ASSESSMENT OF THE SELF-PURIFICATION CAPACITY OF THE MOOI RIVER CATCHMENT

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DECLARATION

I, Thabang George Mmutle, student number _________, do hereby declare that this research project, which has been submitted to the Central University of Technology, Free State, South Africa, for the degree: Master of Engineering in Civil Engineering, is my own work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State. This dissertation has never been submitted before by any person in fulfilment (or partial fulfilment) of the requirements to attain any form of qualification.

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September 2022

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First of all, I would like to thank the Lord God of Mount Zion for affording me the blessing of this magnitude, the strength to persevere and the wisdom to see through all the obstacles in completing this study.

The association and guidance from all the people who helped me complete this master's dissertation.

I'd like to give a huge thanks to my supervisor, Prof A.S. Oke, for his guidance and support.

DEDICATION

I dedicate this project to the Lord God of Mount Zion. I prayed about academic excellence 10 years ago and I appreciate the way it is getting paved in the right path. The wisdom, strength and perseverance you have given me is really unmeasurable.

To my son, I hope to inspire you in every way I can as long as I am still alive.

To my late Father, my Mother, my Sister, my Brothers, Niece and Partner. I know you have been looking forward to my academic success since I finished high school. *This is for you.*

ABSTRACT

Dissolved oxygen is the most essential element in natural water bodies for one of the most important reasons, namely aquatic life. This content is usually affected by the type and amount of pollution introduced in natural water bodies. The dissolved oxygen level is usually lowered at any point where a natural water body such as a river is contaminated (deoxygenation); however, using natural purification forces, rivers work hard to gain back the amount of oxygen lost in the water due to pollution (reoxygenation)

This study articulated the self-purification capacity of the Mooi River catchment as a function of the rate of change of the amount of dissolved oxygen in flowing water to illustrate the purification strength of a river flow segment between sampling points. This is to subsequently present the impact of inflowing pollution from different types of adjacent sources and tributary rivers. This was achieved by conducting measurement of dissolved oxygen and temperature directly from the river, using an electrolyte dissolved oxygen meter. Respective samples (three-litre samples) were also collected at every sampling point for a biochemical oxygen demand laboratory analysis taken over five days. Using the biochemical oxygen demand and oxygen deficit analysis, deoxygenation and reoxygenation factors or constants were determined for every flow segment. The mathematical ratio between the two constants were then used to calculate the self-purification capacity of every segment.

Because the hydraulic dynamics of the river also influence the strength of the river to purify itself, a reoxygenation model of hydraulic properties, such as flow velocity, hydraulic depth and radius, was developed and presented by means of a regression analysis. The findings have proven that, Mooi River's capacity to purify itself is affected by pollution sources around it. With highest BOD values of 2.1, 2.7 and 1.5mg/l recorded during the months of November, December and January respectively, Mooi River shows to be affected more by pollution during the rainy season because of uncontrolled surface run-off wash-ins of adjacent pollution contents into the river. The high purification fluctuations were also due to the increase in hydraulic flow depth during wet season. The strength of purification for the flow segment before the Vaal River confluence (sampling point 9 and 10) is very high, which means that Mooi River does not affect Vaal River in terms of pollution conveyance. This can be clearly depicted from the positive change in dissolved oxygen deficits between sampling points 9 and 10 for the entire study period, (from 3.74 to 2.83mg/l in November), (4.44 to 3.52 in December).

Keywords: river catchment, self-purification, dissolved oxygen, biochemical oxygen demand, oxygen deficit, deoxygenation, reoxygenation, eutrophication, water quality modelling

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DO	Dissolved oxygen
DOS	Dissolved oxygen saturation
k_1	Deoxygenation constant
k_2	Reoxygenation constant
SPL	Sampling point
SSE	Sum of squared estimates of errors
SSR	Sum of squared regression
SST	Total sum of squares
WWTW	Wastewater treatment works

CHAPTER 1

INTRODUCTION

1.1 Background

South Africa is one of the countries that are classified as water scarce countries. It has a mean annual rainfall of 490 mm, which is below the world average of 814 mm. Natural water resources in South Africa include rivers, wetlands, estuaries, springs, and aquifers, and all of them form part of hydrological cycle replenished by rainfall. In the case of rivers, the quality of a river is often a good indication of the way of life within a community through which it flows. It is an indication of the socio-economic conditions and environmental awareness and attitude of its users. All that occurs in a catchment region is reflected in the nature of the water that courses through it, in light of the fact that the consequences of human action and way of life eventually end up in streams, through run-off and different means. This has always called for competency and effectiveness of water resource management that preserves both the quality and quantity of this essential need of life in order to secure ecological sustainable development (Kyei, 2019).

Water quality management entails maintaining the fitness of the water resources in a sustainable manner. This is done by achieving a balance between socio-economic development and environmental protection. Water resource regulators plan, develop and implement water quality management policies to monitor and audit potential threats of pollution affecting the water quality. Usual pollution threats include wastewater treatment effluents, mining effluents, and agricultural run-offs (Abbaspour, 2011).

Contamination of a river at any point along its existing length, diminishes the water quality either physically, chemically, or microbiologically, depending on the source of pollution. This affects the quality of the water sources by diminishing the dissolved oxygen (DO) in the water (deoxygenation), thus affecting, and endangering the water reliant species and the aquatic ecosystem as a whole. However, the quality of the water does not remain the same throughout the existing length of the river. Natural forces of purification come into play by acting upon the pollution elements to bring back the water to its original condition. This process is termedself-purification phenomenon (Garg, 2006).

The self-purification capacity of every river depends on the balance degree between deoxygenation and reoxygenation processes. Deoxygenation refers to the amount of DO used by micro-organisms to oxidise and break down the organic matter in the polluted water over a certain period of time and a certain flow distance, whereas on the other hand, reoxygenation refers to the amount of oxygen that infiltrates the water from the atmosphere to level up the DO content in the water, thus purifying it (Omole & Longe, 2008).

There are other natural factors that affect the self-purification capacity of natural water bodies. These include the water body flow velocity, flow depth, volumetric flow rate andtemperature. There is high flow turbulence at high flow velocities, therefore rapid re-aeration takes place where as in slow or stagnant water bodies, there is low turbulence, and the capacity to maintain high DO concentration is very low; this is likely to lead to anaerobic conditions if theorganic matter in the water is heavy. Rivers with deep flow depths absorb atmospheric oxygenat a very low rate (low diffusion) because they need more time and flow distance for the absorbed atmospheric oxygen to diffuse into the entire cross-sectional volume of the flowing water. At higher temperatures, the rate of biological and chemical activities are high, thereby causing rapid depletion of DO (Garg, 2006).

Water quality modelling is a mathematical process of developing prediction equations that best describe how natural water bodies as part of the aquatic ecosystem react to the changes imposed on them through pollution (Omole & Longe, 2008, 2012). It is very important to develop water quality models for every natural water mass because no model can be representative of every situation in and around every natural water mass in terms of the type of pollution, tropical conditions and hydraulic dynamics. Reoxygenation coefficient modelling is an important part of water quality modelling used to seasonally forecast and monitor the pollution constituents in surface water bodies for better regulation and water resource planning and management. The method was developed in 1925 by Steeter and Phelps (Omole & Longe, 2008). After studying the self-purification dynamics of the Ohio River, they developed the mathematical relationship between deoxygenation and reoxygenation. This has since been an interesting and attractive topic of study throughout the world (Omole & Longe, 2008).

One of the most talked about water masses in the Northwest province of South Africa is the Mooi River catchment. The catchment has been subjected to much pollution throughout the years. The Wonderfonteinspruit, a tributary to Mooi River, is known by research to be a much polluted river containing contaminants from the gold mining sectors and contaminants from the Flip Human Wastewater Treatment Works (WWTWs) in the Northwest province, thus influencing the quality of Mooi River at the point of their confluence. Furthermore, with the effluent from the Kokosi WWTW, the Loopspruit subsequently repeats this influence downstream of the Mooi River. This implies that the quality of the Mooi River is further compromised (Dube, 2019). Include concluding remarks of the introduction.

1.2 Problem statement

Although Mooi River has the potential to purify itself along its existing length, like any other natural river, there are several factors that affect its purification capacity at a larger scale.This includes, but not limited to, all the point and non-point pollution sources. The problem liesin not knowing the extent of the effect of these factors on the self-purification capacity of Mooi River, with which the water quality management system can be sustained. The South African water quality management system does not have self-purification modelling as one of its management tools. In this study, three possible solutions are investigated and evaluated, namely:

- Evaluation of the current self-purification strength of Mooi River.
- Evaluation of the factors affecting the self-purification of Mooi River.
- Development of a reoxygenation model of Mooi River.

1.3 Research questions

1. What are the factors affecting the quality and self-purification capacity of Mooi River? (Point and non-point pollution sources).
2. What is the current self-purification capacity of Mooi River?
3. What is a reoxygenation model of Mooi River catchment?

1.4 Aim and objectives of the study.

The aim of the study was to assess the self-purification capacity of the Mooi River catchment based on the water quality analysis, and to develop and validate a reoxygenation model from the hydraulics parameters of the catchment. This was to be achieved through the following objectives:

1. To determine the self-purification capacity values (*f*) of the Mooi River catchment using deoxygenation and reoxygenation constants from water quality analyses.

2. To develop the Mooi River reoxygenation model using river hydraulic parameters.
3. To validate the developed reoxygenation model with water quality data and comparing it to existing reoxygenation models using a regression analysis.

1.5 Methodology

This study consisted of both field investigations and laboratory analyses of self-purification indicators and its influencing dynamics. The primary purpose of the field investigation was to physically benchmark sampling points and set out a study parameter. Furthermore, these investigations were conducted for the purpose of accuracy in measuring important purification indicators such as DO, pH and the in-situ corresponding temperatures, hydraulic dynamics and evidence of point and non-point pollution sources. Sample collection for laboratory analysis of biochemical oxygen demand (BOD) was done using a five-day BOD analysis method.

In situ DO and corresponding temperatures, together with the BOD determined in the laboratory after five days, were used to generate both deoxygenation and reoxygenation rates, and subsequently, the self-purification rates for every flow segment between sampling points. The hydraulic dynamics of the river, such as flow velocity, flow depth and width, were used to develop the reoxygenation model. To record the impact of weather conditions' variability on water quality, this process of investigations was carried out in both wet and dry seasons.

1.6 Benefits of the study

Mathematical modelling of self-purification and water quality simulation in natural water bodies was one of the most important tools used to achieve effective water resource management. With mathematical self-purification models, the seasonal downstream quality conditions of Mooi River will be able to be predicted in future. Knowing the seasonal self-purification strength of Mooi River will assist the water quality resource management to figure out the pollution limitations that will assist in minimising the treatment costs for potable water treatment companies that extract water from this river or other rivers connected to it as tributaries.

If the benefits of this study were to be stretched and be implemented, this study would assist in repositioning the extraction point of water treatment companies by indicating the most reliable section(s) along the existing length of the river at which the water is less contaminated or where the purification rate is high to reduce the treatment costs. The study can even be used to assist the positioning decisions of new water treatment companies along the length of a river.

1.7 Delimitations of the study

- This study analysed the dissolved oxygen fluctuations and deficits as products of chemical reactions with biodegradable organic matter only. It did not include other independent chemical reactions between dissolved oxygen and other chemical pollutants.
- The study did not include the influence of underground water charge in terms of quality and quantity.

1.8 Outline of the research

This thesis is broken down into the following five chapters:

Chapter 1: This chapter covers the foundation and presentation of the review. To begin with, this section features the issue proclamation, trailed by the exploration questions and points of the review. It additionally incorporates an outline of the examination approach, advantages and delimitations applied to accomplish the necessary consequences of the review.

Chapter 2: This chapter audits a portion of the accessible writing pertinent to this field of study. Past investigations are broke down, considered and utilized as a rule. The various parts utilised in the examination are likewise exclusively analysed and talked about in this chapter.

Chapter 3: This chapter emphasises the system of the examination. It examines the singular units and their usefulness as well as techniques used to conduct the study.

Chapter 4: This chapter focuses on the information examination and results got in the analysis and has four fundamental segments of results. Each segment is examined and portrayed all alone and results are outwardly introduced as diagrams, tables, and pictures.

Chapter 5: The last chapter focuses on the conclusion with respect to the outcomes got in the analysis. The conversation area discusses the outcomes got and the ramifications segment ponders on the different discoveries of the exploration. The end sums up the consolidated result of the conversation and ramifications of the part.

1.9 Summary

A river's self-purification capacity is an important indicator of river health. It serves as an imperative indicator when regulating discharge standards of a natural water mass such as a river. This chapter covered the importance of the study generally and around the specific study area. The next chapter elaborates more on the literature of self-purification and water quality modelling, from the inception stages of the phenomenon conceptualisation down to its application and developments over the years.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 1 focused on the necessity of performing self-purification assessments and various methods of undertaking mathematical water quality modelling of natural rivers. The chapter also focused on giving insight on how different types of pollution affect self-purification capacity of rivers under different climatic conditions. The use of water quality modelling in strategic water quality management has been demonstrated to be beneficial. In this chapter, a detailed review of literature is presented to give an overview of the current knowledge and status quo of the water quality modelling and its impacts in the water resource management communities all over theworld.

Self-purification strength analysis of natural rivers is to facilitate the work of researchers, designers, managers, and planners who are faced with conceiving and solving problems associated with the physical, chemical, and biological processes that lead to water pollution and its control. Theself-purification process of a river is one of the water quality modelling tools to indicate the pattern or trend in which a river can oxidise the pollution present in it by using the DO alreadypresent in it and the oxygen it can absorb from the atmosphere (Mbuyamba et al., 2018).

2.2 Self-purification phenomenon

When any type of pollution is discharged into a natural water course, organic compounds are oxidised by the DO present in the water. Thus, a deficiency of DO is created in flowing water (deoxygenation, i.e. loss of oxygen), but that deficiency is immediately dismissed by the atmospheric oxygen being absorbed into the water (reoxygenation, i.e. gain of oxygenation; Garg, 2006).

The rate at which the DO absorbed into the water can automatically, oxidise the organic matter present in the water, is termed self-purification rate. This phenomenon narrates the outcome of the deoxygenation and reoxygenation processes that continuously occur in a simultaneous manner. The occurrence of "self-purification of running streams" is continually taking place in running streams. The various actions involved are physical, chemical and biological actions (Garg, 2006).

2.3 Self-purification indicators

2.3.1 Dissolved oxygen

DO can simply be described as the amount of oxygen dissolved in water, measured in milligrams per litre (mg/l). This component in water is of great importance to the survival of various aquatic lives, such as fish. The ability of water to hold oxygen in a solution is inversely proportional to the temperature of the water. Generally, the solubility of gas in water drops with temperature increase. Oxygen is one of the strongest oxidising agents found in natural aquatic systems. Oxidation reactions are thermodynamically favoured, but kinetically slow unless microbially mediated. The end products of complete aerobic biodegradation are carbon dioxide and water. Most aquatic habitats are often occupied by fish or other animals requiring a certain amount of DO concentrations for survival (Ugbebor et al., 2012).

2.3.2 Biochemical oxygen demand

Biochemical oxygen demand (BOD) is one of the most important and widely used parameters to characterise organic contamination of water and wastewater. It serves the purpose of measuring the amount of consumed oxygen during the breaking down (oxidation) of organic matter, using both aerobic biological and chemical degradation processes, thus giving an indication of the organic strength of wastewater (Junfei et al., 2016). The conventional BOD method is to incubate the well-known five-day BOD (or BOD_5) in a dark room at 20 ºC for five days. The BOD_5 test is still the most used environmental index for monitoring organic pollutants in water, mainly as proof of compliance to relevant regulations (Omole & Longe, 2012).

2.3.3 Deoxygenation

Deoxygenation rate represents the rate at which DO in water is consumed by the decomposition process of the biodegradable organic matter present in the water. The oxygen is consumed by micro-organisms (bacteria) in an aerobic process to decompose the organic matter. The amount of oxygen needed to decompose organic matter is an indirect measure of the amount of BOD in the water (Jha et al., 2001).

2.3.4 Reoxygenation

Reoxygenation, on the other hand, is the rate at which oxygen from the atmosphere enters the river water to rejuvenate the water quality by replacing the DO used in the organic matter decomposition process. Hence, DO is an indicator of the reoxygenation rate. It is measured in milligram per litre by using a DO meter (Abbas, 2021).

2.3.5 pH, acidity and alkalinity

The pH of water affects the solubility of many toxic and nutritive chemicals; thus, the availability of these substances to aquatic organisms is affected. A lot of metals become more water soluble and more toxic when the acidity of water increases. Toxicity of cyanides and sulphides also increases with a decrease in pH levels (increase in acidity). Ammonia, on the other hand, becomes more toxic with only a slight increase in pH (Walsh & Wepener, 2009).

Alkalinity is the capacity to neutralise acids, and the alkalinity of natural water is deduced mainly from the salts of weak acids. Hydroxide carbonates, and bicarbonates are the most common source of natural alkalinity. The chemistry of carbon dioxide with calcium or magnesium carbonate in the soil yields very extensive quantity of bicarbonates in the soil. Organic acids also form salts that increase alkalinity. Alkalinity itself has little to no significance on public health, although highly alkaline waters are unpalatable and can cause gastrointestinal discomfort (Walsh & Wepener, 2009).

2.3.6 Chemical oxygen demand

The chemical oxygen demand (COD) test is used to measure the chemical oxidation of wastewater through the usage of a strong oxidising agent under acidic conditions. As for BOD, it simply measures the amount of oxygen required as a surrogate for measuring the organic waste component directly. Therefore, the COD test does not necessarily differentiate between biologically active and inert organic matter but measures the total quantity of oxygen required to oxidise all organic matter into carbon dioxide and water. COD values are therefore always greater than BOD values, but the results can be obtained within two hours and the presence of toxic compounds in the sample does not affect COD measurements. In many instances, the BOD–COD ratio is used to provide an indication of the biodegradability of the wastewater. However, the chemicals used, such as acid, chromium, silver, and mercury, produce liquid hazardous waste that requires careful handling and disposal (Bere & Tundisi, 2011).

2.4 Factors affecting self-purification.

2.4.1 Temperature

Aquatic organisms can only survive within a specific range of temperatures. Irrigation run-off and water cooling of power stations may elevate temperatures beyond the acceptable range for some species. The temperature affects the rate of biological and chemical activities, which are enhanced at higher temperatures and depressed at lower temperatures. The DO content of water, which is very essential to maintain aerobic conditions (so as to avoid the anaerobic decomposition and subsequent irritations caused by eruption of foul odours) is also influenced by temperature. At high temperatures, the capacity to maintain the DO concentration is low, while it is high at low temperatures (Hill et al., 2018).

Table 2.1 presents the DO concentration that corresponds to 100% saturation at the noted temperature.

Table 2.1 Solubility of oxygen in water at various temperatures (Garg, 2006)

Temperature (˚C)	Dissolved oxygen (mg/l)	Temperature (˚C)	Dissolved oxygen (mg/l)
0	14.6	16	9,9
1	14.2	17	9.7
2	13.8	18	9.6
3	13.5	19	9.3
4	13.1	20	9.1
5	12.8	21	8.9
6	12.5	22	8.7
7	12.1	23	8.6
8	11.8	24	8.4
9	11.6	25	8.3
10	11.3	26	8.1
12	10.8	28	7.8
13	10.5	29	7.7
14	10.3	30	7.6
15	10.1	31	7.5

2.4.2 Dilution and dispersion

When organic matter is dumped into the river, it is quickly dispersed and diluted. This leads to a reduction in the concentration of waste, which reduces potential wastewater nuisance. The concentration 'C' of the resulting mixture is given by Equation 1.

$$C = \frac{Cs.Qs + Cr.Qr}{Qs + Qr} \tag{1}$$

Where,

Cs = concentration of sewage;

Qs = flow rate of sewage;

Cr = concentration of river; and

Qr = flow rate of river.

This equation is applicable to the concentration of different impurities, such as oxygen content, BOD and suspended sediment (Šaulys et al., 2019).

2.4.3 Sedimentation

The settle-able solids present in effluents will gravitate towards the stream bed, subsequently assisting in the river self-purification. This process helps in eliminating heavy organic suspended solids that cannot flow further downstream of the river (Vaideliene & Mihailov, 2008).

2.4.4 Oxidation

The oxidation of the organic matter present in the sewage effluent will start as soon as the sewage outfalls into the river water containing DO. The deficiency of oxygen so created, will be filled up by the atmospheric oxygen. This is the most important action responsible for affecting self-purification of rivers (Zubaidah et al., 2019).

2.4.5 Reduction

Reduction takes place because of hydrolysis of natural matter settled on the riverbed, either chemically or biologically. Anaerobic bacteria will help in splitting the complex organic constituents of sewage in liquids and gases, thus paving the way for their ultimate stabilisation by oxidation (Zubaidah et al., 2019).

2.4.6 Sunlight

Sunlight has a bleaching and stabilising effect on bacteria. Photosynthesis drives the production of oxygen through algae in the presence of sunlight. Therefore, sunlight helps in purification of streams by adding oxygen through photosynthesis (Sinton et al., 2001).

2.4.7 Turbulence

High turbulence in a flowing river assists in rapid reoxygenation from the atmosphere. Too much turbulence scours the bottom sediment and stops algae growth (Snitynskyi, et al., 2021).

2.4.8 Hydrography

The velocity and surface expanse are mainly affected by the hydrography of a river. High velocity causes turbulence and rapid aeration, while surface expanse will also have the same effect. This is basically the effect of flow regime, as explained by the hydraulic Froude number, using the hydraulic radius and flow velocity (Snitynskyi et al., 2021).

2.5 Pollution of rivers

2.5.1 Pollution profile

Due to the flow characteristics of river water, river ecology is more vulnerable to external pollution. Furthermore, once pollution occurs, it can easily spread to the entire basin. In recent years, water quality has been severely degraded due to the rapid development of the urban economy, rapid population growth, deepening industrialisation, increasing urban water consumption, and the discharge of alluvial pollutants, self-cleaning rivers, and ecological compensation for reduced regulatory capacity (Halder & Islam, 2015).

2.5.2 Sources of urban river pollution

2.5.2.1 Industrial pollution source

This is the most influential source of water pollution. It refers to the by-product water used in the production process discharged by industrial institutions. According to the nature of pollutants, industrial wastewater can be divided into the following:

- Wastewater containing organic matter, such as wastewater from papermaking, sugarcane growing, food processing, printing, and dyeing, and the textile industry.

- Wastewater containing inorganic substances, such as hydraulic washing in coal-fired power plants, ash wastewater, mining waste water, coal washing water from coking processes and coal mining.
- Wastewater containing toxic chemicals, such as industrial waste water from the chemical industry, electroplating and foundry producing metal castings.
- Industrial wastewater.
- Wastewater containing radioactive substances, such as wastewater from nuclear power plants, radioactive mines, and nuclear fuel processing plants.
- Cooling water production, such as wastewater from thermal power plants and steel mills (Musingafi & Tom, 2014).

2.5.2.2 Household pollution sources

Household pollution sources mainly come from cities. It refers to various forms of sewage discharged in the daily life of residents, such as washing clothes, bathing, and washing urinals. The organic matter of domestic sewage is decomposed and discharged into the water bodies. The sewage is grey with poor transparency, has a special smell and contains organic matter, detergent residue, chloride, phosphorus, potassium, sulphate other chemical substances (Halder & Islam, 2015).

2.5.2.3 Agricultural pollution sources

Sources of agricultural pollution mainly refer to the pollution caused by the inappropriate use of pesticides and fertilisers. Activities such as long-term abuse of organochlorine pesticides and organic mercury pesticides, pollution of surface water, aquatic organisms, fish, and shellfish that will have high pesticide residues, as well as biological enrichment of food, will endanger human health and life (Chakraborty et al., 2013).

2.5.3 Analysis of pollutants in rivers

Pollution of urban rivers comes from domestic wastewater, industrial wastewater, early-season rainwater, and urban wastewater. There are many types of pollutants in rivers, including organic pollutants, inorganic pollutants, phytonutrients, and heavy metals in water. According to the pollution situation of urban rivers, the above pollutants are analysed as follows (Chakraborty et al., 2013):

2.5.3.1 Organic pollutants

Common organic pollutants in rivers include phenols, aldehydes, sugars, polysaccharides, proteins, and oils. During the biological oxidation and decomposition of these pollutants in water, large amounts of DO must be consumed. When the amount of oxygen supplied to water is not enough, the oxidation process will stop, causing anaerobic fermentation of organic substances, producing stench, polluting the environment and poisoning the aquatic life. Over time, aquatic organisms in the water die off, exacerbating water degradation and creating a vicious cycle.

These organic pollutants come from municipal and industrial wastewater. In particular, domestic wastewater mainly includes human faeces and detergents; faeces containing a high content of BOD in addition to pathogenic microorganisms, and detergents containing diffused phosphates. Sources of industrial pollution are mainly concentrated in the dyeing and finishing processes in the textile industries, leather manufacturing processes, food processing, papermaking, electroplating and the gas pollution production industries, such as chemical production plants (Radwan et al., 2017).

2.5.3.2 Inorganic pollutants

All types of toxic substances (or energy) that degrade water quality, biotic communities, and sediment quality can be termed as water contaminants. Water pollutants from the chemical point of view of non-toxic inorganic substances are acids, alkalis and general inorganic salts (Radwan et al., 2017).

2.5.3.3 Eutrophication (plant nutrients)

Eutrophication is the process whereby a waterway traps a lot of dissolved nutrients such as nitrogen and phosphorus, which leads to the development of aquatic vegetation resulting in a deterioration of dissolved oxygen. Eutrophication leads to a deterioration in water quality, which leads to cyanobacteria growth on the surface of the water where green algae is the dominant species. This obscures the sun and underwater algae can therefore not receive sunlight and breathe in oxygen, and the water becomes a biological death phenomenon due to lack of oxygen (Tang et al., 2020). Accumulation of organic matter under anaerobic decomposition conditions will produce toxic gases and some plankton will produce biological toxins that are harmful to fish. Because eutrophic water contains nitrate and nitrite, long-term consumption of these substances above a certain water level, can also lead to toxic disease. In addition, the corpses of aquatic organisms cause water odours, affecting the ecological environment and the quality of life of city residents (Jiang et al., 2016).

2.5.3.4 Heavy metals in water

Heavy metals generally refer to a density of greater than 5 g/cm^3 on the periodic table. Metallic elements whose atomic number is greater than 20 mainly refer to the heavy elements with significant biological toxicity such as mercury, cadmium, lead, and refer to the general heavy metals with a certain toxicity, such as zinc, copper, iron and tin. As long as there are trace heavy metals in natural water, toxic effects can be produced, and the microorganisms cannot degrade heavy metals, and heavy metals can be converted into more toxic compounds (Kannan et al., 2021).

The heavy metals in rivers come mainly from two sources: first, heavy metals are widely distributed substances in the earth's crust, which are distributed in the water through the migration cycle of the natural environment; second, non-ferrous metals are widely used in the production and life of human beings. There are different weighty metal contamination, like the burning of petroleum derivatives, mining and refining, and the release of waste water, squander gas and waste build-up from heavy metal industrial enterprises (Jamshaid et al., 2018).

2.6 Effects of pollution on the self-purification capacity of a river

2.6.1 Bacterial growth due to organic matter pollution

When organic matter enters the river, it becomes a source of energy for the decomposition of microorganisms in the water. This excess energy leads to an exponential increase in the number of bacteria in the decomposers and the microorganisms consume DO through respiration. As the population increases, more DO is consumed. When organic matter is depleted, the population will begin to die at some point (Devi et al., 2017). In theory, the microorganisms will gradually die until there are no aerobic substances left. Obviously, the degradation of organic matter in the presence of bacteria will lead to a decrease in oxygen levels, and the introduction of excess organic matter can lead to complete oxygen depletion (Nugraha et al., 2019).

Figure 2.1 shows fluctuations of algae versus bacteria over flow time after pollution is introduced in the water.

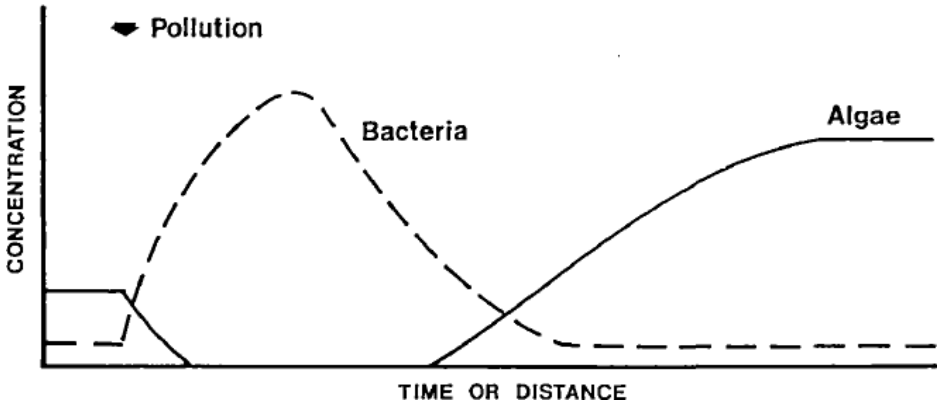

Figure 2.1 Bacteria and algae – Concentration vs time or distance (Whitehead & Lack, 1982)

2.6.2 Pollution impact on dissolved oxygen and biochemical oxygen demand fluctuations over flow time or distance

Figure 2.2 presents the impact pollution has on the fluctuations of DO and BOD over a given flow distance or time in a river. When the DO in the surface water body is exploited by the BOD loading of the contaminant, its level drops drastically, and in severe instances, the water becomes septic (critical point) and ends up with a bad smell. The depletion of DO happens because of the high demand for oxygen by the bacteria responsible for decomposing the pollutants. In order for the surface water to recover from this contamination, it depends on the rate of re-aeration or reoxygenation using the atmospheric oxygen (Das et al., 2016).

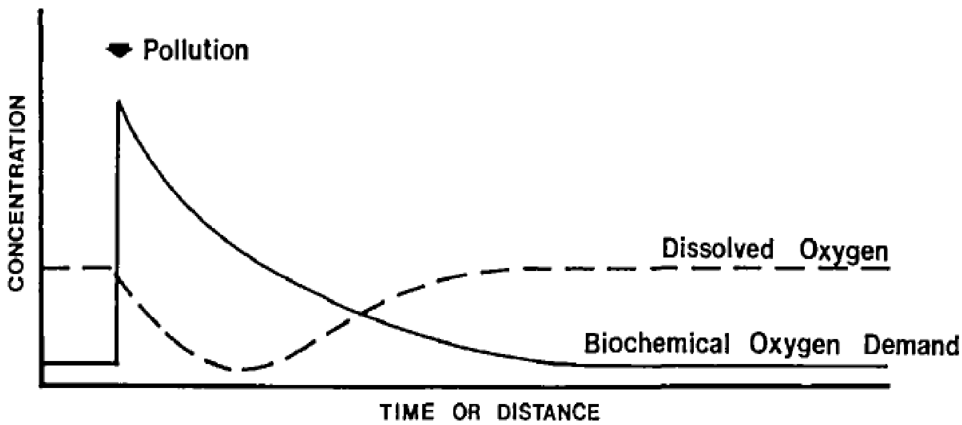

Figure 2.2 Dissolved and biochemical oxygen demand – Concentration vs time or distance (Whitehead & Lack, 1982)

2.6.3 Zones of pollution in a river undergoing self-purification

A polluted stream undergoing self-purification can be divided into the following pollution zones:

a. Decomposition zone
b. Septic zone
c. Recovery zone
d. Clean zone

Figure 2.3 shows the zones of pollution along a river stream.

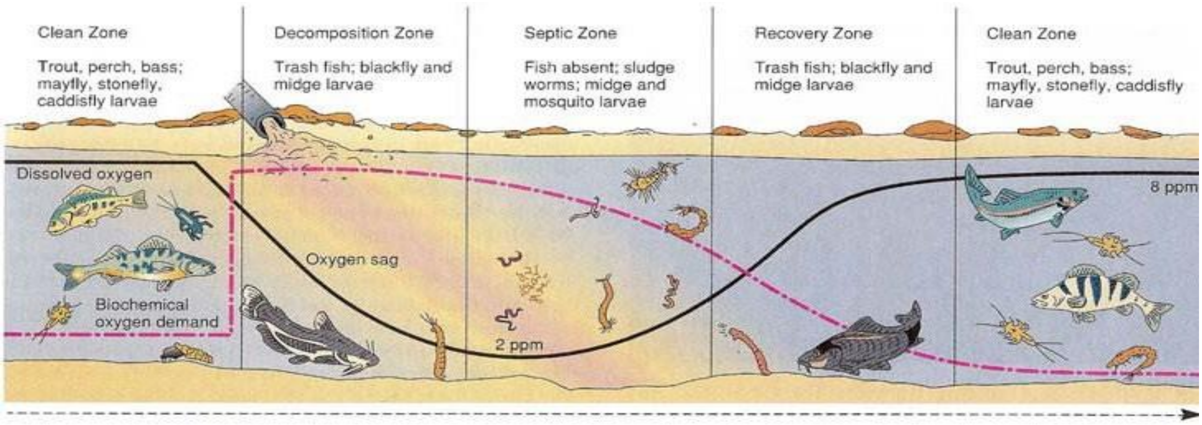

Figure 2.3 Zones of pollution along a river stream (Garg, 2006)

Decomposition zone: This is a zone located within a certain length below the point where the wastewater is discharged into the river. It is characterised by the darkening of the water and the formation of sludge deposits at the bottom of the turbines. The DO drops to approximately40% of the saturation value. The carbon dioxide content increases. Reoxygenation occurs at aslower rate than deoxygenation in this zone. These conditions are not conducive to the development of aquatic organisms, and as the algae die, fish life can feed on fresh organic matter (Das et al., 2016).

Septic zone: This is a heavily polluted zone. It becomes greyer and darker than the previous zone. The DO concentration drops to zero, and anaerobic conditions will occur with the release of methane, carbon dioxide, hydrogen sulphide and other gases. DO rose back to its original level (about 40%). In this area, bacterial colonies will flourish at the top. Anaerobic bacteria will replace aerobic ones, while protozoa and fungi will disappear and reappear. Fish life will no longer exist. Algae and tubifex are also mostly non-existent (Das et al., 2016).

Recovery zone: The river tries to recover from its degraded state to its original state. The water becomes clear and the algae reappears. When the mushrooms decrease, BOD decreases and the DO content increases to more than 40% of the saturation value. Protozoa, rotifers, crustaceans and large plants such as sponges and mosses also reappears (Das et al., 2016).

Clean zone: The river returns to its original state and the DO rises to saturation (Das et al., 2016).

2.7 Water quality modelling

Modelling water quality began with the development of the DO sag by Streeter and Phelps in 1925. The models has been used since then to relate point and nonpoint pollutant discharges to environmental conditions and criteria in the context of mass load allocations and to determine total maximum daily loads (Maamar et al., 2014).

Oxygen resources determine a stream's ability to receive and oxidise sewage. It is the balance between these resources and the demand placed upon them by organic pollutants carried along with a stream that determines the condition of a polluted stream at any given time. In the absence of new pollution, this demand is a progressively decreasing one, as the resources of the stream are composed in part with an influx of oxygen from the atmosphere, which is the state of balance that determines what the stream is like at any given moment (Ahmad & Barzinji, 2019).

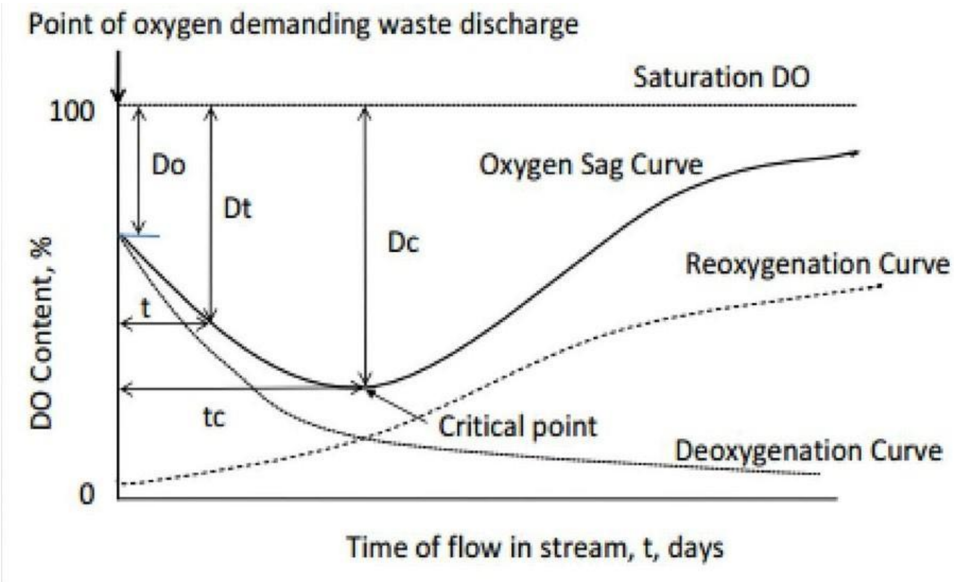

Figure 2.4 River oxygen sag curve (Garg, 2006)

Equations 2, 3 and 4 explain how BOD concentration and DO deficit are derived from Figure 2.4.

$$\frac{dD}{dt} = k_1 L_t - k_2 D \tag{2}$$

$$L_t = L_0 . e^{-k_1 t} \quad (3)$$

$$D = \frac{k_1 L_0}{k_{1-} k_2} . (e^{-k_1 t} - e^{-k_2 t}) + {}_0 . e^{-k_2 t} \quad (4)$$

Where:

D_0 = initial DO deficit;

D = the DO deficit;

k_1 = the BOD degradation constant;

k_2 = the atmospheric re-aeration constant;

L_t = the BOD concentration;

L_0 = the ultimate BOD; and

t = the hydraulic retention time.

The development of Equation 4 is based on two assumptions: a) at any instant, the rate of deoxygenation is directly proportional to the amount of organic material that can be oxidised present in the water, and b) the rate of reoxygenation is directly proportional to the DO deficit. Mathematical expressions for these assumptions are shown in equations 5 and 6.

$$\frac{dD}{dt} = k_1 (L_0 - L_t) \quad (5)$$

$$\frac{dD}{dt} = -k_2 D \quad (6)$$

Where,

$\frac{dD}{dt}$ = the net rate of change in the DO deficit; and

L_t = the BOD at any time t.

Combining the two differential equations and integrating between the limits of *t* is zero at D_0 and *t* is any time-of-travel below D_0 yields the basic equation (Equation 4) as developed by Streeter and Phelps.

Table 2.2 outlines values of reoxygenation coefficients for different type of water bodies at 20 ˚C.

Table 2.2 Values of reoxygenation coefficient (k_2) at 20 ˚C (Garg, 2006)

Description number	Type of water body	Value of k_2 at 20 ˚C
1	Small ponds and backwaters	0.05 – 0.10
2	Sluggish streams, large lakes and impounding reservoirs	0.10 – 0.15
3	Large streams of low velocity	0.15 – 0.20
4	Large streams of normal velocity	0.20 – 0.30
5	Swift streams	0.30 – 0.50
6	Rapids, waterfalls	> 0.50

Efforts to build new and improved water quality models to solve the original shortcomings of Streeter and Phelps model continued after 1925. The Streeter and Phelps model adaptations are still among the most regularly used models. However, the models for water surface quality have gone through three major periods of development (Hellweger, 2015).

The Streeter and Phelps models were modified and further refined throughout the first primary stage, which lasted from 1925 to 1965. The study focused on relationships between various components of river water quality, such as hydrodynamic transmission, sediment oxygen demand, and algae photosynthesis and respiration. The models used during this time were one-dimensional steady-state models based on BOD–DO modelling, and they were successful in predicting water quality (Wu & Yu, 2021).

Between 1965 and 1995, the second stage was an improvement period marked by rapid model development. Prior to 1975, not only DO but also additional components were included (Fan et al., 2012). This included phytoplankton and zooplankton. Different systems were considered, as well as the correlations between biologic growth rate and nutrients, sunlight, and temperature. Two-dimensional and three-dimensional versions of these models were also created. Through that, sediments became a key factor to consider in the interaction processes of these models. After 1995, the third stage was a broadening or deepening stage.

Pollution models have been created to aid in the control of pollution sources. However, wet and dry air depositions of nitrogen compounds and heavy metals have been shown to have an increasing impact on river water quality (Wu & Yu, 2021).

Furthermore, many researchers across the globe have worked extensively to empirically relate the reoxygenation rate k_2 to the hydraulic parameters of the river. The purification capacity indicators are believed to be influenced on a significant scale by hydraulic parameters such as the flow depth, the width and the velocity of the streams. The following equations are some of the hydraulic-driven models developed by various studies across the world – where H is the hydraulic depth, v is the velocity of the stream and T is the actual measured temperature of the stream water, as cited by Chiejine et al. (2015).

Reoxygenation for a slightly slope river, developed by O'Connor (1958):

$$k_2 = \frac{10.046v^{2.696}}{H^{3.902}} \tag{7}$$

Reoxygenation for a medium slope river, developed by Churchill (1962):

$$k_2 = \frac{1.923v^{1.325}}{H^{2.006}} \tag{8}$$

Reoxygenation by considering temperature as an influencing factor, developed by Churchill (1958):

$$k_2 = \frac{5.06v^{0.919}}{H^{1.673}}(1.024)^{T-20} \tag{9}$$

With the values of deoxygenation k_1 and reoxygenation k_2 available, the self-purification factor f can be determined by dividing k_2 by k_1 (k_2/k_1). This value represents the ratio in which the two processes of oxygenation are proportionate to one another, thus indicating the effectivenessof a river to purify itself (Obianyo et al., 2022). The typical values are shown in Table 2.3.

Table 2.3 Values of self-purification constant (*f*) at 20 ˚C (Garg, 2006; Ugbebor et al., 2012)

Description number	Type of water body	Value of f at 20 ˚C (day^{-1})
1	Small ponds and backwaters	0.05 – 0.10
2	Sluggish streams, large lakes and impounding reservoirs	0.10 – 0.15
3	Large streams of low velocity	0.15 – 0.20
4	Large streams of normal velocity	0.20 – 0.30
5	Swift streams	0.30 – 0.50
6	Rapids, waterfalls	> 0.50

2.8 Statistical data analysis

When raw data is collected in the field, it makes no sense until a mathematical analysis is performed on it to gain insight and interpretation. The data itself is very diverse in its form.

There are four different types of data: nominal, ordinal, interval, and proportional. While nominal and ordinal data are categorical, interval and proportional data are continuous (Devore, 2021).

In statistics, regression analysis encompasses a variety of techniques for modelling and analysing multiple variables, where the focus is on the relationship between a dependent variable and one or more independent variables. Specifically, the regression analysis helps to understand how the typical value of the dependent variable changes when one of the independent variables changes, while the other independent variables are held constant (Kumari & Yadav, 2018). Usually, the regression analysis estimates the conditional expectation of the dependent variable, taking into account the independent variables, that is, and the mean of the dependent variable when the independent variables are fixed. Less often, the focus is on the quantum set or other positional parameters of the conditional distribution of the dependent variable with independent variables (Gupta et al., 2017). In all cases, the estimation objective is a function of the independent variables called the regressor. In regression analysis, it is also interesting to describe the change of the dependent variable around the regression function, which can be described by a probability distribution (Jain et al., 2016).

Regression analysis is widely used for prediction and forecasting, where its use has a significant overlap with the domain of machine learning. Regression analysis is also used to understand which of the independent variables are related to the dependent variable and to explore patterns of these relationships. In limited cases, regression analysis can be used to infer a causal relationship between the independent and dependent variables. However, this can lead to delusions or misleading relationships, so it should be exercised with caution (Arayesh, 2015).

A lot of regression analysis techniques have been developed over the years. Familiar methods such as linear regression and ordinary least squares regression are parametric, where the regression function is determined by a finite number of unknown parameters that are estimated from the data. Non-parametric regression refers to the technique that allows the regression function to be within a definite set of functions, which may have infinite dimensions (Zsuzsanna & Marian, 2012).

The performance of regression analysis methods in practice depends on the form of the data generation and how it relates to the regression approach used. Since the true form of the data generation process is often unknown, regression analysis often depends to some extent on making assumptions about the process. These hypotheses can sometimes be tested if large amounts of data are available. Regression models for prediction are often useful even when assumptions are moderately violated, although they may not perform optimally (Uyanik & Güler, 2013).

2.8.1 Microsoft Excel tool

The Analysis ToolPak in Microsoft Excel includes operations such as Analysis of Variance (ANOVA), correlations, descriptive statistics, histograms, percentiles, regression, solver, and t-tests, in addition to fundamental spreadsheet functions. The fact that Excel is so freely available is the key rationale for utilising it for statistical data analysis (Ajibade et al., 2021).

2.8.2 Correlation

Correlation should be employed whenever the relationship between two continuous variables is of interest. Pearson's correlation coefficient, *r*, can be utilised for normally distributed data. The proportion of variation explained by the association, R^2, is the coefficient of determination. Spearman's rank correlation can be employed when the data is not regularly distributed. If the data has many ties (same values), Kendall's *tau* can be employed (Schober et al., 2018).

2.8.3 Regression analysis

Regression analysis is usually applied to naturally occurring variables, but it can also be applied to experimentally modified variables (Foong et al., 2018). Evaluating for the number of instances, checking the accuracy of data entry, looking for missing data, checking for outliers, and checking for normality, are all part of the regression analysis process. The assumption of linearity is also included in the regression analysis (Abulela & Harwell, 2020). Linearity describes the link between the independent variables and the dependent variables as a straight line. Because regression analysis only looks for a linear relationship between the independent and dependent variables, this assumption is crucial. Any nonlinear link between the independent and dependent variables is not taken into account. A bivariate scatterplot can be used to check for linearity between independent variable and dependent variable (i.e., a graph with the independent variable on one axis and the dependent variable on the other). The scatter plot will be oval if the two variables are linearly connected. Equation 10 presents the general form of a basic linear regression (Mishra & Min, 2010):

$$yi=\alpha+\beta xi+\varepsilon i \qquad (10)$$

Where,

α is the intercept, β is the slope, and ε is the error term, which takes up the part of the response variable, yi, that is unpredictable. The x and y represent data quantities from the sample or population in issue and the unknown parameters to be estimated from the data (Foong et al., 2018).

2.8.4 Multiple regression analysis

Standard multiple regression is similar to simple linear regression in that it predicts the dependent variables using numerous independent variables. Standard multiple regression indicates how effectively each independent variable predicts the dependent variable while adjusting for the other independent variables, in addition to telling one the predictive value of the entire model (Uyanik & Guler, 2013).

The significance levels for each independent variable show whether that independent variable, in addition to the other independent variables, is a significant predictor of the dependent variable. As a result, in multiple regression, an independent variable that is a significant predictor of a dependent variable in basic linear regression may not be significant, that is, when other independent variables are added into the equation (Abulela & Harwell, 2020). This is due to the fact that the variance shared by the first independent variable and the dependent variable may overlap with the variance shared by the second independent variable and the dependent variable. As a result, the first independent variable is no longer uniquely predictive, and hence does not appear significant in multiple regression. As a result, a highly significant R^2 can be obtained when none of the independent variables are significant (Mishra & Min, 2010).

2.8.5 Non-linear regression

There is generally an appropriate theory for developing a mechanistic model in scientific applications (Archontoulis & Miguez, 2014). In the unknown parameters, such models are frequently nonlinear (Choi et al., 2015). Nonlinear models are more difficult to fit, necessitating iterative approaches that begin with a guess of the unknown parameters. The current guess is changed with each iteration until the algorithm converges (Ali & Bhaskar, 2016).

2.8.6 Model calibration and validation of water quality data

Theoretical and empirical mathematical models can be distinguished. Theoretical models are best used when all of the underlying processes are well understood and do not vary over time.

Central University of Technology, Free State

Theoretical models, on the other hand, are typically more complex, requiring long periods of observation for calibration, a large number of parameters and variables for measurement, and long time frames for model validation. As a result, the utility of theoretical models in water quality modelling processes is limited (Himesh et al., 2000). On contrary, empirical models (statistically based models) are useful for determining the relationship between time variable parameters. For calibration, they require far fewer time frames and variables. They arepowerful tools for explaining cause-and-effect correlations between parameters, and they are still effective when there is not enough data (Daggupati et al., 2015).

Empirical models, based on their nature, cannot be directly transferred to other geographic regionsor time scales. This is the case when empirical models are based on data collected from individual site surveys. Because water quality parameters vary by location and time, they are not subject to universal laws. Aquatic systems are still poorly understood; therefore, empirical methods are more realistic in the endeavor to comprehend them. The numerical means of testing the accuracy of a model and or comparing its performance is referred to as model validation. If two models are being compared, for example, the model with the lowest error estimate may be judged to be the better model in the given situation, (Smarzyńska & Miatkowski, 2016).

2.8.6.1 Sum of squares due to error

The overall deviation of the response values from the fit to the response values is measured by this statistic. According to Wikipedia, it is also known as the sum of squared estimate of errors, and is abbreviated as SSE. A value that is closer to 0 suggests that the fit is better (Kim 2018).

$$\mathrm{SSE} = \sum_{1} w_i(\gamma_i - \hat{\gamma}_i)^2 \tag{11}$$

2.8.6.2 The R-square

This number indicates how well the fit explains the variation in the data. R-square is the square of the correlation between the response values and the projected response values, to put it another way. It is also known as the multiple correlation coefficient squared or the multiple determination coefficient. The R-square is the ratio of the sum of squares regression (SSR) to the total sum of squares (SST) (Rawski et al., 2016). The term *SSR* is defined as:

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \tag{12}$$

Where,

$$SST = SSR + SSE \tag{13}$$

SSE and SST are defined in Equations 14 and 15.

$$\text{SSE} = \sum_{1} w_i(\hat{\gamma}_i - \bar{\gamma}) \tag{14}$$

$$\text{SST} = \sum_{1} w_i(\gamma_i - \bar{\gamma}) \tag{15}$$

R-square can be any number between 0 and 1, with a higher value suggesting a better match. An R2 score of 0.8234, for example, indicates that the fit accounts for 82.34% of the overall variation in the data around the average. R-square may increase as the number of fitted coefficients in the model grows, yet the fit may not improve. The degrees of freedom adjusted R-square statistic should be utilised to avoid this problem. It is important to note that equations without a constant term can have a negative R-square. R-square is negative if it is defined as the proportion of variation explained by the fit and the fit is really poorer when fitting a horizontal line. R-square cannot be understood as the square of a correlation in this circumstance (Akossou & Palm, 2013).

2.9 South African water quality management system

Water quality management in South Africa has progressed over time, and the Department of Water and Sanitation has been working on an Integrated Water Quality Management system for several years. Initially, management concentrated on reducing pollution sources by enforcing general and effluent regulations. However, as the cumulative consequences of various effluent sources exceeded the assimilative capacity of receiving water bodies, there was a shift in focus to include the receiving ecosystem. The National Water Act developed the concept of source-directed controls and resources-directed measures, building on the understanding of pollution control through effluent standards and resource managementthrough receiving water quality targets (CSIR Environmental Services, 1995).

Finding a suitable balance between safeguarding water resources and utilising water resources for the country's economic and social improvement is at the heart of the dilemma that South Africa faces. One of the goals of developing a Quality Management Policy and an Integrated Water Quality Management Strategy was to achieve this balance between protection and usage, as well as to ensure that environmental impacts and functions are successfully remedied (Molobela & Sinha, 2011).

2.10 Summary

In this chapter, the literature review was presented. First, the self-purification phenomenon was discussed to highlight the background, the rationale and the fundamental principles of water quality modelling. The chapter further elaborated on the self-purification indicators associated with water quality modelling. Pollution effects on natural water masses were also discussed in conjunction with statistical data analysis and the water quality management system. The next chapter focuses on the methodology employed to achieve the aim and objectives of the study.

CHAPTER 3

STUDY METHODOLOGY AND PRACTICAL SETUP

3.1 Introduction

In chapter 2 a detailed review of the literature was presented to give an overview ofthe current knowledge and status quo of the water quality modelling and its impacts in the water resource management communities around the concerned study area of the Mooi River catchment. Chapter 3 focuses on the methods employed to carryout the study, namely the study area, sampling points, data collection, laboratory analysis methods as well as the recording of results and findings.

3.2 Study area

The Mooi River catchment is formed by Mooi River itself as the main river, together with Wonderfonteinspruit and Loopspruit as tributaries (Figure 3.1). The Wonderfonteinspruit confluxes with the Mooi River upstream section from the north-eastern side, creating one volume of water mass concentration. The downstream section of the Mooi River is further joined by the Loopspruit, which also transfers its quality through its quantity into the Mooi River. Along the length of Mooi River lies three storage dams, namely the Klerkskraal, Boskop and Potchefstroom dams receiving water directly from the Mooi River (Barnard et al., 2013).

The capacities of the above dams are 8 Ml, 21 Ml and 2 Ml, respectively. The supply of water to the entire Tlokwe Local Municipality population is by the water stored in these dams through the Tlokwe Local Municipality water purification works. The supply from Boskop Dam to the purification plant is through cemented canals passing through the Potchefstroom city by natural gravitation. Raw water is also sourced directly from the Potchefstroom Dam for purification (Annandale & Nealer, 2011).

The quantity of water is for population sufficiency and the quality is of health importance. With fresh water being a very imperative resource of life to be conserved, all its sources must be monitored and managed as it is becoming scarce in some parts of the world, including South Africa. The quality of water is of great degree to human health. All pollution sources affecting the quality of water in natural water courses should be mitigated if not diminished (Venter et al., 2013).

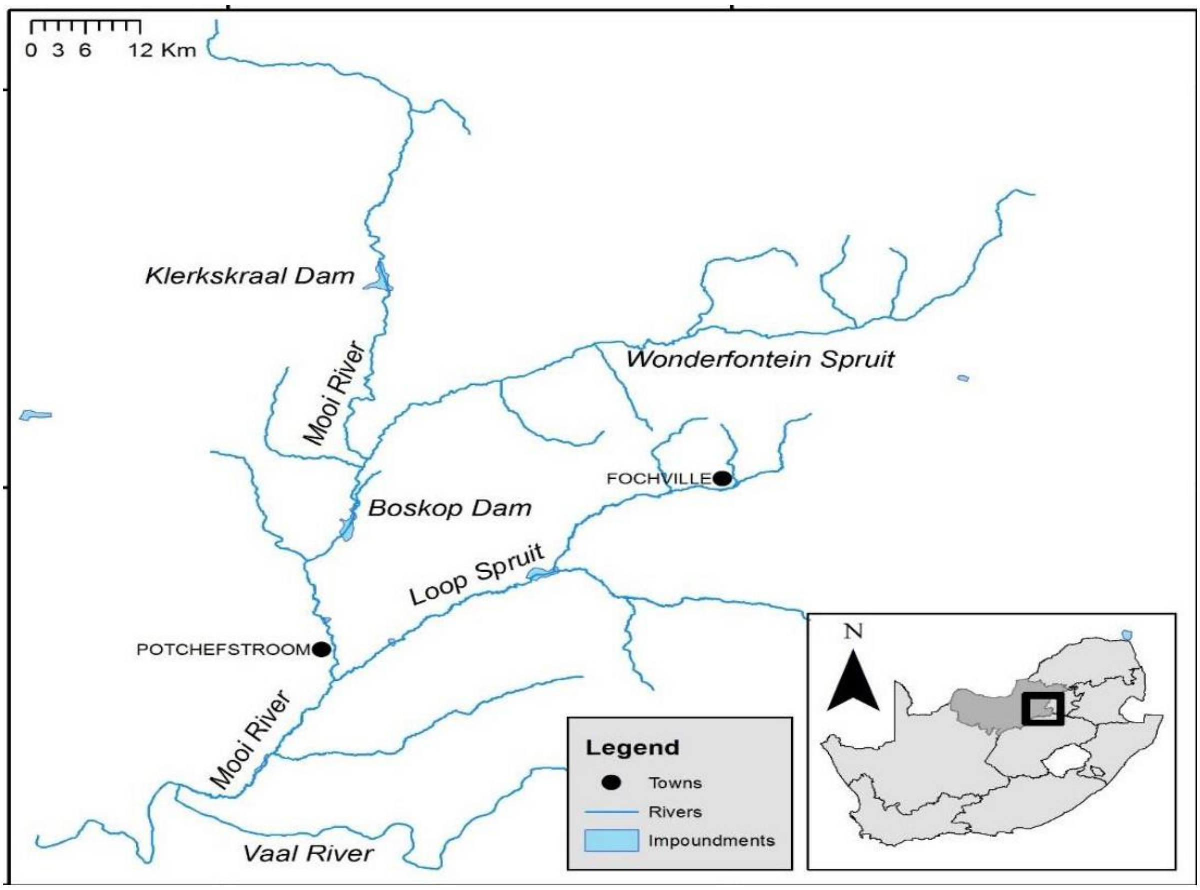

Figure 3.1 Map showing Mooi River catchment and its tributaries (Dube, 2019)

The Wonderfonteinspruit, a tributary to Mooi River, is known by researchers to be a much polluted river containing contaminants from the gold mining sectors and contaminants from the Flip Human WWTW, thus influencing the quality of the Mooi River at the point of their confluence. Furthermore, with the effluent from the Kokosi WWTW, the Loopspruit subsequently repeats this influence downstream of the Mooi River. This implies that the quality of the Mooi River is further compromised (Koekemoer et al., 2021).

3.3 Methodology

Figure 3.2 presents the methodology flow diagram of this study. The flow diagram will be followed by a detailed breakdown of the methodology that was employed for this study.

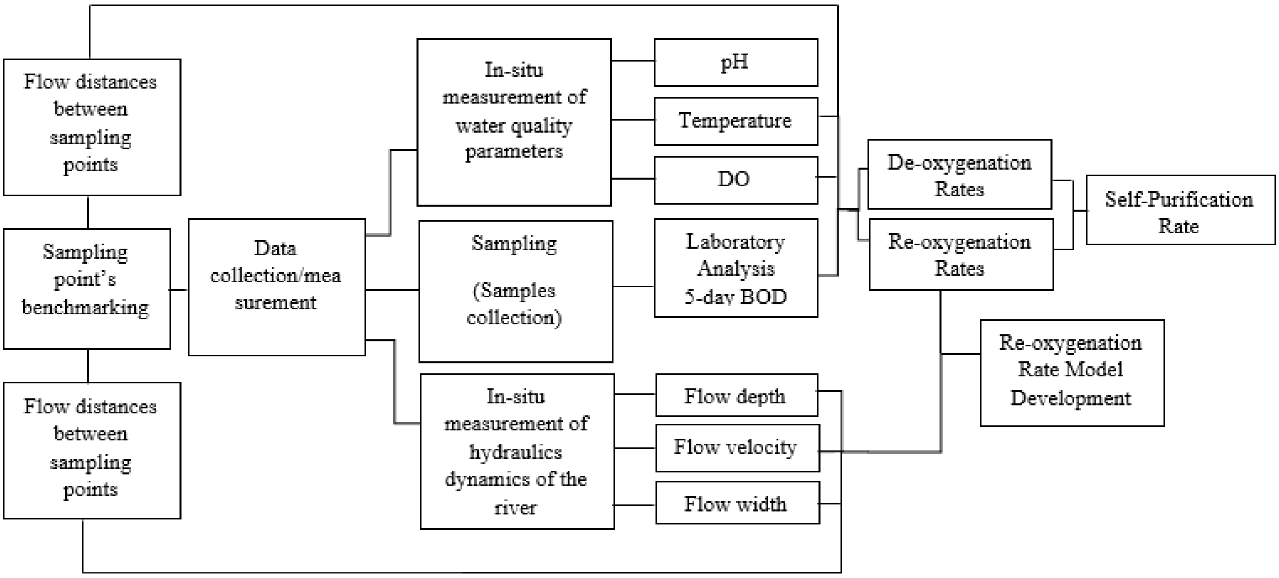

Figure 3.2 Methodology flow diagram

3.3.1 Data collection

The field activities entailed the following: reconnaissance visits and field sampling visits. The field visits enabled a necessary familiarization with the study area and further determination of other pollution sources of the river. Data was collected at reasonable seasonal intervals. One part of the data was determined in situ, while the other part was determined through the laboratory analyses. In situ data was subdivided into physical water quality parameters and hydraulic parameters. The physical parameters that were measured in situ were temperature and hydraulic parameters. The hydraulic parameters that were determined in situ were river velocity, river depth and width. Parameters such as DO and BOD, were further determined in the laboratory, classified as chemical water quality parameters. Furthermore, water quality data was accessed from the website of the Department of Water and Sanitation. To record the impact of weather variability on water quality, samplings from both the dry and rainy seasons were carried out during the following months:

Dry season: April – October (2021)

Rainy season: November – March (2020–2021).

Table 3.1 presents the data collection period with specific dates.

Table 3.1 Data collection period

Rainy season data collection	Dry season data collection
NOVEMBER 2020 2 November	OCTOBER 2020 15 October
DECEMBER 2020 1 December	APRIL 2021 6 April
JANUARY 2021 11 January	JUNE 2021 17 June

Figure 3.3 shows the sampling points.

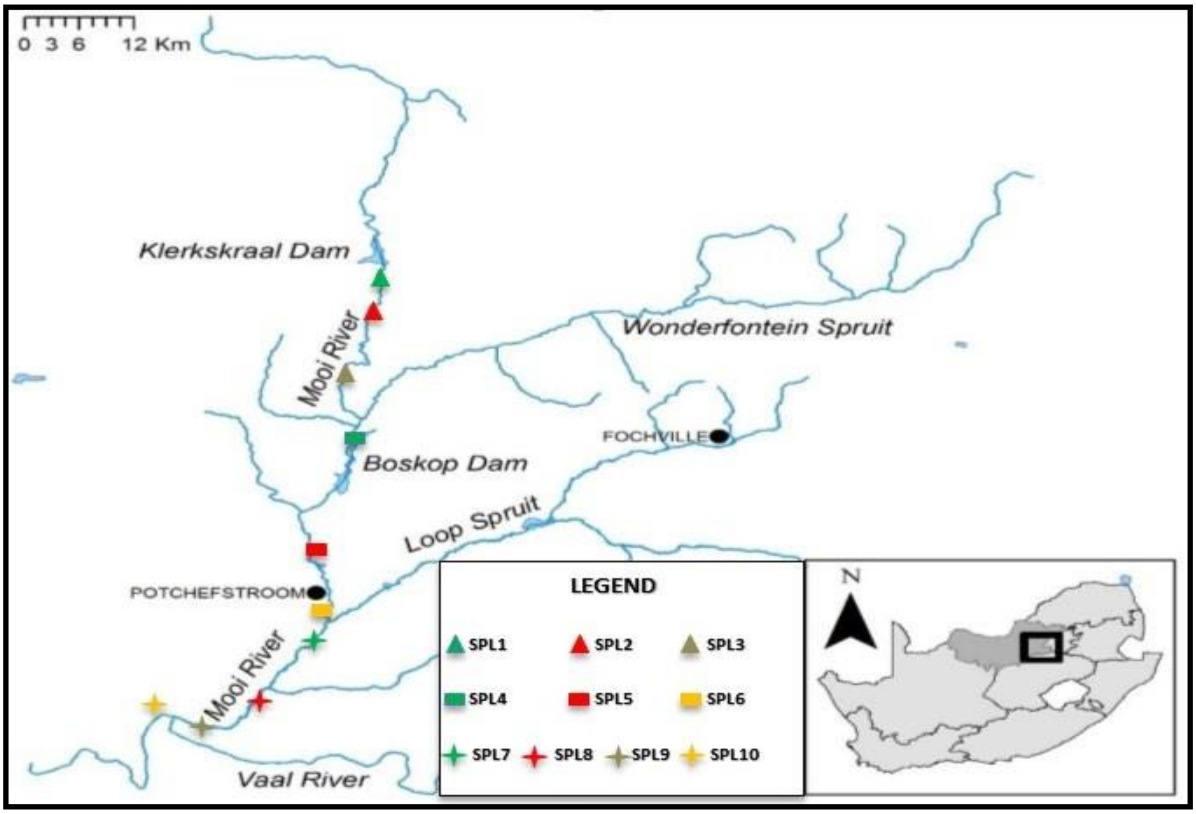

Figure 3.3 Map showing the sampling points

Figure 3.4 presents a detailed flow length of Mooi River from sampling point 1 at Klerkskraal Dam to the last Sampling Point 10 at the Vaal River confluence. The figure also indicates the extent of the non-point pollution sources as well as the point pollution sources influencing the Mooi River's water quality.

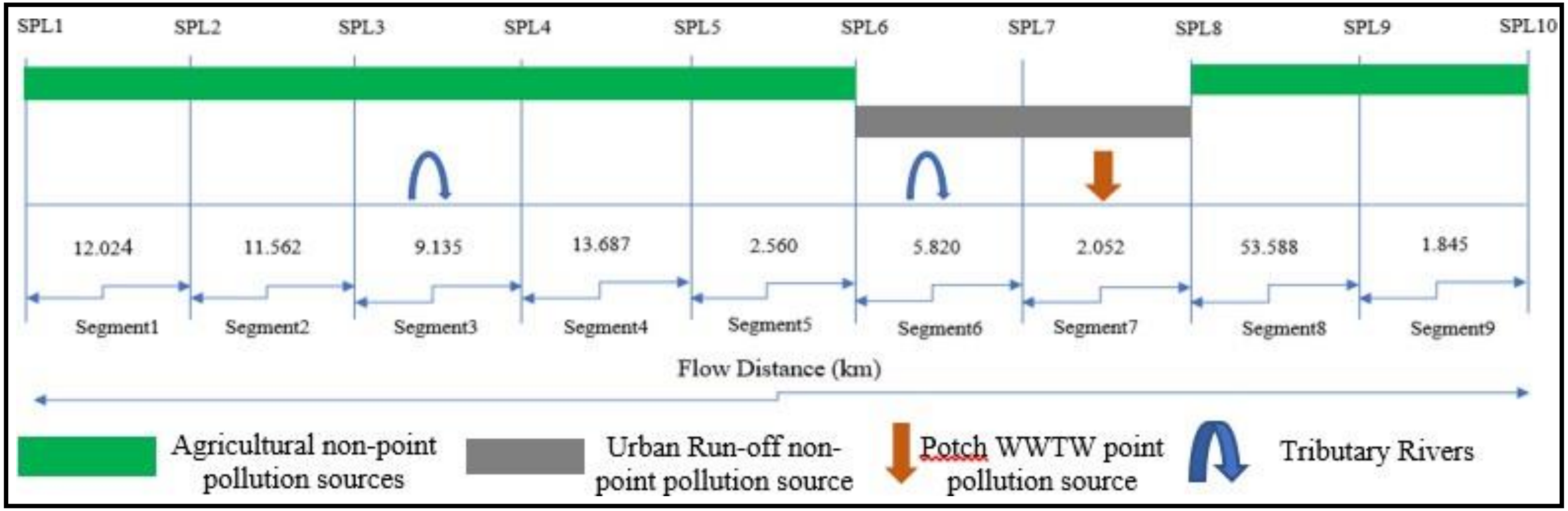

Figure 3.4 Map showing the detailed flow length and the non-point and point pollution sources

Table 3.2 Sampling points and their respective descriptions

Sampling point	Sampling point description	Reason for benchmarking as point of interest
SPL1	Klerkskraal Dam Outlet	To analyse water quality and set it as a starting point quality benchmark.
SPL2	Mooi River Bridge	To measure the progress on the pollution effects on the reoxygenation because the river flows over a large area of agricultural farmlands, which are considered as non-point pollution sources.
SPL3	Mooi River before Boskop Dam and before Wonderfonteinspruit confluence	To measure the reoxygenation progress of the river after a flow distance of 23 km.
SPL4	Boskop Dam inlet/outlet	To analyse how Wonderfonteinspruit had impacted the quality of Mooi River at the point of confluence and to analyse the overall self-purification of a segment between Klerkskraal Dam and Boskop Dam. This is performed to also set a quality benchmark for flow segment between Boskop Dam and Potchefstroom Dam.
SPL5	Potchefstroom Dam inlet/outlet	To analyse the overall self-purification strength of the catchment over a flow segment between Boskop Dam and Potchefstroom Dam and set the water quality as a benchmark for the following flow segment between Potchefstroom Dam and the final sampling point of the catchment.
SPL6	Mooi River at Potchefstroom city Mooi River Mall	To assess how Potchefstroom city pollution impacts the Mooi river.
SPL7	Mooi River + Loopspruit River before the Potchefstroom WWTW* effluent dilution	To assess the quality of the water after Mooi River confluxes with Loopspruit and right before it is mixed with the Potchefstroom WWTW effluent.
SPL8	Mooi River + Potchefstroom WWTW effluent	To assess the water quality of Mooi River after it is mixed with the Potchefstroom WWTW effluent.
SPL9	Mooi River + Potchefstroom WWTW effluent before the Vaal River	To assess the overall self-purification strength of Mooi River before it confluxes with the Vaal River.
SPL10	Mooi River + Vaal River confluence	To assess the quality of the Vaal River and determine any possible effects that Mooi River has on it.

*WWTW = Wastewater treatment works

3.3.1.1 Hydraulic parameters

Hydraulic parameters of the catchment were determined on the field. The width of the river was measured by means of a tape rule on both ends of the riverbanks as well as using Google Earth digital measurement tools The shape of the river cross section was assumed to be a semi-circle if the river is verydeep, therefore the height of the river was taken as half the width measured. The velocity of the river was measured by determining the time it takes for a floating object to travel a distance between two fixed points along a sectioned segment of river length. A stopwatch was used for this exercise.

Figure 3.5 Access of the river midpoint to measure hydraulic depth

3.3.1.2 Temperature

The temperature of the water was measured with the use of a DO meter.

pH and Acidity

pH was determined in-situ using a pH meter. The measurements were performed on all the collected samples to see how the rivers affect one another with the interchange of this acidity water quality parameter.

Figure 3.6 Field measurement of pH using a pH meter

3.3.1.3 Determination of dissolved oxygen and biochemical oxygen demand

The laboratory tests were carried out with the help of the Mid-Vaal Water Company. DO was measured on the field at every sampling point defined by Figures 3.3 and 3.4 and Table 3.2. The BOD was determined using the BOD_5 analysis method where the DO of a sample was measured before and after it was incubated at 20 ˚C for five days. The difference between the two dissolved oxygens (DOS) were taken as the BOD value of the sample.

Figure 3.7 Field measurement of dissolved oxygen and temperature using a dissolved oxygen meter

3.3.1.4 Ultimate biochemical oxygen demand

Ultimate BOD at all sampling points were to be determined in the laboratory using the BOD_5 method and a DO meter.

3.3.1.5 Dissolved oxygen saturation and dissolved oxygen deficits of the catchment streams

At each sampling point, the temperatures measured in the rivers were used to read off dissolved oxygen saturation (DOS) from Table 2.1 These values were further used to calculate and determine DO deficits of each catchment stream.

3.3.1.6 Time of travel

Time to travel from the upstream and downstream sampling and assessment points was determined through the distance between the sampling points and the velocity of flow between these points.

Figures 3.8 and 3.9 depict a normal day of sampling and data collection at the respective sampling points discussed in Table 3.2.

Figure 3.8 Sample collection at Mooi River before Boskop Dam

Figure 3.9 In situ dissolved oxygen measurement at Mooi River before the Potchefstroom wastewater treatment works

3.3.1.7 Calculating deoxygenation constant (k_1)

From Figure 2.4, it can be depicted that the rate at which the BOD in the water was decomposed was directly proportional to the amount of BOD present or remaining in the water, which means that the deoxygenation rate was high when the BOD level was high. Mathematically it is expressed as the following:

$$\frac{dL_t}{dt} \alpha \ L_t$$

$$\frac{dL_t}{d_t} = -k_1 \times L_t \tag{16}$$

$$\int_{L_o}^{L_t} dL_t = \int_{o}^{t} - k_1 L_t d_t$$

$$L_t = L_o \times e^{-k_1 t} \tag{17}$$

Equation 18 presents the BOD remaining in the water after any particular time (*t*) of decomposition. Thus, from the same equation, the deoxygenation constant k_1 can be derived by mathematically solving for k_1 as subject of the equation, as shown in Equation 18; L_o represents the initial/ultimate BOD in the water (initial DO – final DO).

$$k_1 = - l_n \left(\frac{L_t}{L_o} \right) \times \frac{1}{t} \tag{18}$$

The deoxygenation constant indicates the rate at which DO in the water is used through decomposition of organic matter. It is to be further utilised as a purification factor constant to determine the purification capacity of the catchment streams.

3.3.1.8 Calculating reoxygenation constant

The reoxygenation constant k_2 can be derived by using the DO deficits of the water on the upstream sampling points of the catchment determined in the field, together with the DO deficits determined in the downstream sampling points. The formula is derived from the rate relation between the DO deficit and the rate at which the atmospheric air enters the water (reoxygenation), as shown in Figure 2.4. The rate at which the atmospheric air enters the water is directly proportional to the DO deficit in the water; therefore, the following is mathematically computed:

$$\frac{dD}{d_t} \alpha D$$

$$\frac{dD}{d_t} = -k_2 \times D \tag{19}$$

$$\int_{Do}^{D} dD = \int_{o}^{t} -k_2 D d_t \tag{20}$$

$$D = Do \times e^{-k_2 t}$$

From Equation 20, the deoxygenation constant k_2 will be derived by mathematically solving for k_2 as subject of the equation, as shown in Equation 21:

$$k_2 = -l_n\left(\frac{D}{D_o}\right) \times \frac{1}{t} \tag{21}$$

3.3.1.9 Calculating the self-purification factor *f*

The capacity of the catchment to purify itself, can be computed from the deoxygenation and reoxygenation constants.

$$f = k_2 / k_1 \tag{22}$$

Reoxygenation coefficient k_2 modelling: The Microsoft Excel Equation Solver was used to develop the k_2 model equation by relating the calculated experimental k_2 to the stream velocity and stream depth. This was done by reducing the statistical standard deviation between the outcomes of the theoretically calculated k_2 and the outcomes of the k_2 model generated. The Microsoft Excel Solver interpolated for values of a, b and c presented by Equation 23 in order to find this ultimate minimum standard deviation between the theoretically calculated k_2 and the k_2 model values generated.

$$k_2 = a \frac{V^b}{H^c} \tag{23}$$

Where, V is stream flow velocity and H is hydraulic radius; the coefficients were determined by the Excel Solver; and k_2 is the dependent variable. These coefficients are the factors that change and define the different systems in different geographical environments. One of the reoxygenation coefficient models, proposed by Streeter et al. (Longe & Omole, 2012) is defined by Equation 24, while Equation 25 is known as the United States Geological Survey (USGS) equation (Langbein & Durum, 1967):

$$k_2 = 5.026\frac{V^{0.969}}{H^{1.673}} \tag{24}$$

$$k_2 = 11.6325\frac{U^{1.0954}}{H^{0.0016}} \tag{25}$$

Reoxygenation model development by Excel Solver: Figure 3.10 shows the Microsoft Excel Solver tool used to generate or develop the reoxygenation model k_2, using the actual calculated theoretical k_2 and the river hydraulic dynamics measured and presented in Tables 4.8 to 4.13. The model equation is set up to reflect the Froude number equation explaining the flow regime of a river in terms of its flow velocity and hydraulic depth and or hydraulic radius (Smithgall , 2019), as in Equation 23: [$k_2 = a\,\frac{V^b}{R^c}$].

The program interpolates for constants a, b and c, which will yield the minimum sum of squared standard deviations between the calculated k_2s and the hydraulic dynamics k_2s in question. It uses the respective flow velocities and hydraulic radiuses of every sampling point measured and provided as software equation inputs.

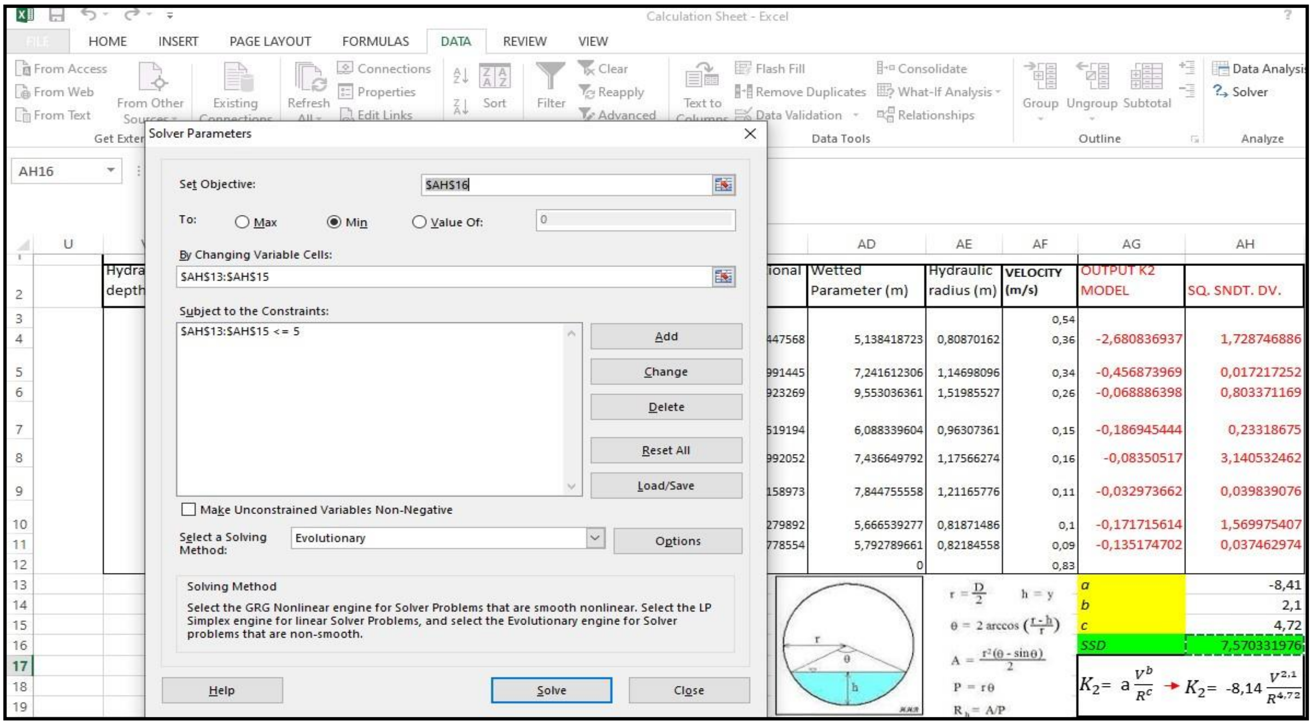

Figure 3.10 Excel Solver

3.4 Summary

This chapter discussed the methodology used in this study. The focus was on the methods employed to carry out the study, namely the study area, sampling points, data collection, laboratory analysis methods as well as the recording of results and findings. The next chapter presents the data collected and the laboratory results, followed by the analysis and discussions of the findings.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Chapter 3 presented the methodology employed to carry out the study from the methods used for data collection, data recording, data analysis and data processing for model development. Chapter 4 hereby presents the actual study data, the results of the data analysis, the results of model development as well as a discussion of the findings and observations fromthe results presented and analyzed.

4.2 Results

4.2.1 Self-purification results by water quality indicators

The measured data, the findings as well as the calculated purification indicators of all the sampling points, are presented in Tables 4.1 to 4.6. The tables present laboratory determined reoxygenation constants by water quality indicators.

The BOD was examined to decide on the sum of organic pollutants within the river system. BOD straightforwardly influences the sum of DO in rivers. The more prominent the BOD, the more quickly oxygen is depleted. This implies that less oxygen is accessible to aquatic organisms (microbes). Usually because of high-impact microbial and biochemical debasement of natural matter that shows in the water.

Table 4.1 November 2020 – Measured water quality indicators and la n capacity

Sampling point	Distance (km)	Tempera-ture (°C)	Saturation DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Distance (m)	Accumulated distance (m)	Time (days)	Deoxygena-tion constant K_1	Reoxygena-tion constant K_2	Self-purification factor, *f*
SPL1 – Klerkskraal Dam outlet	0	23.6	8.520	7.4	5.3	1.120	2.1	0.53	0	0	0.00			0
SPL2 – Mooi River Bridge	12.024	21	8.900	5.2	4.8	3.700	0.4	0.52	12 024	12 024	0.27	6.196	−4.465165149	−0.720651249
SPL3 – Mooi River before Boskop Dam	11.562	21.1	8.850	4.3	3.6	4.550	0.7	0.61	11 562	23 586	0.22	-2.551	-0.942647704	0.369529269
SPL4 – Boskop Dam inlet/outlet	9.135	19.5	9.200	7.4	5.4	1.800	2	0.6	9 135	32 721	0.18	-5.958	5.262543519	-0.883331134
SPL5 – Potchefstroom Dam inlet/outlet	13.687	23.2	8.560	7	6.1	1.560	0.9	0.17	13 687	46 408	0.93	0.857	0.153566537	0.17921035
SPL6 – Mooi River Mall	2.56	23.3	8.540	3.1	1.7	5.440	1.4	0.17	2 560	48 968	0.17	-2.535	-7.166672462	2.827072536
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	5.82	23.2	8.560	2.7	1.8	5.860	0.9	0.2	5 820	54 788	0.34	1.312	-0.220811508	-0.168322838
SPL8 – Mooi River + Potchefstroom WWTW	2.052	24.2	8.380	2.6	1.6	5.780	1	0.3	2 052	56 840	0.08	-1.331	0.173632685	-0.130465581
SPL9 – Mooi River before the Vaal River	53.588	23.8	8.440	4.7	3.9	3.740	0.8	0.35	535 88	110 428	1.77	0.126	0.245652356	1.950843162
SPL10 – Mooi River + Vaal River	1.845	26.7	8.030	5.2	4.6	2.830	0.6	0.34	1 845	112 273	0.06	4.580	4.439181702	0.969156324

Table 4.2 December 2020 – Measured water quality indicators and lal n capacity

Sampling point	Distance (km)	Tempera-ture (°C)	Saturation DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Distance (m)	Accumulated distance (m)	Time (days)	Deoxygena-tion constant k_1	Reoxygena-tion constant k_2	Self-purification factor, *f*
SPL1 – Klerkskraal Dam outlet	0	20.5	9.000	7.8	5.1	1.200	2.7	0.53	0	0	0.00			0
SPL2 – Mooi River Bridge	12.024	22.6	8.640	5.1	4.2	3.540	0.9	0.52	12 024	12 024	0.27	4.105	-4.042194169	-0.984701502
SPL3 – Mooi River before Boskop Dam	11.562	19.3	9.240	4.1	3.4	5.140	0.7	0.61	11 562	23 586	0.22	1.146	-1.699940363	-1.483903471
SPL4 – Boskop Dam inlet/outlet	9.135	21.7	8.760	7.7	5.3	1.060	2.4	0.6	9 135	32 721	0.18	-6.992	8.959405741	-1.281331224
SPL5 – Potchefstroom Dam inlet/outlet	13.687	22.8	8.620	6.8	6.3	1.820	0.5	0.17	13 687	46 408	0.93	1.683	-0.580102053	-0.344614374
SPL6 – Mooi River Mall	2.56	24	8.400	2.9	1.6	5.500	1.3	0.17	2 560	48 968	0.17	-5.482	-6.345167754	1.157402768
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	5.82	23.3	8.540	2.7	1.6	5.840	1.1	0.2	5 820	54 788	0.34	0.496	-0.178092979	-0.359061586
SPL8 – Mooi River + Potchefstroom WWTW	2.052	25.1	8.280	2.2	1.25	6.080	0.95	0.3	2 052	56 840	0.08	1.852	-0.508722936	-0.274713129
SPL9 – Mooi River before Vaal River	53.588	23.3	8.540	4.1	3.4	4.440	0.7	0.35	53 588	110 428	1.77	0.172	0.177389596	1.029368726
SPL10 – Mooi River + Vaal River	1.845	25.9	8.120	4.6	3.8	3.520	0.8	0.34	1 845	112 273	0.06	-2.126	3.696971779	-1.73886741

Table 4.3 January 2021– Measured water quality indicators and labo[illegible]apacity

Sampling point	Distance (km)	Tempera-ture (°C)	Saturation DO (mg/l)	Actual/ in-situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Distance (m)	Accumulated distance (m)	Time (days)	Deoxygenation constant *k*1	Reoxygena-tion constant k_2	Self-purification factor, *f*
SPL1 – Klerkskraal Dam outlet	0	22.6	8.640	7.5	6	1.140	1.5	0.53	0	0	0.00			0
SPL2 – Mooi River Bridge	12.024	22.9	8.610	5.7	5.1	2.910	0.6	0.52	12 024	12 024	0.27	3.424	-3.501592137	-1.02273742
SPL3 – Mooi River before Boskop Dam	11.562	23.3	8.540	5.3	3.8	3.240	1.5	0.61	11 562	23 586	0.22	-4.177	-0.48966241	0.117233805
SPL4 – Boskop Dam inlet/outlet	9.135	21.8	8.740	6.9	5.6	1.840	1.3	0.6	9 135	32 721	0.18	0.812	3.210889347	3.953909312
SPL5 – Potchefstroom Dam inlet/outlet	13.687	22.3	8.670	6.7	6.2	1.970	0.5	0.17	13 687	46 408	0.93	1.025	-0.073260755	-0.071446524
SPL6 – Mooi River Mall	2.56	23.5	8.500	3.8	2.1	4.700	1.7	0.17	2 560	48 968	0.17	-7.021	-4.988922442	0.710529844
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	5.82	24.1	8.390	3.1	1.7	5.290	1.4	0.2	5 820	54 788	0.34	0.576	-0.351109818	-0.609075838
SPL8 – Mooi River + Potchefstroom WWTW	2.052	24.4	8.360	2.8	1.8	5.560	1	0.3	2 052	56 840	0.08	4.250	-0.628798262	-0.147946419
SPL9 – Mooi River before Vaal River	53.588	23	8.600	4.2	3.5	4.400	0.7	0.35	53 588	110 428	1.77	0.201	0.132043843	0.656041506

Table 4.4 October 2020– Measured water quality indicators and labo[illegible] apacity

Sampling point	Distance (km)	Tempera-ture (°C)	Saturation DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Distance (m)	Accumulated distance (m)	Time (days)	Deoxygena-tion constant k_1	Reoxygena-tion constant k_2	Self-purification factor, f
SPL1 – Klerkskraal Dam Outlet	0	21.1	8.880	7.50	6.9	1.380	0.6	0.54	0	0	0.00			0
SPL2 – Mooi River Bridge	12.024	20.8	8.940	6.60	5.8	2.340	0.8	0.36	12 024	12 024	0.39	-0.744	-1.366018742	1.835593806
SPL3 – Mooi River before Boskop Dam	11.562	20.2	9.060	6.40	5.5	2.660	0.9	0.34	11 562	23 586	0.39	-0.299	-0.325659443	1.088231363
SPL4 – Boskop Dam Inlet/Outlet	9.135	20.5	9.000	7.10	6.4	1.900	0.7	0.26	9 135	32 721	0.41	0.618	0.827423352	1.338849659
SPL5 – Potchefstroom Dam inlet/outlet	13.687	22.1	8.690	7.30	6.4	1.390	0.9	0.15	13 687	46 408	1.06	-0.238	0.295948696	-1.243661739
SPL6 – Mooi River Mall	2.56	22.4	8.660	6.70	5.7	1.960	1	0.16	2 560	48 968	0.19	-0.569	-1.855659921	3.261570276
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	5.82	21.7	8.760	6.50	5.9	2.260	0.6	0.11	5 820	54 788	0.61	0.834	-0.232570947	-0.278804221
SPL8 – Mooi River + Potchefstroom WWTW	2.052	22.3	8.670	5.50	4.3	3.170	1.2	0.1	2 052	56 840	0.24	-2.919	-1.424702209	0.488160068
SPL9 – Mooi River before Vaal River	53.588	23.4	8.520	6.40	5.8	2.120	0.6	0.09	53 588	110 428	6.89	0.101	0.058378841	0.580418576
SPL10 – Mooi River + Vaal River	1.845	23.9	8.420	6.70	5.9	1.720	0.8	0.83	1 845	112 273	0.03	-11.182	8.127041197	-0.72681553

Table 4.5 April 2021 – Measured water quality indicators and laborat acity

Sampling point	Distance (km)	Tempera-ture (℃)	Saturation DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Distance (m)	Accumulated distance (m)	Time (days)	Deoxygena-tion constant k_1	Reoxygena-tion constant k_2	Self-purification factor, f
SPL1 – Klerkskraal Dam Outlet	0	22.1	8.690	8.10	7.2	0.590	0.9	0.54	0	0	0.00			0
SPL2 – Mooi River Bridge	12.024	22.3	8.670	7.40	6.3	1.270	1.1	0.36	12 024	12 024	0.39	-0.519	-1.983189495	3.820436466
SPL3 – Mooi River before Boskop Dam	11.562	21.8	8.740	6.90	5.7	1.840	1.2	0.34	11 562	23 586	0.39	-0.221	-0.941974828	4.260921778
SPL4 – Boskop Dam Inlet/Outlet	9.135	20.7	8.960	7.20	6.3	1.760	0.9	0.26	9 135	32 721	0.41	0.707	0.109311921	0.154516971
SPL5 – Potchefstroom Dam inlet/outlet	13.687	21.9	8.720	7.30	6.1	1.420	1.2	0.15	13 687	46 408	1.06	-0.272	0.203255199	-0.746160286
SPL6 – Mooi River Mall	2.56	22.3	8.670	6.10	4.8	2.570	1.3	0.16	2 560	48 968	0.19	-0.432	-3.203544747	7.411656159
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	5.82	22.7	8.630	5.90	5.3	2.730	0.6	0.11	5 820	54 788	0.61	1.263	-0.098625572	-0.07811239
SPL8 – Mooi River + Potchefstroom WWTW	2.052	23.4	8.520	5.40	4.7	3.120	0.7	0.1	2 052	56 840	0.24	-0.649	-0.562237443	0.866239401
SPL9 – Mooi River before Vaal River	53.588	23.8	8.440	6.70	5.9	1.740	0.8	0.09	53 588	110 428	6.89	-0.019	0.084734993	-4.373113147
SPL10 – Mooi River + Vaal River	1.845	24.9	8.310	6.80	5.7	1.510	1.1	0.83	1 845	112 273	0.03	-12.378	5.510570168	-0.445199564

Table 4.6 June 2021 – Measured water quality indicators and laborat acity

Sampling point	Distance (km)	Temperature (°C)-	Saturation DO (mg/l)	Actual/ in situ DO (mg/l)	Five-day DO (mg/l)	DO deficit (mg/l)	BOD (mg/l)	Velocity (m/s)	Distance (m)	Accumulated distance (m)	Time (days)	Deoxygena-tion constant k_1	Reoxygena-tion constant k_2	Self-purification factor, f
SPL1 – Klerkskraal Dam Outlet	0	20	9.100	8.00	7.6	1.100	0.4	0.54	0	0	0.00			0
SPL2 – Mooi River Bridge	12.024	19.5	9.200	7.30	6.5	1.900	0.8	0.36	12 024	12 024	0.39	-1.793	-1.41381366	0.788495895
SPL3 – Mooi River before Boskop Dam	11.562	19.8	9.140	6.40	5.5	2.740	0.9	0.34	11 562	23 586	0.39	-0.299	-0.930174028	3.108291718
SPL4 – Boskop Dam Inlet/Outlet	9.135	19	9.300	7.20	6.2	2.100	1	0.26	9 135	32 721	0.41	-0.259	0.654174736	-2.524860229
SPL5 – Potchefstroom Dam inlet/outlet	13.687	21.5	8.800	6.80	6.1	2.000	0.7	0.15	13 687	46 408	1.06	0.338	0.046198621	0.136791678
SPL6 – Mooi River Mall	2.56	21.5	8.800	6.70	5.9	2.100	0.8	0.16	2 560	48 968	0.19	-0.721	-0.263466887	0.365383474
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	5.82	22	8.700	6.40	5.4	2.300	1	0.11	5 820	54 788	0.61	-0.364	-0.148555976	0.407682757
SPL8 – Mooi River + Potchefstroom WWTW	2.052	22	8.700	5.60	4.4	3.100	1.2	0.1	2 052	56 840	0.24	-0.768	-1.256812583	1.637178805
SPL9 – Mooi River before Vaal River	53.588	21.5	8.800	6.80	6.3	2.000	0.5	0.09	53 588	110 428	6.89	0.127	0.063593908	0.50059461
SPL10 – Mooi River + Vaal River	1.845	23	8.600	6.90	6.6	1.700	0.3	0.83	1 845	112 273	0.03	19.855	6.316833318	0.318149525

Table 4.7 presents field measurements of pH for every sampling point. The pH values from this study were not meaningfully diverse and were within the acceptable limits. They ranged from 7.5 to 8.8, indicating the basic state of the water. There is no health-based guideline value for pH, although a pH of 6.5–8.5 is proposed for drinking water (Saalidong et al., 2022). The pH of Mooi River on its own would not pose any negative effects on the inhabitant biota because most aquatic animals prefer a pH range of 6.5–8.0, which is slightly acidic and slightly alkaline. For instance, aquatic shrimps and crabs require an optimum pH range of 6.8–8.7 for maximum growth and reproduction (Tomasetti et al., 2018).

Table 4.7 Field measurements of pH

Sampling point	pH					
	October 2020	**November 2020**	**December 2020**	**January 2021**	**April 2021**	**June 2021**
SPL1 – Klerkskraal Dam outlet	8.46	8.39	8.22	8.15	8.11	8.22
SPL2 – Mooi River bridge	8.41	7.99	8.10	7.98	8.02	8.04
SPL3 – Mooi River before Boskop Dam	8.25	7.87	7.93	8.02	8.55	7.99
SPL4 – Boskop Dam inlet/outlet	8.15	7.76	7.88	7.96	7.98	7.98
SPL5 – Potchefstroom Dam inlet/outlet	8.25	7.94	7.89	7.72	8.22	8.01
SPL6 – Mooi River Mall	8.27	7.77	7.78	7.89	8.02	8.15
SPL7 – Mooi River +Loopspruit River before the Potchefstroom Wastewater Treatment Works (WWTW)	8.26	7.68	7.72	7.77	8.13	8.23
SPL8 – Mooi River + Potchefstroom WWTW	8.02	7.67	7.65	7.56	7.99	8.11
SPL9 – Mooi before the Vaal River	8.25	7.67	7.55	7.79	8.05	8.01
SPL10 – Mooi River + Vaal River	8.8	7.85	7.77	7.75	8.53	8.33

The pH measurements of the dry season were higher than those of the wet season. This explains the non-acidic rain that dilutes the river system to drive the pH levels towards the low level neutral state. There were no intense gas emissions around the Mooi River catchment, resulting in much more basic rainwater.

Figure 4.1 gives a clear presentation of pH level fluctuations per sampling month of the respective seasons.

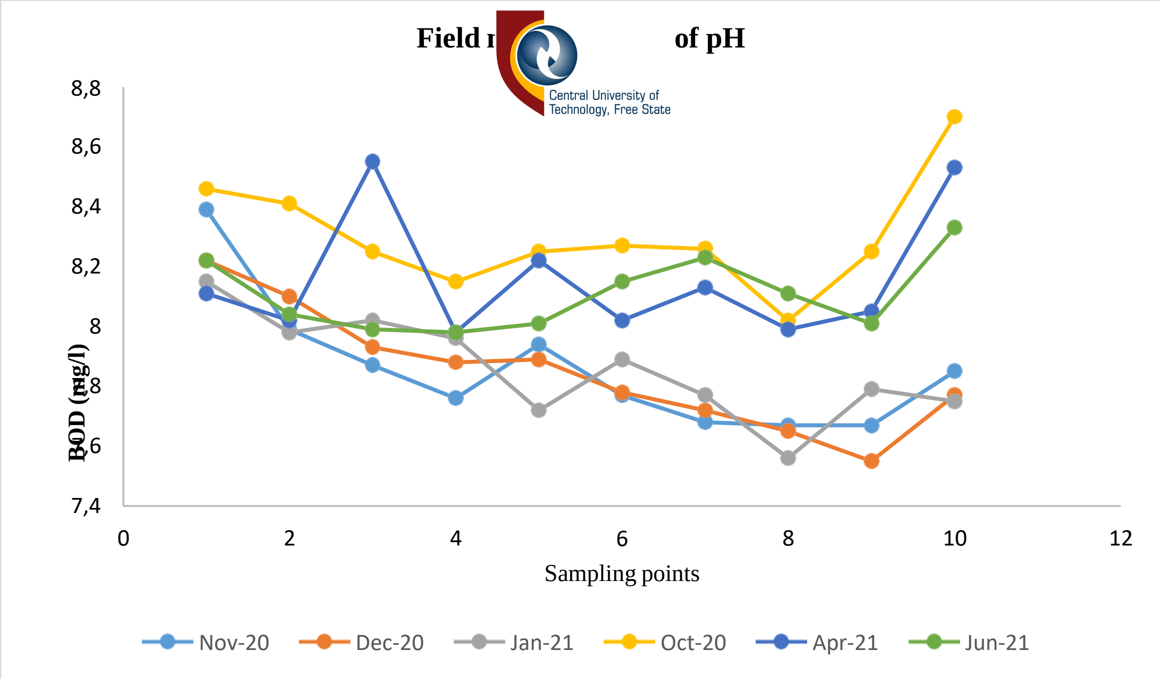

Figure 4.1 pH measurements

Figure 4.2 and 4.3 present fluctuations of water quality or self-purification indicators, namely DO and BOD fluctuations of all sampling points throughout the study seasons.

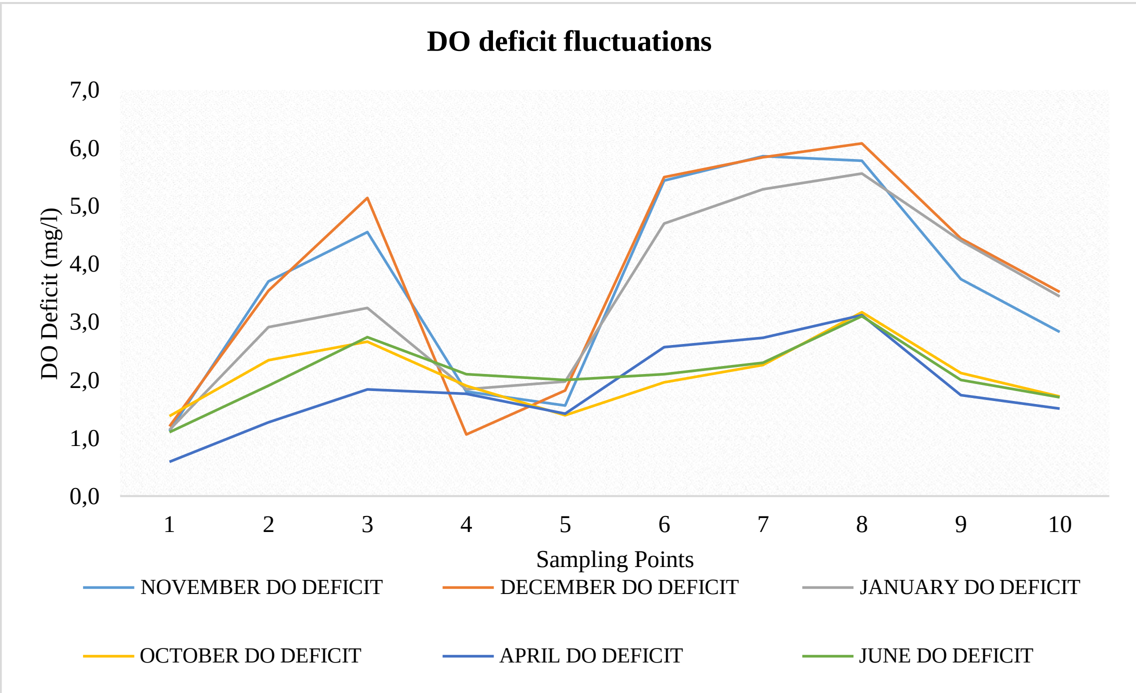

Figure 4.2 Dissolved oxygen fluctuations

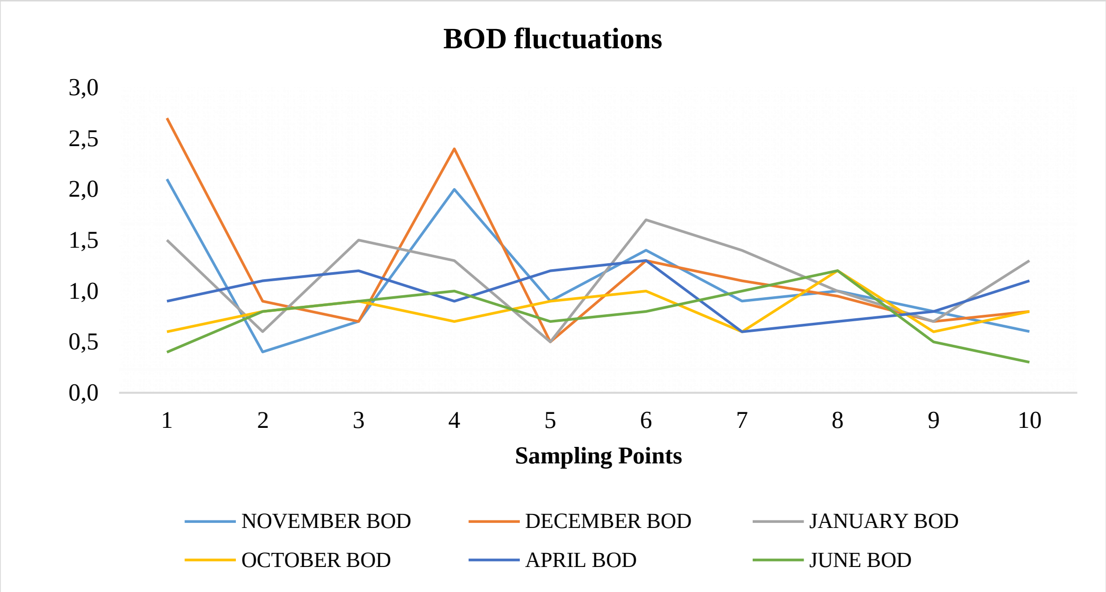

Figure 4.3 Biochemical oxygen demand fluctuations

4.2.2 Results of self-purification capacity and modelling by river hydraulics parameters

The river hydraulics parameters and the reoxygenation constants calculated by influential dynamic hydraulic parameters of the river for all sampling points are further presented in Tables 4.8 to 4.13. Figure 4.4 defines a mathematical derivation of the river hydraulic depth adopted on this study for hydraulic modelling of reoxygenation constant.

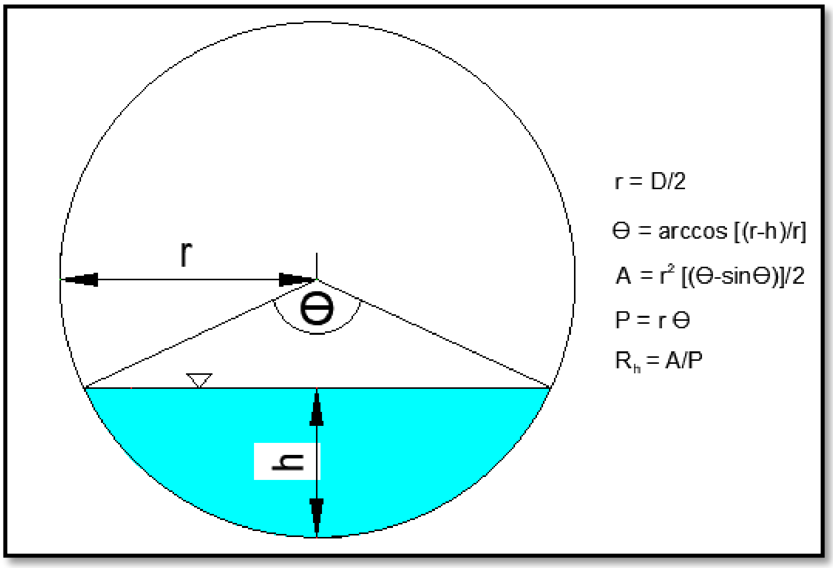

Figure 4.4 Mathematical derivation of hydraulic depth of the river cross-section

A clear indication of the relationship between self-purification capacity of a river and the river hydraulics parameters/features is presented by the results shown in Table 4.8 to Table 4.13 as well as in Figures 4.5 to 4.16. This is the relationship pertaining to the flow velocity, hydraulic depth and radius of a flowing river. For example; the smallest hydraulic depth of 0.7588m recorded for November 2020 with a flow velocity of 0.52m/s flow segment between sampling points 1 and 2 yielded a very significant declination of BOD content. This particular flow segment proves to have highly effective self-purification strength. The results therefore proves to be consistent with the self-purification phenomenon that suggests that the strength of purification in a river is high if the hydraulic depth is low and the flow velocity is fairly high.

The ability of a flowing river to absorb oxygen from the atmosphere (reoxygenation) depends on its flow velocity as well as hydraulic radius and depth (Zubaidah et al., 2019). Reoxygenation rates presented at every sampling point were calculated using the reoxygenation rates that resulted from dynamic analysis of water quality or purification indicators over the flow length of the river as described in the methodology section (3.3).

Table 4.8 November 2020– River hydraulic parameters and reoxygenation model results

Sampling point	Hydraulic depth (m)	Cross-sectional width (m)	$\frac{w}{2} = r$	θ	r^2	Cosθ	Sinθ	Cross-sectional area (m^2)	Wetted parameter (m)	Hydraulic radius (m)	Velocity (m/s)	Output k_2 model	Squared standard deviation
SPL2 – Mooi River Bridge	0.5	3.65	1.825	1.337224257	3.330625	0.2314541	0.9728458	3.703838631	4.88086854	0.758848267	0.52	0.304899466	22.75351643
SPL3 – Mooi River before Boskop Dam	0.51	4.95	2.475	1.426449076	6.125625	0.1438465	0.9896	7.865906351	7.060922926	1.11400 5412	0.61	0.479433335	2.022314484
SPL4 – Boskop Dam inlet/outlet	0.65	6.2	3.1	1.421229493	9.61	0.1490098	0.9888357	12.24201818	8.811622859	1.389303466	0.6	0.444554013	23.21302288
SPL5 – Potchefstroom Dam inlet/outlet	0.55	4.2	2.1	1.351805163	4.41	0.217245	0.9761171	5.026291367	5.677581684	0.885287372	0.17	0.009366465	0.020793661
SPL6 – Mooi River Mall	0.99	5.15	2.575	1.224791876	6.630625	0.3391418	0.9407353	6.005683612	6.307678161	0.952122708	0.17	0.009291777	51.49446276
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	1.12	6	3	1.234587972	9	0.3299101	0.9440124	8.30833877	7.407527835	1.121607499	0.2	0.015103369	0.055655829
SPL8 – Mooi River + Potchefstroom WWTW	1.16	5.1	2.55	1.169486058	6.5025	0.3906248	0.92055	5.266351158	5.964378895	0.882967238	0.3	0.054498598	0.014192931
SPL9 – Mooi River before Vaal River	1.39	5.4	2.7	1.130469012	7.29	0.4262356	0.9046122	5.430256169	6.104532667	0.889544944	0.35	0.087814415	0.024912816

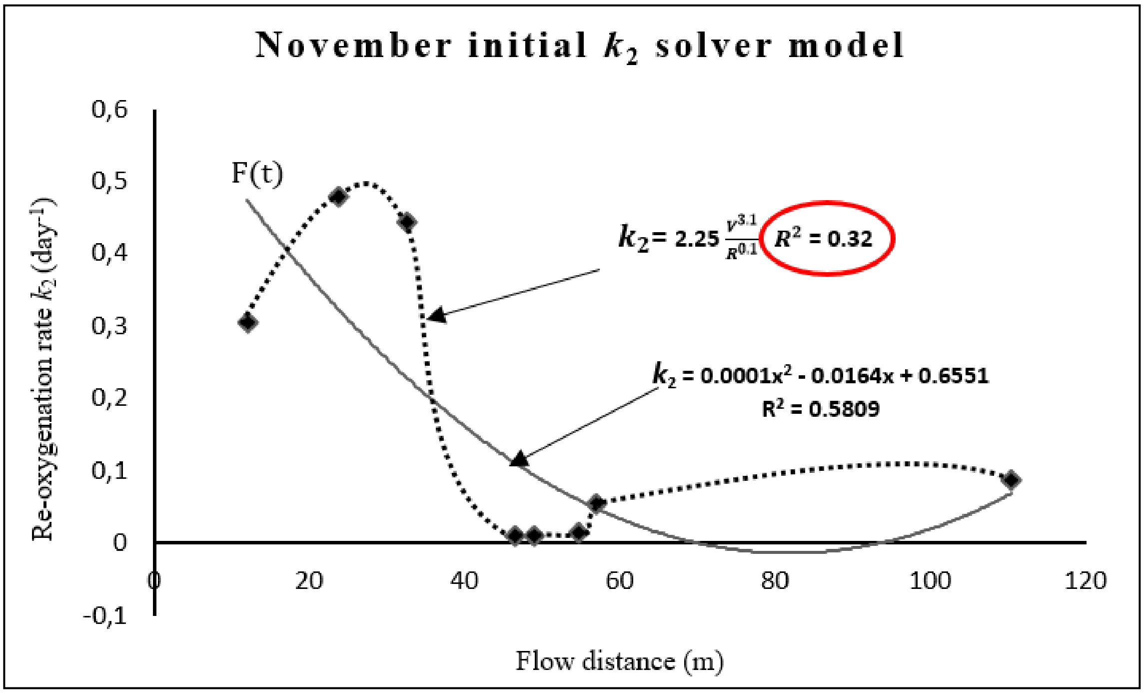

Figure 4.5 November 2020 – Initial k_2 model graph

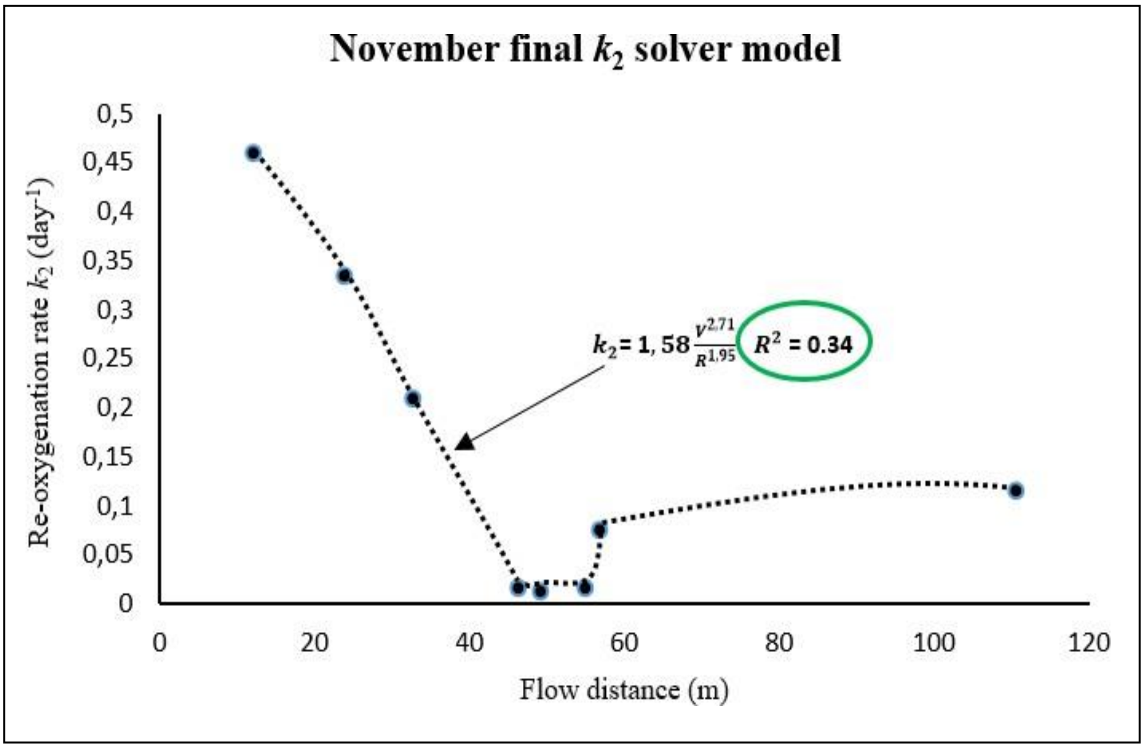

Figure 4.6 November 2020 – Improved k_2 model graph

Table 4.9 December 2020 – River hydraulic parameters and reoxygenation model results

Sampling point	Hydraulic depth (m)	Cross-sectional width (m)	$\frac{w}{2} = r$	θ	r^2	Cosθ	Sinθ	Cross-sectional area (mm^{22})	Wetted parameter (m)	Hydraulic radius (m)	Velocity (m/s)	Output k_2 model	Squared standard deviation
SPL2 – Mooi River Bridge	0.61	3.65	1.825	1.27153	3.330625	0.2948154	0.9555542	3.296725423	4.641099018	0.710332921	0.54	0.10716602	17.21718998
SPL3 – Mooi River before Boskop Dam	0.59	4.95	2.475	1.38174	6.125625	0.1879256	0.9821833	7.333410504	6.839646095	1.072191514	0.59	0.110978564	3.279427357
SPL4 – Boskop Dam Inlet/Outlet	0.63	6.2	3.1	1.43058	9.61	0.1397572	0.9901858	12.417989	8.869596628	1.400062429	0.62	0.107422527	78.35760682
SPL5 – Potchefstroom Dam inlet/outlet	0.57	4.2	2.1	1.34025	4.41	0.2285039	0.973543	4.929485812	5.629073696	0.875718827	0.18	3.28373E-05	0.336556491
SPL6 – Mooi River Mall	0.95	5.15	2.575	1.23854	6.630625	0.3261704	0.945311	6.167902086	6.378515761	0.966980771	0.17	1.89833E-05	40.26139473
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	1.23	6	3	1.20345	9	0.3591351	0.9332856	7.814517708	7.220732058	1.082233442	0.19	3.55166E-05	0.031729761
SPL8 – Mooi River + Potchefstroom WWTW	1.18	5.1	2.55	1.16398	6.5025	0.3956819	0.9183876	5.205880108	5.936329019	0.876952758	0.32	0.001936949	0.260773519
SPL9 – Mooi River before Vaal River	1.42	5.4	2.7	1.12395	7.29	0.4321197	0.9018163	5.352768902	6.069353819	0.881933903	0.4	0.009346908	0.028238345

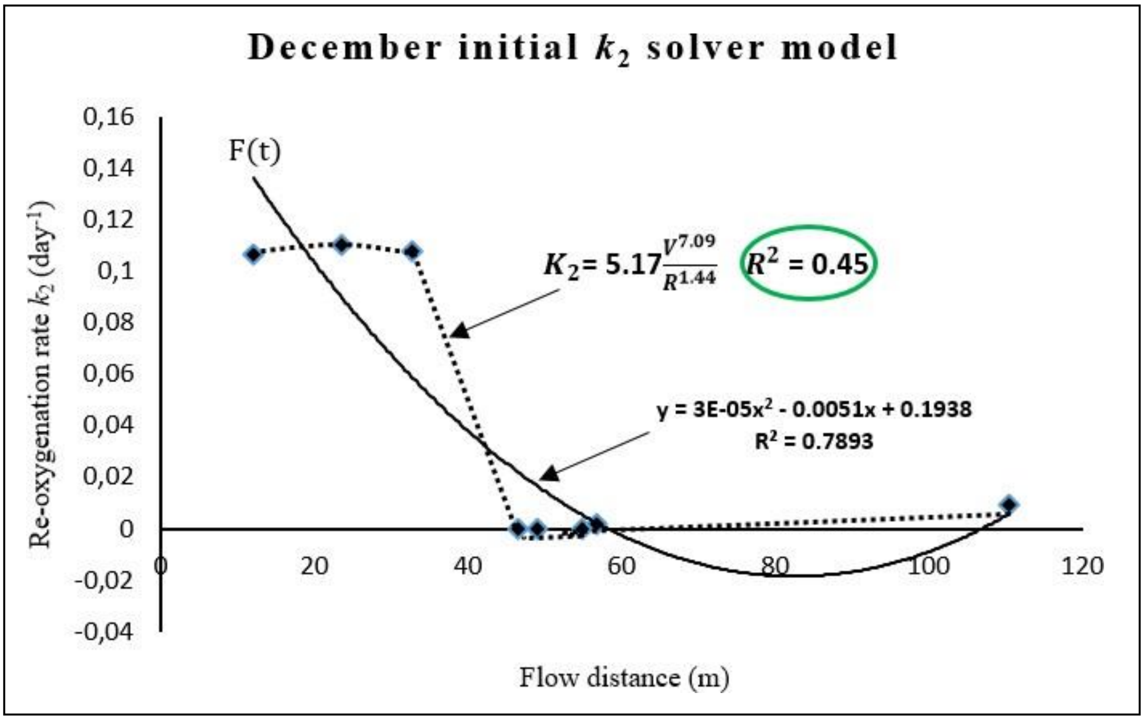

Figure 4.7 December 2020 – Initial k_2 model graph

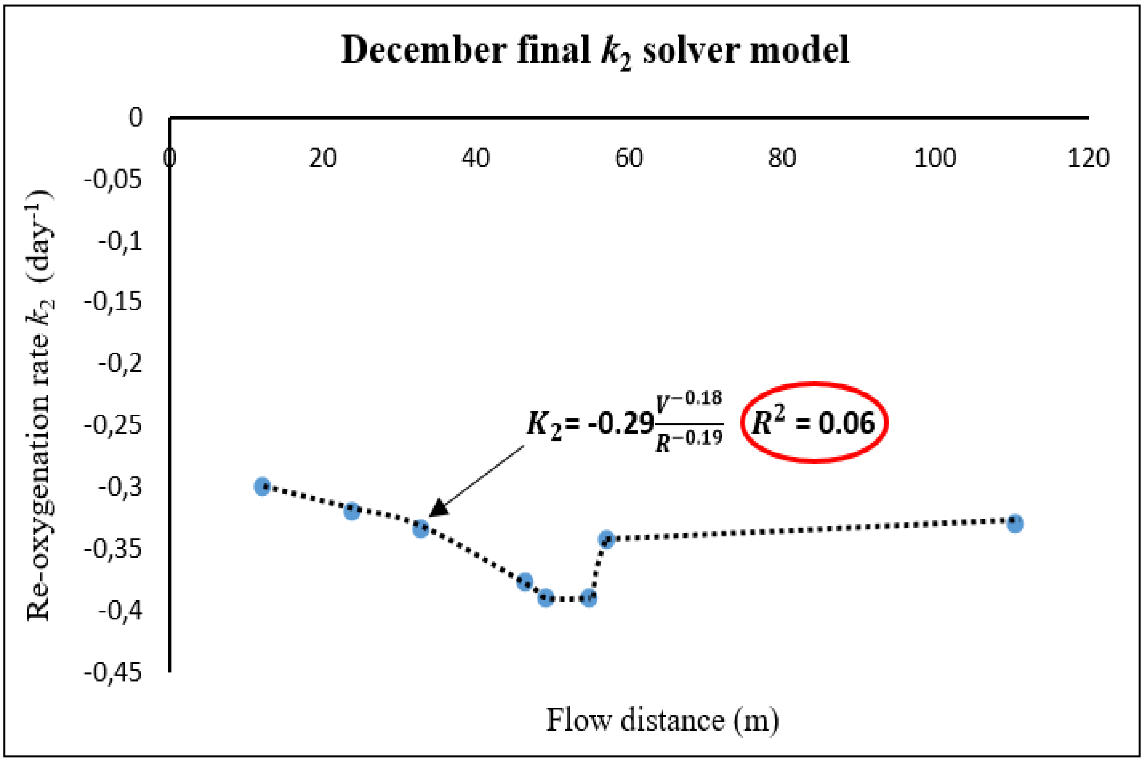

Figure 4.8 December 2020 – Improved k_2 model graph

Table 4.10 January 2021 – River hydraulic parameters and reoxygenation model results

Sampling point	Hydraulic depth (m)	Cross-sectional width (m)	$\frac{W}{2} = r$	θ	rr^{22}	Cosθ	Sinθ	Cross-sectional area (mm^{22})	Wetted parameter (m)	Hydraulic radius (m)	Velocity (m/s)	Output k_2 model	Squared standard deviation
SPL2 – Mooi River Bridge	0.5	3.65	1.825	1.337224257	3.330625	0.2314541	0.9728458	3.703838631	4.88086854	0.758848267	0.59	-3.126874705	0.140413154
SPL3 – Mooi River before Boskop Dam	0.49	4.95	2.475	1.438318948	6.125625	0.1320902	0.9912377	8.00855726	7.119678793	1.124848114	0.59	-0.315762796	0.030241076
SPL4 – Boskop Dam Inlet/Outlet	0.57	6.2	3.1	1.459755282	9.61	0.110813	0.9938413	12.9698939	9.05048275	1.433061004	0.63	-0.076702515	10.80826025
SPL5 – Potchefstroom Dam inlet/outlet	0.57	4.2	2.1	1.340255642	4.41	0.2285039	0.973543	4.929485812	5.629073696	0.875718827	0.19	-1.464772692	1.93630547
SPL6 – Mooi River Mall	0.96	5.15	2.575	1.235051156	6.630625	0.3294728	0.9441651	6.126527934	6.360513454	0.963212794	0.21	-0.835481065	17.25107528
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	1.08	6	3	1.246733934	9	0.3184201	0.9479497	8.503989096	7.480403606	1.136835597	0.23	-0.31623812	0.001216035
SPL8 – Mooi River + Potchefstroom WWTW	1.11	5.1	2.55	1.183787735	6.5025	0.3774199	0.9260422	5.424911799	6.037317447	0.898563285	0.31	-1.219960458	0.349472742
SPL9 – Mooi River before Vaal River	1.37	5.4	2.7	1.134932392	7.29	0.4221937	0.9065056	5.483621149	6.128634916	0.894754089	0.36	-1.238033954	1.877113171

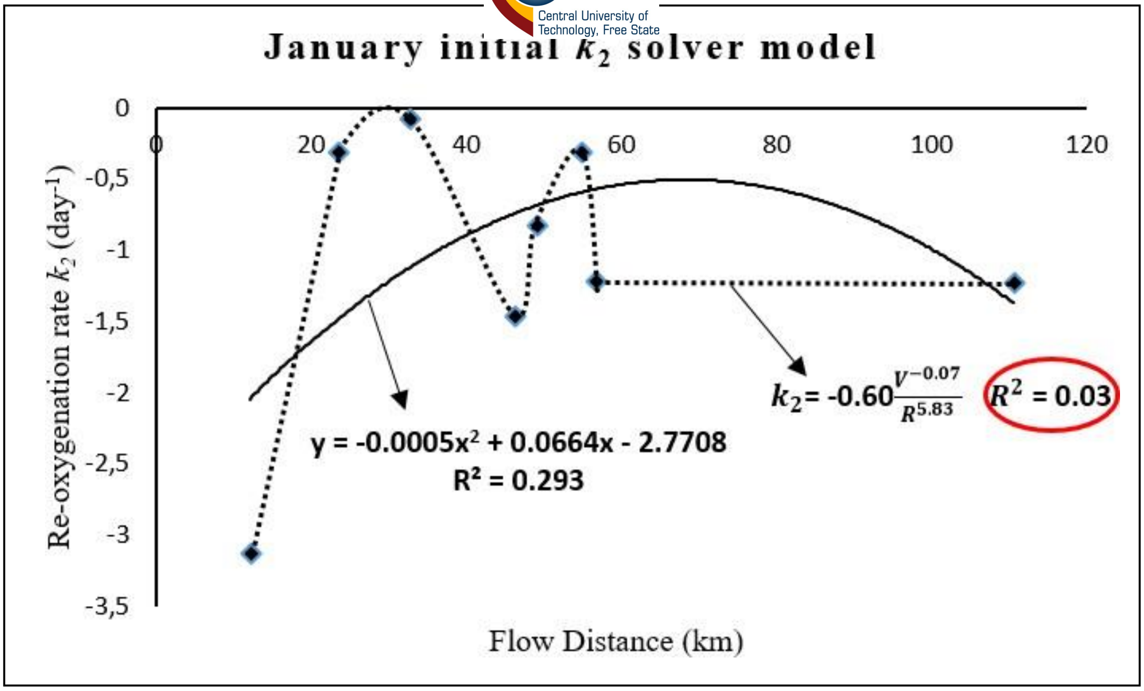

Figure 4.9 January 2021 – Initial k_2 model graph

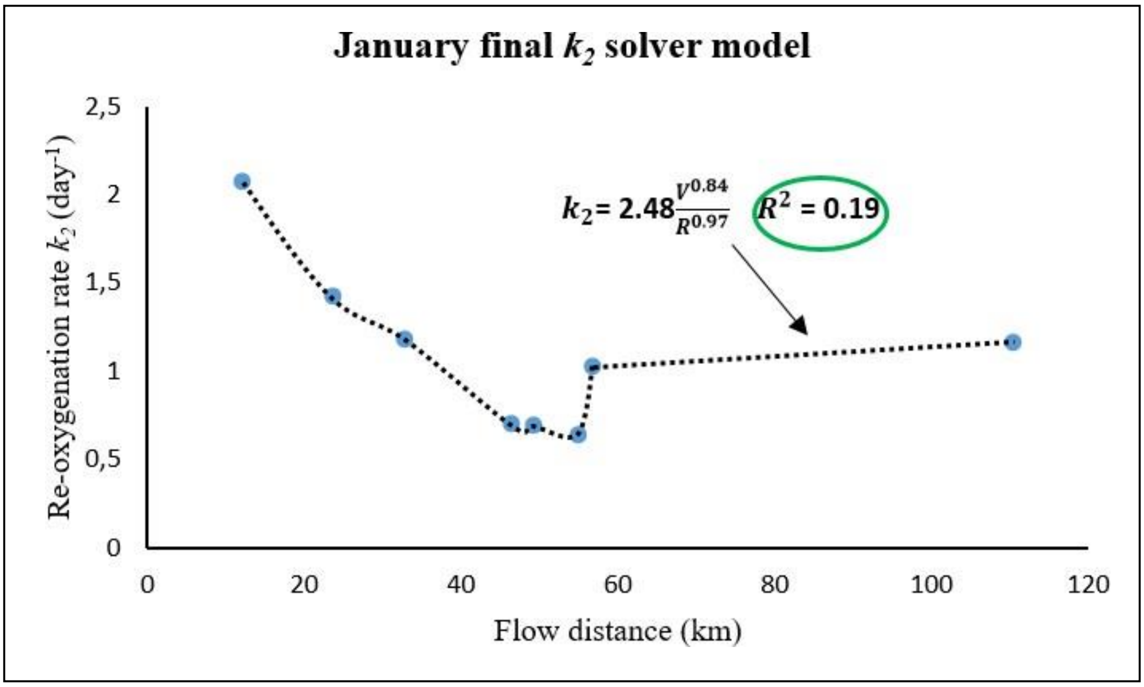

Figure 4.10 January 2021 – Improved k_2 model graph

Table 4.11 October 2020 – River hydraulic parameters and reoxygenation model results

Sampling point	Hydraulic depth (m)	Cross-sectional width (m)	$\frac{W}{2} = r$	Θ	r^2	Cosθ	Sinθ	Cross-sectional area (m^2)	Wetted parameter (m)	Hydraulic radius (m)	Velocity (m/s)	Output k_2 model	Squared standard deviation
SPL2 – Mooi River Bridge	0.4	3.65	1.825	1.407785952	3.330625	0.162289405	0.986743203	4.155447568	5.138418723	0.80870162	0.36	-2.680836937	1.728746886
SPL3 – Mooi River before Boskop Dam	0.45	4.95	2.475	1.462951981	6.125625	0.107635422	0.994190432	8.305991445	7.241612306	1.14698096	0.34	-0.456873969	0.017217252
SPL4 – Boskop Dam inlet/outlet	0.42	6.2	3.1	1.540812316	9.61	0.029979518	0.999550513	14.51923269	9.553036361	1.51985527	0.26	-0.068886398	0.803371169
SPL5 – Potchefstroom Dam inlet/outlet	0.4	4.2	2.1	1.449604668	4.41	0.120895212	0.992665275	5.863519194	6.088339604	0.96307361	0.15	-0.186945444	0.23318675
SPL6 – Mooi River Mall	0.5	5.15	2.575	1.444009668	6.630625	0.126447252	0.991973333	8.742992052	7.436649792	1.17566274	0.16	-0.08350517	3.140532462
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	0.9	6	3	1.30745926	9	0.260304023	0.965526704	9.505158973	7.844755558	1.21165776	0.11	-0.032973662	0.039839076
SPL8 – Mooi River + Potchefstroom WWTW	1.4	5.1	2.55	1.111086133	6.5025	0.443688407	0.896181119	4.639279892	5.666539277	0.81871486	0.1	-0.171715614	1.569975407
SPL9 – Mooi River before Vaal River	1.7	5.4	2.7	1.072738826	7.29	0.477719932	0.878512189	4.760778554	5.792789661	0.82184558	0.09	-0.135174702	0.037462974

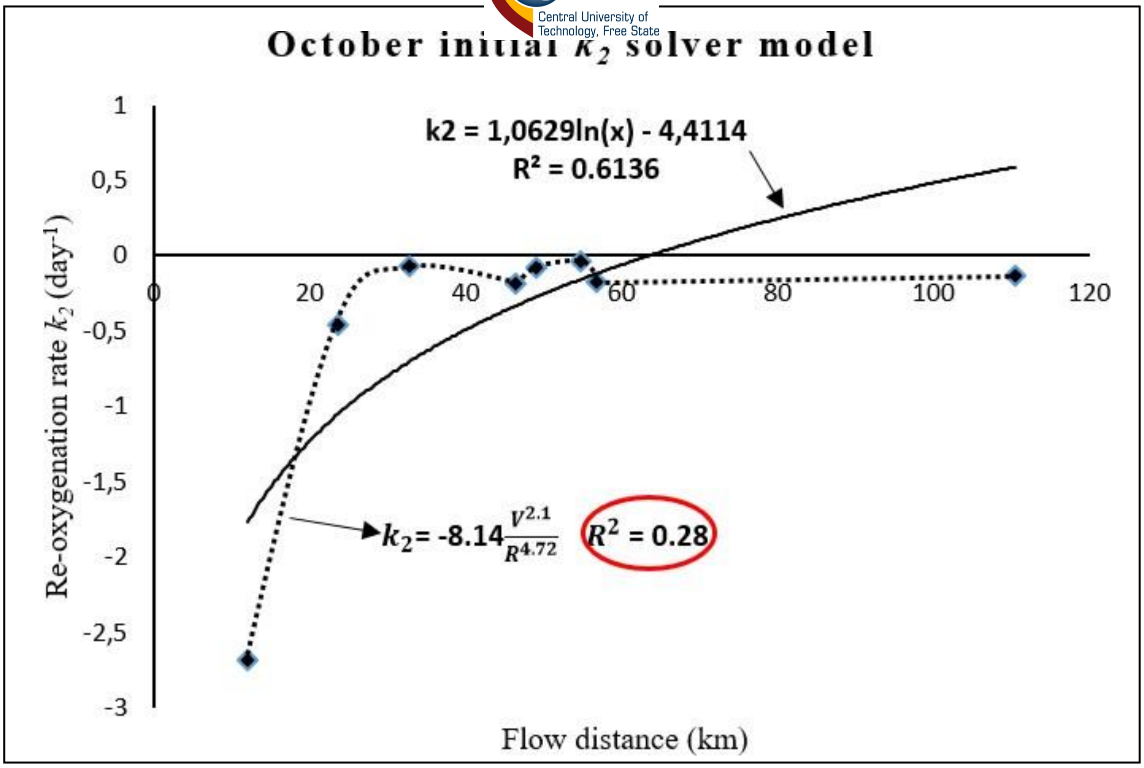

Figure 4.11 October 2020 – Initial k_2 model graph

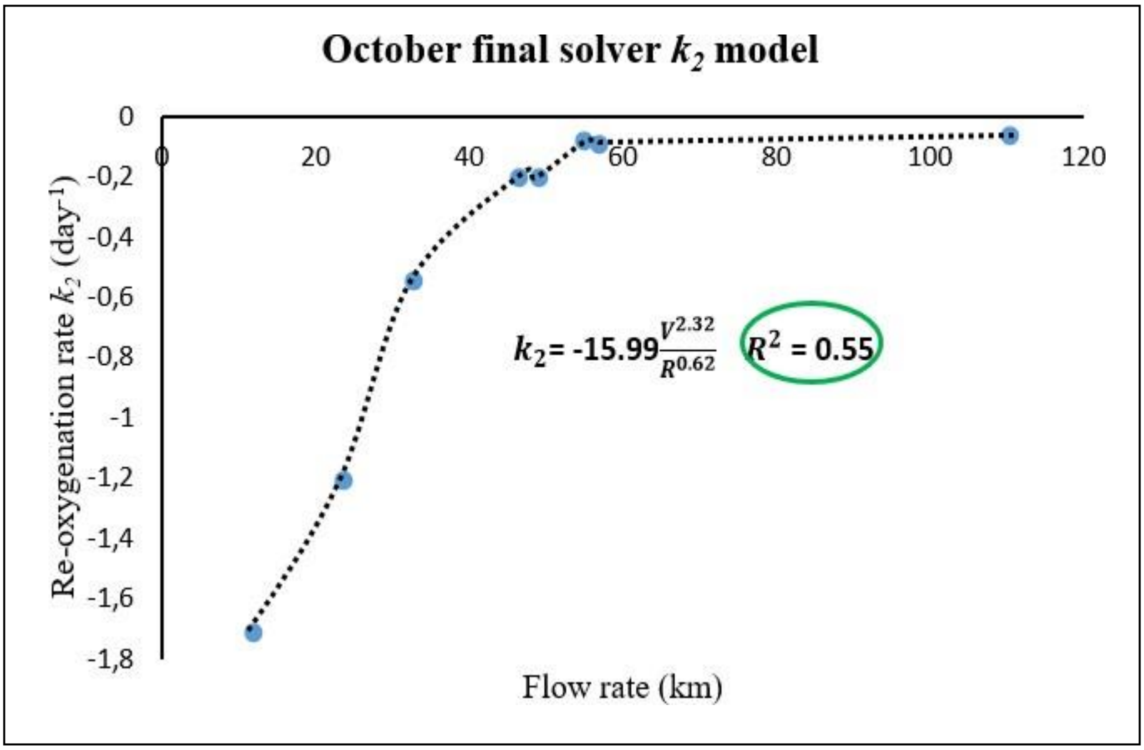

Figure 4.12 October 2020 – Improved k_2 model graph

Table 4.12 April 2021 – River hydraulic parameters and reoxygenation model results

Sampling point	Hydraulic depth (m)	Cross-sectional width (m)	$\frac{w}{2} = r$	Θ	rr^{22}	Cosθ	Sinθ	Cross-sectional area (mm^{22})	Wetted Parameter (m)	Hydraulic radius (m)	Velocity (m/s)	Output k_2 model	Squared standard deviation
SPL2 – Mooi River Bridge	0.51	3.65	1.825	1.330770607	3.330625	0.237727609	0.971331861	3.663215238	4.857312715	0.754164999	0.38	-4.041370611	4.236109507
SPL3 – Mooi River before Boskop Dam	0.53	4.95	2.475	1.414865148	6.125625	0.155300048	0.987867347	7.727165381	7.003582483	1.10331611	0.42	-0.82775937	0.013045171
SPL4 – Boskop Dam Inlet/Outlet	0.46	6.2	3.1	1.517979222	9.61	0.052792551	0.998605501	14.08115139	9.411471177	1.496168997	0.29	-0.090313262	0.039850213
SPL5 – Potchefstroom Dam inlet/outlet	0.42	4.2	2.1	1.4353242	4.41	0.135058127	0.990837677	5.739630516	6.028361639	0.952104545	0.16	-0.218718176	0.178061529
SPL6 – Mooi River Mall	0.53	5.15	2.575	1.426790716	6.630625	0.143508405	0.989649098	8.518813179	7.347972186	1.159342056	0.17	-0.09805922	9.644040362
SPL7 – Mooi River + Loopspruit River before Potchefstroom WWTW	0.97	6	3	1.282603177	9	0.284220356	0.958758984	9.09093921	7.69561906	1.181313568	0.13	-0.051090686	0.002259565
SPL8 – Mooi River + Potchefstroom WWTW	1.43	5.1	2.55	1.104868048	6.5025	0.449252324	0.893404919	4.574533537	5.634827045	0.811832111	0.13	-0.300071577	0.068730941
SPL9 – Mooi River before Vaal River	1.79	5.4	2.7	1.059615409	7.29	0.489207546	0.872167402	4.614165653	5.721923206	0.806401185	0.11	-0.218085897	0.091700491

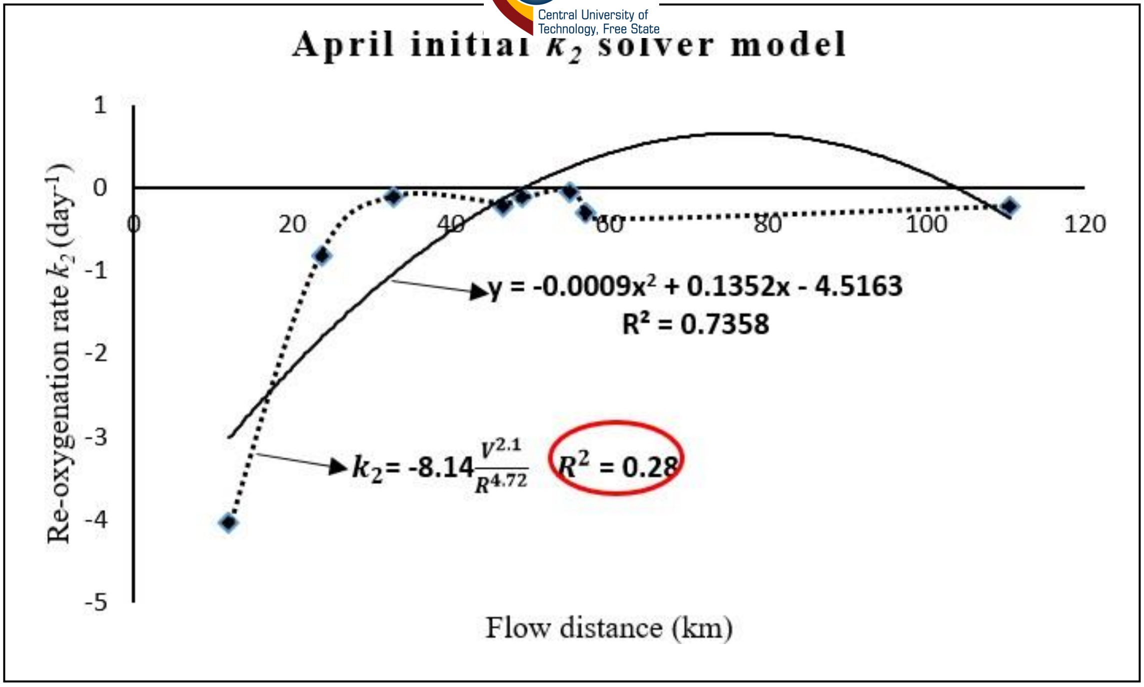

Figure 4.13 April 2021 – Initial k_2 model graph

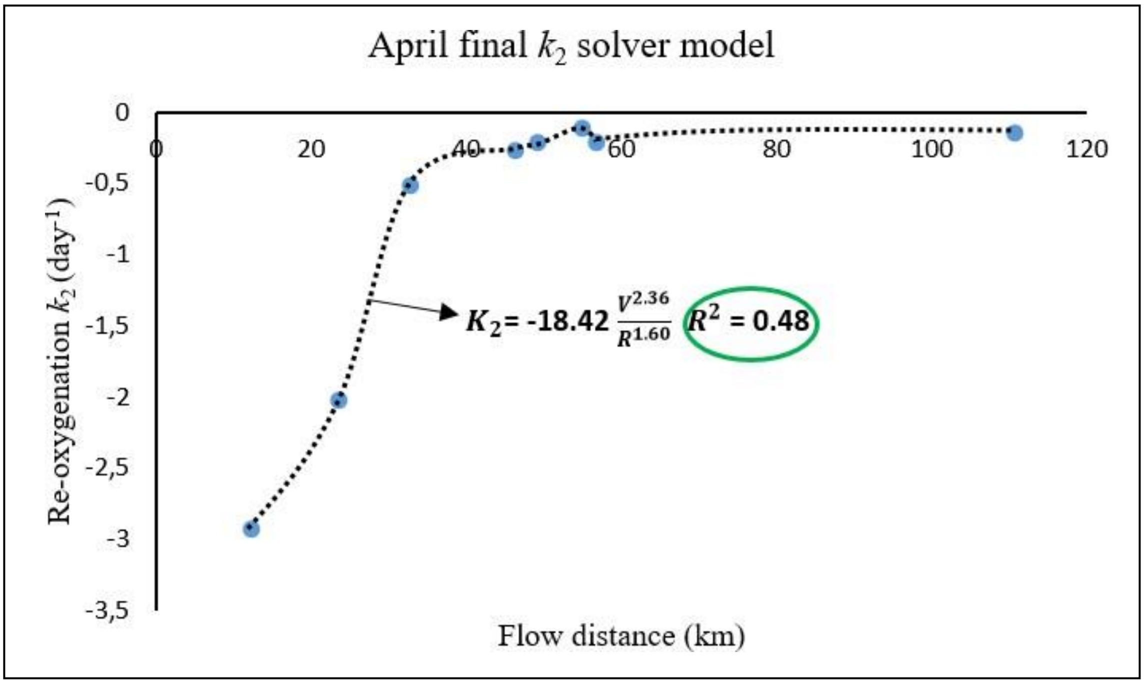

Figure 4.14 April 2021 – Improved k_2 model graph

Table 4.13 June 2021 – River hydraulic parameters and reoxygenation model results

Sampling point	Hydraulic depth (m)	Cross-sectional width (m)	$\frac{W}{2} = r$	Θ	rr^{22}	Cosθ	Sinθ	Cross-sectional area (mm^{22})	Wetted parameter (m)	Hydraulic radius (m)	Velocity (m/s)	Output k_2 model	Squared standard deviation
SPL2 – Mooi River Bridge	0.38	3.65	1.825	1.423327103	3.330625	0.146935298	0.989146106	4.256494206	5.195143928	0.81932171	0.35	- 1.501794201	0.007740576
SPL3 – Mooi River before Boskop Dam	0.43	4.95	2.475	1.475733847	6.125625	0.094919367	0.995484964	8.46097692	7.30488254	1.15826324	0.31	-0.441266893	0.239030186
SPL4 – Boskop Dam Inlet/Outlet	0.38	6.2	3.1	1.564607272	9.61	0.006189015	0.999980848	14.97640058	9.700565086	1.543868883	0.23	-0.127196096	0.610540377
SPL5 – Potchefstroom Dam inlet/outlet	0.39	4.2	2.1	1.45690188	4.41	0.113648368	0.993521036	5.926995173	6.118987894	0.968623451	0.17	-0.387491608	0.188087214
SPL6 – Mooi River Mall	0.46	5.15	2.575	1.467939927	6.630625	0.102675135	0.994714942	9.056156931	7.559890625	1.197921687	0.14	-0.159253404	0.01086045
SPL7 – Mooi River +Loopspruit River before Potchefstroom WWTW	0.87	6	3	1.318631687	9	0.249500724	0.968374612	9.693193682	7.911790123	1.225158091	0.13	-0.136298498	0.000150246
SPL8 – Mooi River + Potchefstroom WWTW	1.29	5.1	2.55	1.135863453	6.5025	0.421349526	0.906898328	4.901209125	5.792903609	0.846071237	0.14	-0.473716545	0.613239405
SPL9 – Mooi River before Vaal River	1.66	5.4	2.7	1.079064259	7.29	0.472153442	0.881516379	4.832200311	5.826946998	0.829285098	0.12	-0.422531748	0.236318154

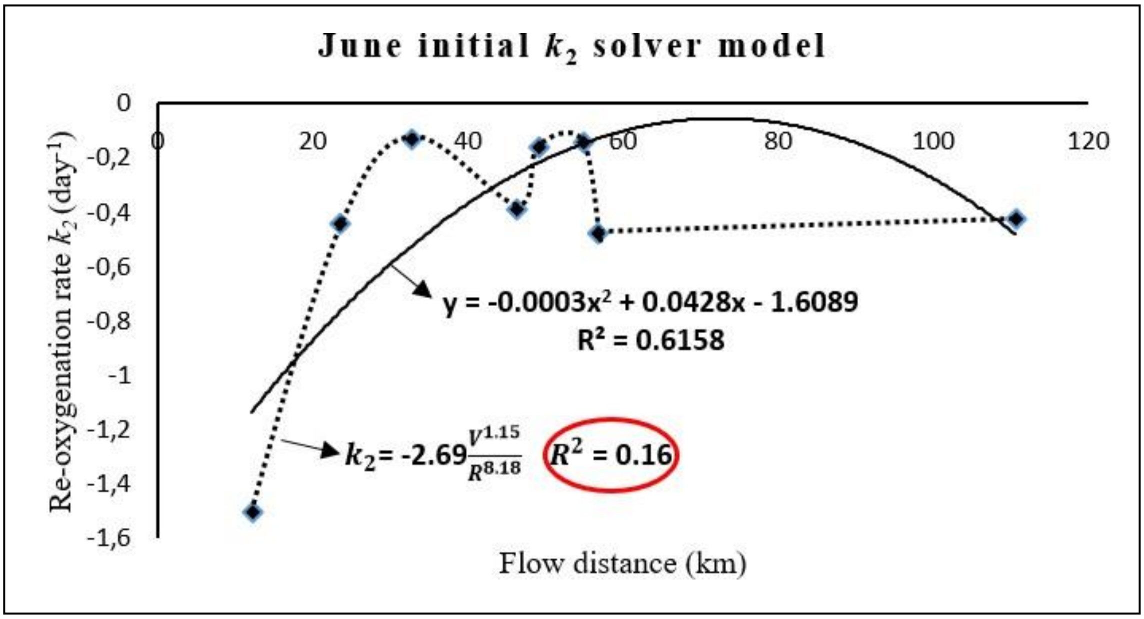

Figure 4.15 June 2021 – Initial k_2 model graph

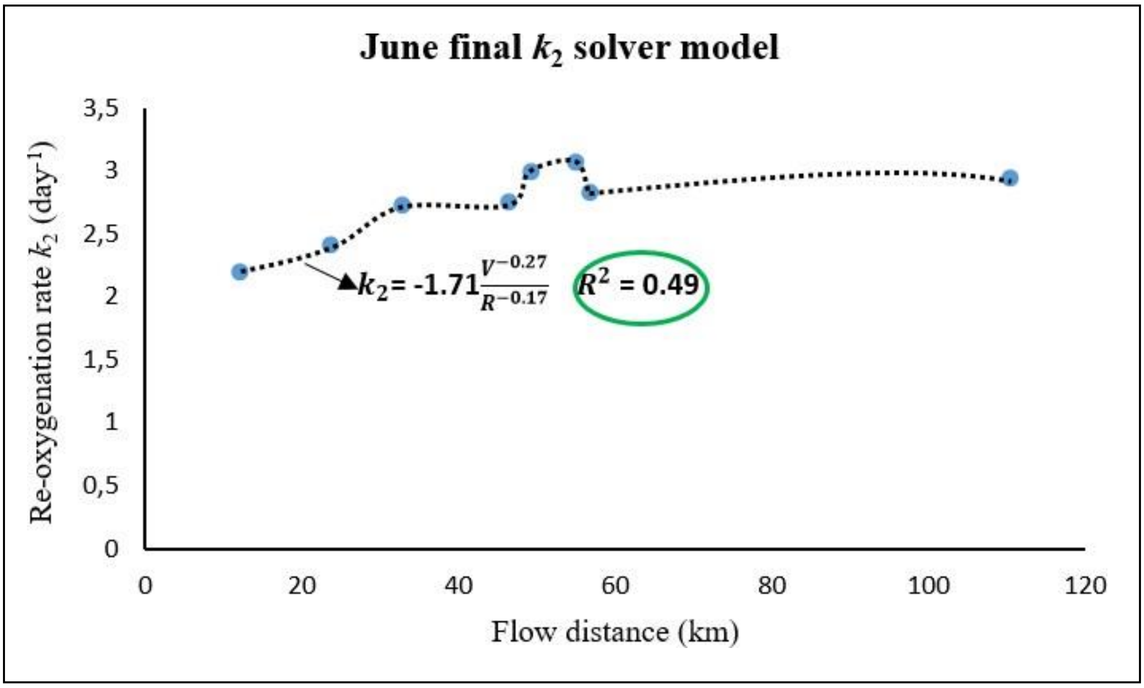

Figure 4.16 June 2021 – Improved k_2 model graph

4.2.3 Results of model comparisons

The model comparison tables are presented below to further gauge the performance of the reoxygenation models that have been developed. Tables 4.14 to 4.19 present model comparisons between the models developed through this particular study, with well-known models of other researchers around the world.

Table 4.14 November 2020 season model – Comparison results

Sampling point	$k_2 = 1.58\frac{V^{2.71}}{R^{1.95}}$	$k_2 = 5.03\frac{V^{0.969}}{R^{1.678}}$	$k_2 = 5.73\frac{V^{0.5}}{H^{0.25}}$	$k_2 = 1.92\frac{V^{1.325}}{H^{2.006}}$
	Mooi River, South Africa,2020	Steeter et al.,1925	Jha et al.,2001	Churchill,1962
SPL2	0.460091929	2.666925072	4.322301671	3.121387991
SPL3	0.335726196	1.403751508	4.078637917	2.284780832
SPL4	0.20890131	0.674943639	3.628717621	1.838996462
SPL5	0.016553938	0.851675793	2.790033732	0.978515839
SPL6	0.014368025	0.648754356	2.725187025	0.681246733
SPL7	0.016215135	0.428963567	1.950808043	0.127530516
SPL8	0.07735947	0.755067647	1.665508346	0.046328309
SPL9	0.115710356	0.677431651	1.505177947	0.027294181
R-squared values	0.341679846	0.367199096	0.746232126	0.663906381
R-squared values (%)	**34**	**37**	**75**	**66**

Table 4.14 shows that the model developed for the month of November produced a precision rate of 34%, which is the lowest of all the models compared with it. The Churchill model produced the best precision rate of 66% for this particular month.

Table 4.15 December 2020 model – Comparison results

Sampling point	$k_2 = -0.29\frac{V^{-0.18}}{R^{-0,19}}$	$k_2 = 5.03\frac{V^{0.969}}{R^{1,678}}$	$k_2 = 5.73\frac{V^{0.5}}{H^{0,25}}$	$k_2 = 1.92\frac{V^{1.325}}{H^{2,006}}$
	Mooi River, South Africa,2020	Steeter et al.,1925	Jha et al.,2001	Churchill,1962
SPL2	−0.299026158	4.237695274	4.912900776	3.24750543
SPL3	−0.318709897	2.597348373	5.29481994	3.856164413
SPL4	−0.332606459	1.764564265	4.942265911	2.319132156
SPL5	−0.37750549	1.107439692	2.742916649	0.609756656
SPL6	−0.388659468	0.980123414	2.368069718	0.187533952
SPL7	−0.389503824	0.871540378	2.490515875	0.181598675
SPL8	−0.341350946	1.92867015	3.023604286	0.289642455
SPL9	−0.328603634	2.211671851	3.121469849	0.24716203
R-squared values	0.4515950447	0.14060797	0.357389589	0.525655806
R-squared values (%)	**45**	**14**	**36**	**53**

The model developed for this month produced an R^2 value of 45%, compared to the highest value of 53% produced by the Churchill model as shown in Table 4.15. Based on the regression analysis literature discussed in chapter 1 pertaining to R^2 values in statistical analysis, the model developed in this study for the month of December 2020 can be taken into consideration with certain limitations. Limitations such as the data size, the larger your data size, the more significance, depth, meaning and credibility. However, the Churchill model can also be used to calculate re-oxygenation constants for this study area during this particular season of December 2020 because of its high precision indicated by its R^2 value.

Table 4.16 January 2021 model – Comparison results

Sampling point	$k_2 = 2.48\frac{V^{0.84}}{R^{0.97}}$	$k_2 = 5.03\frac{V^{0.969}}{R^{1.678}}$	$k_2 = 5.73\frac{V^{0.5}}{H^{0.25}}$	$k_2 = 1.92\frac{V^{1.325}}{H^{2.006}}$
	Mooi River, South Africa,2021	Steeter et al.,1925	Jha et al.,2001	Churchill,1962
SPL2	2.080614965	2.666925072	4.322301671	3.121387991
SPL3	1.420826444	1.403751508	4.078637917	2.284780832
SPL4	1.187015233	0.674943639	3.628717621	1.838996462
SPL5	0.701835786	0.851675793	2.790033732	0.978515839
SPL6	0.695855678	0.648754356	2.725187025	0.681246733
SPL7	0.639472364	0.428963567	1.950808043	0.127530516
SPL8	1.03099712	0.755067647	1.665508346	0.046328309
SPL9	1.173200905	0.677431651	1.505177947	0.027294181
R-squared values	0.1897399367	0.367199096	0.746232126	0.663906381
R-squared values (%)	**19**	**37**	**75**	**66**

The January model produced the lowest precision rate of 19%. This was recorded as the lowest percentage over the entire study period. This is because of rapid change in hydraulic flow dynamics as well as the quality and amount of pollution introduced into the river due to heavy rainfall during this season. This caused a lot of undetected effects of non-point pollution on the sources on the river. These kind of situation usually calls for a larger size of data collection along the river to catch all possible change in quality and hydraulic dynamics.

Table 4.17 October 2020 model – Comparison results

Sampling point	$k_2 = 15.99\frac{V^{2.32}}{R^{0.62}}$	$k_2 = 5.03\frac{V^{0.969}}{R^{1.678}}$	$k_2 = 5.73\frac{V^{0.5}}{H^{0.25}}$	$k_2 = 1.92\frac{V^{1.325}}{H^{2.006}}$
	Mooi River, South Africa,2020	Steeter et al.,1925	Jha et al.,2001	Churchill,1962
SPL2	−1.710431144	4.237695274	4.912900776	3.24750543
SPL3	−1.208376854	2.597348373	5.29481994	3.856164413
SPL4	−0.545938763	1.764564265	4.942265911	2.319132156
SPL5	−0.202243955	1.107439692	2.742916649	0.609756656
SPL6	−0.207716003	0.980123414	2.368069718	0.187533952
SPL7	−0.085614744	0.871540378	2.490515875	0.181598675
SPL8	−0.087392828	1.92867015	3.023604286	0.289642455
SPL9	−0.068310245	2.211671851	3.121469849	0.24716203
R-squared values	0.547351295	0.14060797	0.357389589	0.525655806
R-squared values (%)	**55**	**14**	**36**	**53**

The model that performed well was the model developed in the month of October with an R^2 value of 55% as shown in Table 4.17. This gives a good indication of model reliability and it could be adopted as the overall reoxygenation rate prediction model for Mooi River. This is based on the high precision of the model defined by the R^2 value.

Table 4.18 April 2021 model – Comparison results

Sampling point	$k_2 = 18.42\frac{V^{2.36}}{R^{1.60}}$	$k_2 = 5.03\frac{V^{0.969}}{R^{1.678}}$	$k_2 = 5.73\frac{V^{0.5}}{H^{0.25}}$	$k_2 = 1.92\frac{V^{1.325}}{H^{2.006}}$
	Mooi River, South Africa,2021	Steeter et al.,1925	Jha et al.,2001	Churchill,1962
SPL2	−2.935761768	2.666925072	4.322301671	3.121387991
SPL3	−2.024864671	1.403751508	4.078637917	2.284780832
SPL4	−0.518529778	0.674943639	3.628717621	1.838996462
SPL5	−0.261800851	0.851675793	2.790033732	0.978515839
SPL6	−0.220557557	0.648754356	2.725187025	0.681246733
SPL7	−0.113526502	0.428963567	1.950808043	0.127530516
SPL8	−0.206744753	0.755067647	1.665508346	0.046328309
SPL9	−0.140798852	0.677431651	1.505177947	0.027294181
R-squared values	0.475767556	0.367199096	0.746232126	0.663906381
R-squared values (%)	**48**	**37**	**75**	**66**

The April model did not perform badly as it yielded the third best R^2 value of 48%, as presented in Table 4.18. If the model gives out R^2 of about 50%, it means that approximately half of the observed variation can be explained by the model input. The model can therefore be given credibility with slight limitations.

Table 4.19 June 2021 model – Comparison results

Sampling point	$k_2 = 2.48\frac{V^{-0.27}}{R^{-0.17}}$	$k_2 = 5.03\frac{V^{0.969}}{R^{1.678}}$	$k_2 = 5.73\frac{V^{0.5}}{H^{0.25}}$	$k_2 = 1.92\frac{V^{1.325}}{H^{2.006}}$
	Mooi River, South Africa,2021	Steeter et al.,1925	Jha et al.,2001	Churchill,1962
SPL2	2.200767039	4.237695274	4.912900776	3.24750543
SPL3	2.409287465	2.597348373	5.29481994	3.856164413
SPL4	2.739913807	1.764564265	4.942265911	2.319132156
SPL5	2.750849128	1.107439692	2.742916649	0.609756656
SPL6	3.003608446	0.980123414	2.368069718	0.187533952
SPL7	3.075889599	0.871540378	2.490515875	0.181598675
SPL8	2.834417694	1.92867015	3.023604286	0.289642455
SPL9	2.945157878	2.211671851	3.121469849	0.24716203
R-squared values	0.488736181	0.14060797	0.357389589	0.525655806
R-squared values (%)	**49**	**14**	**36**	**53**

R^2 value of 49% was produced by the model produced in June. The Churchill model produced the best R^2 value of 53% as shown on Table 4.19. The overall impression of the models produced is good. They did not perform bad in terms of model precision. The model validation process was a success for most of the models. This means that there is fairly a significant level of credibility embodied in our models, with limitations pertaining the size of data and high quality techniques of data handling.

4.3 Discussion

4.3.1 Self-purification by water quality indicators

Mooi River stretches for a length of 112 km from the first sampling point (SPL1) at Klerkskraal dam to the last sampling point (SPL12) at Vaal River confluence as shown in Figure 3.3. The results presented on Figures 4.2 and 4.3 show fluctuations of DO deficit and BOD for both the dry and wet seasons, respectively. This presents the insufficiencies of DO in the water due to the biochemical oxidation process of breaking down the pollution organic matter, which requires oxygen. The insufficiencies were calculated with respect to the possible saturation oxygen level of the water at a particular temperature. The analysis of these results yields a clear identification and understanding of all the weak spots and reoxygenation strength along the river length in relation to pollution subjection.

Figure 4.2 shows the oxygen deficits starting at about 1 mg/l for both seasons. This means the water was cleaner at SPL1, which is at Klerkskraal Dam outlet. For both seasons, the quality of the water deteriorated by constantly losing oxygen for a flow distance of about 23.6 km. This resulted in high DO deficit levels. For example, the DO deficit in November 2020 went from 1.12 to 3.7mg/l. The loss of oxygen was due to the breaking down of the organic matter introduced in the water by non-point pollution sources such as agricultural activities adjacent to the river.

The river started to be subjected to high pollution concentrations at Potchefstroom city after flowing for about 46.5 km from the Klerkskraal Dam. The types of city pollution sources affecting the river ranged from industrialisation, physical human littering, exhaust emissions, as well as excessive urban run-off. The oxygen deficit level of the wet season at this point has risen higher than the one of the dry seasons because of the water run-off that carried all the excessive adjacent pollutants into the river during rainy seasons. Low levels of oxygen deficit were recorded between Boskop Dam and Potchefstroom Dam as a result of an effective reoxygenation process.

The BOD contents were high in the rainy seasons. The highest recorded was 2.4 mg/l in December 2020, followed by 2.1 mg/l in November 2020 and 1.7 mg/l in January. The high levels of BODwere influenced by a high content of nutrients introduced into the river through surface run-off.The rainy season meant high hydraulic depth of surface masses through direct recharge from the rain (Watson-Hernández et al., 2022). Together with the slow flow rate of the river, the biodegradability of the organic matter in the water was compromised and so did the self-

purification capacity of the river. The high hydraulic depth of the water negatively impacted the reoxygenation because the absorption and dilution of the atmospheric oxygen was slow through such dynamics. The recordings of BOD during the dry season were low due to the following reasons; Low hydraulic depth of the river influenced the rapid rate of absorption, dilution, and dispersion of atmospheric oxygen into the water, thus influencing effective self-purification. The highest recorded BOD was 1.3 mg/l at Mooi River Mall during the dry season due to direct city pollution into the river.

4.3.2 Self-purification by river hydraulics parameters

The oxygen deficit level of the wet season was also affected by the low flow rate and deep hydraulic depth of the river at this point. The flow rates and hydraulic depths were low during the dry season period. The low flow velocities that were recorded during the wet season did not complement the high hydraulic depths recorded during this particular season. The reoxygenation rate was less in deep slow-moving waters due to the insufficiencies of turbulence, oxygen dilution and dispersion in water (Ain et al., 2019).

The flow velocity influenced the conveyance of the DO since an increment in flow velocity suggests less time is taken for the DO to spread. This exchange happens at the air–water interface. The exchange of DO from the air to the surface of the water body is controlled by the exchange rate and the DO shortage. The exchange rate depends on the turbulence of water close the water surface, which is by and large assessed from the water velocity. Profundity and other water hydraulic parameters such as hydraulic depth and kinematic viscosity.

The presence of rocks along the water course in this study region enhanced mixing. The velocity also affected the spatial distribution of the DO because an increased velocity meant it would take less time for the oxygen to spread. Thus, the combined effect of these two relationships resulted in a lower overall oxygen deficit due to the increased reaeration coefficient, with a more widespread effect of the DO deficit.

For example, a very high hydraulic depth and low flow velocity of 0.99 m and 0.16 m/s, respectively, were recorded at SPL6. All this resulted in high DO deficit levels. The oxygen deficits then declined towards the Vaal River confluence. The flow distance between SPL10 and SPL12 (50 km) allowed for sufficient reoxygenation and recovery from organic matter present in the water.

The highest DO deficits were recorded in the wet season because of the increase in hydraulic depths of the water. High quantities of water in rivers makes it difficult for self-purification to take place effectively (Survilė et al., 2017). The highest deficits were observed between SPL6 and SPL7, Potchefstroom city. This is because of the high rate of urban surface run-off into the river. Urban run-off into the river takes place at a high rate because of the artificial surface that allows less water infiltration (McGrane, 2016).

The contamination washed into the river through urban run-off included exhaust emissions, vehicle wear, road abrasion, car washing, industrial activities, construction activities and physical littering, which have a negative impact on the purification strength of the river. In most cases they result in eutrophication. Eutrophication has shown to be one of the major factors affecting the purification strength of Mooi River, as reflected in Figure 4.17.

Figure 4.17 shows algal blooms and aquatic plants caused by phosphorus and nitrogen as a result of agricultural activities through direct surface run-off into the Mooi River. High DO deficits are caused by the decomposition of dead algae by bacteria as it requires oxygen for the process to take place (Kuparinen & Touminen, 2001).

Figure 4.17 Algal blooming due to eutrophication in Mooi River

4.3.3 Modelling validation discussions

The performance of a model to predict variables in a mathematical equation is very imperative for gauging its reliability (David et al., 2020). The coefficient of determination (R^2) was used to measure the performance of all the models developed for each month of the seasons concerned.

Excel Solver was used to develop river hydraulics reoxygenation models presented in Tables 4.8 to 4.13, using reoxygenation constant values calculated with water quality indicators presented in Tables 4.1 to 4.6 (as shown in Figure 3.10). Thereafter, regression analysis was performed to gauge the performance of every model developed by means of R^2. Using the best line of fit equation on every model, improved reoxygenation models with better R^2 values were generated using Excel Solver as shown in Figures 4.5 to 4.16.

Reoxygenation models developed for the dry and wet seasons yielded fairly good results in terms of precision. However, most of them were outclassed by other existing models developed by other researchers. Generally the modelling was successful based on the reasons alluded under discussions section. From all the models developed in this study, the one that performed well against the models used forcomparisons is the model developed in the October dry season with an R^2 of 55%. The modelsfor this study were, however, reliable due to the fact that they were developed using tropical conditions, hydraulic dynamics and pollution analysis specific to this study area. The exceptional performance of other models in terms of high precision determined by the R^2 values could be explained by the fact that they could have been developed using re-analysis of multiple existing data.

4.3.4 Summary

The self-purification strength of the Mooi River catchment was not consistent along its existing length; it fluctuated from point to point. The negative strength represented the effect that non-point pollution sources have on the purification capacity of the catchment. Eutrophication was another aspectthat influences the self-purification capacity of the catchment.

A lot of DO is consumed during this process, thus interrupts the purification process. Figure 4.2 showed high values of DO deficit during the wet season. This was because of the amount of run-off into the river that negatively impacted the quality of the river by diminishing the DO in the water.

Reoxygenation models developed by this study yielded very significant results in terms of performance gauging, using the regression R^2 precision method. The model developed in October produced a precision value (R^2) of 55% higher than produced through the models developed by other researchers around the world.This means that it has more than half of reliability in terms of defining the dynamics of re-oxygenation of this particular river under given tropical conditions.

CHAPTER 5

CONCLUSION

5.1 Introduction

The purpose of water quality models is to facilitate the work of researchers, designers, managers, and planners who are faced with conceiving and solving problems associated with the physical, chemical, and biological processes that lead to water pollution and its control (Ejigu, 2021). This chapter discusses the conclusion of the findings as well as the recommendations based on the gaps identified by the findings of the study.

5.2 Conclusion

The Mooi River catchment is exposed to a lot of non-point pollution sources, of which the major ones were identified as agricultural activities and urban run-off discharges during the wet season. The high levels of phosphorus and nitrogen caused by excessive use of agricultural pesticides resulted in eutrophication. Furthermore, Mooi River is a slow flowing river at some of the segments, some parts of it are close to stagnant. At deep hydraulic depths, this results in slow atmospheric oxygen infusion, algal blooming and growth of aquatic plants, thus causing rapid depletion of DO. This affects the natural self-purification of the catchment.

Overall pollution content presented by BOD content is high during the wet season. This conforms to reality due to the dilution factor. The rainy season supplies the river with fresh water, thus increasing the river volume. The fresh water passes through the atmosphere, while dissolving atmospheric oxygen during its descent. This makes the DO level to be farther away from the critical point due to the relatively sufficient DO in the river before the introduction of the wastewater.

Disposal of the Potchefstroom WWTW effluent into the Mooi River affects its quality just for a flow distance of less than 10 km. Thereafter, Mooi River regains the capacity to purify itself until it is further affected by agricultural non-point pollution sources downstream. However, Mooi River still carries the potential to purify itself along the flow segments that are less polluted and flow segments that are favored by hydraulic dynamics advantageous to reoxygenation.

5.3 Limitations of the study

This study analysed self-purification strength of Mooi River as a function of DO and BOD fluctuations resulting from organic matter by point pollution sources, organic matter by non-point pollution sources, deoxygenation by decomposition of organic matter and reoxygenation by atmospheric aeration as well as eutrophication. The hydrology and water quality assessment of groundwater was not taken into consideration. However, the model takes into consideration the hydrology of the catchment in terms of the measured discharges at every sampling point.

5.4 Assessment of aim and objectives

5.4.1 Assessment of the aim

The aim of the study was to assess the self-purification capacity of the Mooi River catchment based on the water quality analysis, and to develop and validate a reoxygenation model from the hydraulics parameters of the catchment.

5.4.2 Assessment of the objectives

1. To determine the self-purification capacity values (*f*) of the Mooi River catchment using deoxygenation and reoxygenation constants from water quality analyses.

   The self-purification capacity of Mooi River catchment was determined and found to be compromised by a number of factors, including point and non-point pollution sources, as well as the hydraulic dynamics of the river along its existing length. The results were presented in Tables 4.1 to 4.6.

2. To develop the Mooi River reoxygenation model using river hydraulic parameters.

   The model was developed through the assessment of the water self-purification indicators during the dry and wet seasons. The model was further improved by the mathematical regression analysis and Microsoft Excel Solver, using the suitable trendline of standard deviation minimization.

3. To validate the developed reoxygenation model with water quality data and comparing it to existing reoxygenation models using a regression analysis. The validation is based on the credibility of the model with regards to the extent of precision defined by the R^2 value which justifies the extent at which the model can precisely define the core and important variances of a data sets on different types of samples.

Model validation was done by means of comparison with models developed by other researchers around the world since the inception of the self-purification studies. The model developed in the month of October (dry season) produced a regression precisionvalue (R^2) of 55%, surpassing the most trusted model developed by Churchill in 1956.Equation 16 presents the model with the highest precision value, which was adopted as the Mooi River reoxygenation model developed in this study:

$$k_2 = -15.99 \frac{v^{2.32}}{R^{0.62}} \tag{26}$$

5.5 Recommendations

Water quality management system of South Africa must employ intense purification modelling of its river systems. This will assist in identifying pollution sources that are fatal to the quality of the water in South African water masses. This will also help the water treatment sectors in terms of identifying reliable points of raw water extraction for potable water treatment, thus reducing the treatment costs. Due to the fact that South Africa is one of the countries that are faced with energy deficiency,reducing the water treatment intensity means using less electricity and chemicals during treatment. Recreational economic activities influenced by aquatic life such as fish at places such as the Boskop Dam and Potchefstroom Dam, are also affected by the pollution caused inthe Mooi River.

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