus loading in littoral areas of a stratified lake. *Water Res.,* Volume 43, p. 1654–1666..

Department of Environmental Affairs, 2015. *2013-2014 South African National Land Cover Dataset,* Pretoria: Geoterraimage.

Dijkshoom, J., 2003. *Soil and Terrain database for Southern Africa,* Wageningen: International Soi reference and Information centre.

Dodds, K. et al., 2009. Eutrophication of US freshwaters: analysis of potential economic damages. *Environmental Science and Technology,* 43(1), pp. 12-19.

Downing, T. & Van Ginkel, C., 2004. *Cyanobacteriamonitoring 1990–2000: Evaluation of SA data. WRC Report No1288/1/04.,* Pretoria: water research commision.

Driver, P. M., 2014. *Rainfall variability over southern Africa,* s.l.: Doctoral dissertation, University of Cape Town.

Dufois, F. & Rouault, M., 2012. Sea surface temperature in False Bay (South Africa): Towards a better understanding of its seasonal and inter annual variability. *Continental Shelf Research,* Volume 43, pp. 24-35.

DWAF, 2002. *National eutrophication monitoring programme: implementation manual,* Pretoria: s.n.

DWAF, 2004. *DWAF, A 5-year water resource quality monitoring plan: internal report.,* Pretoria: Directorate: Information Programmes, South African Department of Water Affairs and Forestry.

ESRI, 2007. *ArcGIS desktop help.* [Online]
Available at:
webhelp.esri.com/arcgis/arcgisdesktop/9.2/index.cfm?TopicName=Appying_a_spline_interpolation
[Accessed 12 September 2017].

European Space Agency, 2000. *European space agency (ESA).* [Online]
Available at: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/meris/design
[Accessed 11 October 2017].

Europopean Space Agency, Sentinel 3 team, 2013. *Sentinel-3 User Handbook.* [Online]
Available at: https://sentinel.esa.int
[Accessed 16 June 2018].

Ewerts, H., Swanepoel, A. & du Preez, H., 2013. Efficacy of conventional drinking water treatment processes in removing problem-causing phytoplankton and associated organic compounds.. *Water SA,* Volume Vol 39 (5), p. 739–750.

Fauchereau, N. et al., 2009. Recurrent daily OLR patterns in the Southern Africa?Southwest Indian Ocean region, implications for South African rainfall and teleconnections. *Climate Dynamics,* 32(4), pp. 575-591.

George, D. & Edwards, R., 1976. The effect of wind on the distribution of chlorophyll a and crustacean zooplankton in a shallow eutrophic reservoir. *Journal of applied ecology,* Volume 13, p. 667–690.

Guildford and Hecky, 2000. Total nitrogeTotal phosphorus and nutrient limitation in lakes and oceans: Is there a common relationship?. *Limnology and oceanography 45,* p. volume 6.

Harding, W., 2008. The determination of phosphorus loading limits for South African dams.

Hart, N., Reason, C. & Fauchereau, N., 2010. Tropical-extratropical interactions over Southern Africa three cases of heavy summer rainfall. *Monthly Weather Review*, pp. 2608-2623.

Hickey, J. & Salas, D., 1995. *Environmental effects of extreme floods.* Perugia, Italy, Italy research workshop on the Hydrometeorology.

Holdsworth, 1991. New Health Considerations in Water Treatment. *Avebury Technical.*

Houghton, J. et al., 2001. *climate change 2001: the Scientific basis. Contribution of working goup1 to the assessment reportof the Intergovernmental panel on climate change.,* Cambridge, United Kingdom: IPCC.

Jo¨hnk, K. et al., 2008. 2Summer heatwaves promote blooms of harmful cyanobacteria.. *Global Change Biology,* 14(3), pp. 495-512..

Lakewatch, 2000. *A Beginner's Guide towater management nutrients,* Florida: University of Florida.

Macvicar, C. & DE Villers, J., 1991. *SOIL CLASSIFICATION A TAXONOMIC SYSTEM FOR SOUTH AFRICA.* Pretoria: Soil Classification Working Group.

Mason, S. & Jury, M., 1997. *Climatic variability and change over southern Africa: A reaction on underlying processes. Progress in Physical Geography.* ISSN 0309-1333 ed. s.l.:s.n.

Matthews, M., Bernard, S. & Robertson, L., 2012. An Algorithm for detecting trophic status(Chl-a), cyanobacterial-dominance,surface scums and floating vegetation in inland and coastal waters.. *Remote Sensinf of Environment.*

Matthews, M., Bernard, S. & Winter, K., 2010. Remote Sensing of cyanobacterial dominant algal blooms and water quality parameters in Zeekoevlei,a small hypertrophic lake,using MERIS. *Remote Sensing of Environment,* pp. 114,2070-2087.

Matthews, M. W., 2014. Eutrophication and cyanobacterial blooms inSouth African inland waters:10 years ofMERIS observations. *Remote Sensing of Environment ,* p. 161–177.

McCkenzie, R. & Wegelin, W., 2009. Challenges facing the implementation of water demand management initiatives in Gauteng Province.. *Water SA,* Volume Vol 35 (2), p. 168–174.

Mooij, W., Janse, J., Domis, L. & Senerpont, 2007. Predicting the effects of climate change on temperature on temperate shallow lakes with the ecosystems model PCLake. *Hydrobiologia,* 584(1), pp. 443-454.

Moreno-Ostos, E., Cruz-Pizarro, L., Basanta, A. & George, D., 2009. The influence of wind-induced mixing on the vertical distribution of buoyant and sinking phytoplankton species.. *Aquatic Ecology,* Volume 43, p. 271–284.

Mulenga, H. M., 1999. *Southern African climate anomalies, summer rainfall and the Angola low,* s.l.: Doctoral dissertation, University of Cape Town.

OECD, 2002. *OECD, 10 May, 2002-last update,.* [Online]
Available at: www.chebucto.ns.ca/ccn/info/Science/SWCS/TPMODELS/OECD/oecd.html

O'Neil, J., David, T., Burford, M. & Gobler, C., 2011. The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. *Harmful Algae,* Volume 14, pp. 313-334.

Paerl, H. & Fulton, R., 2006. Ecology of harmful cyanobacteria.. *Ecology of Harmful Marine Algae,* pp. 95-107.

Paerl & Huisman, 2009. Climate Change: Catalyst for global expansion of harnful algal blooms. *Environmental microbiology reports,* Volume 1, pp. 27-37.

Paerl, H. W., 1988. Nuisance phytoplankton blooms in coastal, esturaine and inland waters. *Limnology and Oceanography,* 33(4 part 2), pp. 823-843.

Pretty, J. et al., 2003. Eutrophication costs of freshwater eutophication in England and Wales. *Environmental Science and Technology,* 37(2), pp. 201-208.

Rae, B., Moollan, R. & Clark, R., 1999. Algal toxins in drinking water supplies. *Water Research Commision,* Volume WRC Report No. 549, p. 99.

Rand Water, 2008. [Online]
Available at: http://
www.randwater.co.za./waterandinfrastructuremanagement/pages/waterQuality.aspx
[Accessed 15 November 2016].

Rast, W. & Thornton, J., 1996. Trends in Eutrophication Research and Control. *Hydrological Processess,* p. 295.

Reason, C., Allan, R., Lindesay, J. & Ansell, a., 2000. ENSO and climatic signals across the Indian Ocean basin in the global context: Part 1, Interannual composite patterns. *International Journalof Climatology,* 20(11), p. 1258.

Reason, C., Landman, W. & Tennant, W., 2006. Seasonal to decadal prediction of southern African climate and its links with variability of the Atlantic Ocean. *Bullletin of the American Meteorological Society*, pp. 941-9555.

Republic of South Africa National Water Act., 1998. *REPUBLIC OF SOUTH AFRICA, National Water Act. 1st edn..* Cape Town: Republic of South Africa.: s.n.

Reynolds, C. S., 2006. The ecology of phytoplankton.. *Cambridge.*

Scott, W., 1979. Chemical Control of the Water Hyacinth on Hartbeespoort Dam.. *Water Research Commission, National Institute for Water Research and Hydrological Research Institute..*

Smith, V. H., 1983. Low nitrogen to phosphorus ratio favour dominance by blue green algae. *Science, new series,* pp. 669-671.

South Africa Weather Services, 2018. *Vereeniging Climate data.* s.l.:s.n.

Steward, M., 2015. *SAVE the Vaal Environment.* [Online]
Available at: www.save.org.za
[Accessed 07 03 2017].

Toerien, D., Hyman, K. & Bruwer, M., 1975. A preliminary trophic Status classification of some South African impoundments.. *Water SA,* Volume 1.

Truswell, F., 1970. *An introduction to the historical geology of South Africa.* Cape town: Purnell.

Tyson, P., 1986. *Climatic change and variability in southern Africa.* s.l.:Oxford University Press.

Van Ginkel, C., 2004. *A National survey of the incidence of cynobacterial blooms and toxin production in majour impoundments,* Pretoria, South Africa: Resource quality services report no . N/0000/00/DEQ/503, Department of Water Affairs and Forestry.

van Ginkel, C., Silberbauer, M. & Vermaak, E., 2000. The seasonal and spatial distribution of cyanobacteria in South African surace waters. *Microbial diversity,* Volume 27, pp. 871-878.

Vollenweider, R. A., 1968. Scientific fundementals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorusas factors in eutrophication. *Organisation for Economic Co-operation and Development,* p. 68.27..

Walmsley, R., 1984. A chlorophyll- a trophic status classification system for South Africa. *Journal of Environmental Quality,* Volume 13, pp. 97- 104.

Walmsley, R., 2000. Perspectives on Eutrophication of surface waters. *policy/research document. Water research commission project.*

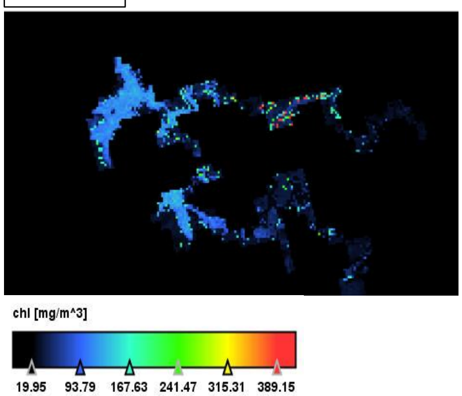
Whitehead, P. et al., 2009. A review of the pontential impacts of climate change on surface water quality. *Hydrological Science journal,* 54(1), pp. 101-123.

Zhang, W. et al., 2017. Spatiotemporal Distribution of Eutrophication in Lake Thai Affected by Wind. *Water.*

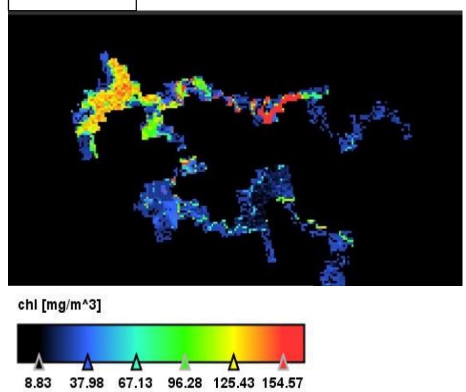
9. APPENDIX

Maps of satellite images from MERIS after the processing of raw imagery and the extraction of Chl-a pixels using the MPH- algorithm.

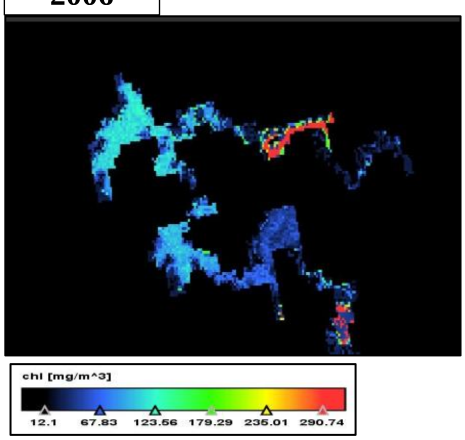
2004



2005



2006



2007