Removal of nitrate in raw water using a vertical roughing filter with an external carbon source

By

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Declaration

I, Lekhooa Ford Mohobane, declare that the content of this dissertation represents my own unaided work. It is being submitted for the MEng Degree at the Cape Peninsula University of Technology, Cape Town. It has not been submitted previously for any degree or examination at this or any other university.

(signature)

Signed in Cape Town, this 26th day of September 2022

Abstract

High accumulation of nitrate above the recommended maximum guideline value has become a common problem in most water supply sources. According to the World Health Organization (WHO), about 30% of water supply sources in the world exceed the maximum nitrate contamination level of 11 mg/L-N / 50 mg/L-NO_3. Consumption of water with high nitrate concentration poses health hazards to both humans and livestock. Several technologies such as reverse osmosis and electrodialysis, have been adopted in removing nitrate from raw water. However, they have drawbacks that include the production of high strength residual brine and low efficiency. Nonetheless, biological denitrification has proved to be an effective technology for nitrate removal and the process can be enhanced by adding an external carbon source. Denitrification in roughing filters has not been widely studied, except in bio-filters and slow sand filters. This research aimed to investigate the efficacy of roughing filters enhanced by an external carbon source in removing nitrate in raw water. Two upward vertical roughing filters in series (UVRFs) were used, one was a vertical roughing filter with ethanol as a carbon source (VRF_{wt}) and the other was a vertical roughing filter without a carbon source (VRF_{wo}). The inflow and outflow of nitrate and other physicochemical parameters were monitored to evaluate their influence on a roughing filter's performance in removing nitrate in raw water. The carbon: nitrogen ratios (C/N ratios) of 1.05, 1.08 and 1.1, were investigated, coupled with a nitrate removal kinetic model. Furthermore, filter design parameters and the effect of biomass on flow rate were also studied.

The average nitrate removal efficiency in a vertical roughing filter with a carbon source was 88%, 70%, and 83%, for carbon: nitrogen ratios (C/N ratios) of 1.05, 1.08, and 1.1, respectively. The drop-in flow rate was 27% for a vertical roughing filter with a carbon source (VRF_{wt}) and was attributed to the biological layer growth, whereas a 15% decline was observed in the vertical roughing filter without a carbon source (VRF_{wo}). The decrease in flow rate was evident at 30-35 days from the start of the filter operation. The removal efficiency was 75%, 43%, and 46% at C/N ratios of 1.05,1.08 and 1.1, respectively. The residual ethanol measured as chemical oxygen demand (COD) in the filter with an external carbon source (VRF_{wt}) ranged between 85 mg/L to 632 mg/L during the filter run. The average residual ethanol measured as COD during the filter rest period ranged between 41 mg/L and 561 mg/L with a removal efficiency of 88%, 49% and 53% at C/N ratios of 1.05,1.08 and 1.1, respectively. The overall average reduction of dissolved oxygen (DO) in the VRF_{wt} at C/N ratios of 1.05, 1.08 and 1.1 was 42%, 54%, and 51% respectively, while DO reduction in the VRF_{wo} was 17% 18% and 17%, respectively. A decline in DO was profound in the VRF_{wt} compared to the $VRF_{wo.}$

The VRF_{wt} showed a high potential for removing nitrate in raw water for potable use. Therefore, when the VRF_{wt} is applied at large scale, it will increase access to water sources that were initially rendered unsuitable to many water utilities due to high nitrate concentrations; thereby increasing their water supply. Importantly, the lack of nitrate in potable water would minimize water-related diseases induced by the use of high nitrate-rich water. Again, the reaction rate order (n) and reaction rate constant (k) determined from the nitrate removal kinetic model can help in assessing the total nitrate removal rate and efficiency in a vertical roughing filter, without the need to operate the filter, thus saving time and money.

Dedication

To my dearest parents and family – for their support, faith, and love.

I can do all this through God who gives me strength.

Philippians 4

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Publications and conference

The findings of this study have been published in the following journal and presented and published in the mentioned conference proceedings.

Peer-reviewed publications

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Nomenclature

Constants

Symbol	Meaning (Units)
A	Cross section area of specimen (cm^2)
BRP	Bacterial Regrowth Potential
BODC	Biodegradable Organic Carbon (mg/L)
BOM	Biodegradable organic matter
CPUT	Cape Peninsula University of Technology
C/N	Carbon Nitrogen Ratio
C_V	Coefficient of variation
C_e	Concentration of nitrate effluent (mg/L)
C_i	Concentration of nitrate influent (mg/L)
COD	Chemical Oxygen Demand (mg/L)
$C_{NO_3^-}$	Nitrate concentration (mg/L)
$dC_{NO_3^-}$	Change in nitrate across the roughing filter (mg/L)
d_c	Column diameter (m)
DWAF	Department of Water & Sanitation
DO	Dissolved Oxygen (mg/L)
$\frac{dC_{NO_3^-}}{dt}$	Kinetic nitrate reaction rate (g/m^3/day)
EPS	Extracellular Polymetric Substances
F_w	Final weight of oven dried filter paper + residue (mg)
h	Pressure head of water (cm)
K	Coefficient of permeability (cm/sec)
k_1	First order reaction rate constant (day^{-1})
k_s	Half saturation constant (mg/L)
k	Reaction rate constant (day^{-1})
k_0	Zero order reaction rate constant (mg/L/day)
L	Characteristic linear dimension (Column diameter) (m)
L	Length of specimen (cm)
MCL	Maximum contaminant level (mg/L)
N_e	Nitrate removal efficiency (%)
NHL	Non-Hodgkin Lymphoma
N	Number of observations/samples

n	Reaction rate order
O_w	Original weight of filter paper (mg)
pH	Potential Hydrogen
q	Discharge (cm^3/sec)
Q	Flow rate through the roughing filter (m^3/day)
Q_w	Water discharge (cm^3)
$r_{NO_3^-}$	Kinetic nitrate reaction rate (g/m^3/day)
R_{max}	Maximum removal reaction rate (g/m^3/day)
R_e	Reynolds number
SANS	South African National Standards
STD_d	Standard deviation
STD_E	Standard error
t_1	Ending time (min)
t_0	Starting time (min)
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids (mg/L)
u	Mean velocity of the fluid (m/s)
$UVRF_s$	Upward Vertical Roughing Filter in series
V	Filtration rate (m/h)
v	Kinetic viscosity (1.004×10^{-6} m$^{2/}$/s at 20˚C)
V_p	Media packed filter volume (L)
V_S	Sample volume (L)
V_T	Total filter volume (L)
$Var(X)$	Variance
V_r	Volume of roughing filter (L)
VRF	Vertical Roughing Filter
VRF_{wt}	Vertical Roughing Filter with a carbon source
VRF_{wo}	Vertical Roughing Filter without a carbon source
WHO	World Health Organisation
$\bar{x}$	Arithmetic mean
x_i	Observations

Abbreviations

kPa	Kilopascal
L	litre
m	metre
mm	millimetre
mg	milligram
psi	pound-force per square inch

Greek Letters

Symbol	**Meaning (units)**
ρ	Density (kg/m^3)
μ	Viscosity (N.s/m^2)

Terms and Concepts

Biodegradable Dissolved Organic Carbon	The amount of organic matter that is biodegraded by a bacterial active sand.
Bacterial Regrowth Potential	The quantification of the bacterial growth that can occur under defined conditions in a sample, such as the presence of organic carbon and other growth promoting compounds.
Carbon source	Organic or inorganic compounds used by Organisms as their source of carbon to build biomass.
Carbon: Nitrogen Ratio (C/N Ratio)	The ratio of the carbon mass to nitrogen mass of a substance.
Extracellular Polymetric Substances	Biomolecules and inert solids that bind cells to each other and to solid material.
Heterotrophic Denitrification	A biological process in which nitrate (NO_3^-) is anaerobically reduced to Nitrogen gas (N_2) by heterotrophic bacteria.
Maximum Contaminant Level	The highest amount of specific contaminant allowed in a substance.
Nitrification	The biological oxidation of ammonia (NH_3) and ammonium (NH_4^+) to nitrate by nitrifying bacteria
Potential Hydrogen	A measure of a solution's acidity or alkalinity and, it is equivalent to 7 for neutral solutions. It increases with increasing alkalinity and decreases with decreasing acidity. The scale that is commonly employed ranges from 0 to 14.
Upward Vertical Roughing Filter in series	A filter media packed with larger diameter particles In which the flow is from the bottom to the top of the filter box. Three filter boxes are usually arranged in series and are packed with successive filter media

Chapter 1 Introduction

High accumulation of nitrate in raw water is becoming a common problem in most water supply sources worldwide (McAdam & Judd, 2006). The World Health Organization (WHO) has established that 30% of water supply sources in the world contain nitrate contaminations of over 24 mg/L (Archna & Ranbir, 2012), whereas in South Africa, many areas experience nitrate concentrations that are greater than 100 mg/L-NO_3^- (Schoeman & Steyn, 2000; Tredoux, 2004). Nitrate occurs naturally in water. However, its elevated levels have been a result of agricultural activities specifically, from crop fertilisation to discharges from animal operations, commercial or industrial activities, and waste water treatment activities (Eljamal *et al.*, 2006; Habboub, 2007; Jensen *et al.*, 2012; Zhang *et al.*, 2018; Xu *et al.*, 2021). Nitrate easily dissolves in water and leaches through the soil into water supplies, thereby accumulating and eventually building up to high levels over time (Dozier *et al.*, 2008).

1.1 Background and Motivation

High level exposure of nitrate in potable water poses a major health hazard such as methemoglobinemia, otherwise called Blue Baby Syndrome. It is a health hazard to infants, pregnant women and animals (Tredoux, 2004; Peechattukudy & Dhoble, 2017). Studies by Cantor (1997) and Gulis *et al.* (2002) have found a strong connection between high nitrate intake and other diseases such as stomach and prostate cancer mortality, colon cancer and non-Hodgkin lymphoma (NHL). Furthermore, a substantial amount of nitrate consumption can also cause abdominal pain, diarrhoea, vomiting, hypertension, central nervous system birth defects, diabetes respiratory tract infections and changes to the immune system (Fewtrell, 2004; Lohumi *et al.*, 2004). Nitrate also poses distinctive water treatment challenges that mostly impact small rural communities (Moore *et al.*, 2011).

To overcome this alarming challenge, a few technology advancements, and methods like reverse osmosis, electrodialysis reversal, iron exchange, biological, chemical denitrification and nano size zero-violent iron (Nzvi) have been adopted as treatment for high nitrate, decrease in nitrogen and other nitrogen species such as ammonia contamination in water. However, drawbacks include high strength brine residual production that lacks residual disposal options, challenges in increasing salt loads, low efficiency agglomeration that forms necklace like structures and high operating cost renders them unsustainable. These drawbacks are mainly experienced in reverse osmosis, ion exchange and electrodialysis reversal removal technologies (Shams, 2010; Jensen *et al.,* 2012; Amen *et al*., 2017; Amen *et al*., 2018; Khalil *et al*., 2018; Takami *et al*., 2019; Eljamal *et al*., 2022) .

In contrast to these adopted technologies and their drawbacks on nitrate treatment in raw water, roughing filtration is identified to be an effective, less costly, reliable and easy treatment process. It has successfully proven to reduce dissolved nutrients, kaolinite clay, coliforms, algae, suspended solids, iron and manganese with more emphasis on high levels of turbid water (Wegelin, 1986; Collins *et al.,* 1994; Jayalath *et al.,* 1994). Despite its success in treating these water quality parameters, there is still limited data on roughing filtration removal efficiency on nitrate in raw water (Kusuma *et al.,* 2016).

Attention has now shifted towards the biological denitrification process in raw water, to achieve potable water. This process utilizes microorganisms to convert nitrate to Nitrogen gas and can be enhanced by an external carbon source (Eljamal *et al*., 2006; Eljamal *et al.,* 2009).The biological denitrification process is accomplished either by autotrophic-inorganic or heterotrophic-organic bacteria. The energy and carbon origin for these bacteria is inorganic or organic compounds respectively (Matějů *et al*., 1992; Shrimali & Singh, 2001). Several studies found biological denitrification to be the most effective technology for removing nitrate in water (Gómez *et* al., 2000; Shams, 2010). It has therefore progressed over the years to large-scale plants (Soares, 2000). Nevertheless, biological denitrification has not yet been explored in roughing filters, except in bio-sand filters and slow sand filters (Mutsvangwa & Matope, 2017).

A study by Kusuma *et al.* (2016) suggested that more investigations into designing roughing filters to eliminate nitrate in water are required. Therefore, it was crucial to evaluate the performance of a vertical roughing filter in removing nitrate in raw water for potable use, with and without an external carbon source. A carbon source is mostly required to increase production and cell growth since heterotrophic bacteria needs organic carbon to enhance the denitrification process. This investigation of a vertical roughing filter for removing nitrate in raw water for potable use contributes to the nitrate treatment technologies that are currently in use. It will also contribute to the enhancement of water quality regionally, locally, and internationally. Hence, this research analysed the effectiveness of a vertical roughing filter in removing nitrate in raw water for potable use, with an external carbon source.

1.2 The Research Problem

Lately, nitrate concentration has increased and continues to increase alarmingly above the World Health Organization (WHO) drinking water guidelines, which stipulate that the maximum concentration level should be less than 50 mg/L NO_3^- or 11 mg/L as nitrate-Nitrogen (WHO, 1995; WHO, 2011). Excessive nitrate concentration in water is a global issue, and South Africa has been declared one of the countries to have highly elevated nitrate concentrations in raw water (Schoeman & Steyn, 2000; Tredoux, 2004). Some regional areas such as the Moretele District in the Northwest Province, Springbok Flats in Limpopo Province and Kudumane District in the Free State Province have shown high nitrate concentration levels of over 50 mg/L NO_3^- (Tredoux, 1993; Tredoux, 2004; Talma *et al.*, 2006; Maherry *et al.*, 2010).

1.3 Research Question

What is the effectiveness of a vertical roughing filter with an external organic Carbon source in removing nitrate in raw water for potable use?

1.4 Aim, Objectives and Outcomes

The aim of this research was to investigate nitrate removal in raw water for potable use, using a vertical roughing filter with an external organic carbon source. Therefore, to accomplish this aim, the following objectives were explored:

- To investigate the accustomed design parameters, process capabilities and nitrate concentration for optimal nitrate removal using a conventional vertical roughing filter, with and without a carbon source.
- To determine the optimum time and depth for removal of nitrate in a vertical roughing filter.
- To investigate the optimum Carbon: Nitrogen (C N) ratio for optimum nitrate removal and the relationship between physicochemical parameters that include pH, dissolved oxygen (DO), chemical oxygen demand (COD), temperature, turbidity and nitrite in a vertical roughing filter.
- To investigate the effect of the biomass growth on filter operation and the quality of treated water with regard to residual Carbon, to meet water quality standards.
- To develop a mathematical model to predict removal of nitrate in a vertical roughing filter using an external organic carbon source.

This research intended to investigate the effectiveness of a vertical roughing filter with an external carbon source, in removing nitrate in raw water, and the expected outcomes were to reveal.:

- The design parameters and process capabilities for effective nitrate removal when using a conventional vertical roughing filter, with and without a carbon source.
- The optimum time and depth for effective removal of nitrate in a vertical roughing filter.
- The optimum carbon: nitrogen (C/N) ratio for optimum nitrate removal and the relationship between physicochemical parameters in a vertical roughing filter.
- The effect of the biomass growth on filter operation and the quality of treated water with regard to the residual cCarbon, to meet water quality standards.
- The predictive nitrate removal model in a vertical roughing filter, using an external carbon source.

1.5 Scope and delineation

The scope of the research is focused solely on investigating the removal of nitrate in raw water, using a vertical roughing filter with ethanol as an external carbon source. The sample water that was used in the research was from surface water and the source was Kuils River in the Western Cape Province. The research only focused on the filtration rate, filter depth and media size as the main design parameters for the vertical roughing filter. Other variables that can affect the removal of nitrate and the quality of treated effluent water include the carbon: nitrogen ratio (C/N), process capabilities. Residual carbon and biomass were also considered. Physicochemical characteristics of water tested in the research included dissolved oxygen (DO), nitrate, nitrite, pH, chemical oxygen demand (COD), temperature, turbidity, and Total Suspended Solids (TSS). The study did not analyse phosphates, total and soluble Kjeldahl Nitrogen (TKN) parameters, major cations, and anions, metals, and organics, including biodegradable organic Carbon (BDOC) and bacterial regrowth potential (BRP).

1.6 Assumptions

The study aimed to achieve optimal removal efficiency of nitrate in raw water, using a conventional up-flow vertical roughing filter at laboratory scale. It was assumed that denitrification through an up-flow vertical roughing filter in series (UVRFs) is an effective technique to remove nitrate in water. It was also assumed that nitrification will take place at the top where there is oxygen whilst denitrification will happen at the zone near the base of the filter where there is low oxygen.

Three packed media sizes of granite gravel with successive media grading's of 13 mm, 9 mm and 6 mm and a filter depth of 1 m were assumed to achieve the optimal removal efficiency by enhancing the filter performance. Removal of nitrate was assumed to increase as the raw water flows from high-grade media to low-grade media. Ethanol at a C/N ratio ranging between 1.05 - 1.1 was assumed to be appropriate to enhance the denitrification process. It was further assumed that the filter with a limited supply of food substrate for microbial growth (ethanol) will result in a slower biofilm development and therefore low nitrate removal in the water. The total water inflow was assumed to be equal to the total outflow. Therefore, no accumulation would result in the roughing filter.

1.7 Research Context and Significance

This research study mainly falls within civil engineering, water and environmental engineering under water and wastewater treatment, primarily focusing on improving water quality. Special emphasis was placed on the reduction of high nitrate levels in raw water for potable use. This technology can improve the economies of scale of water utilities in South Africa and other less developed countries, when operated as a full-scale design. In addition, when VRF_{wt} is applied at large scale, it will increase access to water sources that were initially rendered unsuitable to many water utilities due to high nitrate concentrations; thus, increasing their water supply. Importantly, the absence of nitrate in potable water can reduce water related diseases caused by the intake of high nitrate-rich water. Other risks to human health problems such as spontaneous abortions in females, birth defects and respiratory tract infections can also be reduced.

1.8 Summary of the Methodology

Two experimental vertical roughing filter models were built; one was used with an external organic carbon source and the other without a carbon source. Ethanol (C_2H_5OH) was used as an organic carbon source to enhance the denitrification process. The raw river water was measured to obtain the initial nitrate concentration. Due to low nitrate concentrations, the raw water was spiked with potassium nitrate (KNO_3) to increase the nitrate concentration. The experimental investigation for this research was conducted at the Cape Peninsula University of Technology (CPUT) laboratories. The roughing filter columns were packed with granite gravel as filter media. The successive filter media sizes of 13 mm, 9 mm and 6 mm were attained through sieving. Water samples were collected from the inlet, outlet and intermediate sampling points on each of the two laboratory-scale roughing filters. The optimum C/N ratio and filter depth, the effect of biomass on flow rate and a predictive model for nitrate removal were investigated. Design parameters and process capabilities for effective nitrate removal were also investigated.

1.9 Organisation of the Research

This research encompasses a full understanding of nitrate effect in potable water and the effectiveness of a vertical roughing filter with an external organic carbon source, in removing nitrate in raw water for potable use. The research is subdivided into six main chapters that include:

Chapter 1 - **Introduction:** This chapter serves as a general introduction to the research topic. In the chapter, the motivation and background to the research is introduced and discussed. The research problem and question, aim, objectives and outcomes are also stated. The chapter further discusses the research significance, its delineation as well as a summary of the methodology.

Chapter 2 - **Literature Review and Theory:** This chapter contains in-depth discussions of the literature regarding the removal of nitrate in raw water using a vertical roughing filter with ethanol as an external carbon source. The current and emerging theories on nitrate prevalence, nitrate chemistry, nitrate sources, and nitrate reduction treatment methods are reviewed. The implications linked to nitrate exposure as well as current research on the use of roughing filters in eliminating nitrate in raw water are also discussed.

Chapter 3 - **Research Methodology:** The nitrate measurement from the experimental procedure to the analysis of data is presented. The UVRFs design principles, guidelines and concepts adopted in this research are explained in detail. Furthermore, a developed nitrate removal rate model equation for removing nitrate in roughing filters is presented.

Chapter 4 - **Results:** The results of the laboratory experiments are reported in this chapter. The findings obtained are well interpreted, arranged, and combined to explain the outcomes, the research question, objectives and aims of the study. In this chapter, the data is arranged and presented in the form of figures, graphs, and tables.

Chapter 5 - **Discussion:** The data presented in Chapter 4 is interpreted and critically discussed in line with relevant literature, to demonstrate the findings in relation to the study aim and objectives.

Chapter 6 - **Conclusions and Recommendations:** This chapter presents a summary of the study and the findings of the research problem. The results are summarised, and conclusions are drawn in light of the findings and the literature reviewed. Shortcomings of the filter system are highlighted, and recommendations are made regarding possible future research on the use of a vertical roughing filter in removing nitrate from raw water.

Chapter 2 Literature Review and Theory

This section presents a review on the nitrogen cycle, nitrate chemistry, sources and problems associated with nitrate, nitrate prevalence, other nitrate removal techniques and their limitations and the current status of roughing filters with regards to the removal of nitrate.

2.1 Introduction

The World Health Organization (WHO) identifies surface and ground water as a useful water supply source for communities. However, these resources are being highly polluted by certain agricultural, domestic, and industrial activities that lead to an increase in nitrate contamination.

The quality of potable water is therefore altered, due to pollution caused by these activities. Habboub (2007) stated that raw water can be denitrified to reduce high nitrate contamination for potable use.

2.2 Nitrogen Cycle and Nitrate Chemistry

Nitrogen is a significant component of protein and nucleic acid and is for the most part required in incredible amounts in most life forms, in contrast to oxygen and carbon.

Water and soil contain nitrogen that originates from fertiliser application, animal tissue and dead plants, manure, atmospheric deposits, and waste material.

The atmosphere stores most of the earth's Nitrogen as 78% N_2 gas. Inorganic nitrogen is primarily formed by the: ammonia (NH_3), nitrite (NO_2), nitrate (NO_3^-) and nitrogen gas (N_2) (Gale *et al.*, 1993).

An illustration of the nitrogen cycle is presented in Figure 2.1 below. Initially, any nitrogen generated enters the cycle from chemical production via nitrogen fertilizers and industrial fixation, nitrogen fixation through manure and legume and electrical discharge through rain clouds. Naturally, the cycle can work in cropland and regular environments.

A short supply of nitrogen is mostly experienced in regular environments due to the poor cycling efficiency of the nitrogen, which results in low level losses. By contrast, nitrogen abundance in some ecosystems usually results in high potential losses (Habboub, 2007).

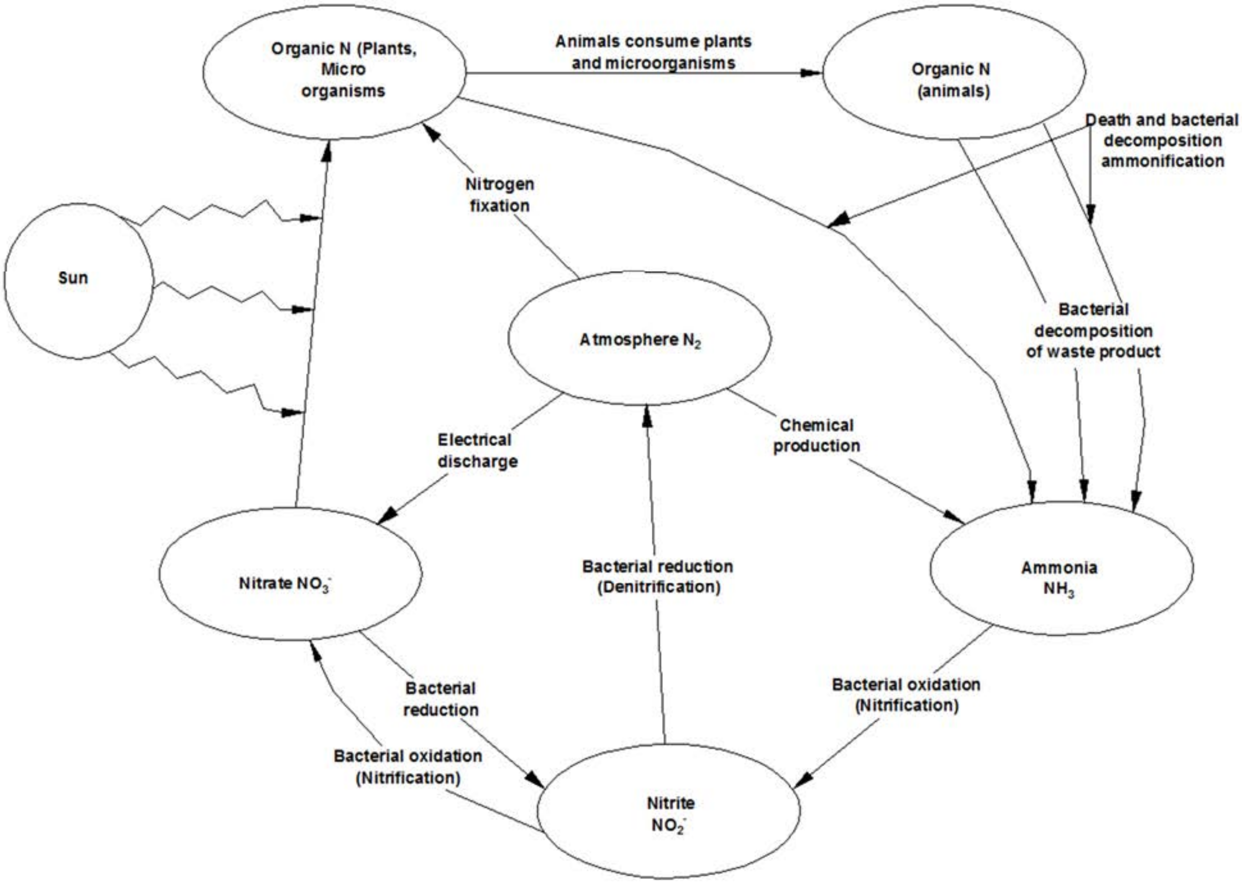

Figure 2.1 A representation of a simplified Nitrogen cycle in nature (Habboub, 2007)

2.3 Nitrification

Nitrification takes place when nitrogen as ammonia is biologically oxidized aerobically and reduced by ammonium oxidizing bacteria; a nitritation process to nitrite or by nitrite oxidizing bacteria to nitrate through a nitritation process. As a chemoautotrophic process, it is considered exceptionally important in regulating the water quality of aquatic environments and the nitrogen cycle (Kowalchuk & Stephen, 2001). Carbon dioxide (CO_2) is used as a carbon source in an exergonic process to oxidize ammonia (NH_3) to nitrate (NO_3-), which provides enough energy to produce new cells. It can occur in root zone territories, soil water interfaces and vigorous locales of the water section (Reddy & D'Angelo, 1997).

Approximated dissolved oxygen (DO) levels at 1 mg/L are shown to be the limiting concentration for the nitrification process (Hammer & Knight, 1994; Lee *et al.,* 1999). The chemical oxidation processes are illustrated by the chemical reactions (1), (2), (3) and (4).

Mineralization

Organic: $N \xrightarrow{\qquad\qquad} NH_4^+$ (1)

Nitritation: $2NH_4^+ + 3O_2 \xrightarrow{\text{Ammonia oxidizing bacteria}} 4H^+ + 2H_2O + 2O_2^-$ (2)

Nitratation: $2NO_2^- + O_2 \xrightarrow{\text{nitrate oxidizing bacteria}} 2NO_3^-$ (3)

$2NH_4^+ + 4O_2 \xrightarrow{\qquad\qquad} 4H^+ + 2H_2O + 2NO_3^-$ (4)

2.4 Denitrification

This process happens under anoxic conditions where nitrite and nitrate are biologically reduced and released as nitrogen gas, with the assistance of chemoorganotrophic, phototrophic and lithoautrophic denitrifying microbes, in a series of specific stages (Kadlec *et al*., 2000). Nitrogen oxides act as terminals by accepting electrons along the transport chain in the microbial process. Electrons are conveyed from natural mixes to a more oxidized structure, as shown in the chemical reactions (5) and (6).

$6(CH_2O) + 4NO_3^- \xrightarrow{\qquad\qquad} 6CO_2 + 2N_2 + 6H_2O$ (5)

$2NO_3^- \xrightarrow{\text{Nitrate reductase}} 2NO_2 \xrightarrow{\text{Nitrite reluctance}} 2NO \xrightarrow{\text{Nitric oxide reluctance}}$

$NO_2 \xrightarrow{\text{Nitrous oxide reductase}} N_2$ (6)

2.5 Nitrate in Drinking Water

2.5.1 Sources of nitrate

Nitrogen is the most abundant element present on earth in its many forms and is required by most organisms for survival. In cases where total Nitrogen levels are high, nitrate is mostly found to be dominant over the other forms of Nitrogen that include ammonium (NH_4^+), ammonia (NH_3), and nitrite (NO_2^-). Nitrate can exist naturally at concentrations less than 3 mg/L nitrate-Nitrogen (Wall, 2013). The source of nitrate in surface water can differ with time and space (Zhang *et al*., 2018). In South Africa, it has been suggested that nitrate-nitrogen standards in drinking water should be kept below 4.4 mg/L for provision of a higher margin of health safety (Kross *et al., 1992)*. The potential sources of nitrate in the environment are therefore discussed in this section.

2.5.1.1 Naturally occurring nitrate

Nitrate contamination in water can be caused by naturally occurring processes. Habboub (2007) found that Nitrogen in the atmosphere is converted into nitrate that is deposited into the soil by rain during a lightning storm. The study further stated that infiltration may also cause high nitrate concentrations in shallow subsurface aquifers, through evapotranspiration and can eventually reach higher concentrations up to 60 mg/L nitrate-Nitrogen during storm events (McQuillan & Space, 1995). Furthermore, geological formations and sedimentary deposits with high organic matter also contribute to high nitrate concentrations in water. Nitrifying microorganisms known as Nitrosomonas can also form nitrite in galvanised steel pipes when there is an absence of oxygen in drinking water, just as the water becomes stale. Figure 2.2 below shows the various stages nitrate experiences from when it is applied and as it moves and connects to surface water, groundwater and drinking water. It also indicates the various connections groundwater has with different bodies, primarily potable water. Moreover, interruption to the environment can happen from eutrophication as nitrate moves into surface water and wetlands.

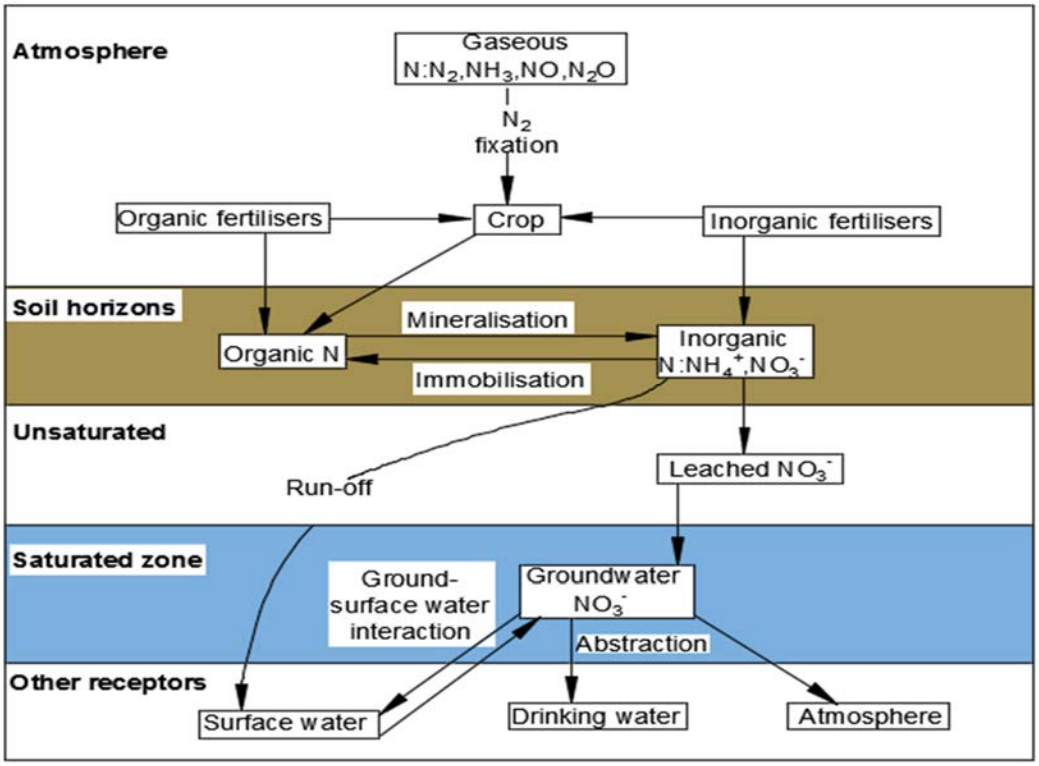

Figure 2.2 Movement of nitrates in different stages in the environment (Nadin, 2014)

2.5.1.2 Human and animal waste

The primary sources of nitrate into surface and groundwater are typically generated from human practices (Tredoux, 2004; Xu *et al.*, 2021). Humans and livestock contribute substantially to elevated levels of nitrate in surface and ground water. In fact, nitrate rich by-products are discharged directly into water bodies by industrial facilities, wastewater treatment plants, biological waste, and landfill leachates. On the other hand, effluent leakage in septic systems from homes also contributes to high levels of nitrate in both surface and groundwater (Aghapour *et al.*, 2016; Tang *et al.*, 2018).

2.5.1.3 Agriculture

Nitrogen is found abundantly in fertilizers used in agriculture, turf, and gardening. Normally, Nitrogen fertilizers can either take a form of inorganic fertilizers or organic sources such as manure. High nitrate levels can be experienced in regions of intensive agricultural production, where application of these fertilizers takes place. Rural areas are found to be mostly affected by nitrate pollution in water (Haas *et al*., 2017). Nitrogen can reach surface and ground waters as flowing nitrate from fields and leaching from manure in livestock operations (Della Rocca *et al*., 2005; He *et al*., 2011; Nadin, 2014). Other potential sources of nitrate in water include the waste generated from dairies, craped feeding operations, stockyards, open feedlots, and other equipment for holding and raising animals. Moreover, these facilities greatly contribute as high sources of Nitrogen and add various nutrients to groundwater. This is despite the fact that most people are concerned about surface water effects, smell, and flies, as issues brought about by animal waste. Estimates showed that 0.1 to 0.4 kg of Nitrogen per kilogram of animal weight is contained in animal waste. The total Nitrogen concentration range of 150 to 500 mg/L can be found in dairy waste (Habboub, 2007).

2.5.1.4 Industrial use of nitrate

Nitrate concentration is found to be greater in industrial regions than in rural areas due to high Nitrogen compounds usage in industrial settings (WHO, 1995). Some of the Nitrogen compounds that are mainly utilised in industries include; urea, nitric acid, ammonium nitrate and, anhydrous ammonia. Additionally, a few of the nitrate applications in industries include processing of metal, rubber production, textile industry raw material, household cleaners, manufacturing of plastic and, paper. Therefore, high nitrate concentration levels depend on the available source or results from improper handling, use and disposal of these compounds (Habboub, 2007).

2.6 Problems Associated with Nitrate Contamination

Many harmful effects to animals, humans and the environment are usually caused by nitrate concentration being greater or equal to 10 mg/L Nitrogen-nitrate in water (WHO, 1995; Knobeloch *et al*., 2000). These effects are described as follows:

2.6.1 Human and animal health effects

When nitrate is ingested at high concentrations in organic form, it causes methemoglobinemia otherwise called Blue Baby Syndrome. Nitrate (NO_3^-) can be synthetically decreased to an increasingly reactive form as nitrite (NO_2^-) by indigenous bacteria in the stomach or small intestines.

Methemoglobin is then formed when haemoglobin combines with nitrite that is consumed through the walls of the small digestive system into the circulation system.

Thus, it hinders the movement of oxygen through the circulatory system, which can cause death as the methemoglobin concentration increases. The human body is not usually capable of converting methemoglobin back to effective haemoglobin, that is capable of carrying oxygenated blood around the body (Habboub, 2007).

In new-born children, Blue Baby Syndrome is normally brought about by mixing their formula with water containing a nitrate-Nitrogen concentration above 10 mg/L. In any case, not just new-born children are susceptible. Methemoglobinemia can also affect adults with diseases or medications that reduce stomach acid rates (Habboub, 2007).

In addition, excessive nitrate in water sources may cause several health problems that include diarrhoea, diabetes, respiratory tract infections, abdominal pain, vomiting, changes to the immune system, spontaneous abortions and hypertension (Fewtrell, 2004; Lohumi *et al.*, 2004; Nadin, 2014; Jensen, 2015; Tang *et al.*, 2018; Zhang *et al.*, 2021). Van Grinsven *et al.* (2006) showed that substantial amounts of nitrate intake cause birth defects that include neural tube and impulsive abortion in pregnant women.

A study by Habboub (2007) found that animals such as sheep, cattle and horses that consumed water contaminated with nitrate at concentrations greater than 300 mg/L Nitrogen-nitrate can either be poisoned or die from the high nitrate concentration.

Likewise, at lower concentrations of 100 to 300 mg/L Nitrogen -nitrate, nitrate poisoning can increase the occurrence of stillborn calves, lower milk production, vitamin A deficiency, abortions, cystic ovaries, retained placenta and reduced weight gains in animals. Faries *et al.* (1991) recommended 100 mg/L Nitrogen-nitrate as a nitrate limit in drinking water for livestock. Table 2.1 below presents a range of nitrate contamination limits in drinking water.

Table 2.1 Nitrate contamination of drinking water limit ranges (Daniels & Mesner, 2010)

Nitrate level, ppm (Parts per million)	Interpretation
0 - 10	Safe for humans and animals. Concentrations of more than 4 ppm, however, are an indication of potential sources of emissions, which can cause environmental problems.
11 - 20	Generally safe for human adults and livestock. Not suitable for children, since they cannot consume and excrete nitrate from their digestive systems.
21 - 40	Should not be used as a source of drinking water but short-term usage is suitable for use by adults and all livestock, unless food or feed sources are very high in nitrates.
41 - 100	Risky to adults and to young animals. When feed is low in nitrates, it’s potentially suitable for mature livestock.
Over 100	Cannot be used for human or animal drinking water.

2.6.2 Environmental effects

As early as the 1970s, nitrate concentration was identified as increasing in rivers and streams. Natural water bodies are for the most part sources of municipal water supplies and water-based recreation. In this manner, the nutrient loading effect on the quality of water and productivity are important (Habboub, 2007). Eutrophication in marine ecosystems and fresh surface water is found to be the result of an excessive release of Nitrogen into the environment that leads to increases in nitrate concentrations (Zhang *et al.*, 2021).

The increase in nitrate loading into rivers and coastal streams promotes rapid growth of algal blooms in the receiving water sources, with high salt concentrations (Habboub, 2007). The cause of a deadly Pfiesteria blooms in rivers and streams and is associated with animal waste Nitrogen. Smith *et al.* (1987) discovered that runoff from cropped lands had high Nitrogen loading, due to an increase in Nitrogen fertilization rates, while nitrate and ammonium high concentrations are associated with runoff from animal feedlots (Beaulac & Reckhow, 1982).

2.7 Nitrate Prevalence

Recently, it has been revealed that a great number of areas around the world have been faced with the issue of nitrate contamination in surface and groundwater (Kapoor & Viraraghavan, 1997; Shrimali & Singh, 2001). However, 33% of the world population is assessed to rely on groundwater for drinking (UNEP, 2002). Furthermore, a high increase of nitrate concentration in groundwater has become a cause for concern, as an exponentially increasing population requires food.

Consequently, there is a need to dispose of waste and treat water, all of which indirectly contribute to rising nitrate levels in groundwater. Equally significant is the increasing interest in improved water quality in the developing world and stronger water safety legislation has strengthened the need for nitrate remediation systems (UNEP, 2002).

Reviews have been conducted by various organizations in various parts of the world to examine the degree of this contamination. Presented data shows that organic Nitrogen compounds and ionic forms that include ammonium (NH_4), nitrite (NO_2) and nitrate (NO_3^-), dissolved Nitrogen gas (N) and ammonia (NH_3) may also be found in natural water (Sunitha, 2013).

It has also been discovered that many places such as West and Central America, China, India, Namibia and Botswana have exceeded the World Health Organisation (WHO) maximum nitrate contamination level of 50 mg/L-NO_3^- *(*Alabdula'aly ***et al.,*** 2010; Chaudhary *et al.*, 2015; Peechattukudy & Dhoble, 2017; Zhang *et al.*, 2021).

As previously mentioned, in South Africa, areas such as Moretele District in the Northwest Province and Kudumane District in the Free State Province experience high nitrate concentrations of 173 mg/L- NO_3^- and 130 mg/L- $NO_{3,}^{-}$ respectively (Schoeman & Steyn, 2000). Areas such as the Western Cape, Limpopo and the Northern Cape Province have also shown signs of nitrate contamination. However, they still need further investigations on nitrate concentration levels in raw water (Tredoux, 1993; Maherry *et al*., 2010). To date, nitrate levels have been measured in South Africa, but only through a limited number of repeated analyses for contamination point sources with entirely predictable results (Tredoux, 2004). Figure 2.3 below represents the areas of high nitrate contamination in groundwater in South Africa, Botswana, and Namibia.

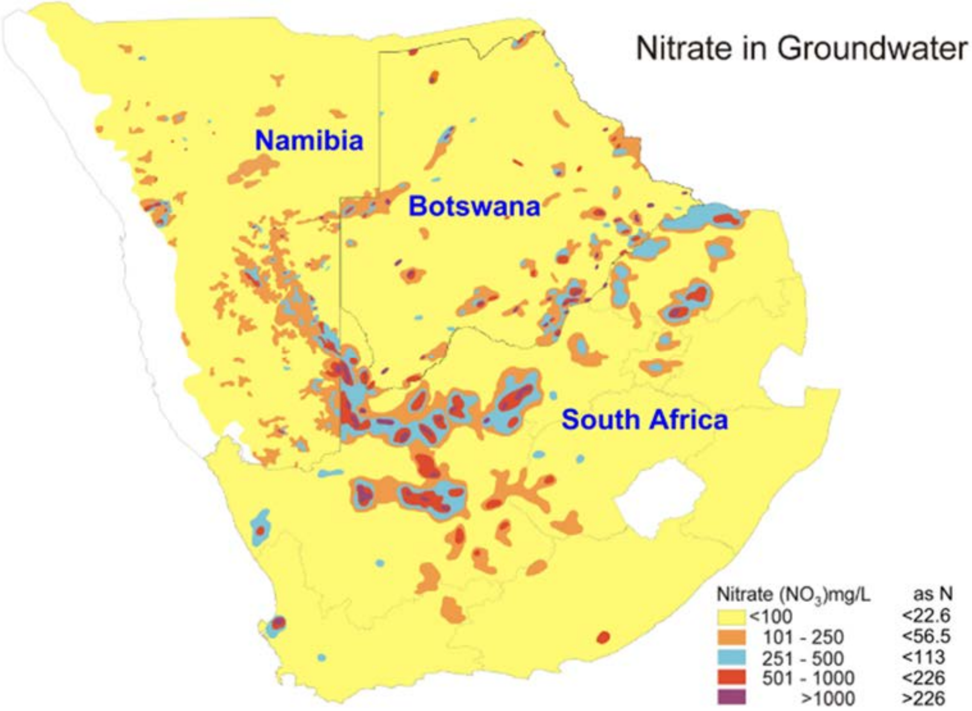

Figure 2.3 Areas of high nitrate concentration in groundwater in South Africa, Botswana and Namibia (Tredoux, 2004).

2.8 Summary

In this section, nitrate (NO_3^-) pollution in surface water was brought into focus as part of the primary inorganic forms of nitrogen. There is no doubt that the activities generated from humans, animals, agriculture, and industries contribute greatly to surface and groundwater source pollution in an attempt to provide sustainable food security and economic development. The discussions in this section have shown that there are harmful effects to humans, animals and the environment that are associated with high nitrate contamination (≥11 mg/L-N) in water. These effects are found to be deadly and cause several health problems in adults and babies such as diarrhoea, diabetes and methemoglobinemia. Moreover, the increase in nitrate concentration has been identified as promoting rapid growth of algal blooms in rivers and streams. It was also shown that a great number of areas around the world have been faced with the issue of nitrate contamination in surface and groundwater.

Many places such as West and Central America, China, India, Namibia, and Botswana have exceeded the World Health Organisation (WHO) maximum nitrate contamination level of 50 mg/L-NO_3^-. This also includes South Africa, with areas such as Moretele District in the Northwest Province and Kudumane District in the Free State Province that experience high nitrate concentrations of 173 mg/L-NO_3^- and 130 mg/L-NO_3^- respectively. Increasing interests in improved water quality and stronger water safety legislation are shown to strengthen the need for nitrate remediation systems in developing countries. However, to date, nitrate levels have been measured in South Africa, but only through a limited number of repeated analyses for contamination point sources, with entirely predictable results.

2.9 Nitrate Removal Techniques and their Limitations

Water with high nitrate levels is highly recommended for treatment to meet the regulated nitrate maximum concentration level (MCL). So far, a number of technologies have been identified as treatment alternatives for high nitrate contamination in water. These technologies result in drawbacks that include high strength brine residual production that lacks residual disposal options, challenges in increasing salt loads, low efficiency and high operating costs thus rendering them unsustainable. Again, in view of nitrate high solvency, resistance to change its structure, low adsorption and co-precipitation abilities in water, it was discovered that ordinary drinking water treatment techniques, for example, coagulation and filtration alone cannot efficiently remove nitrate (Luk & Au-Yeung, 2002; Archna & Ranbir, 2012). Some of the factors that are considered for feasibility of each removal technology include residual handling, cost, water quality improvements and post-treatment requirements, as discussed in this section.

2.9.1 Ion exchange (IX)

This process occurs in a resin bed that contains solid base anion (SBA) exchange. The resins act as a section which nitrate concentrated water passes through and the nitrate ions are traded for chloride or bicarbonate ions. Either sodium chloride concentrated solution or sodium bicarbonate can be utilised to create the depleted resins (Kokufuta *et al.,* 1988). Despite the fact that ion-exchange processes use resins to exchange nitrate with either bicarbonate or chloride ions, this can lead to corrosive wastewater that contains nitrate and the exchanged ions (Reddy & Lin, 2000; Song *et al.*, 2012). Additionally, the waste brine needs further treatment and this may lead to increased economic costs (Bhatnagar & Sillanpää, 2011). Ion exchange has shown approval for removing nitrate because of the lower financial cost compared to alternative removal processes. However, this has been outdated, as recent studies report bio-denitrification as the least expensive method (Canter, 2019).

Additionally, a decrease in the system's effectiveness and nitrate exchange can take place if the water in use contains a high level of sulphates. High nitrate concentrations can be experienced in the treated water when the resin is saturated, thus, realising nitrates instead of sulphates. Water corrosion can also take place due to nitrate ion exchange. Ion exchange requires maintenance; and therefore, it can be expensive. The brine accumulated from backwashing can contain high nitrate concentration and hence requires careful disposing (Habboub, 2007).

2.9.2 Reverse osmosis (RO)

A reverse osmosis membrane contains osmosis cells that can be used to extract nitrate from polluted water by reversing the usual osmotic flow of water under pressures of up to 300 to 1500 psi (2068 to 10342 kPa). The successful membranes that are used in nitrate extraction consist of polyamides, composite material, and cellulose acetate. However, with time, reverse osmosis membranes can be associated with some problems that include compaction, deterioration, and fouling as a result of deposition of organic matter, suspended and colloidal particles, soluble materials and threats such as pH variability and chlorine exposure. Certainly, there is still a need for pre-treatment in a reverse osmosis process for effective treatment (Archna *et al.*, 2012).

Nevertheless, 83% to 92% of nitrates are separated from water through the membrane since it acts as a sieve. However, 90% can only be removed at nitrate-Nitrogen levels greater 110 mg/L. Its performance is influenced by several factors such as membrane selection and proper maintenance, including water pressure and temperature. Even though reverse osmosis can also remove nitrate effectively, it can also be expensive and is a slow inefficient process. For instance, 90% of the incoming water can be washed with a few cubic meters of purified water produced a day. It also requires storage tanks, an activated carbon filter, a membrane, and a sediment filter. Reverse osmosis is therefore more convenient for the treatment of water, with high total dissolved solids (TDS) ranging from 5000 to 35000 mg/L (Habboub, 2007).

2.9.3 Electrodialysis

Electrodialysis reversal (EDR's) is an electrochemical process in which ions pass through a semi-porous membrane as a result of electrically charged membrane surfaces. The membrane selectively separates the ions from the approaching influent water by being pulled in to the electrically charged membrane surface. The contaminants are separated into ions by the use of positive (anode) and negative (cathode) electrodes (Washington State Department of Health, 2018). The process relies on the electrical charges that get attracted to the opposite poles that result in Total Dissolved Solids (TDS) reduction (Habboub, 2007). Typically, an electrodialysis reversal process consists of a multi-cell pair membrane layer, each comprising a cation transfer membrane, a demineralised flow spacer, an anion transfer membrane, and a concentrated flow spacer, which are costly. The primary drawback of EDR is that it is not ideal for high TDS concentrations, and not appropriate for high ion (Fe) rates and chlorine or hardness and low-density current. Again, there is a change in the effluent pH that can require adjustment (Washington State Department of Health, 2018). Ions are transferred through membranes with a less concentrated solution in electrodialysis into a more concentrated solution owing to direct electrical current transmission. This method is expensive and requires close supervision (Kapoor & Viraraghavan, 1997).

2.9.4 Chemical denitrification

Zero-valent metal's electron-donating ability can reduce the number of ions in water. Research has shown that such metals boost water management processes, thus enabling toxins like nitrate to be removed. The reduction of nitrate from drinking water has proved successful with the use of zero-valent aluminium and iron metals for chemical denitrification (Shrimali & singh, 2001; Luk & Au-Yeung, 2002). The metals are discussed as follows:

2.9.4.1 Nitrate reduction with Iron

The reduction of nitrate (NO_3^-) has been accomplished using zero-valent iron. Iron is oxidised to ferrous ion (Fe^{2+}), converting nitrate to either ammonia (NH_3) or Nitrogen (N_2) steam. Oxidation of ion (II) oxide (FeO) to Fe^{2+} is an anodic half-reaction in which anaerobic and aerobic processes contain electron acceptors such as H^+ or dissolved oxygen that undergoes a cathodic half reaction.

The final products for the chemical nitrate reduction by iron are either N_2 or NH_3, according to experimental conditions (Yang & Lee, 2005; Kumar & Chakraborty, 2006). This innovation has been considered inadequate for use because of a few downsides; for example, long response time, pH limitations, a large demand of iron and its relative need of post-treatment to remove ammonia (Luk & Au-Yeung, 2002; Kumar & Chakraborty, 2006).

2.9.4.2 Nitrate reduction with aluminium

Nitrate removal can also be accomplished by the use of zero-valent aluminium powder, which can be further reduced to ammonia or nitrogen gas. There are a few drawbacks with the use of this process, such as pH restrictions, the need for post-treatment to extract ammonia and low performance, primarily in extracting nitrate from water with large concentrations of initial nitrate (Kapoor & Viraraghavan, 1997; Luk & Au-Yeung, 2002; Kumar & Chakraborty, 2006).

2.9.5 Membrane bioreactor

Membrane bioreactor technologies use membrane separation to provide biological treatment of water (Judd, 2008). Production of high-quality water can be achieved by utilising a membrane bioreactor (MBR). Several MBR technologies have been established to extract nitrate from water through porous membranes, a supply of gas, dense membranes or by rejecting biomass. Ergas and Rheinheimer (2004) investigated an MBR for nitrate removal, in which the nitrate polluted water was transferred through the lumen of the microporous tubular membrane of the heterotrophic membrane bioreactor (McAdam & Judd, 2007). The denitrification process took place at the membrane shell site. At an influent concentration of 200 mg/L- NO_3^-, the MBR achieved over 99 % nitrate removal. Again, a bench-scale microporous membrane was also investigated on nitrate removal from groundwater through molecular diffusion. The process achieved removal efficiencies that ranged from 92% - 96%, at an initial influent concentration range of 20-40 mg/L NO_3^-N (Mansell & Schroeder, 2002).

2.9.6 Nanofiltration

Nanofiltration has likewise made an unexpected improvement in drinking water creation for nitrate removal (Archna & Ranbir, 2012). This process was initially utilised in the conditioning of water. However, it has since been found to have properties that remove micro-pollutants such as nitrate, fluoride, viruses and arsenic (Amouha *et al.*, 2011). Nanofiltration can be supported as a nitrate expulsion system because of the reliability of the membrane and the absence of a need for added substances (Mahvi *et al*., 2011). Nanofiltration is frequently utilised as a process for water that will be utilised as drinking water because of the water softening properties the process can offer. Nanofiltration is likewise used for the removal of pesticides in groundwater, which may coincide with agricultural areas of increased nitrate applications (Nadin, 2014).

2.9.7 Autotrophic denitrification

Autotrophic denitrification is achieved through denitrifying microorganisms which use inorganic materials other than natural carbon as electron givers, while decreasing nitrate to essential Nitrogen gas (Zhou *et al.*, 2011). Of late, autotrophic denitrification is exceptionally gaining acknowledgment in light of the fact that it does not require the use of a natural carbon source for giving electrons. Rather, it uses inorganic carbon compounds, for example, Carbon dioxide (CO_2) and the bicarbonate ion (HCO_3^-) as carbon sources. Hydrogen and sulphide ion are the substrates needed for autotrophic denitrification (Zhou *et al*., 2011). However, the regulation of autotrophic denitrification is more complex than heterotrophic denitrification, due to the three-phase process; these being gas, liquid and solid phases.

This also demands digitisation and biomass removal post-treatment, which often has a lower growth rate than heterotrophic. Therefore sludge output is poor (Monoushiravan *et al*., 2013). Denitrification using hydrogen and sulphide ions is discussed as follows:

2.9.7.1 Denitrification using hydrogen

There is detailed literature on the need for biological denitrification of hydrogen-oxidizing organisms (Smith *et al.*, 1994; Rezania *et al.*, 2005). The reports indicate that molecular hydrogen and inorganic carbon such as Carbon dioxide (CO_2) and bicarbonate (HCO_3^-) can be utilised by autotrophic microorganisms like parcoccus, as a substrate or for generating energy. Gros *et al*. (1988) investigated an autotrophic denitrification plant that comprised four repaired fixed film up-flow nitrate removal reactors for evacuating nitrate in groundwater in which hydrogen was used as a substrate.

A double layer filter was used to remove the solids as denitrified water passed through. The complete removal of Nitrogen-nitrate was achieved successfully by the plant. The concentration of nitrate influent was reduced from 80 to 25 mg/L of nitrate. However, there are just a few recognized bacteria that can oxidize and denitrify hydrogen, thus, reducing the autotrophic denitrification efficiency. Autotrophic denitrification is found to prevail more in groundwater (Smith *et al*., 1994).

2.9.7.2 Denitrification using sulphur

Sulphur and all its compounds have been identified as successful electron donors for autotrophic bacteria in treatment of potable water (Darbi *et al.*, 2003; Moon *et al*., 2008). An investigation has been conducted for removing nitrate from groundwater at varying concentrations of 95, 57 and 10 mg/L using sulphur and limestone autotrophic denitrification.

The observations showed nitrate removal efficiency to be greater than 95% at a Sulphur: Limestone ratio of 3:1 (Darbi *et al*., 2003). However, removal of nitrate in autotrophic denitrification is followed by the release of hydrogen ions which reduces the pH level. Thus, pH correction is important to maintain an optimal pH level of between 6.4 and 6.8 for bacterial activity (Monoushiravan *et al.,* 2013). Table 2.2 below presents a comparison of available technologies mostly used for nitrate removal in water.

Table 2.2 Comparison of the technologies for nitrate removal in different water sources (Shams, 2010)

Method	IX	RO	ED	Chemical	Biological	Hydrogenotrophic
Status	Full scale	Full scale	Full scale	Research phase	Full scale	Pilot plant research phase
Application	Groundwater,Wastewater	Groundwater,Industrial waste	Specialized wastewater	Groundwater and surface water	Wastewater,Surface water	Better for groundwater
Start-up period	Minutes	Minutes	Minutes	Hours	Weeks	Weeks
Waste period	Brine regenerant	High TDS disposal	High TDS disposal	None	Biomass disposal	None
Pre-treatment	Sulfate, Organics,Chloride	Fouling control	Fouling control	Lime softening	Dissolved oxygen	H_2 addition
Temperature	Insignificant	Insignificant	Insignificant	25°C (Al)	2-6° C (lower limit)	20°C (Optimum)
Optimum pH	Insignificant	Insignificant	Insignificant	≤ 4.5 (Fe) 1-9.3 (Al)	Insignificant	7
Operation	Stable	Stable	Complex	Stable	Close Monitoring	Monitoring
Maximum reported efficiency	90%	97%	65%	70%	100%	96%
Cost	Moderate	High	High	High	Moderate	Moderate
Post-treatment	Corrosive product	Corrosive product	Corrosive product	ammonia	Microorganisms	Microorganisms
Advantages	Short time period, Simple and effective, relatively low costs	Short time duration, reduced hardness	Easy separation, reduced hardness	High efficiency	Very selective reduction	Lower microbial biomass, fairly cost efficient
Disadvantages	Disposal problems	High demand for pre-treatment and post-treatment, difficulties in disposal	Demand for pre-treatment, close monitoring, Expensive problems with disposal	Ammonia post-treatment, costly, pH-constraints, lime softening	Post-treatment contamination, low reaction rate, temperature limitations	Long time, pH limit, explosion and safety issues, temperature limitations

2.9.8 Biological denitrification

Using a biological process for drinking water treatment has become increasingly common because of the issues that are related to other processes on nitrate removal and performance efficiency. The chemical and physical methods like electrodialysis, ion exchange, and reverse osmosis each show poor nitrate removal selectivity (Hell et al., 1998). Again, these processes are associated with high operating costs and problems of disposal that are linked to the nitrate brine that is produced (Della Rocca et al., 2007). Generally, these methods are more widely used to eliminate non-nitrate inorganics. Moreover, some studies found biological denitrification to be the most efficient technique for removing nitrate in water, since it only attempts to remove nitrate and does not interfere with other background ion concentrations. This method uses microorganisms to reduce nitrate to Nitrogen gas. Despite its widespread use in wastewater treatment, the method was well investigated in drinking and groundwater treatment applications in laboratory studies and eventually developed in full-scale plants (Janda *et al*., 1988; Liessens *et al*., 1993; Soares, 2000). In fact, biological denitrification occurs when bacteria breathe anaerobically using nitrate instead of Oxygen as an electron-acceptor with a gradual reduction of nitrate to Nitrogen gas. Its steps can be summarised as shown by chemical Equation 2.1:

$$NO_3{}^- \rightarrow NO_2{}^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \uparrow \qquad (2.1)$$

Biological denitrification is an effective technology for total nitrate removal in water and the process is enhanced by an external carbon source (Yang *et al*., 2012; Washington State Department of Health, 2018). The suitable organic carbon and energy sources are required for use as a treatment system, even if they occur naturally (Kapoor & Viraraghavan, 1997; Soares, 2000; Shrimali & Singh, 2001).

The biological denitrification process is activated by either autotrophic or heterotrophic processes. The key distinguishing attribute between heterotrophic and autotrophic denitrification processes is the type of electron donor each process utilises. The carbon and energy sources for heterotrophic and autotrophic denitrification are organic and inorganic compounds respectively (Soares, 2000). The type of Carbon source utilised can strongly affect the rate of the denitrification process. Studies by Eljamal et al. (2007) and Eljamal *et al.* (2008) reported that the most important factor that affect the bacterial activity in porous media is the availability of organic carbon. Heterotrophic denitrification has gained extensive application over autotrophic denitrification, due to its high effectiveness and use of simple reactors. There are several common carbon compounds that can be utilised as electron donors for heterotrophic bacteria such as ethanol, glucose, sucrose, acetic acid, sugar, methanol and acetone. Other basic carbon sources discovered for use in heterotrophic denitrification include wheat, straw, plant pruning, industrial wastes, municipal and agricultural waste, commercially available starches, and alcohols. In contrast to other organic sources of carbon, methanol, ethanol and acetic acid are said to be practically effective carbon sources in the removal of nitrate, due to their degradable and simple nature (Xu *et al*., 2011; Shen *et al*., 2013). However, methanol results in toxic effects at high concentration, due to excess residual carbon detected in the effluent water. Methanol is also shown to produce an excessive growth of biomass. These effects limit its usage at only low concentrations. Sucrose and glucose have a likelihood of forming biomass, which results in turbidity increase in the effluent. On the other hand, ethanol was proven to have better results than methanol and acetic acid in an anoxic condition, using a static bed column (Mutsvangwa & Matope, 2017)

Most of the reviewed literature states ethanol as a safe organic carbon source and its use as a carbon source in water treatment has shown effective success over years (Gómez *et al.*, 2000; Magram, 2010; Monoushiravan *et al.*, 2013). This is due to its degradable nature and the absence of toxic effects. Ethanol is also affordable and has no limits of usage set on it in treatment of raw water for potable use. Ethanol is therefore, suitable as a replacement for other carbon sources in the denitrification process. Nitrate removal from water supplies using methanol, ethanol, and acetic acid is not well known (Monoushiravan *et al.*, 2013). These nitrification processes are discussed below.

2.9.8.1 Heterotrophic denitrification

It is a form of biological denitrification that arises when an organic compound is used as a fuel and energy source. Several specific carbon compounds, such as ethanol, acetic acid, commercially available sugars, starches, methanol and acetone, can be used as electron donors (Hamlin *et al.*, 2008; Fernández-Nava *et al.*, 2010; Xu *et al.,* 2011; Shen *et al.*, 2013). Numerous natural materials have become breakthroughs as organic sources of carbon that can be used in heterotrophic denitrification, including products such as wheat straw and plant pruning. Although the method is cost-effective, the process of pre-treatment takes longer, and is also complicated (Zhao *et al.*, 2011). The form of carbon source used may have a significant effect on the denitrification rate (Shen *et al.*, 2013). Hamlin *et al.* (2008) showed that methanol, acetic acid, starch as glucose and molasses as sucrose denitrification levels were 670, 670, 680 and 670 g/day nitrate–Nitrogen, respectively.

Nonetheless, Xu *et al.* (2011) considered polycaprolactone and polylactic acid to be ideal sources for denitrification of carbon. Denitrification levels were found to decrease when a dose of 0.07 and 0.008kg / m^3.d was added as sucrose and cellulose (Mercado *et al.*, 1988), respectively. Instead, high denitrification levels can be achieved through the use of acetic acid (Akunna *et al.,* 1993). The method is also highly efficient and requires simple reactors, thus establishing its extensive application. Practically, ethanol, acetic acid, and methanol are clear and readily degradable substrates that are widely used as carbon sources for extracting nitrate from drinking water (Zhao *et al.*, 2011).

2.9.8.2 Methanol as a Carbon source

Unlike other organic carbon sources, methanol has been used primarily as an alternative source of carbon for wastewater denitrification because it generates lower bacterial cells and is cost-effective (Her & Huang, 1995; Hamlin *et al.*, 2008). Chang *et al.* (2010) used a single inch gravel filter media to extract nitrate from water, with methanol as a carbon source to evaluate the filter performance under anoxic conditions. At a temperature of 12°C, approximately 20 mg/L of nitrite was reported to have achieved more than 90% removal. However, the effluent water was found to still require post-treatment from the excess carbon.

Similarly, Croll et al. (1985) investigated the use of an upward fluidised sand bed using a methanol-fed spring stream and an addition of phosphate to meet nutrient requirements. The investigation proved the plant's efficiency in nitrate removal of 14 mg/L- NO_3-N. However, during a one-year experimental duration, high concentrations of nitrite were observed at irregular intervals (Monoushiravan *et al*., 2013). Also, Liessens *et al.* (1993) conducted research using a fluidized semi-industrial bed system with methanol as a source of Carbon, to eliminate nitrate from surface water. The plant achieved nitrate removal of 9 kg NO_3/m^3. d with post residual methanol treatment required. Nonetheless, the prevailing drawback to utilizing methanol as a Carbon source is the likelihood of a toxic residual in denitrified water (Cherchi *et al.*, 2009; Jensen *et al*., 2012). Stouthamer (1992) also found that formaldehyde is emitted as a toxic by product when methanol is oxidised. Therefore, due to methanol possible toxicity problems, it is still not highly favourable for use for nitrate removal process (Monoushiravan *et al*., 2013).

2.9.8.3 Acetic acid as a carbon source

Acetic acid has been shown to be more advantageous as a source of carbon over methanol in a number of its qualities. These characteristics include high buffering capacity, no toxic effects, high denitrification and being readily metabolised. It is therefore considered convenient in the denitrification process to extract nitrate from drinking water. As an investigation, a packed bed reactor with acetic acid as a carbon source was used in which nitrate removal efficiency of approximately 100 % was almost achieved at a nitrate-Nitrogen influent concentration of 100 mg/L (Dahab & Lee, 1988).

Furthermore, a study by Boeckle *et al*. (1986) analyzed the removal efficiency of a fixed film reactor, followed by a heterotrophically denitrified aquifer recharge. The analyses utilized small amounts of acetic acid as substrates, in combination with phosphate to provide energy to the microorganisms. The removal rate of nitrate was later found to be 2.5 to 3.5 kg/m^3. d at influent concentrations of 55 to 100 mg/L, respectively, with the effluent containing 1 mg/L of residual acetic acid. However, significant decrease in the rate of removal was observed when the reactor was operated at lower concentrations of 0.1 mg/L acetic acid instead of 1 mg/L.

2.9.8.4 Ethanol as a carbon source

A fluidised bed reactor was used in an investigation by Croll *et al*. (1985), in which ethanol was applied at a dose of 33 mg/L at short intervals, to remove dissolved oxygen (DO) and nitrate-Nitrogen (NO_3-N) at concentrations of approximately 12 mg/L DO and 13 mg/L NO_3-N respectively. The ethanol requirement was 0.5 mg ethanol/mg DO, and 2 mg NO_3-N ethanol/mg. A sequencing batch reactor with a high concentration of nitrate when using ethanol as a source of carbon was investigated for its removal efficiency in denitrification of drinking water (Mekonen *et al*., 2001). It was found that nitrate concentrations can be sufficiently reduced to allowable levels of less than 10 mg/L as N at an ethanol dose of 2 COD/N.

Ethanol as a source of carbon was also used in a pilot-scale design with a packed bed reactor having a mineral medium to remove nitrate from groundwater. The findings were further used to completely eliminate Nitrogen and organic compounds in nitrate contaminated water, using a full scale reactor (Rogalla *et al*., 1991). Moreover, ethanol was used as a carbon source in two full-scale biological nitrate removal processes, with capacities of 35-70 and 80 m^3/h; wherein acetic acid was initially used for a limited period of time before ethanol was used. At an ethanol dose of 3.1 g/g NO_3-N, a removal efficiency of 72% was achieved and the average consumption range for ethanol was 0.65-0.75 g/g N (Richard, 1989).

Therefore, to get control over the toxic problems associated with using methanol as an electron donor in the removal of nitrate contaminated water, ethanol has been approved to be an alternative safe organic carbon source. Moreover, dosage limits have not been set for ethanol use in potable water (Monoushiravan et al., 2013).

2.9.9 Summary

Water with high nitrate levels has been recommended for treatment to meet the regulated nitrate maximum concentration level (MCL). So far, a number of technologies that include Reverse Osmosis (RO), Electrodialysis, Chemical Denitrification, Membrane Bioreactor, Nanofiltration, Autotrophic Denitrification and Biological Denitrification have been identified as treatment alternatives for high nitrate contamination in water. However, these chemical and physical methods showed a tendency to result in drawbacks that include the production of high strength residual brine and low efficiency. Nonetheless, biological denitrification has proved to be an effective technology for nitrate removal and the process can be enhanced by adding an external carbon source.

Several studies have shown methanol, ethanol, and acetic acid to be practically effective organic carbon sources for nitrate removal, due to their degradable and simple nature. These carbon sources act as fuel or a source of energy for microorganisms during denitrification when nitrate is reduced to nitrogen gas. However, it was revealed that methanol is associated with toxic effects at high concentration due to excess residual carbon detected in the effluent water, thus, limiting its usage at only low concentrations. Conversely, ethanol was stated as a safe organic carbon source, as its use in water treatment has shown effective success over the years. Therefore, it was used in this study. The section also shows a lack in denitrification studies in roughing filters, except in bio-filters and slow sand filters.

2.10 Nitrate Removal in Filters

Water filters are available in various types and functions under different conditions. They have a common objective of separating a solid from a fluid (Water), by introducing a medium that only water will flow through (Shoemaker, 2014). Modern conventional treatment processes disinfect influent water in filters that inhibit microbial development. These conventional filters rely solely on physical processes for straining larger organic matter, and their removal rate is approximately 30 % (Simpson, 2008). Filters that do not disinfect influent water are considered bioactive. This biological behaviour can improve treatment performance and can be used to remove contaminants (Evans, 2010).

Furthermore, a biological mass or "biofilm" will start to develop on filter media when microbial growth in the filters is permitted. A portion of waterborne nutrients, dissolved organic matter, minerals and microorganisms can be removed using this biofilm (Simpson, 2008). The feasibility and efficacy of various filter types such as bio-filters, rough filters, slow sand filters and rapid sand filters have been explored for extracting dissolved nutrients, coliforms, suspended solids, iron and manganese and high turbidity in water, through biological denitrification (Wegelin, 1986; Collins *et al.*, 1994; Wegelin, 1996; Galvis, 1998). The viability and effectiveness of these different filter types for use in drinking water treatment is discussed.

2.10.1 Bio-sand filters

The bio-sand filter is regarded to be a slow sand filter adjusted to meet household needs, which is why it is usually referred to as a point of use (POU) water filtration system and mainly under the heading of a physical, chemical and biological filtration system (Murphy *et al.*, 2010). The technology is still evolving and is using construction materials which are readily and easily available and hence are cost effective. However, the process is associated with low quality nitrate removal in water. Therefore, utilising an external carbon source at a regulated carbon: nitrogen ratio (C/ N) is required, in order to improve the quality of nitrate removal through denitrification (Mutsvangwa & Matope, 2017). Commonly used pre-treatment processes such as coagulation and sedimentation may result in limitations of nutrients in bio-filter influent water. The design parameters for bio-filters are typically limited to media configuration, backwash strategy, and load rate. Bio-filtration is believed to benefit from the reduction of dissolved organic and inorganic contaminants. Chlorinated backwash and other biomass control strategies are employed by many utilities to increase the efficiency of the filters and to reduce head loss. Nonetheless, these employed activities damage bioactivity and cannot remove primary bio-filter foulant extracellular polymer materials (EPS) (Chance & Brown, 2010)

2.10.2 Conventional slow sand filters with a carbon source

When denitrification under anoxic conditions takes place, nitrate is broken down to diatomic gaseous nitrogen. Therefore, an external source of carbon is required in low carbon content waters. Slow sand filtration is a competent technique for treating water to remove bacteria, viruses and reducing biodegradable organic matter (BOM) detected in water (Collins *et al.*, 1994). Several studies used traditional slow sand filters, with various external C:N sources of carbon to help heterotrophic denitrification processes. Those include sources of carbon such as ethanol, sucrose, acetic acid, ethyl alcohol and methanol (Gómez *et a*l., 2000; Aslan & Cakici, 2007). High removal levels in the contaminated water with concentrations of effluent varying from 0 mg/L to 5 mg/L were achieved while evaluating the influence of the different carbon sources. Aslan and

Cakici (2007) used conventional slow sand filters to eliminate nitrate from raw water. An organic source of carbon at a C/N ratio range of 1.1-3.0 was used to support the heterotrophic denitrification process. The process achieved 94% nitrate-Nitrogen removal efficiency. However, strict requirements are set on the quality of the water source, to prevent early filter clogging. The attention given to the quality of the source of water is a key limitation to using slow sand filtration (Wegelin, 1996).

2.10.3 Roughing filters

Filtration is one of the popular and most basic surface water pollution treatment techniques (Wegelin, 1996). Since the mid-1800s roughing filtration has been used in water treatment for pre-treatment of highly turbid water. However, it was overshadowed by the advent of chemical and mechanical water treatments. Nonetheless, roughing filters re-emerged in the 1970s and 1980s due to the lack of modern mechanical equipment or the use of chemicals; mostly in developing nations (Cleary, 2005).

Roughing filters are the most widely used pre-treatment technologies to reduce suspended solids in highly turbid water and are often utilized before slow sand filters and chlorination. They mainly reduce turbidity and floating solids concentrations in raw water (Wegelin, 1986). In some cases, roughing filters are operated in the absence of slow sand filtration, provided that the raw water source is less turbid and has only minor bacteriological contamination. They can also minimize filter blocking algae, stable colloidal suspensions and pathogens without the use of coagulants (Cleary, 2005). Biological, chemical and adsorption processes are supported by small filtration rates used in roughing filtration. As a result, roughing filters can slightly improve the quality of bacteriological water, apart from solid water separation (Wegelin, 1996).

In developing countries, roughing filtration in water supply systems has become an appropriate technology for water treatment. Roughing filters can easily be maintained, require no use of chemicals, have a long running period and can also be operated and maintained by unskilled staff with a basic training (Nkwonta & Ochieng, 2009). Roughing filter systems have also proven that, given their activities at cold conditions with so many other pollutants and the highly varied water conditions, they can still deliver exceptional quality water (Nkwonta, 2010). Shoemaker (2014) proposed a roughing bio-filter ahead of the conventional processes such as coagulation and sedimentation as an alternative to polishing bio-filters. The proposed idea was to alleviate any nutrient limitations that usually occur during the process and cause adverse effects. Nkwonta,

(2010) concluded that the potential for applications to small scale systems gives renewed interest to rough filtration. However, there is still limited data on vertical roughing filter efficiency, mainly on nitrate removal in raw water for potable use.

2.10.3.1 Horizontal roughing filters

The filter commonly comprises three compartments which are consecutively packed with coarse filter media. Horizontal roughing filters have an extensive filter length and simple layout. Influent water flows horizontally through the inlet chamber with a series of different graded filter materials that are divided by punched walls. Horizontal roughing filters respond less to filtration rate adjustments, thus, limiting effective denitrification. Khezri *et al.* (2015) found that at filtration rates of 0.5 m/h, 1 m/h and 1.5 m/h, the total nitrate reduction was 25%, 32% and 34%, respectively. Again, low sensitivity takes place during the penetration of suspended solids in the three filter layers, towards the base of the filter (Wegelin, 1996; Habboub, 2007). Due to the filters' horizontal flow design, there is high exposure of oxygen in the filter that favours nitrification and limit denitrification for effective total nitrate removal. In addition, the filter media is not submerged in water during operation, thus, limiting its performance for effective biological treatment. Figure 2.4 below shows the design and layout of a horizontal roughing filter.

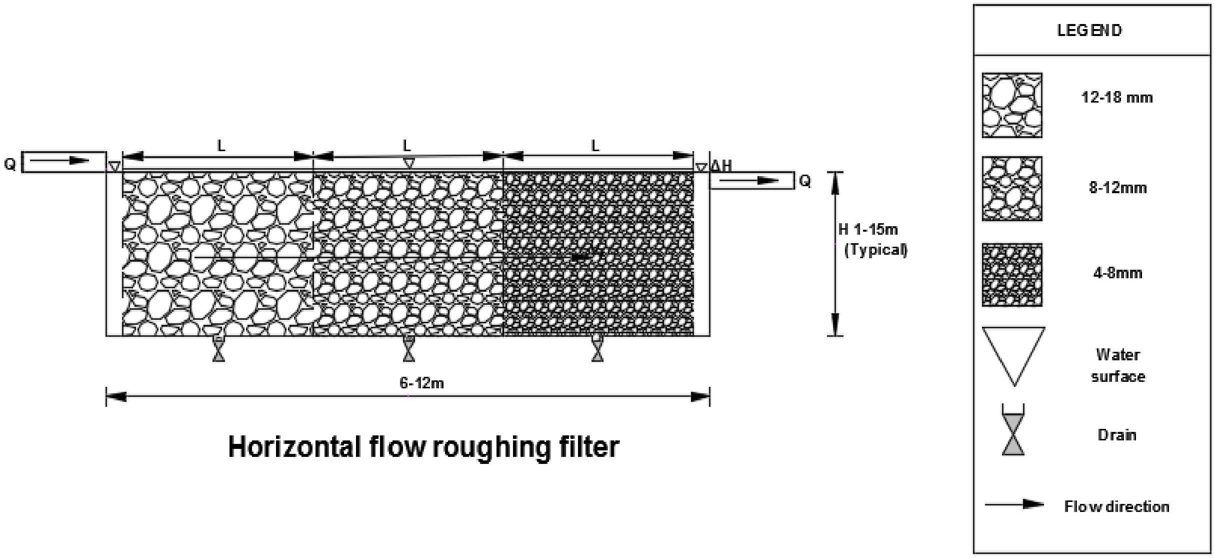

Figure 2.4 Layout and design of horizontal roughing filter (Wegelin, 1996)

2.10.3.2 Vertical roughing filters

These types of roughing filters comprise 3 or 4 filter compartments, each filled with successive gravel media or can include one compartment with successive multiple gravel media packed in layers that are positioned one over the other. When using multiple numbers of individual compartments in series, optimum treatment in roughing filters is generally achieved, thus, resembling the hydraulic behaviour of a plug-flow system. Therefore, a roughing filter with 3 stages is expected to perform better than a roughing filter with 2 stages (Galvis *et al.,* 1996; Cleary, 2005). The raw water flows in sequence down or up the filter compartments packed with successive course, medium and fine gravel material. The vertical roughing filter operates as either down-flow or up-flow (Wegelin, 1996). A study by Habboub (2007) stated that denitrification was the only process capable of reducing nitrate concentration during downward percolation. In contrast to the horizontal flow roughing filter, the vertical roughing filter direction of flow makes it favourable for nitrate removal.

Moreover, for high removal efficiency of nitrate (NO_3^-) to occur due to biological denitrification process, two distinct zones are usually necessary, being the anoxic and aerobic zones. Denitrification usually take place at the zone near the base of the filter, where there is low oxygen. Anoxic conditions are experienced at low dissolved oxygen in the presence of nitrate, while aerobic conditions occur under the existence of oxygen (Shrimali & Singh, 2001; Mutsvangwa & Matope, 2017).

Nitrification involves the conversion of ammonium into nitrate by bacteria and possibly the process takes place in the aerobic zone, located near the top end of the filter media that is exposed to oxygen. On the other hand, denitrification is the organic depletion of nitrate by facultative heterotrophic bacteria to nitrogen gas (Habboub, 2007). This process is carried out under anoxic conditions and was envisaged to occur at the bottom of the filter media, where there is low dissolved oxygen. Kusuma *et al.* (2016) achieved a total nitrate removal in dry season and wet season of 72.6 % and 44.2 %, respectively, using a combination up-flow roughing filter in series with a geotextile membrane.

However, vertical roughing filters for removing nitrate in water are still not widely researched (Kusuma *et al.*, 2016). The total %age removal of nitrate in dry season at 1 m/h and 3 m/h filtration rates is shown in Figure 2.5 below and the filter media specifications and layout of a downward flow, upward flow and a roughing filter in layers are illustrated in Figure 2.6 below.

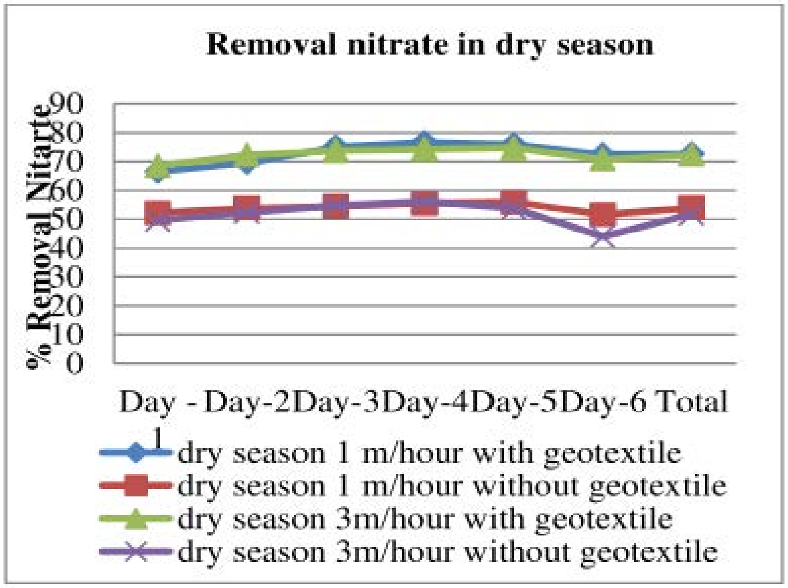

Figure 2.5 The %age of total nitrate removal in dry season at a velocity of 1 m/h vs 3 m/h (Kusuma *et al.,* 2016)

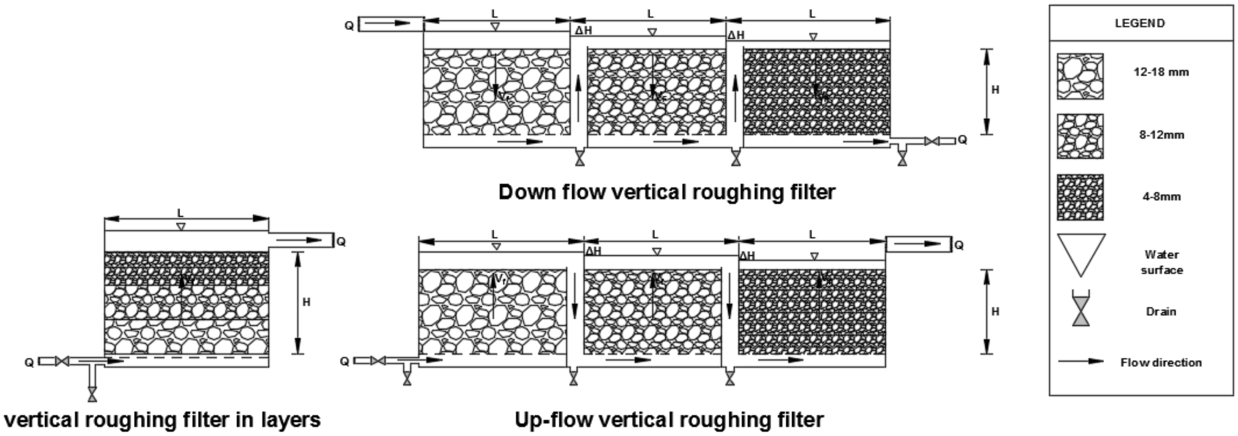

Figure 2.6 Layout and design of vertical roughing filter (Wegelin, 1996)

Moreover, a study by El-Taweel & Ali (2000) evaluated a roughing filter, followed by a slow sand filter in treating raw river water from the Nile river. The filter was to treat biological characteristic and chemical characteristics that included nitrate. The roughing filter bed comprised different layers of basalt furnace slag, gravel, and sand in decreasing sizes in the direction of flow. The filter did not use a carbon source and the results indicated a 7.7 % nitrate removal efficiency, from 0.13 mg/L-N to 0.12 mg/L-N. Furthermore, Zeng *et al.* (2020) investigated ammonium removal from raw water using a biological up-flow roughing filter packed with ceramic media. The study accomplished an average reduction of 51 % at a flow rate of 4 m/h, in which the NH_4^+-N effluent was below 0.5 mg/L.

2.10.4 Summary

The types of filters and their functions under different conditions were discussed in this section. A common objective with these filters is to separate a solid from a fluid (water) by introducing a medium that only water will flow through. Moreover, several studies have explored the feasibility and efficacy of various filter types such as bio-filters, roughing filters, slow sand filters and rapid sand filters for extracting dissolved nutrient, coliforms, suspended solids, iron and manganese and high turbidity in water through biological denitrification. However, the primary focus was on roughing filters as they have been shown to slightly improve the quality of bacteriological water, apart from their most widely used ability of reducing suspended solids in highly turbid waters.

Roughing filtration in water supply systems in developing countries is found to be an appropriate technology for water treatment. However, a gap was identified in the literature of limited data on vertical roughing filter efficiency, mainly on nitrate removal in raw water for potable use. Roughing filters commonly comprises of a horizontal and vertical flow direction. However, horizontal roughing filters have shown to respond less to filtration rate adjustments, thus, limiting effective denitrification. Contrarily, denitrification is stated to be the only process capable of reducing nitrate concentration during downward percolation in contrast to a horizontal direction. Therefore, this study adopted a vertical roughing filter due to the direction of flow that makes it favourable for nitrate removal.

2.11 Nitrate Reaction Rate Kinetics

Nitrate reaction rate kinetics have been applied in the modelling of nitrate removal, both in surface and groundwater environments. Several removal kinetics have been used to predict the efficiency of nitrate removal in water and they include removal kinetics such as the Reaction Rate Order model (first and zero order), the Monod Model and the Efficiency Loss Model. A study by Messer *et al. (*2017*)* compared these four nitrate removal kinetics using a mesocosm scale system for restoration of two distinct wetlands, in order to determine the best model for the monitored removal rates of nitrate from agricultural drainage water.

The best results were achieved when using first order and the Efficiency Loss Model at measured and predicted nitrate-nitrogen removal rates. However, Ebeling and Wheaton (2006) found the first order and zero order reaction models to best fit the ammonia-nitrate removal kinetics, when using a bubble washed bead filter. Moreover, Foglar *et al.* (2005) and Dhamole *et al*. (2007) experimental observations have shown that denitrification reaction follows zero order kinetics when using a continuous flow denitrification reactor and a sequencing batch reactor, respectively. Conversely, Sun *et al*. (2009) and Krishna Mohan *et al*. (2016) found that denitrification rate kinetics generally followed the Monod Model when using a sequence batch reactor in an anoxic up-flow anaerobic sludge bed and a granular sludge sequencing batch reactor, respectively. The different nitrate removal kinetics are discussed as follows:

2.11.1 Reaction rate order model

The approach to establish biological filter design equations can be based on the premise that the reaction rate is proportional to the n^th^ power of concentration (Ebeling & Wheaton, 2006). The design equation for the reaction rate can be classified into simple equations of the first order and zero order. Equation 2.2 expresses the reaction rate order and constant for acquiring the kinetic reaction rate:

$$r_{NO_3^-} = \frac{dC_{NO_3^-}}{dt} = k \times C_{NO_3^-}^{n} \tag{2.2}$$

Where:

$r_{NO_3^-}$= Kinetic nitrate reaction rate (mg/L/day)

$\frac{dC_{NO_3^-}}{dt}$= Kinetic nitrate reaction rate (mg/L/day)

$dC_{NO_3^-}$= Change in nitrate across the roughing filter (mg/L)

$C_{NO_3^-}$= Nitrate concentration (mg/L)

k= Reaction rate constant (day^{-1})

n= Reaction rate order

The reaction rate order (n) and reaction rate constant (k) can be determined by fitting a regression plot of kinetic removal rate versus the nitrate concentration. The reaction rate order determines how the concentration of nitrate affects the removal rate, while the reaction rate constant determines how the nitrate concentration decreases over time.

The reaction constant value can vary during the reaction, due to some physical variables such as temperature. As a result, a small rate constant indicates a slower reaction in nitrate removal, while a larger rate constant indicates a faster reaction in nitrate removal.

2.11.1.1 Zero order kinetic reaction rate model

The model assumes that the reduction in contaminants is independent of the NO_3^- concentration. Nitrate models of zero order have been used in wetlands in order to model nitrate-Nitrogen (NO_3^--N) removal, which assumes a constant NO_3^-N consumption rate (Messer *et al.,* 2017). It further assumes that the system is closed, anoxic, fully or partially mixed independent of the hydraulic loading rates; and those other kinetic reactions occurring within the system have little or no influence on it. It was therefore, hypothesized that the assumed conditions suited the denitrification process that occurred at the zone near the base of the filter, where there is low dissolved oxygen concentration. The kinetic reaction rate can be modelled as a zero order reaction rate when high inflow nitrate concentration greater than 1 mg/L are experienced (Ebeling & Wheaton, 2006; Messer *et al.*, 2017). The reaction rate is determined with the use of Equation 2.4.

$$r_{NO_3^-} = \frac{dC_{NO_3^-}}{d_t} = k_0 \times 1 \qquad (2.3)$$

$$r_{NO_3^-} = \frac{dC_{NO_3^-}}{d_t} = k_0 \qquad (2.4)$$

Where:

k_0 = Zero order reaction rate constant (mg/L/day)
n= Reaction rate order (n=0)

2.11.1.2 First order kinetic reaction rate model

The model assumes that NO_3^- reduction rates are directly proportional to the concentration of NO_3. The model also assumes that the nitrate concentration is substantially lower than the half-saturation constant (k_s), that the system is well mixed and has no significant water loss or gains influences and depends on only one reactant (Messer *et al.*, 2017). In this research, it was assumed that there is no accumulation in the roughing filter, so the total water inflow would be equal to the total outflow. Therefore, water loss or gains during the filtration process was not experienced. The reaction rate can be modelled on a first order reaction depending on the inflow concentration, where the nitrate concentration is relatively low at concentrations less than 1 mg/L (Ebeling & Wheaton, 2006). The reaction rate can be expressed as previously shown in Equation 2.2, where:

k_1= First order reaction rate constant (day^{-1})
n= Reaction rate order (n=1)

2.11.2 Efficiency Loss Model

The model accounts for the process rates efficiency in relation to a decrease in NO_3^--N concentration over time. The removal rates are proportional to the NO_3^--N concentration rate order of less than 1. The model assumes that the concentration of nitrate is significantly lower than the half saturation constant, that the system is well mixed, and has no significant influence from water loss or gain. The model assumes, however, a power relation in which the order is less than 1 (O'Brien *et al.,* 2007; Messer *et al.*, 2017). The model is expressed as previously shown by Equation 2.2, where:

n= Reaction rate order ($0 < n <1$)

2.11.3 Monod Model

The Monod Model is often referred to as the Theoretical Michaelis-Menten Model. It often describes biologically mediated reactions that presents low concentration for first order decay kinetics and higher concentration for zero-order kinetics, which results in hyperbolic interrelation between the rate of removal and NO_3^-N concentrations (Messer *et al.*, 2017). The model interpolates between zero order and the first order decay model. The model assumes that the system is in a steady state without intermediate or product inhibitions (Messer *et al.*, 2017). The Monod removal model can be expressed as shown in Equation 2.5.

$$r_{NO_3^-} = \frac{dC_{NO_3^-}}{dt} = \frac{R_{max} \times C_{NO_3^-}}{k_s + C_{NO_3^-}} \qquad (2.5)$$

Where:

R_{max}= Maximum removal reaction rate (mg/L/day)
k_s= Half saturation constant (mg/L)

The half saturation constant (k_s) and maximum removal reaction rate (R_{max}) are graphically determined using a Lineweaver-Burke plot with the measured values from the results dataset. This is achieved by plotting the inverse of the removal rate $\frac{1}{r_{NO_3^-}}$ versus the inverse of the total loading rate $\frac{1}{C_{NO_3^-}}$. From the plot, k_s represents the concentration at which the removal rate of nitrate (NO_3^-) was at half the removal rate of maximum NO_3^- ($R_{\max}$). Therefore, at the point where R_{max} is equal to half, the nitrate concentration $C_{NO_3^-}$ is assumed to be equal to $k_{s.}$. The Lineweaver-Burke plot is achieved by inverting Equation 2.5 to formulate a linearized Equation 2.7 as shown:

$$\frac{1}{r_{NO_3^-}} = \frac{k_s + C_{NO_3^-}}{R_{max} \times C_{NO_3^-}} = \frac{k_s}{R_{max} \times C_{NO_3^-}} + \frac{C_{NO_3^-}}{R_{max} \times C_{NO_3^-}} \qquad (2.6)$$

$$\frac{1}{r_{NO_3^-}} = \frac{k_s}{R_{max}}\left(\frac{1}{C_{NO_3^-}}\right) + \frac{1}{R_{max}} \qquad (2.7)$$

2.11.4 Stover Kincannon Model

Generally, there are certain models used to explain biological reactor kinetics. Several studies suggested two models that assume a steady state relationship, as presented by Equations 3.6, 3.9 and 3.14 (Kincannon & Stover, 1983; Yu *et al.*, 1998; Nor Faekah *et al.*, 2020). Kinetic modelling is an important method of analysis for reactor performance prediction. The Stover-

Kincannon Model considers the rate of removal of substances to be the function of the organic loading rate at steady state (Nga *et al.,* 2019). Nga et al. (2019) further showed that the main distinction between the Stover Kincannon model and the Monod model is the addition of the concept of total organic loading rate, QS_i/V to the Stover Kincannon Model. Depending on the substrate concentration, organic substrate removal from the anaerobic filter was determined based on the substrate removal rate (Nor Faekah *et al.,* 2020*)*. The original Stover-Kincannon model is expressed as in Equation 2.8.

$$\frac{dc_{NO_3^-}}{dt} = \frac{U_{max}\,(QC_i/A)}{K_B+(QC_i/A)} \tag{2.8}$$

Where:

U_{max}= Maximum utilization rate constant (mg/L/d)

k_B= Saturation value constant (mg/L/d)

A= Area of roughing filter (m^2)

Q= Flow rate through the roughing filter (L/day)

C_i= Concentration of nitrate inflow (mg/L)

The original Stover Kincannon Model used the surface area (A) to reflect the relation with the overall attached active biomass concentration growth inside a rotating biological contactor, neglecting the suspended biomass. However, the anaerobic filter volume (V) can be used instead of the surface area of the support media, when using an anaerobic filter system (Yu *et al.*, 1998); the reason being that, in the anaerobic filter the raw water flows through a bed of biomass, either as attached biofilm on the filter media or as suspended growth solids within the filter bed. Previous studies have shown that suspended biomass between the media void spaces is a key factor in generating high and stable removal efficiency in anaerobic filters (Song & Young, 1986; Tay *et al.*, 1996). The modified Stover Kincannon Model is given by Equation 2.9.

$$r_{NO_3^-} = \frac{dc_{NO_3^-}}{dt} = \frac{Q\,(C_i-C_e)}{V_r} \tag{2.9}$$

$$\frac{dc_{NO_3^-}}{dt} = \frac{U_{max}\,(QC_i/V_r)}{K_B + (QC_i/V_r)} \tag{2.10}$$

Where:

V_r= Volume of roughing filter (L)

The maximum utilization rate constant and saturation value constant are graphically determined from linearizing Equation 2.8 by plotting the inverse of the removal rate $\frac{1}{r_{NO_3^-}} = \frac{V_r}{Q\,(C_i - C_e)}$ versus the inverse of the total loading rate $\frac{1}{(QC_i\,/V_r)}$ as shown by Equation 2.12.

$$\frac{V_r}{Q\,(C_i - C_e)} = \frac{k_B + (QC_i/V_r)}{U_{max} \times (QC_i/V_r)} = \frac{k_B}{U_{max}(QC_i/V_r)} + \frac{(QC_i/V_r)}{U_{max}(QC_i/V_r)} \tag{2.11}$$

$$\frac{V_r}{Q\,(C_i - C_e)} = \frac{k_B}{U_{max}}\frac{1}{(QC_i/V_r)} + \frac{1}{U_{max}} \tag{2.12}$$

The value of k_B is estimated from the linear regression plot where the intercept is $\frac{1}{U_{max}}$ and $\frac{k_B}{U_{max}}$ as the slope. The nitrate concentration in the filtrate when using a roughing filter can be predicted by the use of Equation 2.13 as shown.

$$C_e = C_i - \frac{U_{max}\,C_i}{K_B + (QC_i/V_r)}$$

(2.13)

Moreover, studies by Kincannon and Stover, (1983) and Iza *et al*. (1991) have demonstrated that removal rate and efficiency depend not on organic concentration or hydraulic loading rate, but rather on the volume of organics added to the biological reactors.

2.12 Summary

In this section, nitrate reaction rate kinetics applied in the modelling of nitrate both in surface and groundwater environments were discussed. It is evident that several removal kinetics have been used to predict the efficiency of nitrate removal in water using filtration systems. However, there is currently no standardised way to report roughing filter performance in nitrate removal, in order to facilitate the end user selection among the different roughing filer types. An attempt to address the issue was by developing a predictive nitrate removal rate model empirically from analysis of laboratory test results. The zero-order kinetic reaction rate model was considered an appropriate model for nitrate removal in a vertical roughing filter in this research since it assumes an anoxic system that is conducive for denitrification; also, since the zero-order kinetic model is considered appropriate in modelling high inflow nitrate concentrations greater than 1 mg/L

2.13 Conclusion

From the reviewed literature, it is evident that contamination of nitrate in potable water poses a health hazard and has a negative effect on the receiving freshwater bodies. Due to these problems, several technologies have been effectively used in removing nitrate in raw water for potable use. However, these technologies have been associated with drawbacks that hinder effective nitrate removal. They produce a high content of brine residue and are associated with increasing salt loads, and have low efficiency and high operating costs which renders them unsustainable. Gómez *et al.* (2000) stated biological denitrification process as a suitable technology for total nitrate elimination in water. The process also affirms sub-merged filter technology to be competent in the biological treatment of raw water. According to Habboub (2007), denitrification has effectively removed nitrate through downward percolation, as opposed to a horizontal flow.

Therefore, the use of a vertical roughing filter over the horizontal filter was considered in this research, due to its direction of flow, its sub-merged nature, and the presence of two distinct zones for nitrification and denitrification during the filter operation. The literature indicated that denitrification has not yet been investigated in vertical roughing filters for removing nitrate in raw water for potable use. It is also evident from the literature that several nitrate reaction rate kinetics have been applied in the modelling of nitrate removal, both in surface and groundwater environments to predict the efficiency of nitrate removal. The zero-order kinetic reaction rate model was considered an appropriate model for nitrate removal in a vertical roughing filter in this research since it assumes an anoxic system that is conducive for denitrification and also, since the zero-order kinetic model is considered appropriate in modelling high inflow nitrate concentrations greater than 1 mg/L. Generally, the research aims at investigating nitrate removal in raw water using a vertical roughing filter with an external carbon source, in order to attain potable water.

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Chapter 3 Methodology

3.1 Introduction

This project intended to investigate a vertical roughing filter with an external carbon source to eliminate nitrate from raw water. This chapter describes the equipment used, the practical procedures carried out and the methods applied to prove the effectiveness of using ethanol as a carbon source in a vertical roughing filter.

A bench-scale model was constructed to verify if implementing a vertical roughing filter could be a suitable technology to remove nitrate from raw water using varying media sizes at laminar flow rate.

Two vertical roughing filter models were constructed and operated intermittently, one was used with an organic source of carbon and the other without a carbon source. The roughing filter columns were packed with granite gravel as filter media.

The filter media was prepared by sieving the gravel material in order to attain three successive media particle sizes. Water samples of both these roughing filters were collected for laboratory testing from the feed tank, available sampling points and the outlet. A model for the predictive removal of nitrate in vertical roughing filters was also developed empirically from analysis of laboratory test results.

The predictive nitrate removal in the vertical roughing filter was described by a zero-order kinetic rate model. The experimental investigation for this research was conducted at the Cape Peninsula University of Technology (CPUT) laboratories.

3.2 Research Design

The raw water sample used in the study was surface water sourced from Kuils River situated at Stikland industrial in the Western Cape Province, South Africa. The system efficiency was compared to previous similar studies in filtration at a laboratory scale that employed a carbon source to enhance the nitrate removal effectiveness.

To achieve the mentioned objectives, the research design was structured as represented by the experimental framework in Figure 3.1 below.

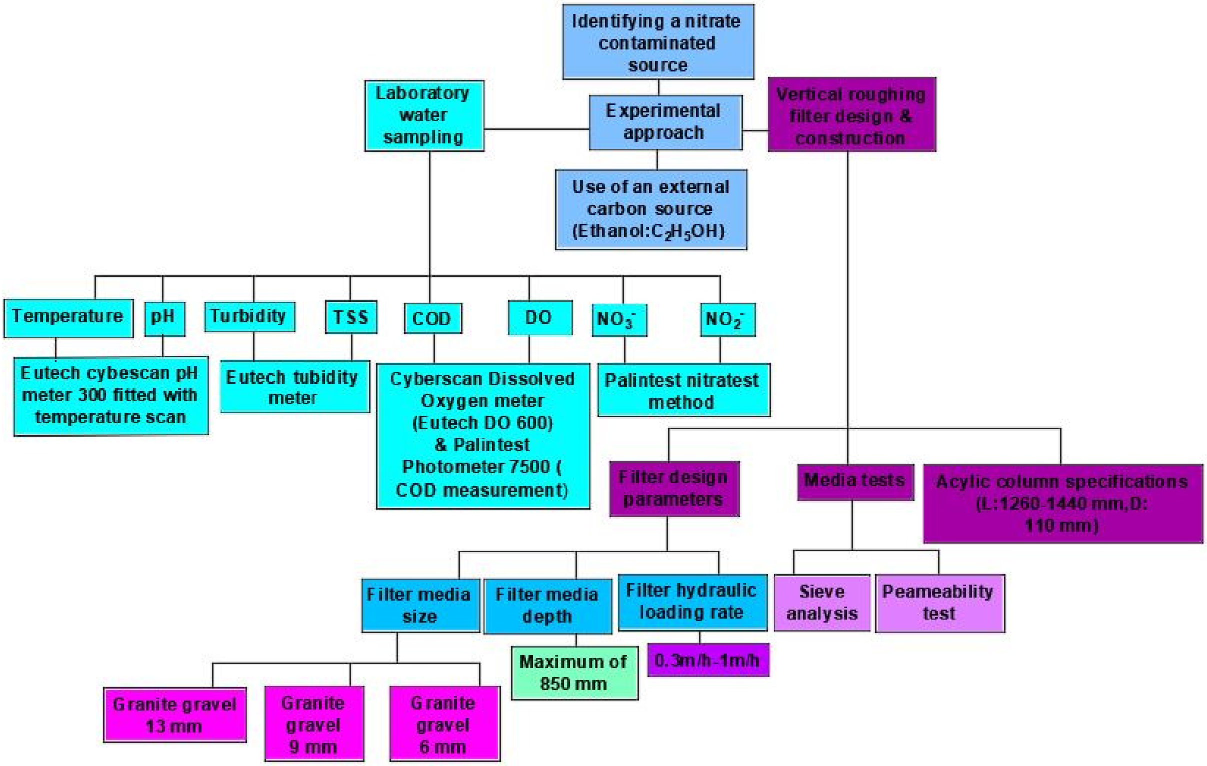


Figure 3.1 Experimental and design approach framework carried out in the research study

3.2.1 Construction of a laboratory-scale roughing filters

Two experimental vertical roughing filter models were constructed. One was used with an organic source of carbon and the other without a carbon source. Ethanol (C_2H_5OH) was selected as an organic carbon source to enhance the denitrification process due to its easily degradable nature, a safe organic carbon source, less costly, has no usage limit set on it in water treatment and most of the reviewed literature showing its treatment success practically over the years (Monoushiravan *et al.,* 2013; Mutsvangwa & Matope, 2017). Design parameters that include media size, hydraulic loading rate, and filter depth were analysed on optimal nitrate removal.

Upward vertical roughing filter in series (UVRFs) design principles and guidelines by Wegelin (1996) and Lin *et al.* (2006) were adapted in this research. The study by Lin *et al.* (2006) showed that the upward and descending movement through the connector lines minimized the likelihood of particles settling at the bottom of each column and in joints that connect the lines. The minimal settlement of particles at the base improves the filter removal efficiency and design. Again, sampling points and drainage ports were mounted through each column wall. This filter configuration allowed the opportunity to sample along the filter depth without interfering with the filter flow rate and each packed media during the filter operation. Furthermore, Lin *et al.* (2006) filter media preparation and column packing procedures were followed; the study indicated that the influence of media size on treatment performance can only be evaluated if the uniformity of different sized media is consistent and generally high. A roughing filter packed with poor uniformity media is likely to outperform a filter packed with high uniformity media of similar average size. As a result, packed media with low uniformity were employed in this research. To support chemical and biological processes to effectively take place during filtration, small filtration rates ranging between 0.3 m/h to 1 m/h were preferred by Wegelin (1996). However, the filter conduct of each media size was evaluated at lower standard hydraulic loading rates within the ranges of 0.03 m/h to 0.1 m/h, in order to provide a more contact time for microorganism activity in the filter, thus improving the removal efficiency. Three columns with successive filter media gradations were installed in series as column 1 (13 mm), column 2 (9 mm), and column 3 (6 mm). The use of three different filter media sizes helped to accomplish efficient treatment, as compared to one media size packed in one long filter.

The ideal C/N ratio for microbial activity was accessed and monitored to achieve maximum nitrate removal in the effluent with less excess Carbon. Monitoring points were available along each column at 270 mm, 750 mm, and 1000 mm from the bottom inlet. This provided the ability to assess the effect of different depths in the filter for effective nitrate removal.

3.2.2 Data

Physicochemical characteristics of water that can affect nitrate removal including pH, temperature, turbidity, total suspended solids (TSS), chemical Oxygen demand (COD), dissolved Oxygen (DO) and nitrate (NO_3^-) and nitrite (NO_2^-) were tested and monitored before, during and after the experimental process.

3.2.3 Research equipment and material

All equipment and material that was required and used in the research is described in section 3.3.2. This included mainly two peristaltic pumps for each of the filter models, three different size filter media of granite gravel, laboratory columns and fittings, two feed tanks each having a volume of 20 L and ethanol as a carbon source.

3.2.4 Presentation and analysis of results

The results obtained in the laboratory experiment were analysed by making comparisons with results obtained by other researchers on the use of roughing filters and other technologies for removal of nitrate in water.

Comparisons were also done with the SANS (241) and WHO guidelines for drinking water. In summary, the results were presented graphically, in bar charts, as equations and in tabular format, as described in section 3.3.7.

3.3 Research Methodology

The research was experimental and required the analysis of the effectiveness of the vertical roughing filter for treating nitrate in raw water. The methods and equipment used to produce the data and the physicochemical test analysis are discussed in this section.

3.3.1 Data

A permeability test was performed to determine the permeability coefficient that normally influences the flow rate. A suitable C/N ratio that can enhance the denitrification process for optimum removal of nitrate and also act as an indicator of the efficiency of COD for denitrification was investigated regarding its effectiveness for removing nitrate in raw water.

The effective time and depth at which high quality of effluent water with regard to nitrate removal was achieved was measured. The rate of biofilm growth that affects the filters smooth operations for a consistent optimum nitrate removal was investigated. The results obtained from filter length, filtration rate and the filter media size were applied in a nitrate removal model development, for predicting nitrate removal efficiency in vertical roughing filters. The physiochemical and design parameters are discussed as follows:

3.3.1.1 Physiochemical parameters

This section presents the physiochemical water parameters that were measured and monitored during the filter run, in order to analyse their effect on the filter performance for effective nitrate removal.

Potential hydrogen (pH)

To determine the pH of the water, a Eutech Cyberscan pH meter 300 fitted with a temperature test was used. The probe of the meter was firstly rinsed with distilled water to clear off any impurities. The probe was inserted in a laboratory jar filled with raw water to take a pH reading.

The pH of the influent was monitored in order to maintain suitable pH ranges for an effective denitrification process. The absolute denitrification is achieved at pH ranges of 7- 8.5, while the pH values below 6 and above 8.5 contribute to a rapid decline in denitrification activities (Drtil *et al.,* 1995; Wang *et al.,* 1995). Figure 3.2 below shows a Cyberscan Eutech pH meter fitted with a temperature test.

Figure 3.2 Eutech Cyberscan pH meter 300 fitted with a temperature test

Temperature

A Eutech Cyberscan pH meter 300 fitted with a temperature test was used to measure the water temperature. The probe of the meter was firstly rinsed with distilled water to remove any impurities. The probe was then inserted into a laboratory jar filled with raw water to take temperature readings in °C. Temperature is an essential element affecting denitrification because denitrification reduces significantly at low temperatures. Temperature influences the growth rate of denitrifying species with a high growth rate at elevated temperature. A study by Liao et al., (2018) achieved nitrate removal above 97% at optimal reaction temperatures of 15°C – 35°C. Therefore, all experiments were conducted at room temperature. Moreover, temperature and dissolved oxygen effects can be observed in denitrification when a lower solubility of oxygen at high temperatures occurs. As a result, the biological organic production increases and vice versa (Gauntlett & Craft, 1979).

Turbidity

Turbidity was measured using a Eutech turbidity meter TN-100. The meter uses sample cuvettes that were rinsed in distilled water before filling them up with water. The sample cuvette was then placed in a hole on the turbidity meter to allow readings to be taken in Nephelometric Turbidity Units (NTU). The total filter depth of vertical roughing filters limits the turbidity application to a range of 50 to 150 NTU in influent water. Turbidity measurement is a crucial water quality parameter that is controlled by the existence of suspended particles in water. The bulk of the particles can accumulate in the filter bed and cause clogging which decreases the filter performance. Figure 3.3 below shows a Eutech turbidity meter.

Figure 3.3 Eutech Turbidity meter TN-100

Dissolved Oxygen (DO)

The dissolved oxygen in the influent was measured using a Cyberscan Oxygen Meter (Eutech DO 600). The raw water was filled in a laboratory glass jar and the testing probe was rinsed in distilled water before being embedded in the water. Optimum denitrification happens when the oxygen levels become reduced at ranges < 0.2 mg/L and nitrate is the main source of oxygen for heterotrophic bacteria (Mutsvangwa & Matope, 2017). It was found that a concentration of DO greater than 0.2 mg/L significantly decreases the denitrification rate (Jørgensen & Sørensen, 1988). Therefore, DO concentration during the denitrification process was monitored to achieve efficient nitrate removal. Stable dissolved oxygen readings were taken after the meter was switched on at mg/L. Figure 3.4 below represents a Cyberscan Dissolved Oxygen meter (Eutech DO 600) with a testing probe.

Figure 3.4 Cyberscan Dissolved Oxygen meter (Eutech DO 600**)** with a testing probe

Chemical Oxygen Demand (COD)

A Palintest Photometer 7500 was used to measure the COD and the test was conducted in accordance with the Palintest COD/2000. First, the sample was prepared by adding 2 ml of raw water into the reagent tube and allowing it to mix. A reagent blank was also prepared using deionised water and adding 2 ml into the reagent tube and allowing it to mix. Both tube tests were placed in a tube test heater for digestion at a temperature of 150°C for 2 hrs.

After cooling, the deionised water blank tube test was placed into a Palintest Photometer 7500. The second tube test with a raw water sample was placed into the Photometer after removing the first sample and the COD reading was then taken. The COD test was also conducted in order to measure ethanol that was used as a carbon source before, during and after the filtration process. All the readings were taken in mg/L O_2. Figure 3.5 below depicts a photometer used to measure COD.

Figure 3.5 Palintest Photometer 7500 for measuring COD and a thermoreactor TR 320 for COD digestion process.

Total Suspended Solids (TSS)

During the roughing filter operation, two stage solid particle removal takes place. The first phase reflects a time in which the efficiency of the removal of particles stays consistent, as solid deposition increases, whereas in the second phase, the efficiency of removal is reduced due to increased particle deposition and filter penetration (Collins, 1994). To monitor and maintain the suspended solids for effective filter performance, the raw water suspended solid concentration was determined. Figure 3.6 shows the range of solid matter that is usually present in natural surface waters.

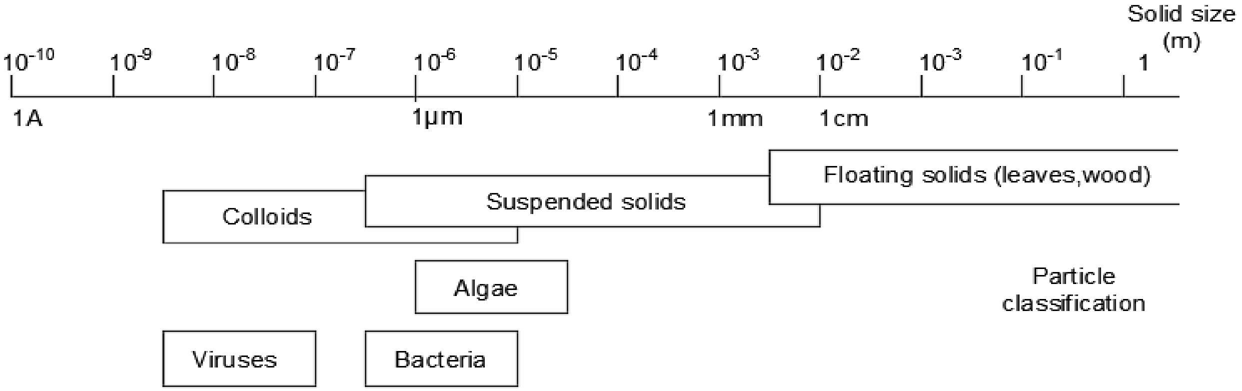


Figure 3.6 Common natural surface water solid matter range sizes and particle classification (Lin *et al.,* 2006)

In this research, the TSS measurement was carried out using a 47 mm diameter standard filter paper to filter the samples using laboratory vacuum filtration. The residual filter paper was oven-dried for 30 min at 110°C after filtration. A laboratory scale with precision of ± 0.001 g was used to weigh the filter paper before and after filtering the sample. The blank filter paper was weighed before and after drying for each sample batch, to make up for water loss in the filter paper during drying. The weight of the dry blank filter paper was measured against the original weight on all filter papers in the respective batch of analyses. The final concentrations of TSS were determined using Equation 3.1 given as:

$$TSS = \frac{(F_w - O_w) \times 10^6}{V_s} \qquad (3.1)$$

Where:

TSS = Total suspended solids (mg/L)

F_w = Final weight of oven dried filter paper + residue (mg)

O_w = Original weight of filter paper (mg)

V_s = Sample volume (L)

Figure 3.7 below depicts instruments used for conducting a TSS laboratory test.

Figure 3.7 Standard duty piston pressure and vacuum pump (Model 2534), 1000 mL vacuum flask, filter paper and a laboratory analytical scale for TSS measurement.

Nitrate (NO_3^-) and Nitrite (NO_2^-)

The nitrite was conducted by a Palintest Nitricol method in which one tablet reagent was added to a sample of water under test. The tablet was crushed in a test tube in which ten ml of water sample was added and allowed to mix. The mixture was left to stand for 10 min to allow for full colour development. The colour intensity produced was proportional to the nitrite concertation in the water. The resulting nitrite concentration was measured using a Palintest Photometer 7500 in mg/L NO_2.

A Palintest nitratest method was used to test nitrate in which a 20 ml water sample was added in a nitratest tube. The nitrate was first reduced to nitrite using a zinc based nitratest powder and nitratest tablet, which supports rapid flocculation after 1 min of contact time. The test was conducted in a nitratest tube that enabled settlement and easy decanting of the sample. A single Nitricol tablet was then added to the solution after decanting 10 ml into a round test tube. The tablet was crushed and allowed to mix and dissolve. The mixture was left to stand for 10 min to allow for full colour development. The intensity of the colour generated from the test was proportional to the nitrate concentration. The nitrate concentration was measured by using a Palintest Photometer 7500 in mg/L NO_3 and mg/L-N. Figure 3.8 below represents a Palintest Photometer 7500 that was used to measure the nitrate and nitrite concentrations in the laboratory.

Figure 3.8 A Palintest tube test with reagents and Palintest Photometer 7500 for measuring nitrate and nitrite concentrations.

3.3.1.2 Design parameters

The principal design parameters that affect the removal of nitrates in roughing filters are presented in this section. Treatment performance increased with increase in filter depth, decrease in media size and decrease in the loading rate.

Media size

Gravel is a type of media commonly used in roughing filters. However, an alternative can be any insoluble, clean, and mechanically resistant material. The benefit of using different grading size in roughing filters allows particles to be penetrated throughout the filter bed. It often leverages the wide storage capacity given by larger media, as well as the high-level efficiencies of removal offered by the small media. The filter media size gradually decreases in the direction of water flow, whereas the uniformity of the filter media is maximized to improve the filter storage capacity in the filter pores and to facilitate the filter cleaning (Lin *et al*., 2006). Table 3.1 below shows commonly used filter media grading in roughing filters.

Table 3.1 Common roughing filter media grading for rough filters (Wegelin, 1996)

Roughing Filter Description	**Filter media size (mm)**		
	1st fraction	**2nd fraction**	**3rd fraction**
Course	24-16	18-12	12-8
Normal	18-12	12-8	8-4
Fine	12-8	8-4	4-2

Flow rate

It is necessary to operate roughing filters at laminar flow conditions, to optimize removal performance, since sedimentation is the main removal mechanism in rough filtration (Lin *et al.*, 2006). The Reynolds number can be used to calculate flow conditions through porous mediums, as shown by Equation 3.2 (Wegelin, 1996; Lin *et al.,* 2006).

$$R_e = \frac{V - d_c}{v} \tag{3.2}$$

Where:

Re= Reynolds number
d_c= Column diameter (m)
V= Filtration rate (m/s)
v= Kinetic viscosity (1.004×10^{-6} m$^{2/}$/s at 20˚C)

The filter is therefore recommended to operate at constant flow rates, to achieve laminar flow conditions (Wegelin, 1996). The laminar flow is characterized by a uniform flow of fluid which occurs in small numbers of Reynolds (Re < 10) whereas turbulent flows occur at larger Reynolds numbers (Re >100) and is characterized by spontaneous forces. Previous research found that high removal efficiencies are associated with lower rates of hydraulic charge when flowing in laminar flow (Lin *et al.,* 2006).

Filter depth

Longer filter depths are usually correlated with better average removal efficiencies. Nevertheless, removal efficiencies that occur gradually in series of small amounts often decrease with changes in the filter duration, due to the initial removal of large filter particles. The rate of decline depends on the design variables of the filters, and on the size and composition of the particles in suspension. The use of various media sizes with a shorter filter help to accomplish efficient treatment, as compared to one media size filled with a long filter (Lin *et al*., 2006; Nkwonta, 2010). Figure 3.9 below shows the effect of filter length and the use of varied media size in rough filters for turbidity removal, as roughing filters were initially designed for highly turbid water.

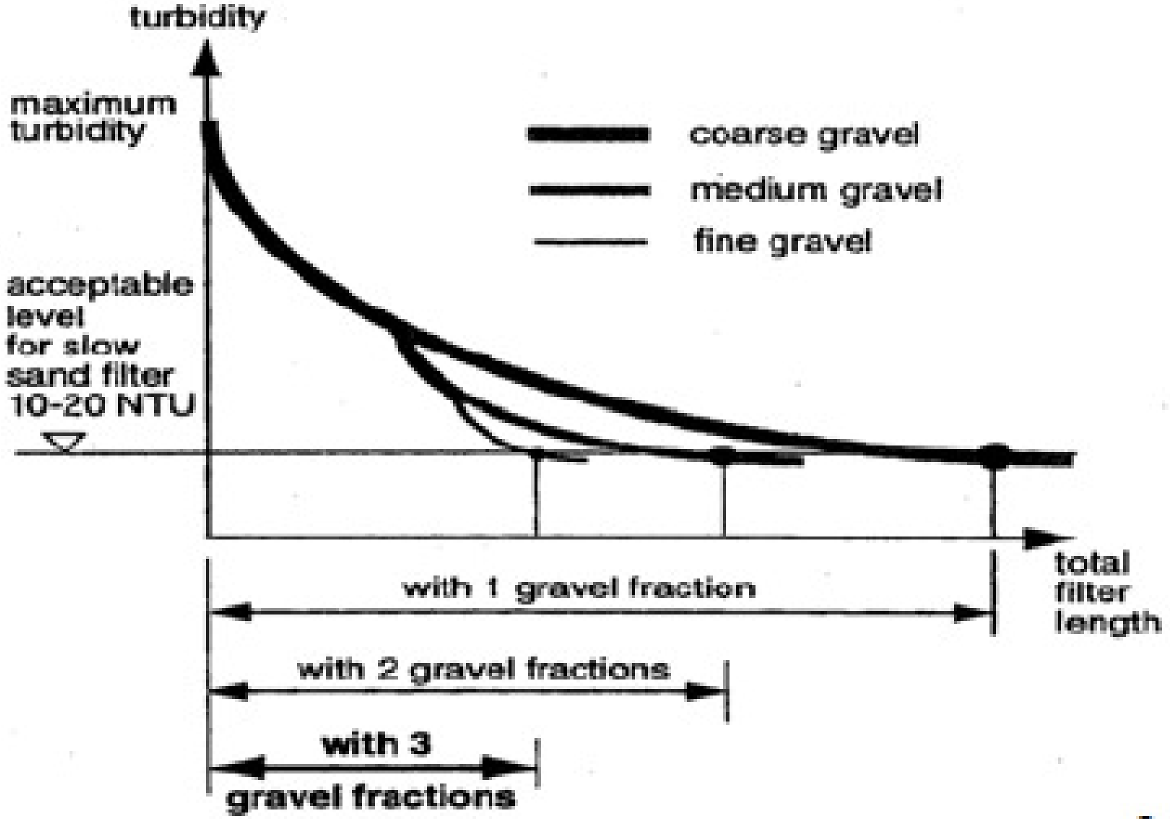


Figure 3.9 Significance of filter length and varied media size in roughing filters (Lin *et al.,* 2006)

3.3.2 Research equipment and material

This section describes the equipment and material used in acquiring the results and data. It also describes the procedures and methods used to process the data.

3.3.2.1 Filter media

Roughing filters are considered as space filters because the solids penetrate deep into the bed of the filter. Therefore, the density of the filter bed grain is a significant parameter to consider. One of the important factors for effectively removing nitrate from raw water is by reducing the pores of the media grains in the filter bed. Small media grain size is said to have a greater adsorption region and therefore, has a higher effect in water treatment (Wegelin, 1996). The impact of media size on treatment results can only be measured if consistent and preferably low uniformity of different media sizes are established. The low uniformity media packing allowed for a more in-depth evaluation of the media size as one of the design parameters that can have an influence on the treatment efficiency (Lin *et al.,* 2006).

In this research, laboratory columns were packed with granite gravel that was sourced from Lafarge Mixing Company in Western Cape Province, South Africa. The gravel material was further sieved to attain three high uniformity grading sizes of normal media as given by Wegelin, (1996). Each filter media was packed in constant increments and tapped down before adding additional media to reduce the porosity until the column is filled up to a required depth. Three successive filter media with grain sizes of 13 mm, 9 mm, and 6 mm respectively, were attained. The use of varied filter media grades in a raw filter facilitates the penetration of particles into the filter bed. It also takes advantage of the extensive storage space provided by larger media and the high efficiency of removal provided by smaller filter media (Nkwonta & Ochieng, 2010). By measuring the accumulated volume of water in a 1 litre graduated cylinder from the media packed column under saturated conditions, the porosity of the filter media was determined, as described in section 3.3.4.2 The gravel media was washed fully with treated tap water, in order to clean the media before packing and wash off any potential impurities. A 2 cm depth of a 19 mm granite media was placed on the perforated plate and distilled water was supplied to the column through the drainage port connected to the tap. Each filter media was packed in constant increments of 10 cm and tamped down before adding additional media to decrease the porosity until the column is filled up to a height of 850 mm. A temporary perforated plate was mounted above the filter media and pressed tightly against the media and enabled the open top to overflow and drain. This procedure allowed the media to settle and create a tighter packing orientation, prevent the fluidizing of the media during filling and also to remove air bubbles from pore spaces. Figure 3.10 below shows the 13 mm, 9 mm, and 6 mm filter media gradations, as well as the cleaning process of the media to remove any attached sand and clay particles.

Figure 3.10 Granite gravel filter media size 13 mm, 9 mm, and 6 mm before and during cleaning off attached sand and clay particles.

3.3.2.2 Chemical and clay spike

Effective biological denitrification requires carbon as a substance which enhances the performance of microorganisms to remove nitrate from raw water and restore its quality to safe drinking water standards. The average nitrate concentration of raw water from the river was 2.76 mg/L-N and hence was not enough for effective denitrification. The raw water was spiked with potassium nitrate (KNO_3) to increase the nitrate concentration while ethanol (C_2H_5OH) was used as an organic carbon source to enhance the vitality of the denitrification process in removing nitrate from water.

Contrarily, methanol guarantees the highest denitrification levels. However, it is harmful due to some of the residual concentrations of carbon compounds in the effluent and results in fast growth of biomass (Shrimali & Singh, 2001; Mutsvangwa & Matope, 2017). Ethanol is therefore considered the most appropriate source of carbon for nitrate removal and has no dosage limits set in drinking waters. Again, the raw river water was measured to obtain the initial turbidity concentration. Due to low turbidity concentrations obtained in the raw water, the raw water was spiked with earthenware clay before running the filter to increase the turbidity. Figure 3.11 below shows ethanol used as a carbon source and Figure 3.12 below shows potassium nitrate used to spike the raw water to increase the nitrate concentration.

Figure 3.11 Ethanol as a Carbon source

Figure 3.12 Potassium nitrate powder

Figure 3.13 below shows the earthenware clay used to spike the raw water to increase the turbidity.

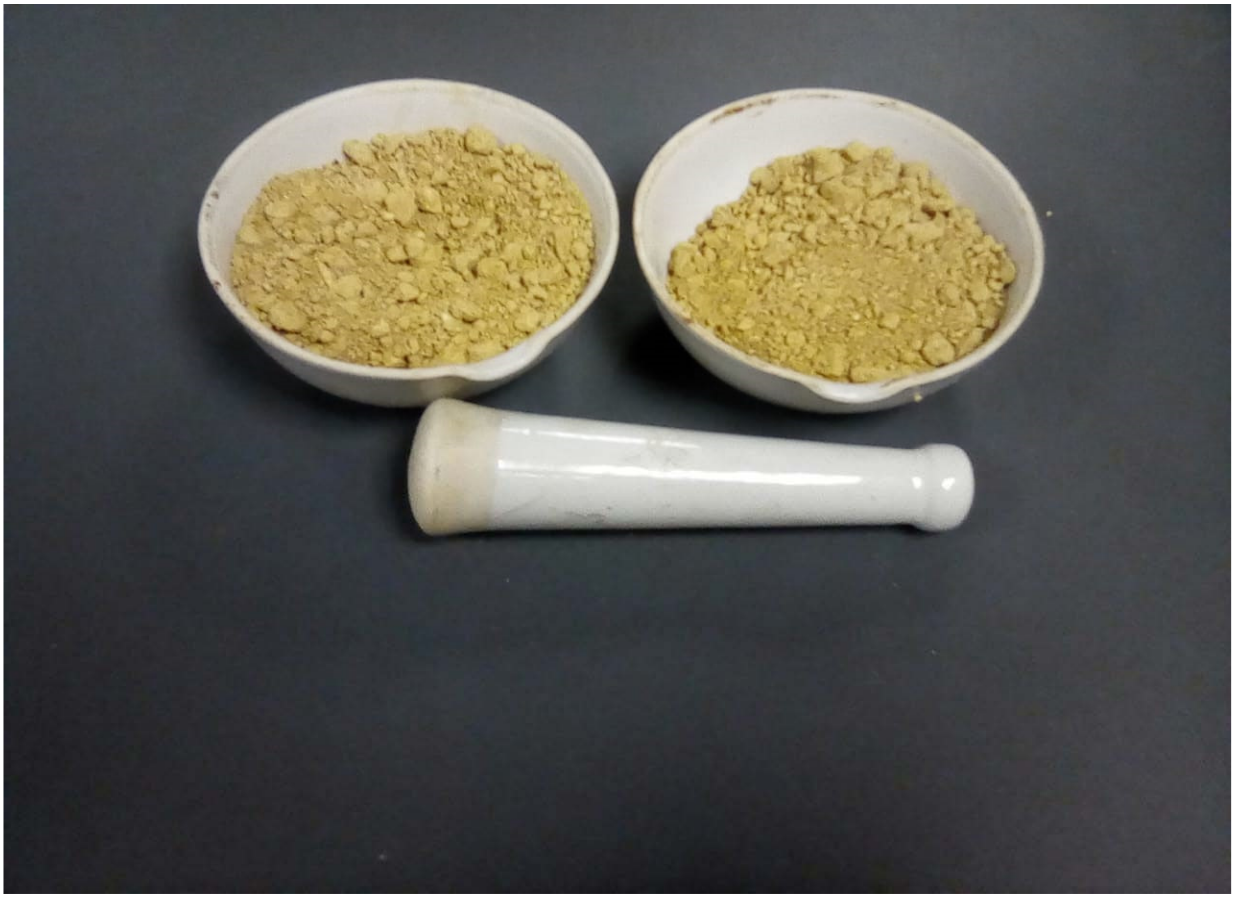


Figure 3.13 Earthen clay

3.3.2.3 Feed tank

The feed tank had a capacity of 20 L. and was used as a main storage unit for the influent raw water. It was connected to the rest of the filter columns by pipe fittings and valves. The water was continually and consistently stirred with a submersible air circulating aquarium pump, to keep any particles in suspension.

3.3.2.4 Pumps

In combination with the constant-head feed tank, two peristaltic variable speed pumps driven by a 41 W and 75 W motor respectively and controlled by a variable speed drive capable of delivering a maximum of 0.2 m^3/h of water. The pumps were used to transfer the raw water from the feed tank to the filter columns through the inline tube connections. A 6 W submersible circulation wave pump was used to constantly and continuously stir the water in the feed tank, to keep particles in suspension. The peristaltic and submersible circulation pumps used for running the filter system are depicted in Figure 3.14 below.

Figure 3.14 Peristaltic pumps (Gilson Minipuls 3 and cole Palmer 7520-40 console drive masterflex) and a submersible circulation wave pump (RS-108A).

3.3.2.5 Palintest Photometer

The Palintest Photometer 7500 was used to determine the chemical oxygen demand (COD). It was used for optimum efficiency in tandem with the Palintest reagents. This is based on optical absorbance concepts and visible light dispersal concepts. Optical absorbance utilizes Palintest photometric reagents by interacting with different analytes to produce clear colours. Using the photometer and results, the intensity of the emitted colour was determined relative to the calibration data processed, to provide the final result. When the test was completed, the results were converted into alternate units of expression such as mg/L to ppm.

3.3.3 Conceptual diagram of a roughing filter with an external carbon source

Figure 3.15 below illustrates how the biological process sequentially takes place in the filter and involved bacteria in each process step. The biological nitrogen removal is a two-step, sequential process. Normally, nitrification occurs first, followed by denitrification.

However, due to the upward flow direction of the filter in this study, the raw water first passed through the anoxic zone, which is highly favourable for denitrification. The anoxic zone is defined by the absence of oxygen and the presence of nitrate. Both nitrification and denitrification processes have to be effective for nitrogen removal to be successful, since only denitrification will remove nitrogen compounds from water (Ginige, 2003).

As shown in Figure 3.15 below, the nitrification process occurs in two stages in the presence of oxygen, with ammonia (NH_4^+) being oxidized to nitrite (NO_2^-) by ammonia oxidizing bacteria (AOB) under aerobic conditions and then to nitrate (NO_3^-) by nitrite oxidizing bacteria (NOB). Denitrification, on the other hand, is a process mediated by denitrifying bacteria (DNB) in which nitrate or nitrite is converted into nitrogen gas (N_2) through intermediates of nitric oxide (NO) and nitrous oxide (N_2O) in the absence of oxygen (Wang *et a*l., 2021). Furthermore, during the heterotrophic denitrification process, ethanol was employed as an electron donor for oxidizing nitrate-nitrogen to nitrogen gas.

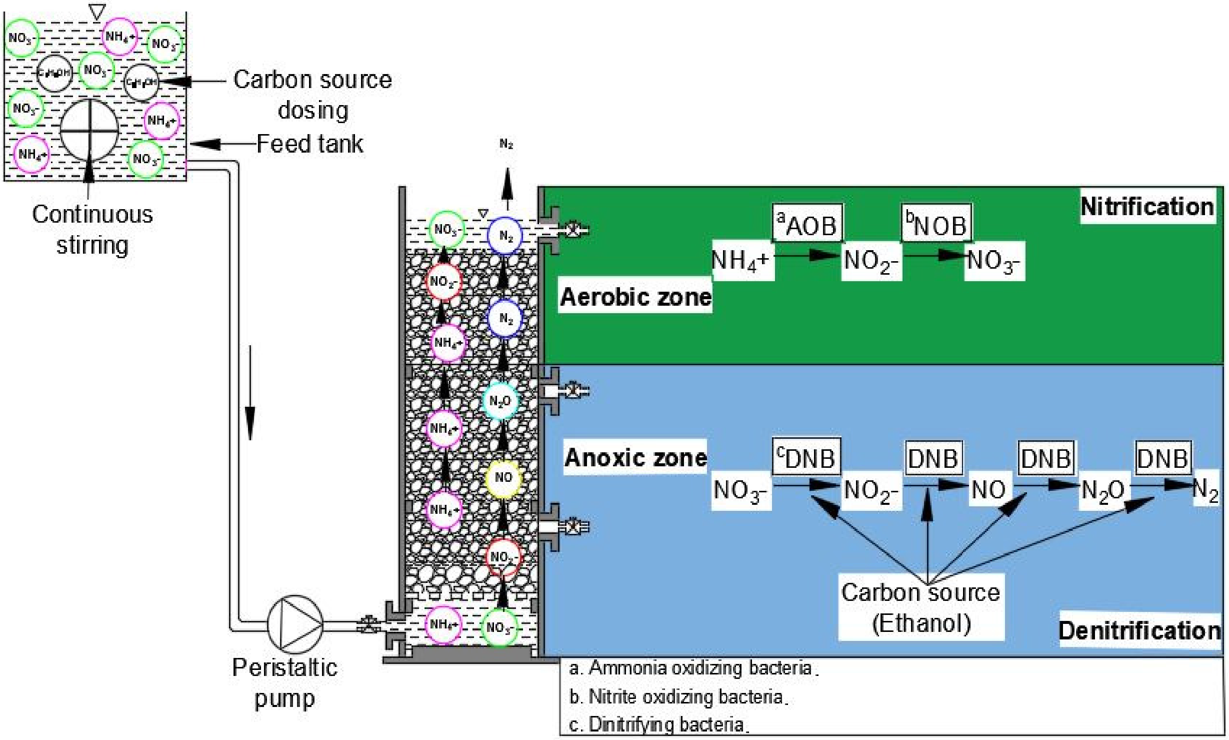


Figure 3.15 Conceptual diagram of a biological process of nitrate removal in a vertical roughing filter with an external carbon source.

Moreover, Figure 3.16 below illustrates a three stage upward vertical roughing filter in series water treatment concept. The high nitrate contaminated raw water underwent a step-by- step treatment through a series of columns with successive filter media gradations installed in series: - column one (13 mm), column two (9 mm), and column three (6 mm).

The use of multimedia (three different filter media size) helped to accomplish efficient treatment, as compared to one media size packed in one long filter. In each stage, high inflow nitrate concentration was gradually reduced, with the help of attached microorganisms on the filter media to attain treated raw water outflow.

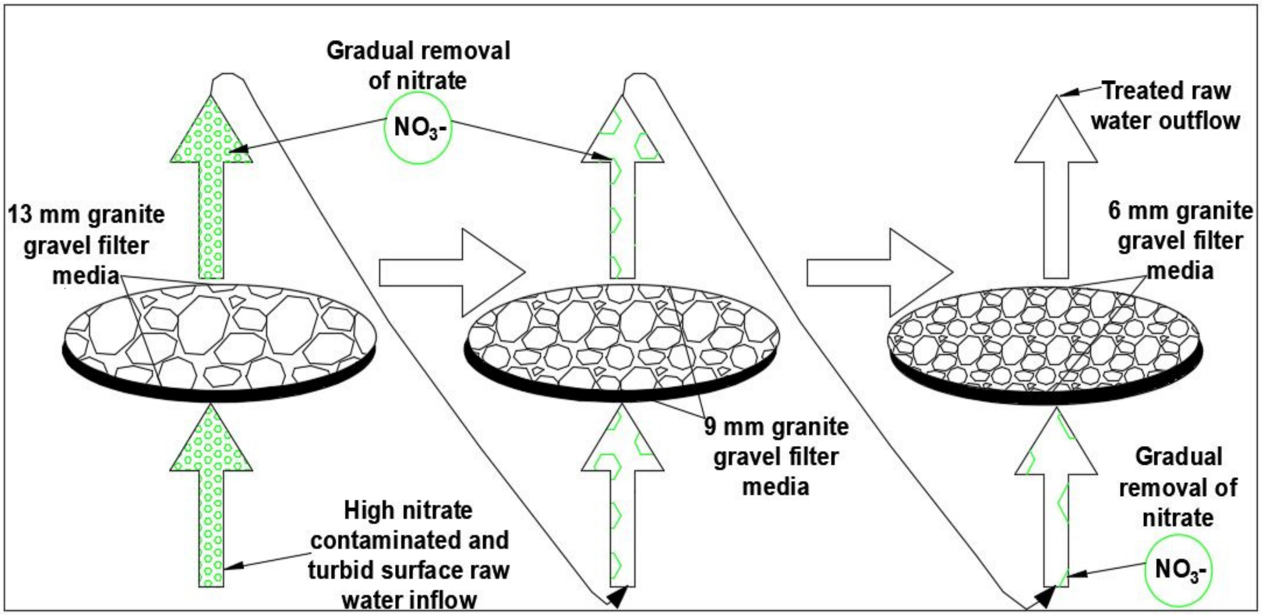


Figure 3.16 A three stage up-ward vertical roughing filter in series water treatment concept

3.3.4 Experimental approach

Roughing filters are suitable for highly turbid water. Therefore, the source of water was surface water from Kuils River located in Stikland industrial in the Western Cape Province as shown in Figure 3.17. A study by Murphy *et al.* (2010) showed denitrification increasing when surface water was used in their experimental investigation. The increase was considered to be caused by the high carbon content present in the inflow water. The raw water was collected a day before the planned roughing filter experiment and was stored at room temperature until sampling. A COD test was performed to establish the quantity of the spiked ethanol as residual Carbon in the filtrate. The COD was measured using a photometer. A high carbon content in raw water can lead to an increase in the denitrification process which increases the nitrate removal rate. The COD test was conducted primarily to measure and compare the ethanol concentration inflow to the concentration obtained in the filtrate, in order to assess organic removal performance and the quality of the filtered water with regard to the presence of residual carbon. An up-flow vertical roughing filter (UVRFs) was adopted to overcome the head loss usually experienced in vertical roughing filters (Lin *et al*., 2006). The upward flow direction of water also promoted the effectiveness of the carbon source for denitrification, as compared to a downward flow direction. This is because in an upward flow direction, denitrification occurred near the base of the filter media, where there was less oxygen and the carbon source was used up as it entered the filter to provide energy for bacteria activity. The denitrification process happened prior to the nitrification process that was hypothesised to occur near the top of the filter media, where there is excess oxygen. Figure 3.17 below shows the source and sample area of the raw water.

Figure 3.17 Sample area, Kuils River, Stikland industrial, Western Cape, South Africa. Top left: location in South Africa (Google Earth, 2020). Bottom left: Topographic plan view (Google Earth, 2020). Bottom right: Kuils River channel

3.3.4.1 Up-flow roughing filter operation and maintenance

The influent water was supplied at the filter bottom in an up-flow direction. The filter was installed in series with the filter media packed in separate compartments. The filter media was totally submerged under a maintained 100 mm water depth for smooth operations. The filter was operated at laminar flow within the range of 0.03 m/h to 0.1 m/h, in order to provide for more contact time for microorganism activity in the filter, thus improving the removal efficiency. The filters were operated for 12 hrs during the day and thereafter rested for 12 hrs. As suggested by Cleary (2005) a speed of 30 m/h is required during drainage to cause turbulent flow conditions in the media pores to eliminate solid deposits from the media. Draining the roughing filters twice leads to the removal of more than 70 % of the deposited solids from the filter (Rajapakse & Ives, 1990; Cleary, 2005). Roughing filter drainage can also return the filter efficiency to almost its original state. The cleaning frequency depends on the solid particles loading and biological activity in the filter (Wegelin, 1996) and in a conventional filter, the cleaning frequency occurred normally once in every four weeks. The up-flow method was used to clean the filter where an increased upward water flow generated a turbulent condition in the interstitial pores and removed particles that had been deposited on the media.

3.3.4.2 Experimental approach for the filter media

Sieve analysis

The sieve analysis was conducted on the coarse aggregates obtained from a commercial source and were passed through a series of stainless-steel sieves. This was achieved by following a standard sieve analysis procedure, in order to attain suitable filter media gradations to be used in the vertical roughing filter, as mentioned in section 3.3.3. The procedure also separated some of the fines that would cause clogging in the filter during filtration. The standard sieve sizes used in this procedure are given in Table 3.2 below, while Figure 3.18 below represents the sieve analysis equipment that was used in the laboratory.

Table 3.2 Sieve sizes for sieve analysis

Sieve size	Particle size (mm)
0.53 in	13.2
3/8 in	9.51
0.265 in	6.73
No. 4	4.75
No. 8	2.36
No. 16	1.18
No. 30	0.6
No. 40	0.425
No. 50	0.3
No. 100	0.15
No. 200	0.075
Pan	

Figure 3.18 A sieve analysis to attain gravel filter gradation

Permeability test

A permeability test was carried out to calculate the permeability coefficient of the filter media that was used in developing a nitrate removal model. A laboratory permeameter was used to determine the permeability of each filter media. Each filter media specimen was placed into a permeameter mould and the raw water from the constant head tank was fed through the media. The permeability cell consisted of pressure points at different levels which were attached to the tubes of the manometer fixed at a graduated scale stand. A schematic diagram and a laboratory setup of a constant head permeability test was arranged, as illustrated in Figure 3.19 below.

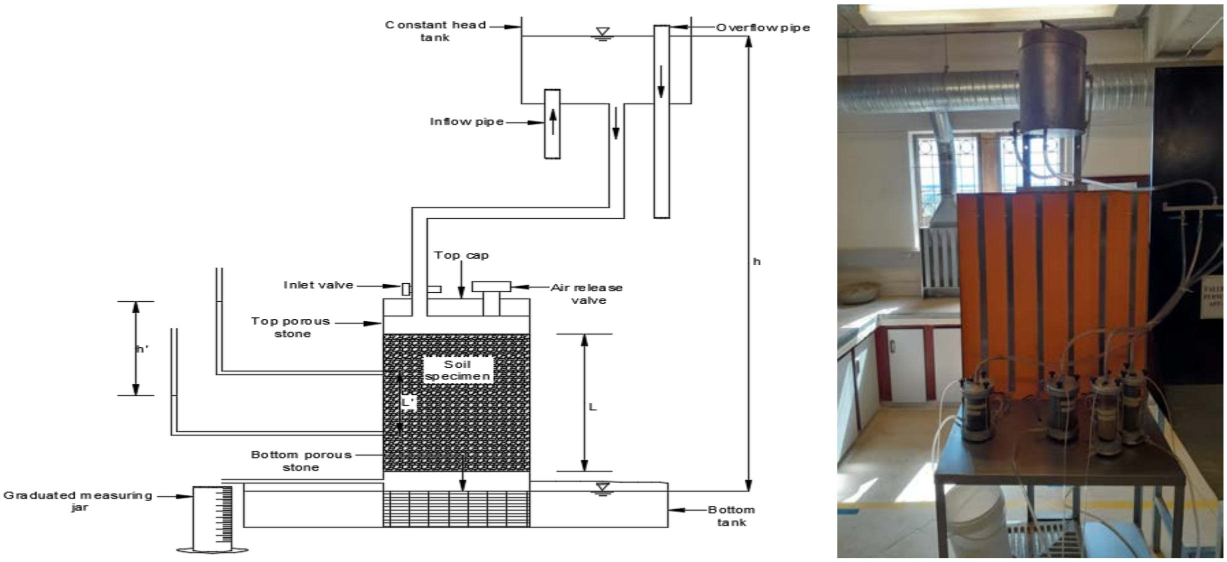


Figure 3.19 A schematic diagram and a laboratory setup of a constant head test.

The water at the inlet supply was regulated in such a way as to maintain a constant head throughout the test phase. Once a constant rate of flow was set, water was collected for a specified time in a graduated flask. The permeability coefficient was determine using Equation 3.3 as given.

$$K = \frac{QL}{tAh} \tag{3.3}$$

Where:

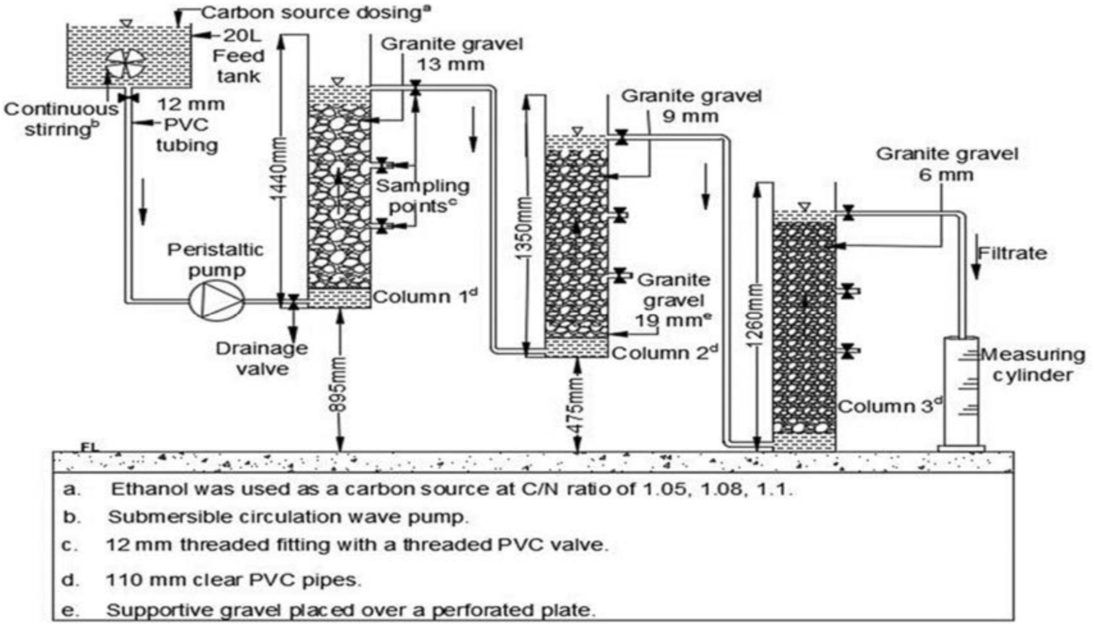
K = Coefficient of permeability (cm/sec)
Q = Water discharge (cm^3)
t = Duration of water collection discharge (sec)
L = Length of specimen (cm)
h = Pressure head of water (cm)
A = Cross section area of specimen (cm^2)

3.3.4.3 Laboratory setup and column specifications

The following section presents the model design specifications and the laboratory setup procedures.

Laboratory up-flow vertical roughing filter setup

To simulate an up-flow vertical roughing filter in series (UVRFs), a design by Lin *et al.* (2006) was adopted for this research. Three acrylic columns were connected, with each having a total length of 1000 mm and internal and external diameters of 110 mm and 170 mm, respectively. The raw experimental water was continuously pumped into the columns packed with filter media of granite gravel. The upward and descending movement through the connector lines minimized the likelihood of particles settling at the bottom of each column and in joints that connect the lines. The minimal settlement of particles at the base improves the filter removal efficiency and design (Lin *et a*l., 2006). Consistent hydraulic loading across each column and accommodation of influent, and drainage ports were accomplished by raising the floor and positioning it to support 850 mm of filter media above it. A perforated acrylic plate with perforations of diameter 5 mm was positioned on the mounted ledge 30 mm above the column base. A supportive gravel of 19 mm granite was placed over the perforated plate in each column throughout the experiment, with a thickness of 50 mm. End caps that are fitted with O-rings were used to seal each column to prevent leakage. 13 mm threaded polyvinyl chloride (PVC) fittings for the inflow, outflow and drainage ports were mounted through the column wall. Figure 3.20 below shows a UVRFs design model schematic.



a. Ethanol was used as a carbon source at C/N ratio of 1.05, 1.08, 1.1.

b. Submersible circulation wave pump.

c. 12 mm threaded fitting with a threaded PVC valve.

d. 110 mm clear PVC pipes.

e. Supportive gravel placed over a perforated plate.

Figure 3.20 Laboratory design model of an up-flow roughing filter in series (Wegelin, 1996; Lin et al., 2006).

Column specification

Figure 3.21 below presents the column specifications of a laboratory design model for a UVRFs.

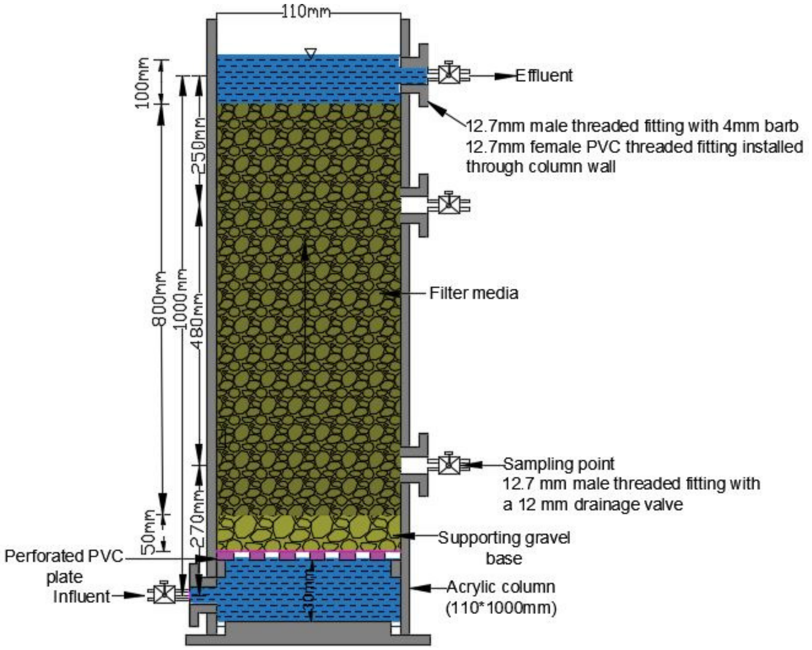


Figure 3.21 Laboratory up-flow vertical roughing filter in series column specifications in accordance with Lin *et al*., (2006)

The vertical roughing filter system was set up in the laboratory, as shown in Figure 3.22 below.

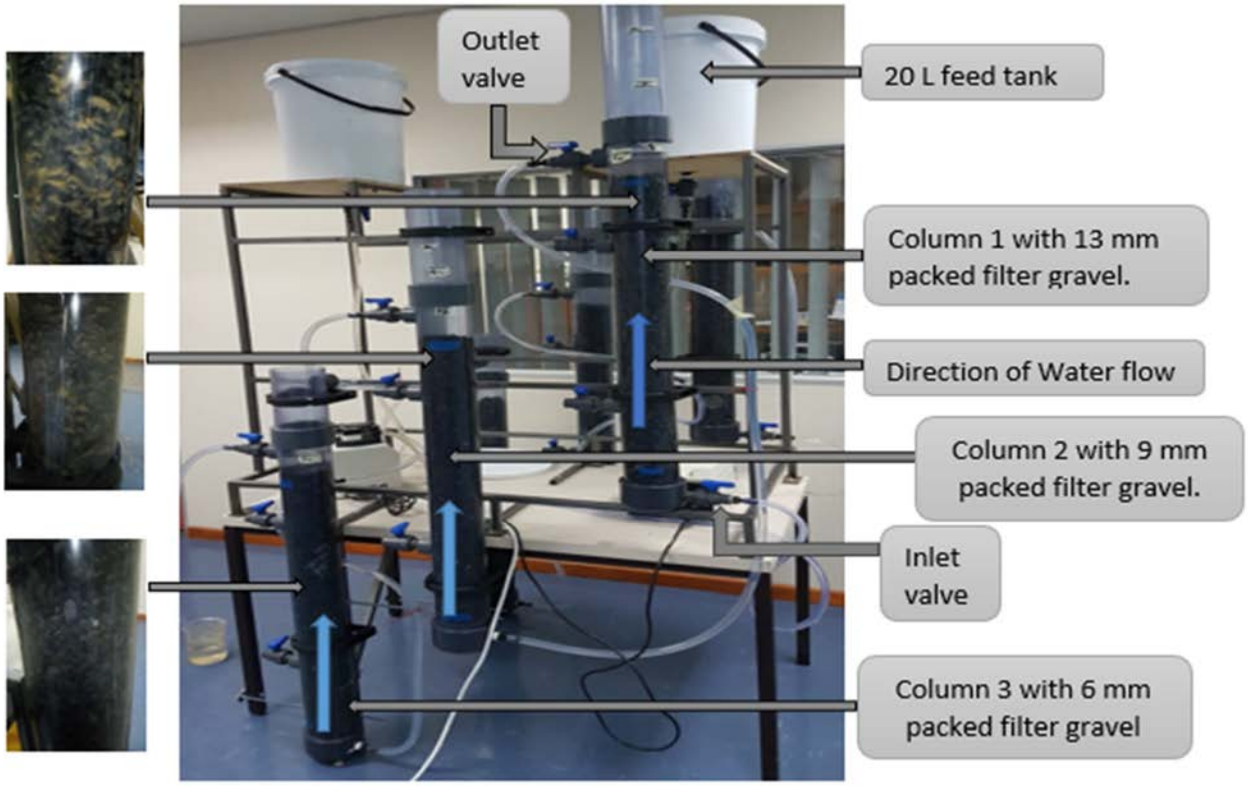


Figure 3.22 An Up-ward vertical roughing filter system laboratory setup.

3.3.4.4 The predictive nitrate removal model in a vertical roughing filter

There are several models that have been used to describe the overall kinetics of biological reactors, such as the first order model, zero order model, Monod Model, Stover-Kincannon Model, and the Efficiency Loss Model, as discussed in section 2.10. In this research, an empirical approach was applied to evaluate the nitrification and denitrification reaction rate kinetics. A laboratory investigation was conducted using an upward roughing filter for a period of 30 weeks, to test its efficiency in removing nitrate from raw river water to enable potable use. Each filter column had a total capacity of 9.5 L before filter media packing and 3.3 L when packed with filter media. A suitable kinetic removal rate model was established from the laboratory test results observations and analysis, and further used to determine the model reaction rate order and the reaction rate constant. The removal of nitrate in an upward vertical roughing filter process by heterogeneous microorganisms was evaluated based on the change in concentration of nitrate across the filters $(C_i - C_e)$, divided by the hydraulic retention time $\frac{V_r}{Q}$. Also, the approach used to develop the equation was based on the assumption that the kinetic rate of the reaction was proportional to the nth power (reaction rate order) of the concentration, where (k) is the reaction rate constant and $C_{NO_3^-}$ is the nitrate concentration as presented in the results section 4.16. A regression analysis was carried out on the datasets from the filter with and without a carbon source to evaluate a relationship that most closely fits the data between the kinetic reaction rate $\left(\frac{Q\,(C_i - C_e)}{V_r}\right)$ for the removal of nitrate and the variables that include inflow nitrate concentration (C_i), outflow nitrate concentration (C_e) and total organic loading rate (QC_i/V).

Thereafter, the corresponding reaction rate order (n) was then obtained by plotting a log-log plot of the experimental data, in which the slope corresponded to the order of the reaction. Moreover, the reaction rate constant (k) was estimated from a regression analysis of the slope of the trend line obtained from a plot of outflow nitrate concentration C_e versus the time sampling interval. The reaction rate order (n) determines how the concentration of nitrate affects the removal rate, while the reaction rate constant (k) determines how the nitrate concentration decreases over time. The reaction constant value can vary during the reaction due some physical variables such as temperature. As a result, a small rate constant indicates a slower reaction in nitrate removal, while a large rate constant indicates a faster reaction in nitrate removal. The empirical predictive model for the denitrification of nitrate was established using the model parameters as discussed:

Nitrate concentration used in the vertical roughing filter

This takes into consideration the performance of the denitrification process compared to the reduction of nitrate concentration over time. The inflow and outflow nitrate concentration were key parameters considered in the removal of nitrate. Nitrate concentrations of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N were investigated during the experiment in order to observe the effectiveness of the filter on nitrate removal. These nitrate concentrations were achieved by spiking the raw influent water with potassium nitrate (KNO_3) with each trial experiment. Throughout the nitrate removal process, the effect of ethanol as a carbon source was measured as COD as mentioned in section 3.3.3. The nitrate %age efficiency removal was determined as shown by Equation 3.4:

$$N_e = \frac{C_{i-}C_e}{C_i} \times 100 \qquad (3.4)$$

Where:

N_e= Nitrate removal efficiency (%)

Raw water flow rate

Previous research has shown that substantial efficiencies in solid removal can only be attained under laminar flow conditions, due to the primary mechanism in roughing filtration being sedimentation (Wegelin, 1996; Lin *et al.,* 2006). The higher the flow rate, the lesser time a particle needs to travel the distance to settle and either stick or be adsorbed onto the surface and layers of the filter media (Wegelin, 1996; Affam & Adlan, 2013). During the filter run, the change in flow rate through the vertical roughing filters was monitored and determined by taking the average flow rates over a significant portion of the fluid cycle. Each filter was provided with an empty 1 L measuring cylinder at the beginning of each cycle.

The starting time (t_0) at which water was pumped into the filter was recorded using a stopwatch. The time at which the water level reached the 1 L mark in the receiving vessel was registered, and termed t_1. The measured flow rates within the range of 0.009 m^3/h -0.029 m^3/h through the vertical roughing filters were evaluated using Equation 3.5.

$$Q = \frac{V_s \times 60sec}{1\text{min}(t_1 - t_0)} \qquad (3.5)$$

Where:

Q= Flow rate (L/m)
V_s= Volume of collected filtrate sample (L)
t_0= Start time (min)
t_1= End time (min)

Filter depth

The pore spaces get narrower as solid particles are deposited in the filter bed; therefore, they experience increased shear forces. This allows separation and deeper penetration of the solids into the filter bed. Improved efficiencies in cumulative removal usually associate with longer filter depths (Wegelin, 1986; Collins *et al.*, 1994). However, vertical roughing filters have a comparatively small filter depth and, due to structural limitations, are restricted to 1 m for each compartment. In this research, the filter consisted of a total depth of 3 m for the three filter columns connected in series. Thus, various media sizes could use a shorter filter of several media sizes (Lin *et al.*, 2006; Nkwonta & Ochieng, 2010). Therefore, the use of successive granite gravel filter media was investigated as specified by Figure 3.2.2 in section 3.3.4.3.

Inflow filtration rate

The filtration rate has a major impact on the removal treatment. Effective filtration in roughing filters is better accomplished at low filtration rate so as to maintain particles gravitationally on the media surface (Boller, 1993). Wegelin (1996) found that vertical-flow roughing filters, particularly when loaded with large quantities of solid matter, can be vulnerable to hydraulic fluctuations. At higher filtration levels, settled matter may be re-suspended, allowing solids to move through the filter as discussed in section 3.3.4.1.

Nitrate and carbon source dosage

The raw river water was measured to obtain an average initial nitrate concentration of 2.76 mg/L-N. Due to low nitrate concentrations in the raw water, the raw water was spiked with potassium nitrate (KNO_3) to increase the nitrate concentration. Effective C/N ratios for nitrate removal found from the literature were 1.05,1.08 and 1.1 (Matějů *et al.*, 1992; Gómez *et al.,* 2000; Mutsvangwa & Matope, 2017) and were applied in this research. The inflow nitrate concentrations which were used in this study were 15 mg/L-N, 25 mg/L-N and 50 mg/L-N respectively, at C/N ratios of 1.05, 1.08 and 1.1, respectively. The C/N ratio range was selected on the basis of the optimum carbon-nitrogen ratio defined in the studies by Matějů *et al.*, (1992), Gómez *et al.,* (2000), Habboub, (2007) and Mutsvangwa & Matope, (2017).

The selected range for nitrates was based on values in South Africa, although some areas have experienced high nitrate concentrations above 100 mg/L-NO_3 equivalent to 23 mg/L-N in raw water. It was also with reference to the South African National Standards (SANS 241) and WHO guidelines for drinking water quality of 11 mg/L-N in drinking water. The C/N ratios were also applied to determine the required ethanol dosage to be used as a carbon source. The nitrate dosage calculations for obtaining the targeted nitrate concentrations of 50 mg/L-N are presented in Table 3.3 below while the carbon source dosage calculations for the filter with a source of carbon are as shown in Table 3.4 below. Detailed dosage calculation tables for the nitrate concentration of 15 mg/L-N and 25 mg/L-N are represented in Annexure A.

Potassium nitrate stock solution is described with its molecular mass in this work as follows:
Atomic mass from the periodic table = N-14_g, K- 39_g, O-16_g
Potassium nitrate (KNO_3) molecular weight = (39x1) + (14x1) + (16x3) = 101 g/mol
Nitrate (NO_3) molecular weight = (14x1) + (16x3) = 62 g/mol

Table 3.3 Potassium nitrate dosage calculation for 50 mg/L- N targeted concentration

Item	Potassium nitrate detailed dosage calculations
1	The potassium nitrate molecular equation is given by KNO_3 and therefore has a molecular mass of 101g/mol
2	Fractional composition of nitrate = molecular weight of NO_3 divide by molecular weight of KNO_3 =$62/101 = 0.614\, g/mol$. This means that NO_3 makes 61.3 % in the KNO_3.
3	The targeted nitrate concentration required into the UVRF is dependent on the filter volume. All dosages were performed in the 20 L feed tank.
4	The required mass of potassium nitrate was determined from the equation given: $C_s = \frac{M_{KNO_3} \times x_{NO_3}}{V}$ $\frac{C_s \times V}{x_{NO_3}} = M_{KNO_3}$ Where: C_s= Concentration of a substance (mg/L) M_{KNO_3}= Mass of potassium nitrate (g) x_{NO_3}= Fractional composition of nitrate (g/mol) V= Volume of water (L) $\frac{0.22 \times 20}{0.614} = 7.166\text{g}$
5	The potassium nitrate dosage required is 7.166g

Ethanol as a carbon source is described with its molecular weight in this work as follows:
Atomic mass from the periodic table = C-12_g, H-1_g, O-16_g
Ethanol (C_2H_5OH) molecular weight = (2x12) + (5x1) + (16x1) =46 g/mol

Carbon molecular weight = (2x12) = 24 g/mol

Table 3.4 Ethanol dosage calculation at C/N ratio of 1.1

Item	Ethanol detailed dosage calculations
1	Ethanol molecular equation is given by C_2H_5OH and therefore has a molar mass of 46 g/mol.
2	The Carbon equivalent in the C_2H_5OH equation is 24 g/mol. The amount of carbon in ethanol is therefore 24/46 x 100 % = 52.17 %.
3	The concentration of nitrate to be used in the equation is 50 mg/L and the C/N ratio established from the literature review is 1.1.
4	Nitrate (NO_3^-) and nitrogen (N) ratio 14 + (3x16)/14 = 4.430
5	The C / N ratio is therefore 1.08 which gives 1.1x 4.430 = 4.873 ethanol.
6	The carbon concentration is 50 mg/L x 4.873 = 243.65 mg/L of carbon.
7	Concentration of ethanol is given by 243.65 mg/L divided by the %age of carbon in ethanol = 243.65/0.522 = 466.762 mg/L of ethanol.
8	Required ethanol volume = ethanol concentration / ethanol density = 466.762 mg/L divided by 789 mg/mL = 0.592 ml/L
9	The capacity of the feed tank is 20 L, hence the required dose = 20 L x 0.592 ml/L =11.84 ml of carbon as ethanol.

Biological layer development

The process of denitrification in UVRFs is biological and takes place under a fixed film growth process in which the bacteria develop on the gravel media layer. The biological filter media ripening increases the removal efficiency in roughing filters, because the filter media becomes stickier (Collins *et al.*, 1994). The key significance of biological development is the increase of water purification by the use of chemical microbiological oxidation and predatory activity during the removal of pathogens into inorganic compounds. The organic layer typically requires 20-30 days to mature in a new filter, depending on the inflow water quality condition (Mahlangu, 2011). However, due to operating the filters intermittently in this research, the maturity was evident at 30-35 days. The biofilm's effectiveness depends mainly on carbon as the source of food for microorganism development. A consistent daily regime of at least 20 L of raw river water and the addition of ethanol as a carbon source were continuously pumped into the filter and was the source of food. It also requires a suitable ambient water temperature for biofilm microorganisms to stay alive. The experimental work in this research was performed at room temperatures between 18 °C to 28 °C, and as mentioned, denitrification is optimum at temperatures between 15 °C to 60 °C. The rate of biofilm development in both the filter with and without the use of a carbon source was evaluated through the nitrate concentration in the filtrate and decrease in the outflow rate. It was expected that the filter with limited supply of food substrate for microorganism growth will result in a slower biofilm development and therefore low nitrate removal in the water. Therefore, sampling began from day one before maturation and persisted during the maturation period.

As illustrated by figure 3.23 biofilms are made up of microbial cells that are embedded in an extracellular organic polymer matrix. As suspended microbial cells adhere to a surface, they begin to extend vertically into the bulk raw water by enclosing themselves in an adhesive matrix of extracellular polymeric substances (EPS) generated by the cells. Biofilms are composed of a base film zone that is directly connected to the support and a surface film that extends from the base film into the bulk liquid. The vertical and horizontal voids serve channels through which water can flow (Shoemaker, 2014).

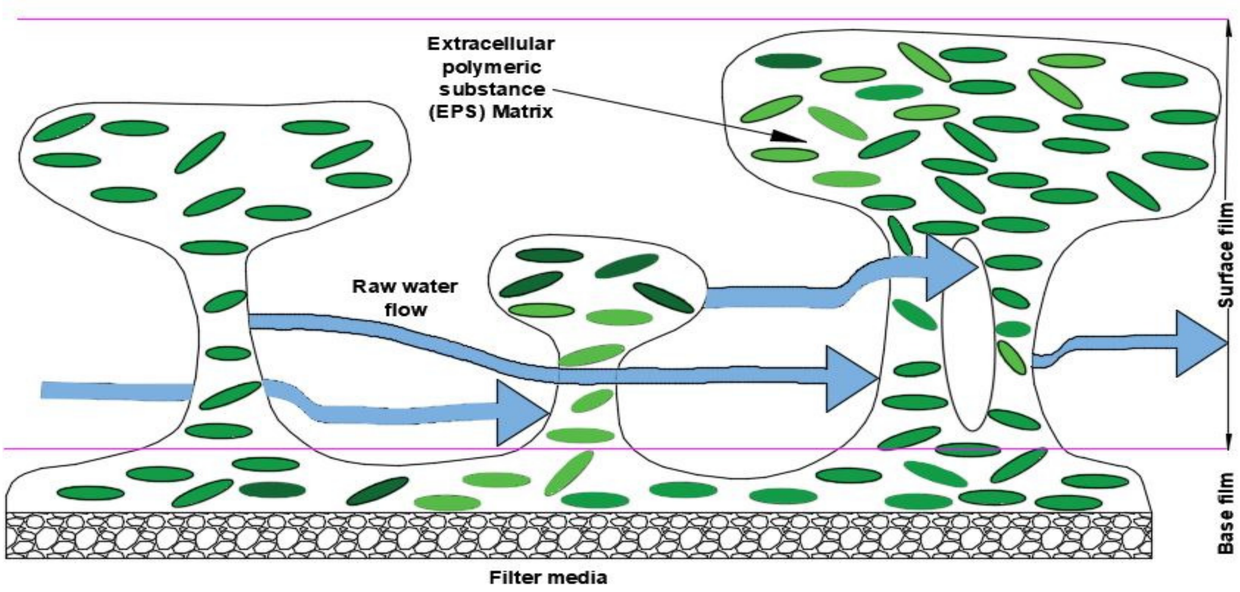


Figure 3.23 Schematic of a biofilm composition and interaction with the flowing raw water (Shoemaker, 2014)

3.3.5 Experimental procedure

During the experiment, the water was constantly and continuously stirred to keep any particle in suspension in the primary feed tank, using a power circulation aquarium pump. Ethanol as an external carbon source was dosed and added to the raw water inside the 20 L feed tank connected to the filter that used a carbon source. In conjunction with the two feed tanks, peristaltic pumps were used to inject and regulate the flow of water through each filter column and maintain the filtration rate within ranges of 0.03 m/h - 0.1 m/h. Furthermore, the filtrate was collected from the third column using a 1 litre graduated cylinder, in order to monitor the volumetric flow rate along the filter. Due to the convenient configuration of the URFs, the filtrate from each media column was also sampled without interfering with the filtration rate. This was achieved by having three monitoring points at different depths along each column, in order to provide a way to determine the effect on effective removal of nitrate with filter depth and length.

3.3.6 Sample collection and analysis

Water samples of 250 ml were collected in a beaker from the sampling points of each of the two constructed roughing filters at laboratory scale. Samples were collected after attaining steady-state flow conditions along each filter column. In both filters, each parameter had one sample replicate obtained from each filter column from the three sampling points. Since the filters were only used intermittently, they were operated for 12 hrs during the day and were non-operational (Shut off) during the night for 12 hrs. The filter system was not continuously operated in order not to overheat the pumps. Meanwhile, long pause periods (>48 hrs) were avoided, as this may kill the biological layer due to nutrient depletion, as recommended by Mahlangu (2011). The samples were taken both while it was operating (during the filter run) and before the filter was run. Each time a new test run was performed, the head of water that was maintained in the columns was flushed out. The sampling frequency was once a week and was increased gradually to a frequency of three, as the filter matured with time. All data analyses were conducted daily in order to evaluate the effectiveness of the filter on nitrate removal with time. Moreover, the first three nitrate and COD sample batches were analysed by an external laboratory, in order to get a comparison of the results that were analysed from the university laboratory. The results comparison to the external laboratories also assisted in verifying the accuracy of the instrument used in the CPUT laboratory, as part of quality control assurance. The samples that were analysed externally were collected in 500 ml sample containers, as shown in Figure 3.24 below. The 76 containers were rinsed with deionised water and left to try before collecting the water samples. Table 3.5 below represents the tested physicochemical water quality parameters, weekly sample frequencies and the duration the roughing filter was operated.

Table 3.5 Sampling frequency of the physicochemical water quality parameters and duration of the filter operation.

Physicochemical water quality parameters	Sample frequency (weekly)	Roughing filter operation (weeks)
Nitrate	1-3	30
Nitrite	1-3	30
pH	1-3	30
COD	1-3	30
DO	1-3	30
Temperature	1-3	30
Turbidity	1-3	30
TSS	1-3	30

Figure 3.24 below depicts the nitrate and COD sample containers used for external laboratory analysis.

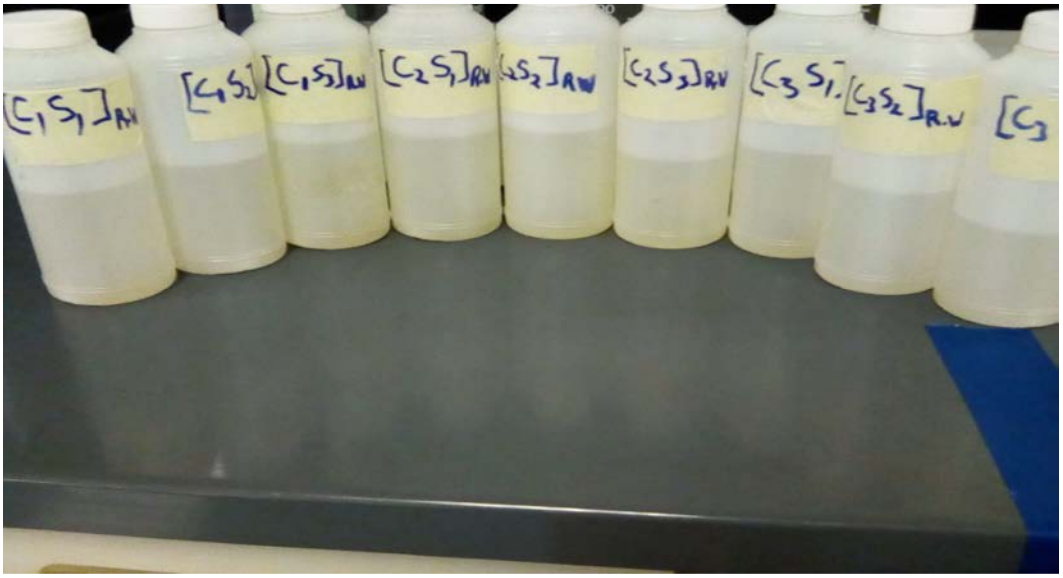


Figure 3.24 Nitrate and COD sample containers for external laboratory analysis.

3.3.7 Validation of results and quality control

Calibration of instrument

The Photometer 7500 model was firstly calibrated using the calibration standards. The calibration was conducted once a month to check standard values and standard measurements.

a. Standard value check

Each standard has two values assigned for two individual wavelengths. The order defined on the photometer display was followed, to adjust the values to match the given standard certificate values.

b. Standard measurement check

The check standards were inserted in the photometer in a defined order following the guides displayed on the screen. The results were displayed on the screen with a pass upon the completion of the sequence. However, for results with a failure display, the check was repeated. Figure 3.25 shows the check standards that were used to calibrate the Photometer 7500.

Figure 3.25 Photometer calibration check standards

Quality control

A standard solution of known concentration was measured after calibration to verify the accuracy of the instrument. Thereafter, 7 tests to establish the error were performed on the standard solution. The standard error (STD_E) was established by first calculating the variance (S^2) and standard deviation (S) of the replicate measurements, as follows:

Measure of standard deviation: A measure of the degree of agreement or precision among replicate analyses of a sample (Mutsvangwa, 2010). The standard deviation was calculated from Equations 3.6 - 3.9, as shown:

$$\bar{x} = \frac{x_1 \times x_2 + \ldots. + x_{n-1} + x_n}{n} \tag{3.6}$$

Where:

$\bar{x}$= Arithmetic mean

x_i= Observations

n= Number of observations/samples

$$s = \sqrt{\frac{(x_1-\bar{x})^2+(x_2-\bar{x})^2+\ldots.+(x_n-\bar{x})^2}{n-1}} \tag{3.7}$$

$$s = \sqrt{\frac{\sum(x_i-\bar{x})^2}{n-1}} \tag{3.8}$$

Where:

s= Standard deviation

Measure of variance: The square of the standard deviation (Mutsvangwa, 2010). The variance was calculated using Equation 3.9 as shown:

$$Var\ (X) = s^2 = \frac{\sum(x_i-\bar{x})^2}{n-1} \tag{3.9}$$

Where:

$Var(X)$= Variance

Measure of Coefficient of variation: It measured the variability of the sample results thus eliminating the unit of measurement from standard variation by dividing by the mean of the acquired sample results. The coefficient of variation was calculated using Equation 3.10.

$$CV = \frac{S}{\bar{x}} \tag{3.10}$$

Where:

CV = Coefficient of variation

Measure of the standard error: The standard error was calculated using Equation 3.11, as shown:

$$STD_E = \pm \frac{S}{\sqrt{n}} \tag{3.11}$$

Where:

STD_E= Standard error

Figure 3.26 below shows the standard solutions of known concentration for nitrite, nitrate, pH, turbidity, and COD respectively, that were used in the laboratory to verify the accuracy of each instrument.

Figure 3.26 Standard solutions of known concentration for instrument verification

Testing of samples

The raw water samples were tested after instrument calibration, instrument verification and error calculation. The instrument was verified with the standard solution, following each data set test on the raw water. In cases where the result was not within the error range, the previous tests were rejected, and the calibration and verification were performed again. The instrument error range check for pH measured using a Eutech cyberscan pH meter 300 fitted with a temperature test, DO measure using a cyberscan dissolved oxygen meter (Eutech DO 600**)** with a testing probe and turbidity measured using a Eutech turbidity meter TN-100 were conducted after four test runs. Four measurements were also replicated, and the average was determined. Any outliers were not considered in the calculations.

3.3.8 Analysis and presentation of data

The previously mentioned filter design parameters in both the vertical roughing filter with and without a carbon source, were analysed on their effectiveness in removing nitrate by testing the filtrate quality against the total filter length at a specified time. The %age efficiency removal was calculated from the inflow and outflow results, and further presented in a bar chart in both filters. Also, each physicochemical parameter was monitored and measured before, during and after the filtration process to find each parameter's effect on the nitrate rate of removal. Each measurement was tabulated and the variation in nitrate concentration during the process for each parameter was graphically presented. To find the quality of the filtrate on residual carbon, the results obtained from the COD test were used to quantify the quality of the filtrate on residual carbon. Flow rate variations in both filters with and without a carbon source were recorded daily, in order to monitor them as the biofilm (active biomass) growth took place in the filter. These results were further applied in a model development for nitrate removal in a vertical roughing filter, using an organic source of carbon. As mentioned earlier in Section 3.3.3.4, several nitrate removal kinetics are used to predict the efficiency of nitrate removal in water. In this study, nitrate removal kinetics were investigated to establish the appropriate approach to apply in the model development. Furthermore, the filtrate was compared with the South African Water Quality guidelines for domestic use, South African National Standards (SANS 241) and WHO guidelines for drinking water quality. Again, the results obtained from this research were evaluated by making comparisons with results obtained by other researchers on the use of roughing filters and other technologies for removing nitrate in raw water for potable use.

3.4 Conclusions

The facility, equipment and materials and appropriate methodology for this study were introduced and discussed in this chapter. A bench-scale model to verify the implementation of a vertical roughing filter as a suitable technology to remove nitrate from raw water were described. The methods used to produce and process the data in order to obtain physicochemical parameter results have been discussed. The literature was used for the analysis of design parameters for the upward vertical roughing filter construction. The methods used for analysis of the results and the suitable methods applied to establish the relevant predictive nitrate removal model were discussed. The conceptual illustration of the biological treatment process that takes place in the roughing filter with a carbon source was also presented and discussed.

Chapter 4 Results

4.1 Introduction

This chapter presents the results and analysis in detail. The study's aim was to investigate nitrate removal in raw water for potable use, using a vertical roughing filter with an external organic carbon supply. The raw water and the filtrate were examined using the physiochemical parameters given in Table 3.5. The results of all tests included the initial and final concentrations of the measured parameters, the flow rate measurements, the removal efficiency of the filters on each measured parameter, and the validation of the data. Again, sieve analysis and permeability tests were performed on the gravel material used as a filter medium to determine particle size distribution and the permeability coefficient used in the development of the removal model. The removal model was created using model parameters such as filter flow rate, inflow and outflow nitrate concentration, filter depth, and filter volume.

4.2 Kuils River Raw Water Quality

This section presents the findings of Kuils River raw water laboratory analysis. The findings indicate the quality of the initial raw water before filtration. The water parameters examined were pH, turbidity, dissolved oxygen, temperature, chemical oxygen demand (COD), total suspended solids (TSS), nitrate, and nitrate concentrations. Table 4.1 below shows the results while Annexure B provides detailed tables of raw water quality data.

Table 4.1 Kuils River average raw water quality results

Physicochemical water quality parameters	Total number of samples	Initial raw water average concentration for a 15 mg/L-N batch	Initial raw water average concentration for a 25 mg/L-N batch	Initial raw water average concentration for a 50 mg/L-N batch	Total average concentration of raw water
Nitrate (mg/LNO_3)	20	10.52	12.61	13.32	12.15
Nitrite (mg/L-NO_2)	20	0.09	0.05	0.11	0.08
pH	20	7.16	6.95	7.06	7.06
COD (mg/L-O_2)	20	87.3	147.77	786.55	340.54
DO (mg/L)	20	6.1	6.33	5.94	6.12
Temperature (̊C)	20	23.29	22.38	24.85	23.51
Turbidity (NTU)	20	377.1	286.37	505.75	389.74
TSS (mg/L)	20	26.95	33.74	22.88	27.86

4.3 Sieve Analysis

This section presents the findings of a sieve analysis test on three aggregate media sample sizes of 1000g each. Annexure C provides raw data on detailed particle distribution tables for the filter media. To determine whether each medium is represented by the required particle size, a gradation curve was plotted as shown in Figure 4.1 below. The plot is derived from the particle distribution represented by Table 4.2. Detailed particle distribution plots for each filter media are attached in Annexure C.

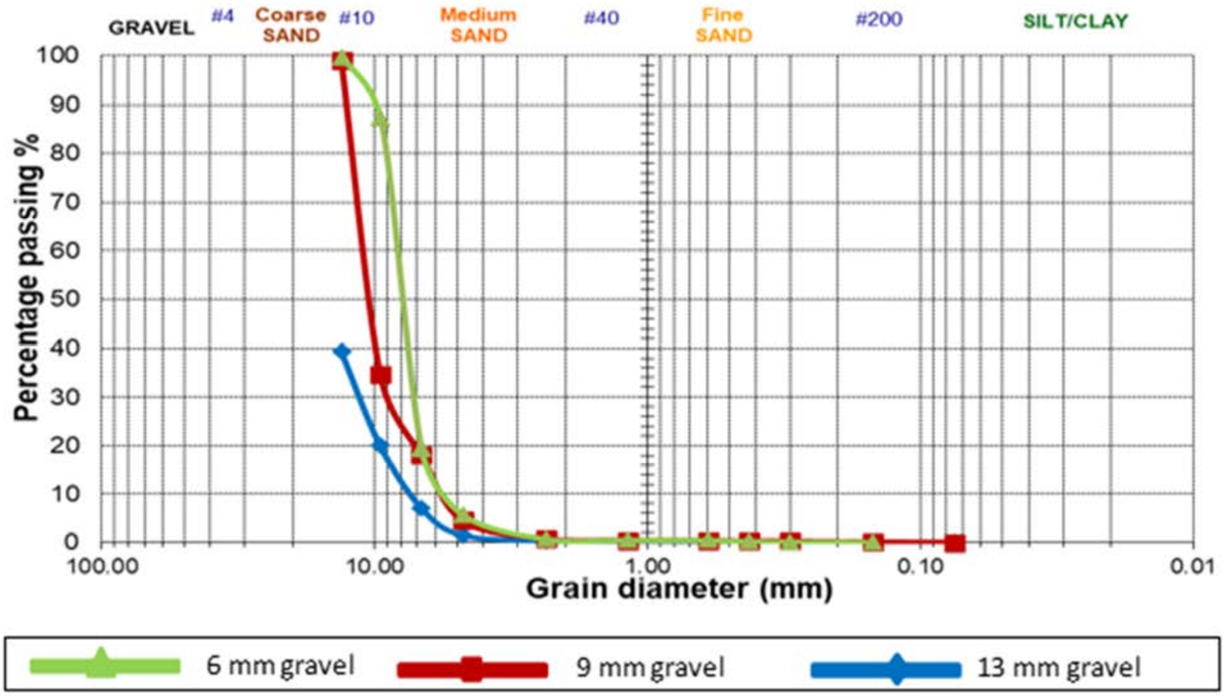


Figure 4.1 Particle size distribution curve for granite gravel used as filter media.

The logarithm plot in Figure 4.1 above was used to compute the uniformity coefficient (C_u) and coefficient of curvature (C_c), which are computed from extrapolating 10, 30 and 60 % of the material that passed through the corresponding sieve (Isik & Cabalar, 2018). The results that conform to the 10, 30 and 60 % material passing are shown in Table 4.3, while Figure 4.2 depicts the various gravel grain sizes after sieving.

Coefficient of curvature (C_c)

The coefficient of curvature is the parameter that evaluates the variation in the soil particle size (Das & Sivakugan, 2016). The coefficient is evaluated using Equation 4.1, as shown.

$$C_c = \frac{D_{30}^2}{D_{10} \times D_{60}} \qquad (4.1)$$

Coefficient of uniformity

The coefficient of uniformity evaluates the consistency in the particle size. A C_u of 1 indicates that all the grain size are the same (poorly graded) while a $C_u > 1$ indicates grain sizes that span within a large range (uniformly graded) (Das & Sivakugan, 2016). A well graded material therefore should meet a criterion: $Cu > 1 < Cc < 3$. This parameter is evaluated using Equation 4.2.

$$C_u = \frac{D_{60}}{D_{10}} \qquad (4.2)$$

Table 4.2 Filter media parameter classification

Sample media size	D10 (mm)	D30 (mm)	D60 (mm)	Cc	Cu	Material gradation
13 mm gravel	7.339	10.489	0	0	0	poorly graded
9 mm gravel	5.548	8.730	10.975	1.252	1.978	well graded
6 mm gravel	5.359	7.163	8.39	1.141	1.566	well graded

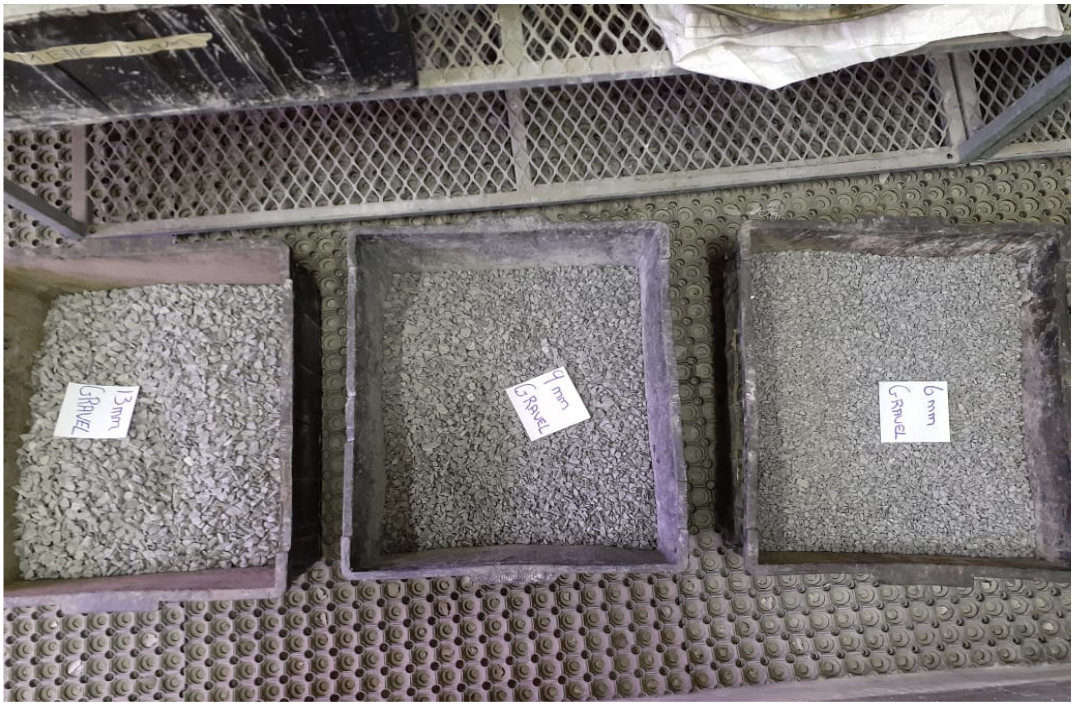


Figure 4.2 The 13 mm, 9 mm, and 6 mm filter media aggregates after sieving

4.4 Permeability Test

A permeability test was performed to estimate the permeability coefficient of the granite gravel filter medium. The permeability test results for each medium size are presented in Table 4.3 below. Zhan *et al*. (2022) also found that the permeability coefficient of gravelly soils is mostly less than 10^{-5} cm/sec. Annexure D contains sample calculations for the permeability coefficient of the filter medium.

Table 4.3 Permeability test results for 13 mm, 9 mm, and 6 mm granite gravel media size

Filter media size (mm)	Cross section area of specimen (cm^2)	Length of specimen (cm)	Duration of water collection discharge (sec)	Water discharge (cm^3)	Pressure head of water (cm)	Coefficient of permeability (cm/sec)	Coefficient of permeability (m/day)
13	95.033	7	60	793.9	6.5	0.149	128.736
	95.033	7	120	1697.9	16.4	0.064	55.296
	95.033	7	240	3961.2	13	0.094	81.216
	95.033	7	360	6812.8	9.4	0.148	127.872
Average						**0.114**	**98.280**
9	95.033	7	60	1307.6	9	0.178	153.792
	95.033	7	120	2203.1	10	0.135	116.64
	95.033	7	240	4444.8	10	0.136	117.504
	95.033	7	360	6145.3	11	0.114	98.496
Average						**0.141**	**121.608**
6	95.033	7	60	812.9	17.5	0.082	70.848
	95.033	7	120	1512.7	11	0.112	96.768
	95.033	7	240	3037.4	12	0.112	96.768
	95.033	7	360	5054.2	7.5	0.199	171.936
Average						**0.126**	**109.080**

4.5 Roughing Filter Flow Rate

The initial flow rate in the vertical roughing filter without a Carbon source (VRF$_{wo}$) was 0.133 l/m and reduced to 0.113 l/m, resulting in a 15% flow rate drop at the end of the filter operation. In the vertical roughing filter with a carbon source (VRF$_{wt}$), the flow rate dropped by 27% from 0.133 L/m to 0.096 l/m. Figure 4.3 represents the daily decrease in flow rate in the filter, with and without a carbon supply throughout the course of the test period. Annexure E provides a table of the daily observed filter flow rates in the filter with and without a carbon supply.

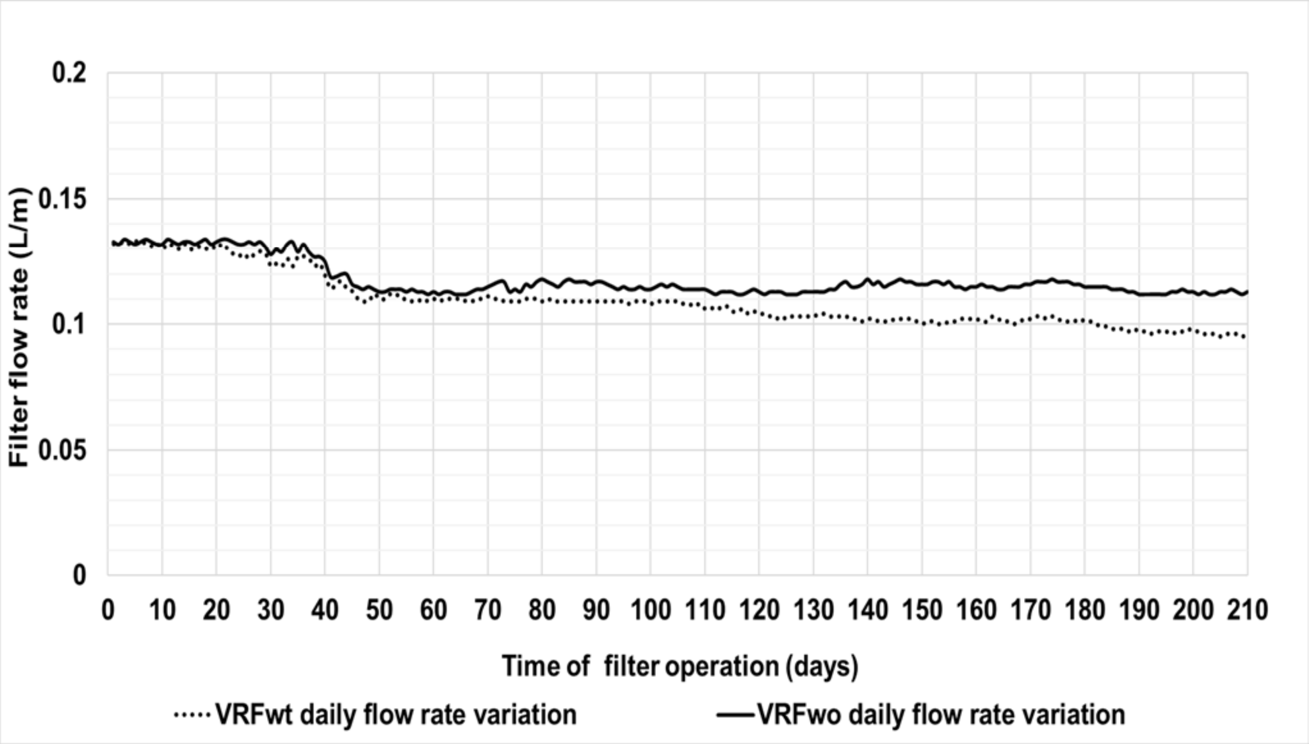


Figure 4.3 Daily flow rate variation in the filter with and without a carbon source

4.6 Potential of Hydrogen (pH)

This section presents the pH findings from raw water and filtrate testing in both the filter with and without a carbon source during the sampling period. Annexure F provides detailed tables on the daily pH variation with depth in the filter with and without a carbon supply.

4.6.1 pH at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N

Figure 4.4 below represents the roughing filter results with and without a carbon source. The pH in both filters fluctuated during the filter operation, with a total initial raw water average pH of 7.16. The filter with a carbon source resulted in a 5% pH reduction at 270 mm depth and a 6% decrease at 750 mm and 1000 mm depths. The total average pH dropped by 5%, and the average pH with depth ranged between 6.5 and 7.2. The average pH with depth in the filter without a carbon supply ranged between 6.8-7.5. At depths of 270 mm, 750 mm, and 1000 mm, the pH increased by 4%. Overall, pH increased by an average of 4%.

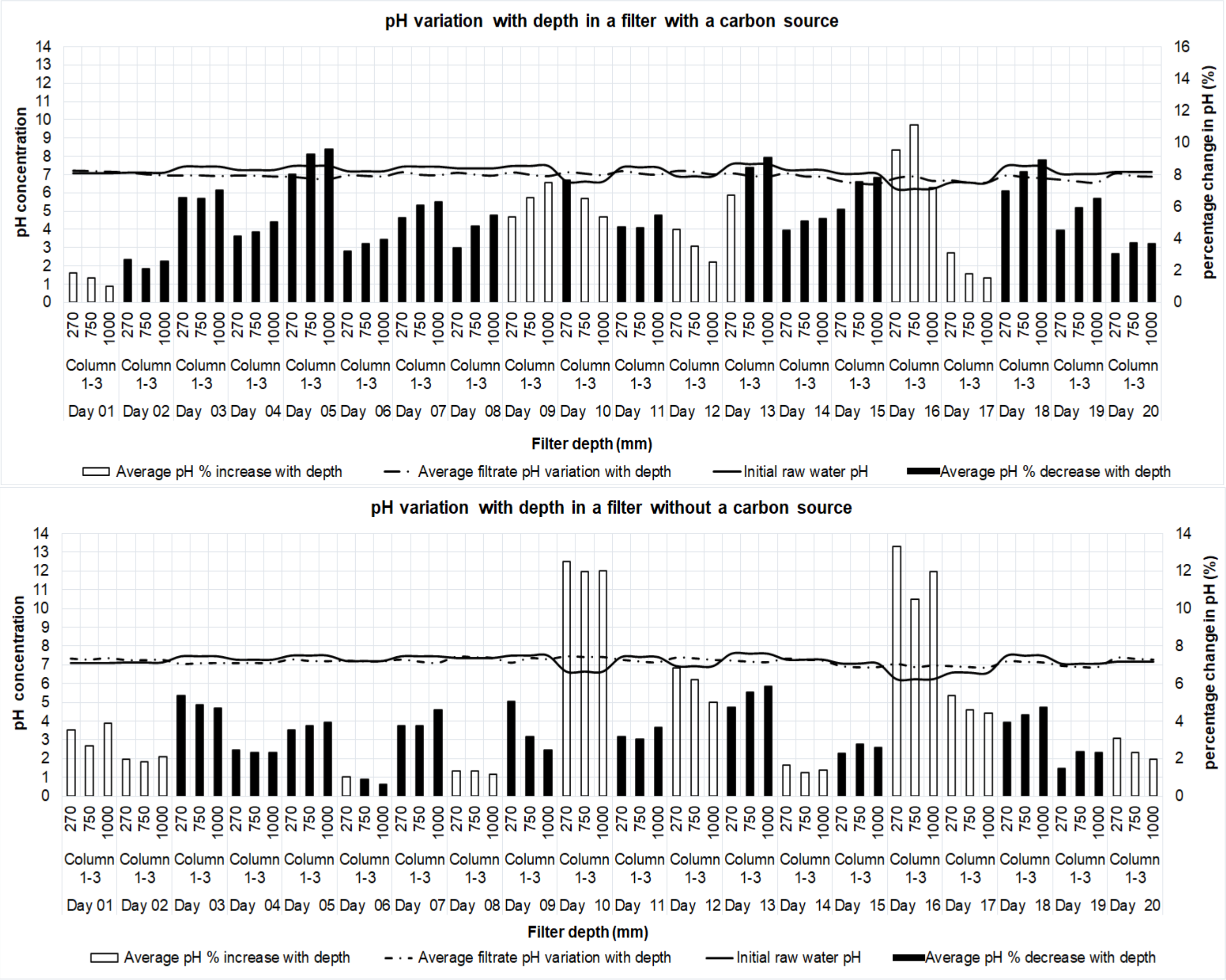


Figure 4.4 Overall average pH variation in a filter with and without a source of carbon at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

Figure 4.5 below shows the pH results recorded from the filtrate in both the filter with and without a carbon source, during the filter flush and filter run. The raw water pH ranged between 6.2 and 7.5 and had an average pH of 7.16. The filter with a carbon source resulted in a 5% pH decrease during the filter run and a 15% reduction before the filter run, whereas the filter without a carbon source resulted in a 4% pH rise during the filter run and a 7% drop in pH before the filter run.

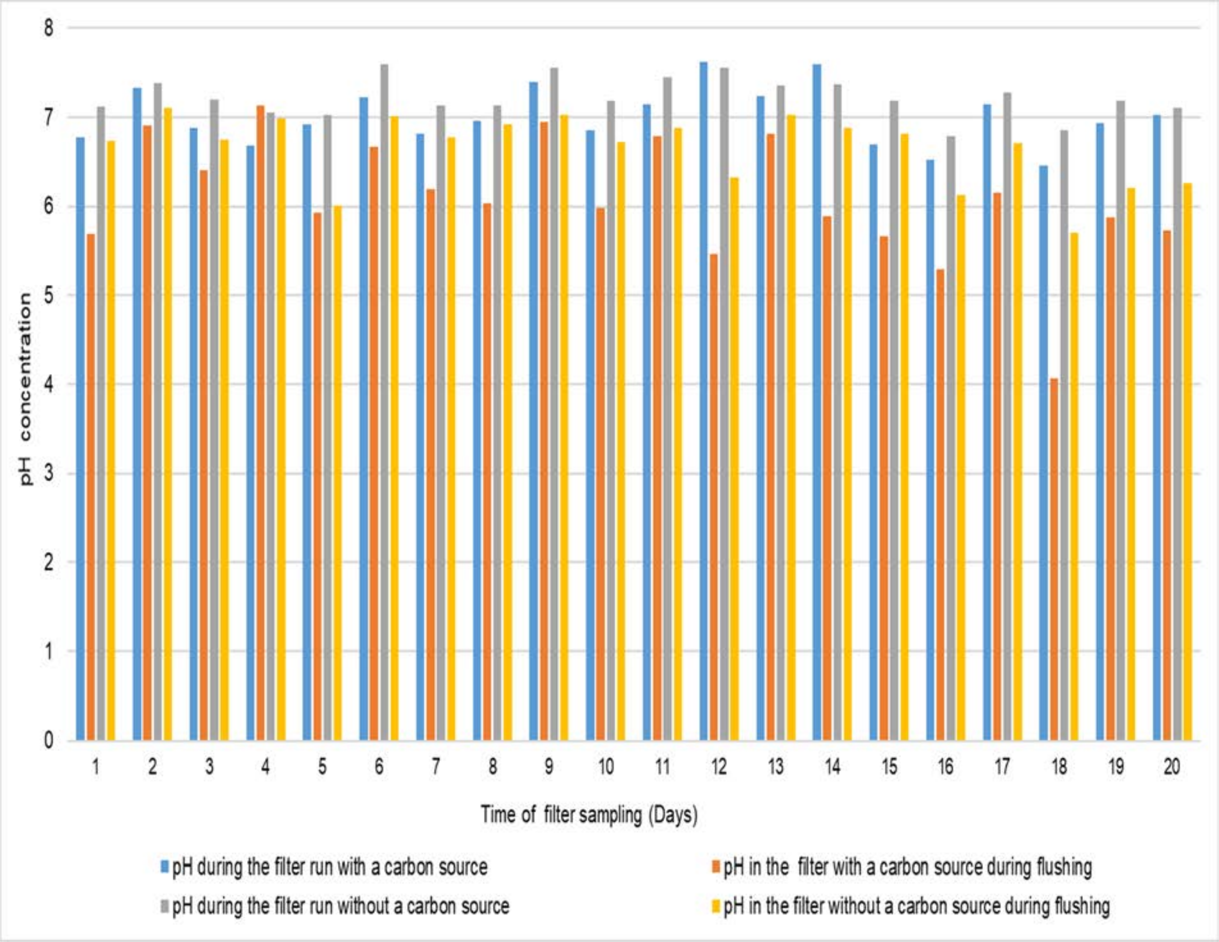


Figure 4.5 pH during and before the filter run in the filter with and without a carbon source.

4.6.2 pH at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

The pH results from the roughing filter with and without a carbon source are shown in Figure 4.6 below. There was a pH variation in both filters during the filter operation, with an initial average pH of raw water as 6.95. The filter which employed a carbon source resulted in a 4% pH drop at 270 mm and 750 mm depths and a 5% pH decline at a 1000 mm depth. The average overall pH declined by 5%, and the pH at varied depths ranged from 6.3 to 7.5. The average pH at various depths in the filter without a carbon supply was within the range of 6.7 to 7.8. The filter resulted in a 5% pH drop at a depth of 270 mm and a 6% decrease at depths of 750 mm and 1000 mm. In all, the pH was down by an average of 5%.

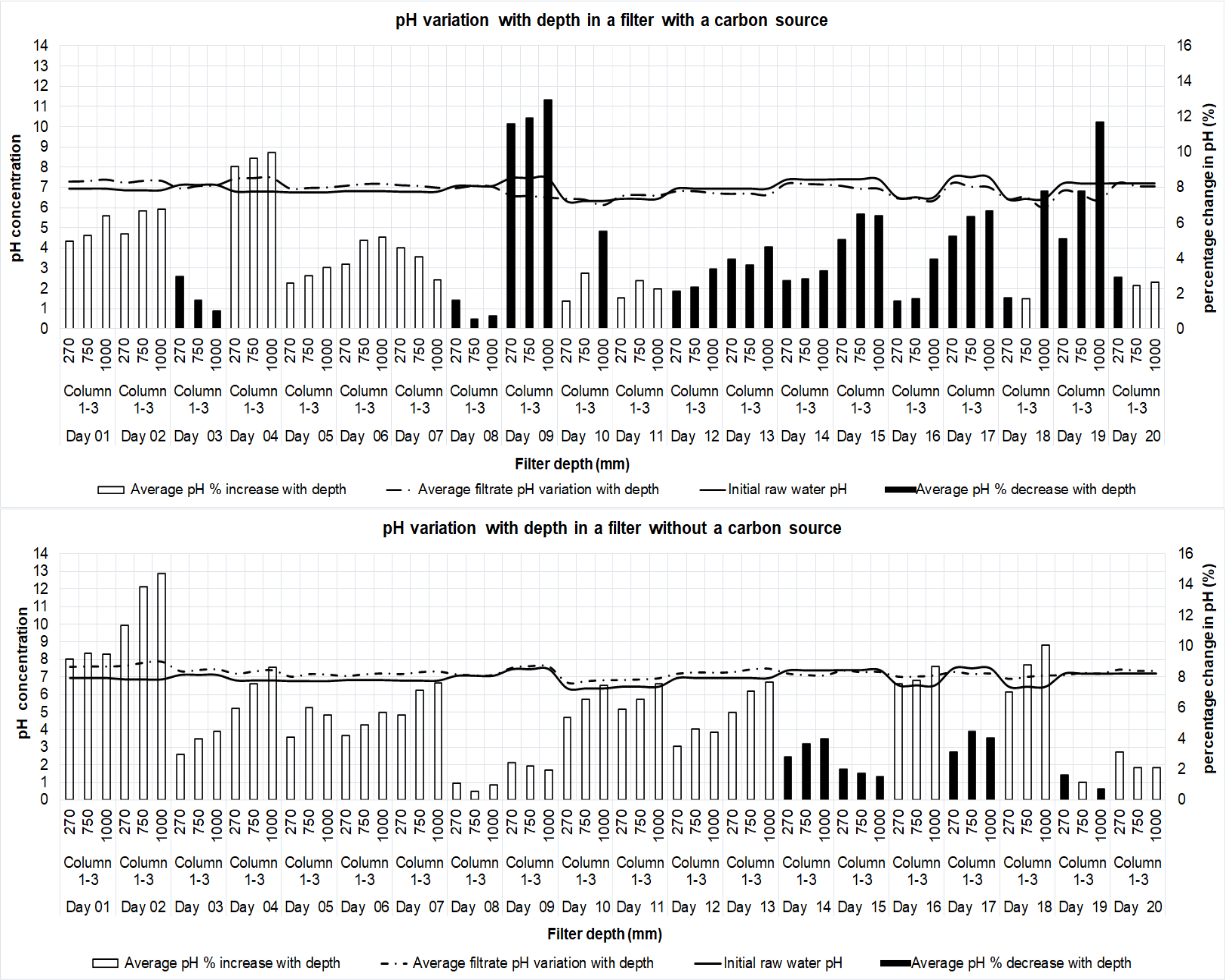


Figure 4.6 Overall average pH variation in a filter with and without a source of carbon at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

Figure 4.7 below shows the pH of the filtrate before and after running the filters with and without a carbon source. The pH of raw river water ranged from 6.4 to 7.5, with an average of 6.95. The filter with a carbon source resulted in a 5% pH decrease during the filter run and a 19% reduction before the filter run, whereas the filter without a carbon source resulted in a 6% pH rise during the filter run and a 10% reduction before the filter was run.

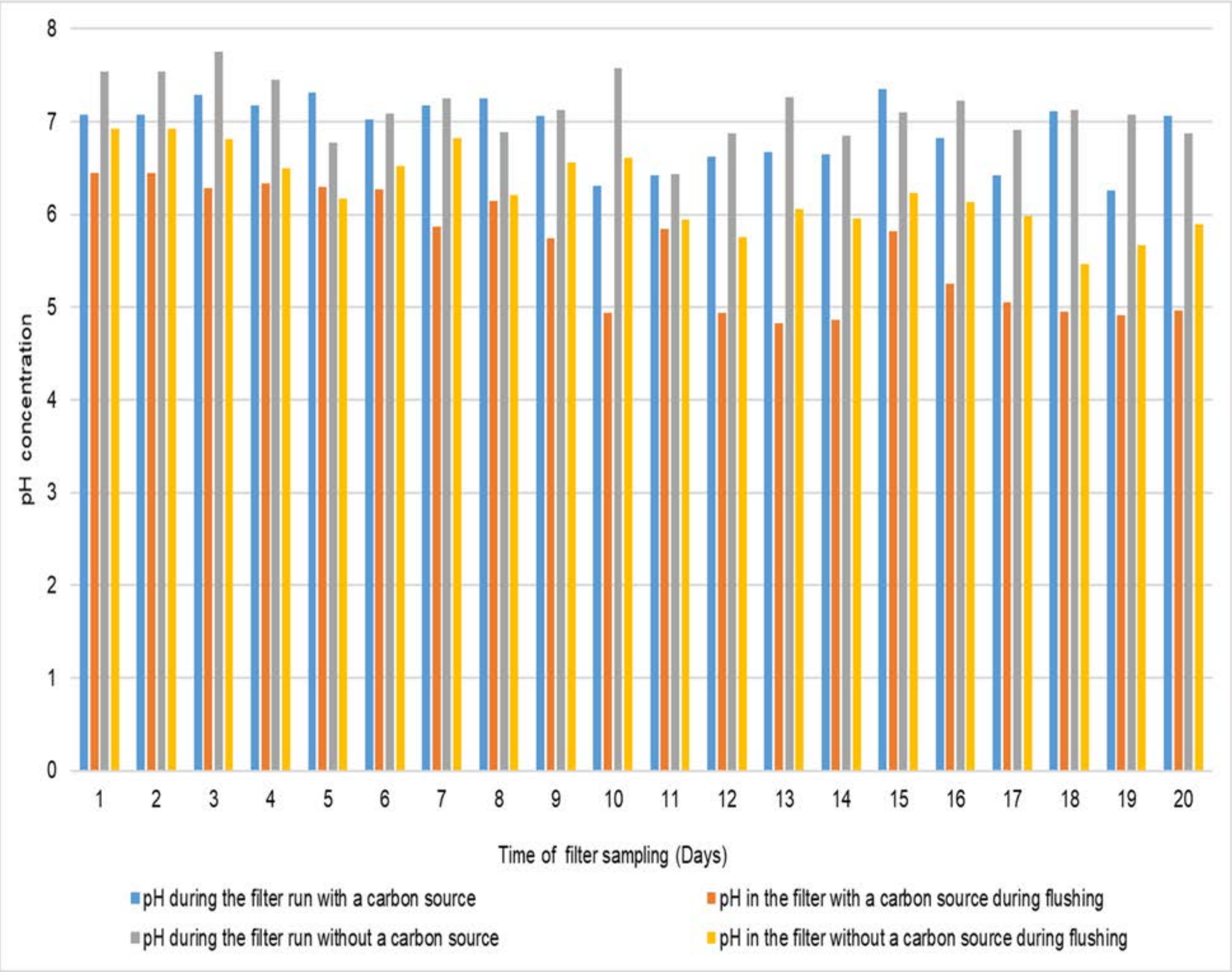


Figure 4.7 pH during and before the filter run in the filter with and without a Carbon source.

4.6.3 pH at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figure 4.8 below shows the pH results from the filter with and without a carbon source. The pH varied in both filters throughout the filter operation, and the total initial raw water average pH was 7.06. The filter with a carbon source resulted in a 4% pH rise at depths of 270 mm and 1000 mm, and a 5% drop at depths of 750 mm.

The total average pH dropped by 4%, and the average pH with depth varied within the range of 7.0 and 7.7. The average pH depth in the filter without a carbon source was within the range of 7.05 - 7.55. The filter resulted in an average 4% pH rise at all levels, with the average pH depth varying within the range of 6.5 and 7.2.

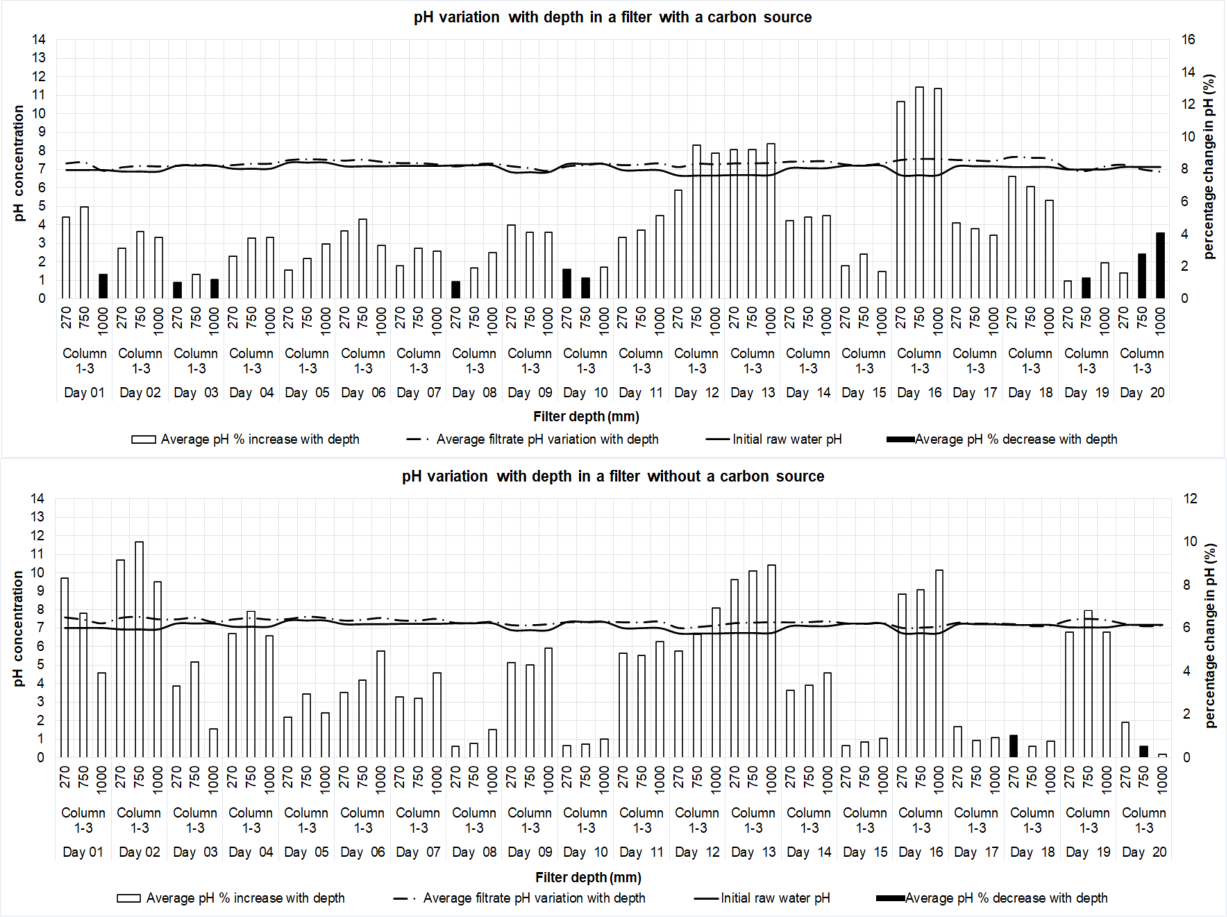


Figure 4.8 Overall average pH variation in a filter with and without a source of Carbon at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

Figure 4.9 below shows the pH of the filtrate before and after running the filters with and without a carbon source. The pH of raw river water ranged from 6.7 to 7.4, with an average of 7.06. The filter with a carbon source resulted in a 5% pH rise during the filter run and a 20% decrease before the filter run, whereas the filter without a carbon source resulted in a 4% pH increase during the filter run and a 9% reduction before the filter was run.

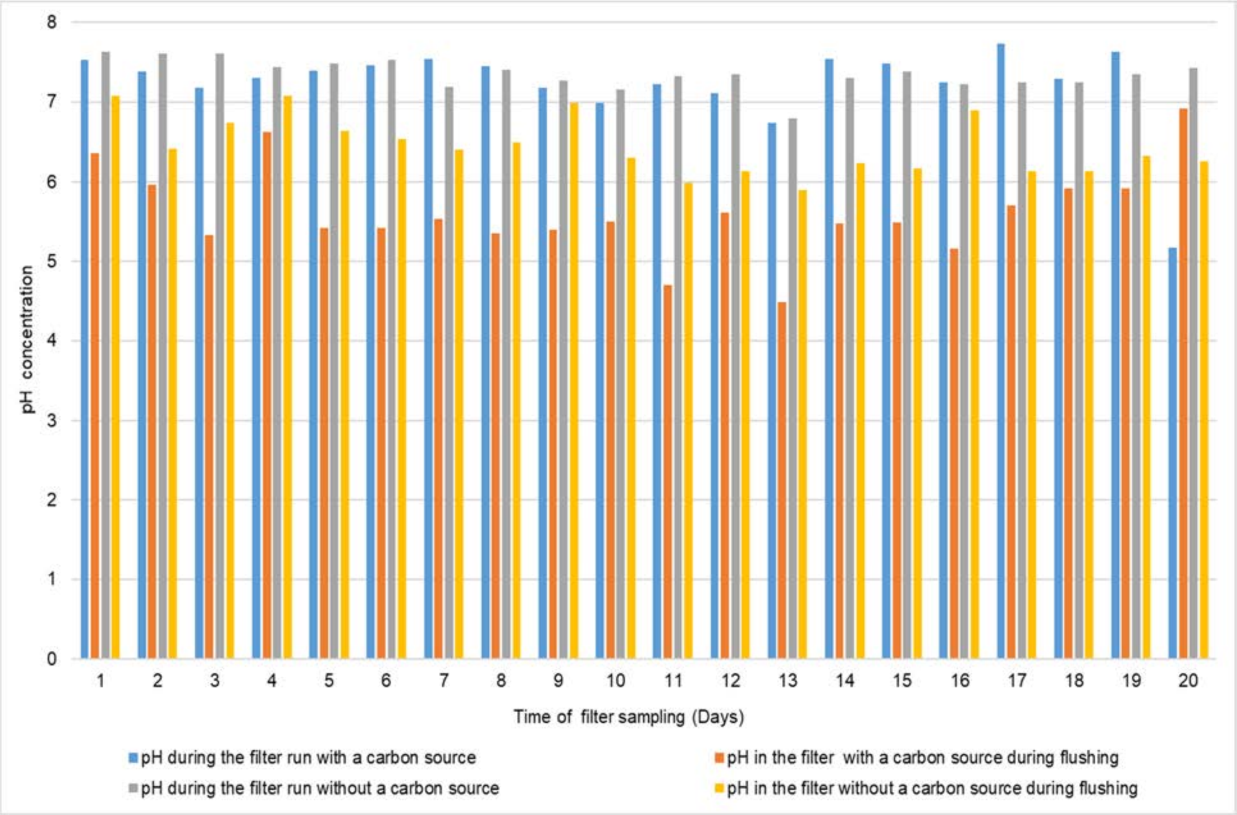


Figure 4.9 pH during and before the filter run in the filter with and without a carbon source.

4.7 Temperature

Temperature influences the growth rate of denitrifying organisms, with higher growth rates at higher temperature. This section presents the temperature data acquired from raw water and filtrate tests in the filter with and without a carbon source during the sampling period. Annexure G provides detailed tables on the daily temperature change with depth in the filter with and without a carbon supply.

4.7.1 Temperature at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N

The temperature results from the roughing filter with and without a carbon source are presented in Figure 4.10 below. The filters were both run at room temperature, hence there was no temperature control, and the average temperature of the initial raw water was 23.29℃. The average temperature change with depth in both filters was within the range of 23℃ and 25℃. At all three sampling depths, an average 3% rise in temperature was recorded in the filter with a carbon source. In general, a 3% average temperature rise was observed. In the filter without a carbon source, an average 3% rise in temperature was recorded at depths of 1000 mm, while average temperature increases of 4% were measured at depths of 250 mm and 750 mm, respectively. Also, an overall 3% average temperature rise was observed.

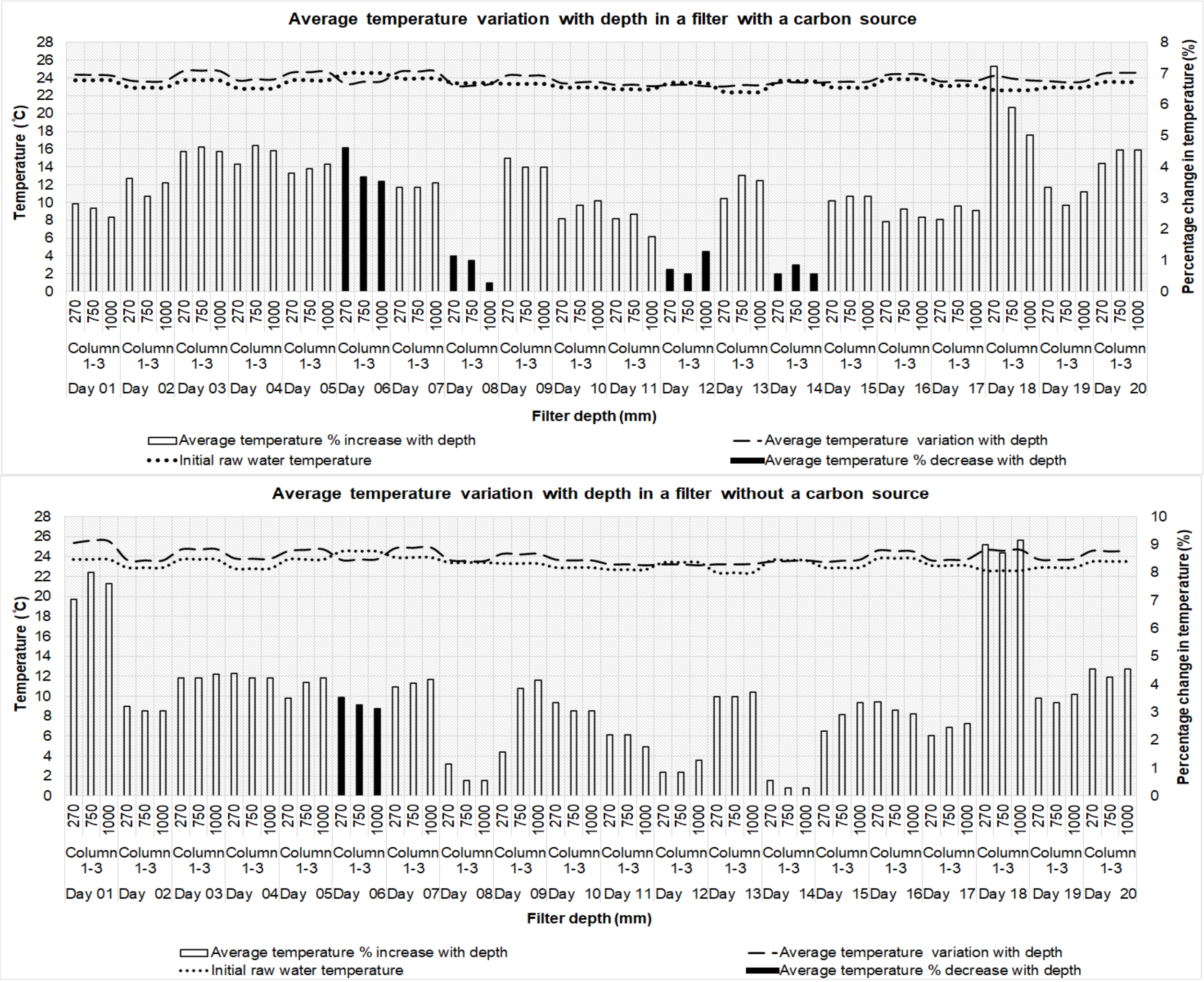


Figure 4.10 Overall average temperature variation in a filter with and without a source of carbon at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

4.7.2 Temperature at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Figure 4.11 below shows the temperature results from the roughing filter with and without a carbon supply. The filters were both run at ambient temperature. The average temperature of the initial raw water was 22.38℃. In both filters, the average temperature variation with depth was within the range of 19℃ and 26℃. At all three sampling depths, an average 6% rise in temperature was recorded in the filter with a carbon source. Overall, there was a 6% rise in average temperature.

In the filter without a carbon source, an average temperature rise of 6% was recorded at depths of 1000mm and 750 mm, respectively, with an average temperature increase of 5% at depths of 250 mm and 750 mm. The average temperature increased by 5%.

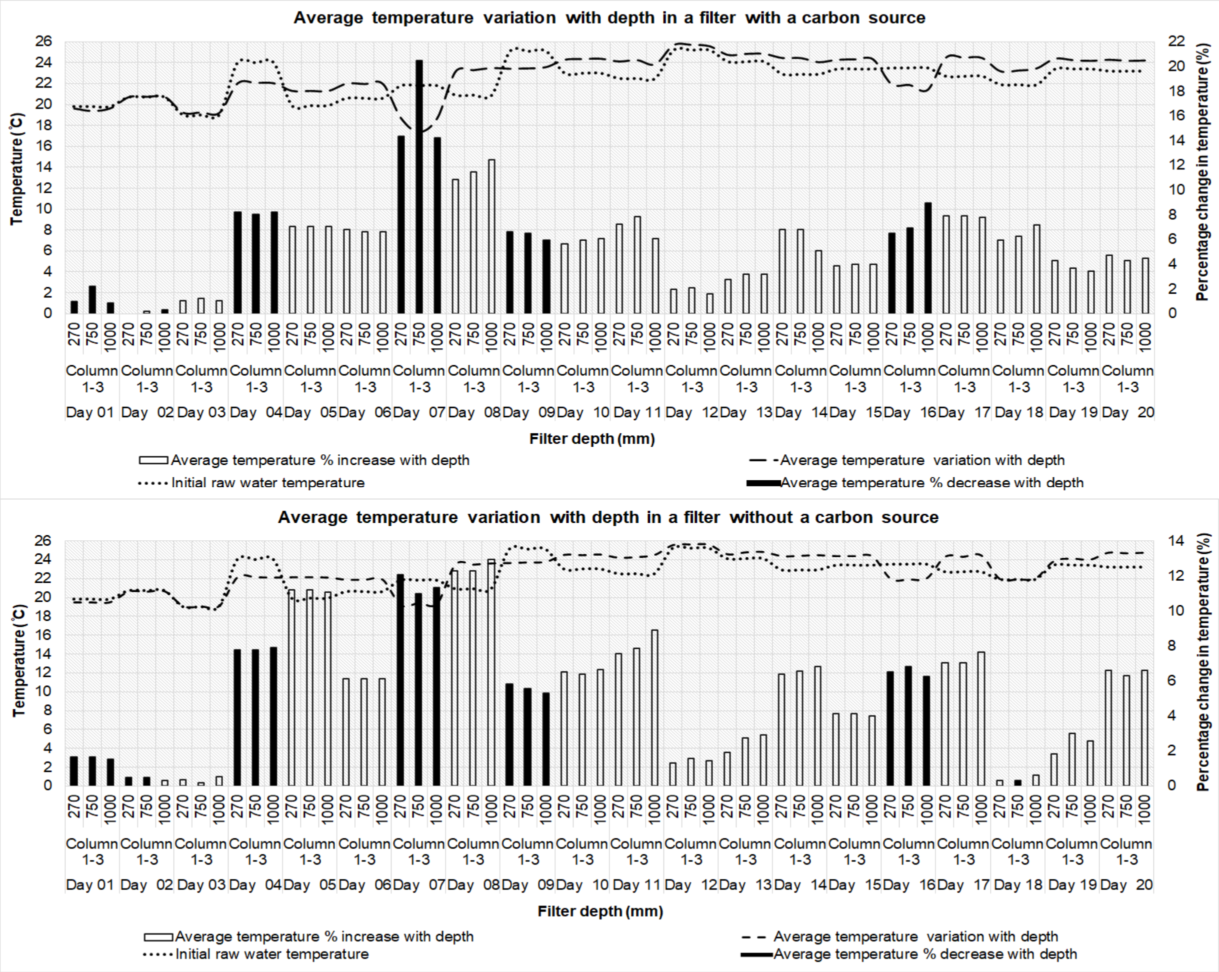


Figure 4.11 Overall average temperature variation in a filter with and without a source of carbon at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

4.7.3 Temperature at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figure 4.12 below shows the temperature results from the roughing filter with and without a carbon supply. Both filters were run at ambient temperature. The average temperature of the initial raw water was 24.85℃. In both filters, the average temperature difference with depth was between 23℃ and 28℃. At all three sampling depths, an average 3% rise in temperature was recorded in the filter with a carbon source. In the filter without a carbon source, an average 2% rise in temperature was recorded at depths of 1000 mm, while an average 3% increase was noted at depths of 250 mm and 750 mm. Overall, the average temperature increased by 3%.

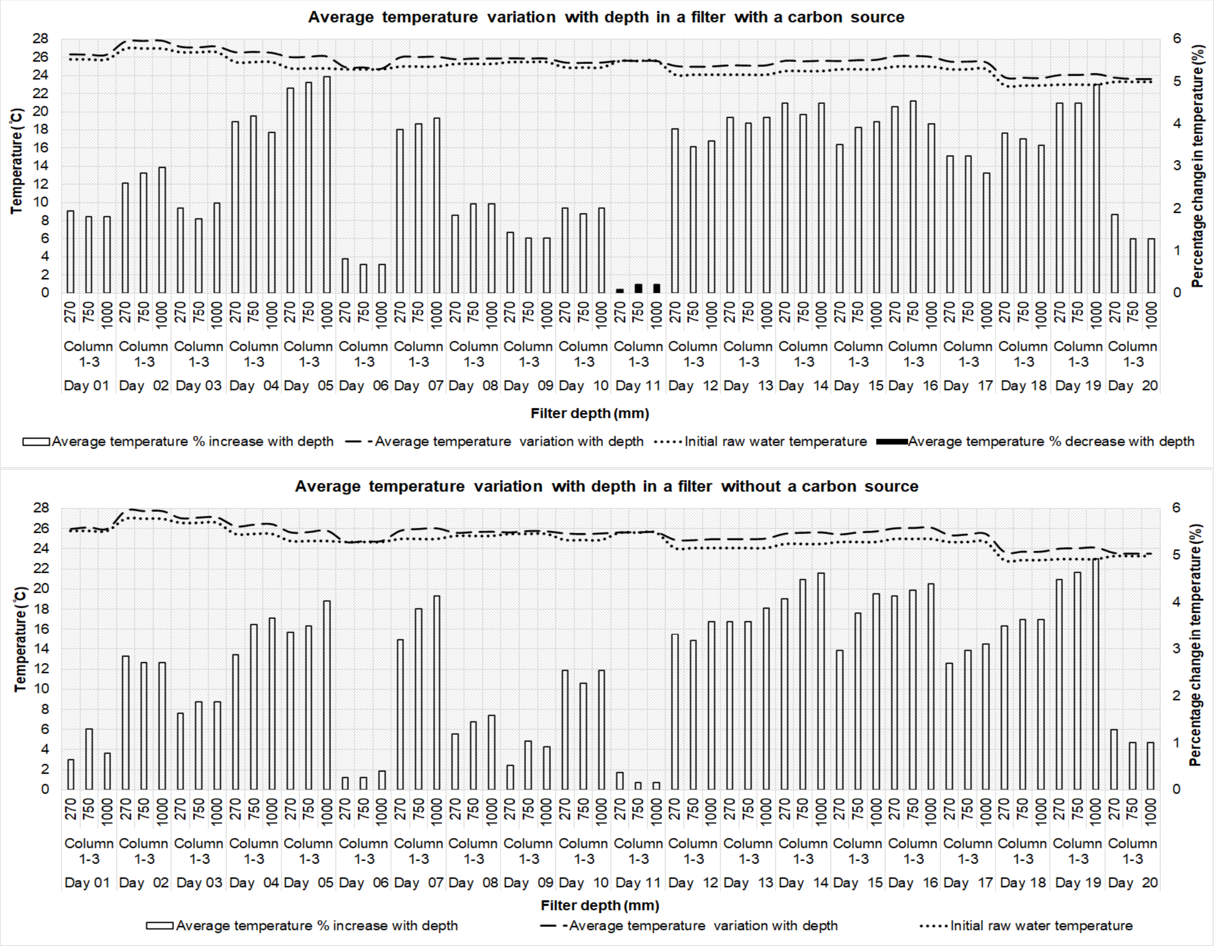


Figure 4.12 Overall average temperature variation in a filter with and without a source of carbon at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

4.8 Dissolved Oxygen (DO)

Many variables, including temperature, salinity, organic content, and air pressure, can impact on dissolved oxygen concentration. However, only the temperature was measured in this study. This section presents the dissolved oxygen findings from raw water and filtrate testing in both the filter with and without a carbon source during the sampling period. Annexure H includes detailed tables and graphical representation of the daily DO variations with depth in the filter with and without a carbon supply.

4.8.1 Dissolved oxygen at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N

Figure 4.13 below shows dissolved oxygen fluctuations in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply. The initial raw river water had an average DO concentration of 6.1 mg/L in both filters. The average filtrate DO concentration with depth ranged from 2.3 mg/L to 4.3 mg/L in the VRF_{wt}. A 47% average drop in DO was mostly recorded at a depth of 270 mm, while average DO decreases of 43% and 35% were observed at depths of 750 mm and 1000 mm, respectively. In general, DO dropped by 42% in the filter with a carbon source. In the VRF_{wo} an average filtrate DO concentration with depth ranged within 4.7 mg/L to 6.4 mg/L. A 20% average drop in DO was mostly observed at a depth of 270 mm, while average DO decreases of 19% and 12% were detected at depths of 750 mm and 1000 mm, respectively. In general, a 17% drop in DO was recorded in the filters without a carbon source.

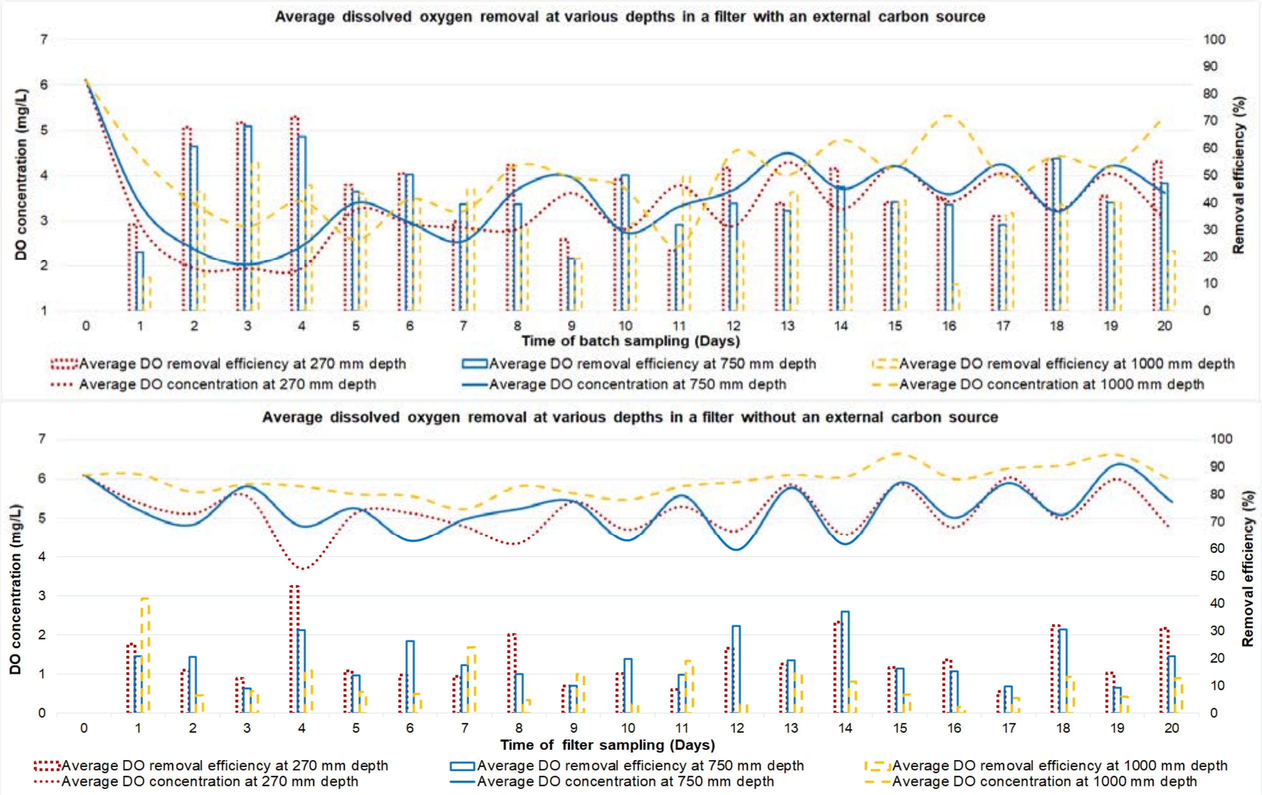


Figure 4.13 Average DO removal at varied depth in the filter with and without a carbon source at C/N ratio of 1.05 and inflow DO concentration of 6.1 mg/L.

Figure 4.14 below represents the DO found in the filtrate during and before running the filters with and without a carbon source. The DO of raw river water ranged from 4.2 mg/L to 7.4 mg/L, with an average of 6.1 mg/L. The filter with a carbon source reduced DO by 45% during the filter run and by 63% before the filter run, whereas the filter without a carbon source reduced DO by 17% during the filter run and by 33% before the filter run.

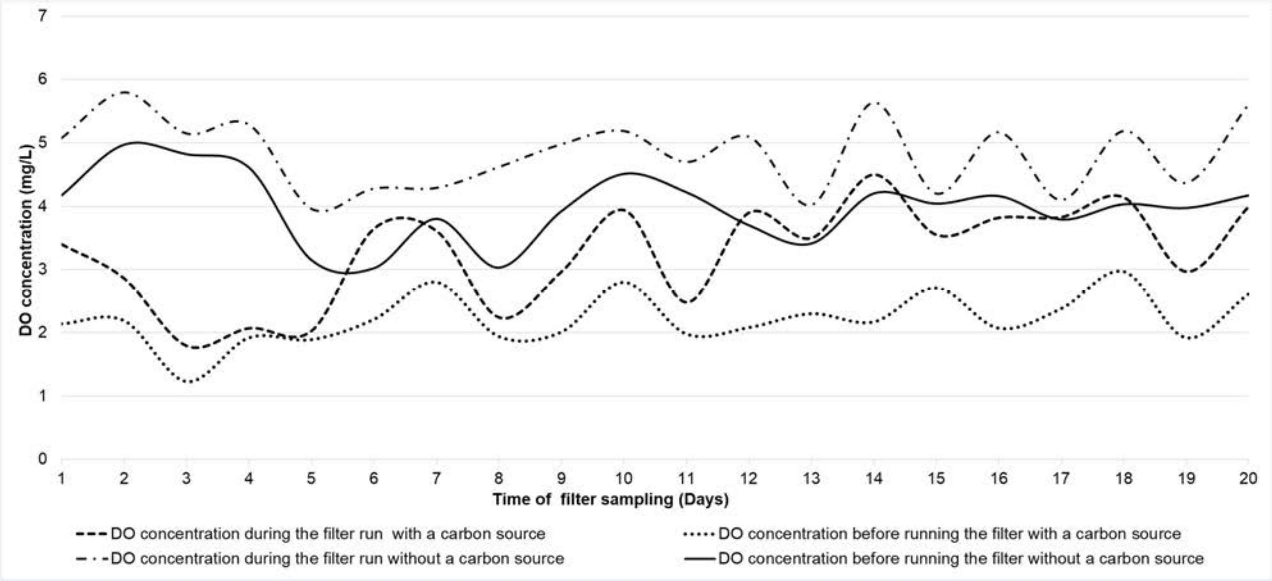


Figure 4.14 Dissolved oxygen concentration during and before the filter run in the filter with and without a carbon source.

4.8.2 Dissolved oxygen at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Figure 4.15 below shows dissolved oxygen fluctuations in the filter with an external carbon (VRF_{wt}) and without (VRF_{wo}). The initial raw river water had an average DO content of 5.94 mg/L in both filters. The average filtrate DO concentration with depth in the VRF_{wt} was within the range of 0 to 3.7 mg/L. A 55% average drop in DO was mostly recorded at a depth of 270 mm, with average DO decreases of 54% and 53 % observed at depths of 750 mm and 1000 mm, respectively.

In general, the filter with a carbon source reduced DO by 54%. The average filtrate DO concentration with depth ranged within 0 to 7.6 mg/L in VRF_{wo}. A 19% average drop in DO was largely observed at 270 mm depth, while average DO reduction of 18% and 16% were detected at 750 mm and 1000 mm depths, respectively. Overall, the DO reduction in the filter without a carbon source was 18%.

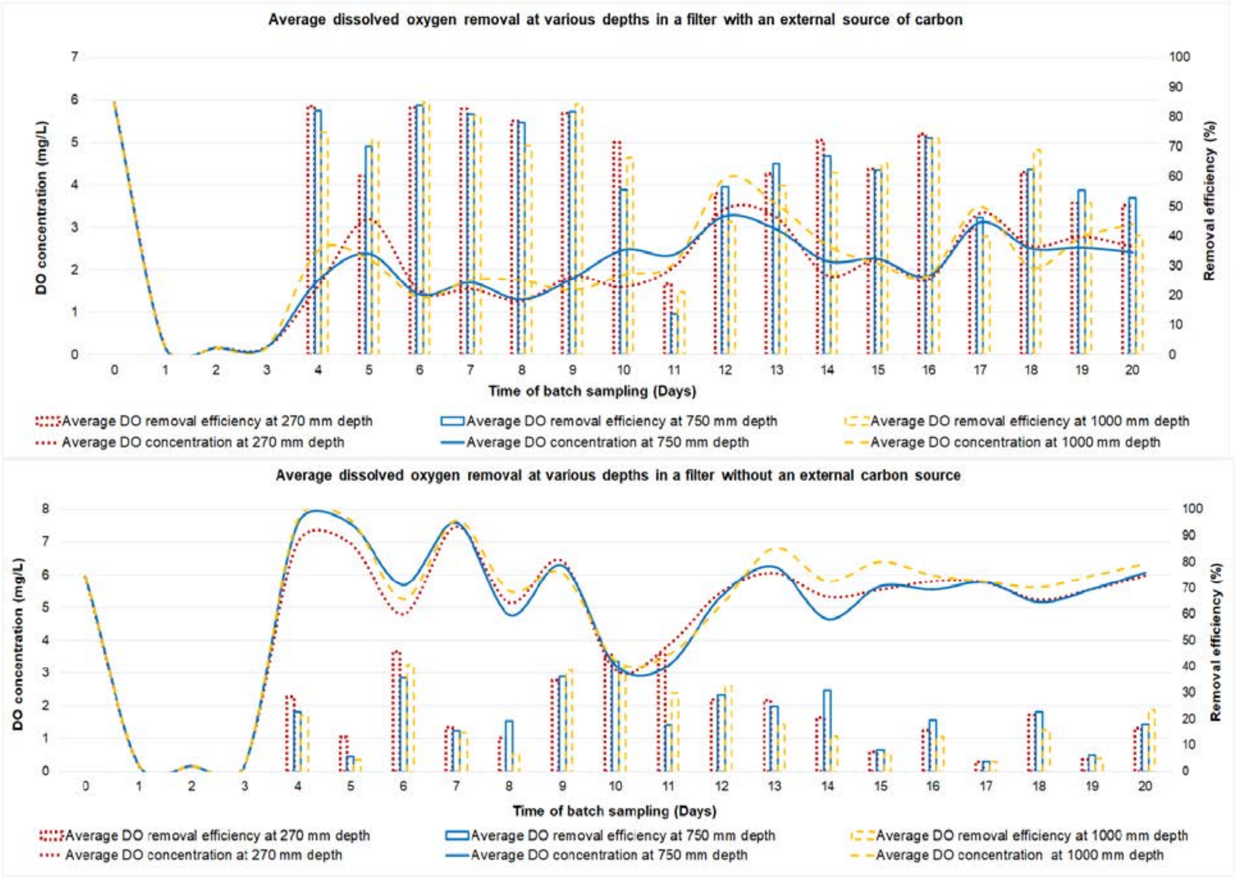


Figure 4.15 Average DO removal at varied depth in the filter with and without a carbon source at C/N ratio of 1.08 and inflow DO concentration of 5.94 mg/L.

Figure 4.16 below represents the DO measured in the filtrate during and before running the filters with and without a carbon source. The DO of raw river water ranged from 0 to 9.8 mg/L, with a pH of 5.94 mg/L on average. The filter with a carbon source reduced DO by 60% during the filter run and by 68% before the filter run, whereas the filter without a carbon source reduced DO by 25% during the filter run and by 47% before the filter run.

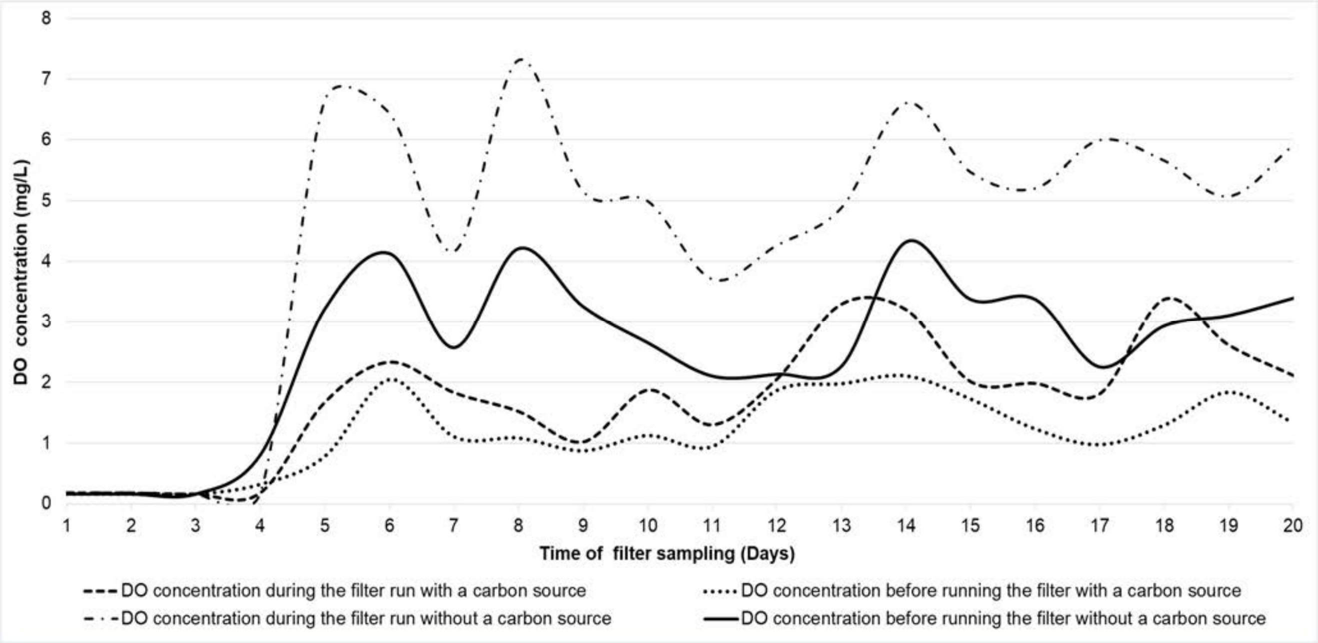
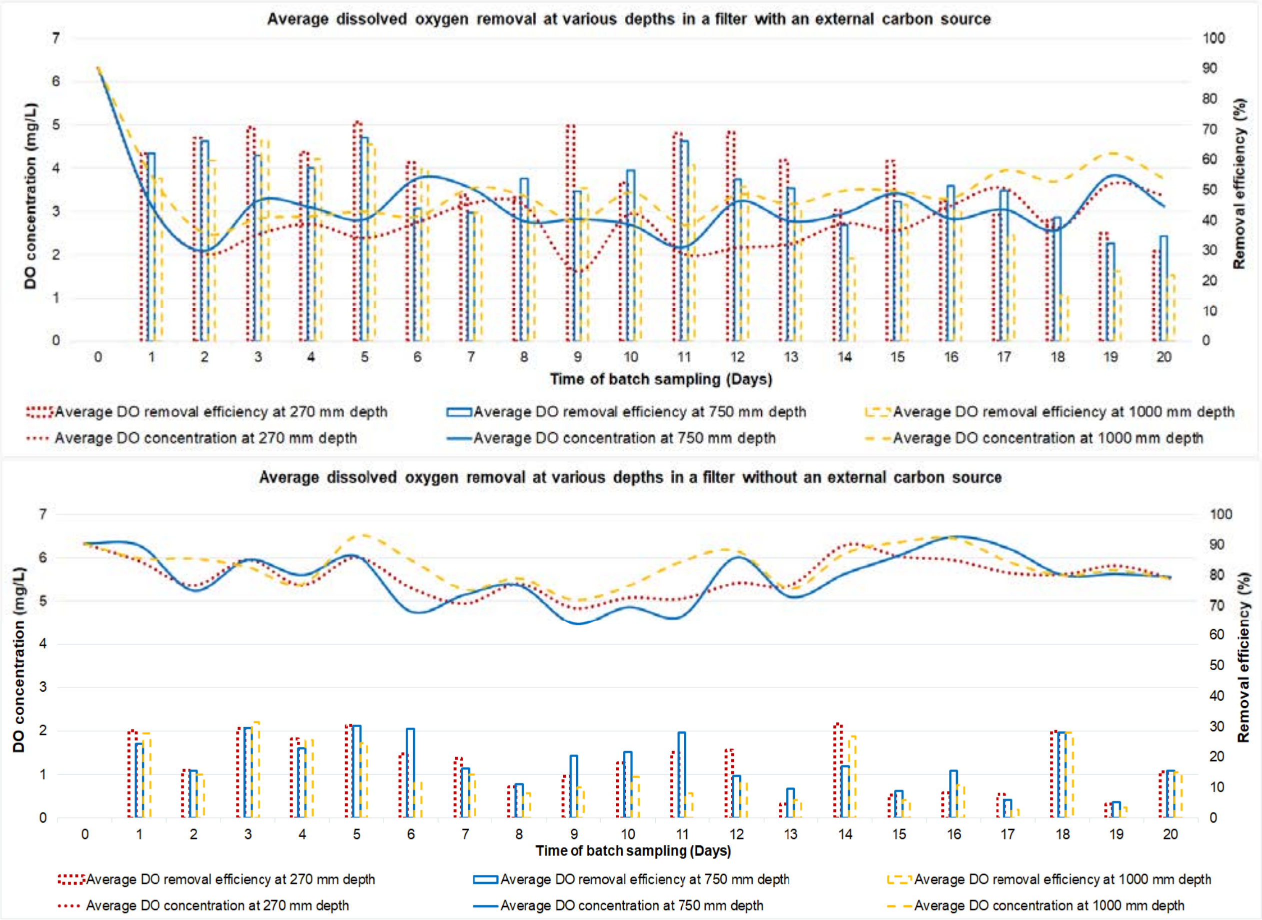


Figure 4.16 Dissolved oxygen concentration during and before the filter run in the filter with and without a carbon source.

4.8.3 Dissolved oxygen at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figure 4.17 below shows dissolved oxygen fluctuations in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply, respectively. The initial raw river water had an average DO concentration of 6.33 mg/L in both filters. The average filtrate DO concentration with depth ranged within 2.2 mg/L to 3.95 mg/L. A 55% average drop in DO was mostly observed at a depth of 270 mm, while average DO decrease of 51 and 45% were observed at depths of 750 mm and 1000 mm, respectively. A total DO reduction of 51% was observed in VRF_{wt}. An average filtrate DO concentration with depth ranged within 4.8 mg/L to 6.3 mg/L in a VRF_{wt}. There was an 18% average DO reduction at depths of 270 mm and 750 mm, while a 17% increase was observed at 1000 mm. In general, a 17% reduction in DO was recorded in a VRF_{wt}.



Average dissolved oxygen removal at various depths in a filter with an external carbon source

Average dissolved oxygen removal at various depths in a filter without an external carbon source

Figure 4.17 Average DO removal at varied depth in the filter with and without a carbon source at C/N ratio of 1.1 and inflow DO concentration of 6.33 mg/L.

Figure 4.18 below represents the DO measured in the filtrate during and before running the filters with and without a carbon source. The DO of raw river water was in the range of 4.3 mg/L to 8.7 mg/L, with an average pH of 6.33 mg/L. The filter with a carbon source resulted in a 57% DO reduction during the filter run and a 71% reduction before the filter run, whereas the filter without a carbon source resulted in a 17% DO reduction during the filter run and a 41% reduction before the filter was run.

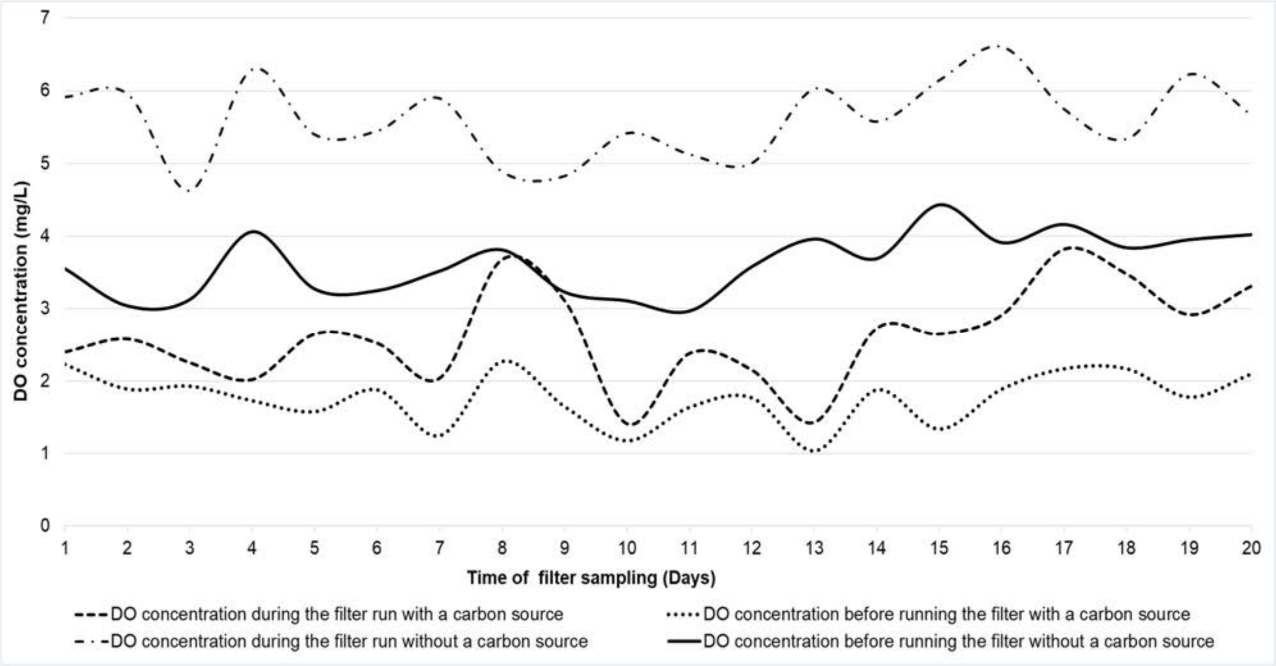


Figure 4.18 Dissolved oxygen concentration during and before the filter run in the filter with and without a carbon source.

4.9 Chemical Oxygen Demand (COD)

This section presents the chemical oxygen demand findings acquired from the tested raw water and filtrate in the filter with a carbon source during and before the filter run. Annexure I contain detailed tables on the daily quality of the filtrate in terms of residual carbon in the filter with a carbon source.

4.9.1 Chemical Oxygen demand at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N

Figure 4.19 below shows the residual carbon measured in the filtrate when employing a filter with a carbon source. The COD of raw river water ranged from 45 mg/L to 112 mg/L, with an average COD concentration of 87.3 mg/L before ethanol dosage. The filter removal efficiency of COD during the filter run was 75%, whereas the removal efficiency prior to the filter run was 88%.

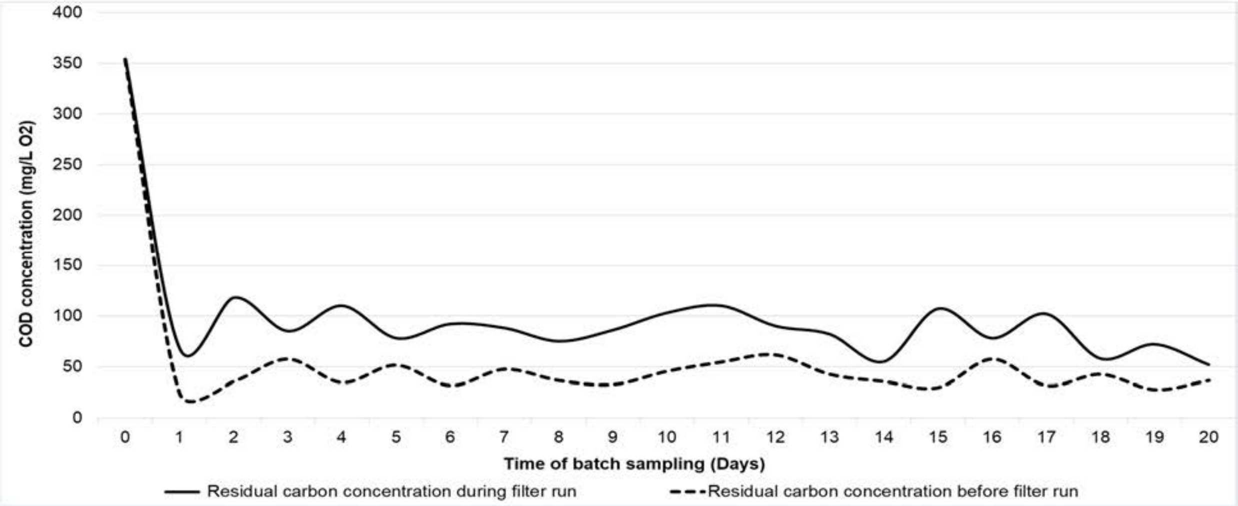


Figure 4.19 Residual Carbon trend measured as COD during and before filter run in the filter that used ethanol as a carbon source.

4.9.2 Chemical oxygen demand at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Figure 4.20 shows the residual carbon measured in the filtrate when employing a filter with a carbon source. The COD of raw river water ranged from 106 mg/L to 288 mg/L, with an average COD concentration of 147.8 mg/L before ethanol dosage. The filter removal efficiency during the filter run was 43%, while the removal efficiency prior to the filter run was 49%.

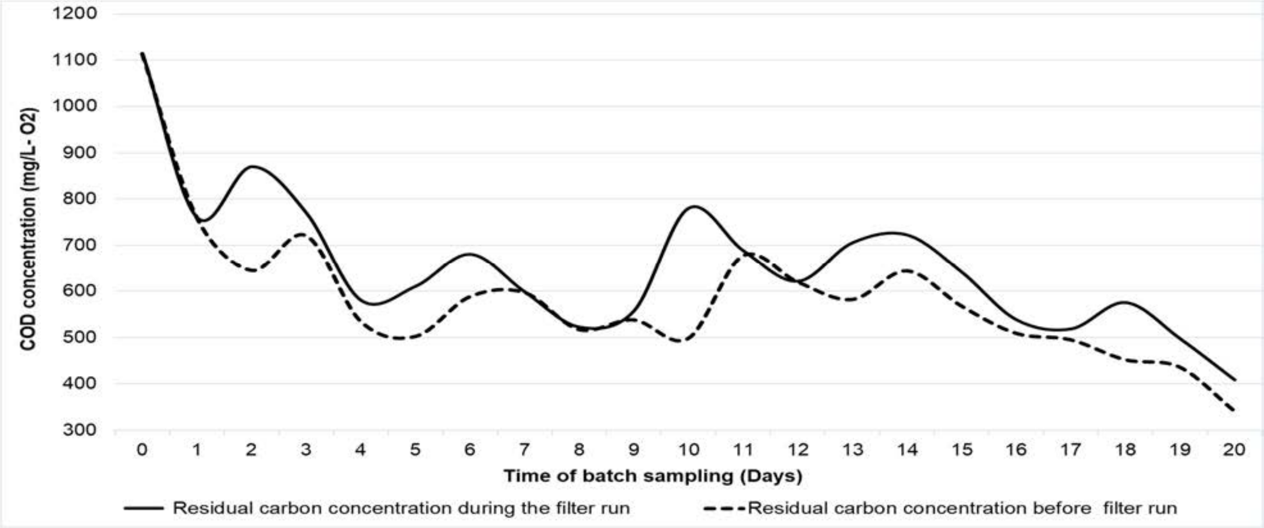


Figure 4.20 Residual carbon trend measured as COD during and before the filter run in the filter that used ethanol as a carbon source.

4.9.3 Chemical oxygen demand at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figure 4.21 represents the residual carbon identified in the filtrate when employing a filter with a carbon source. The COD of raw river water ranged from 685 mg/L to 940 mg/L, with an average COD concentration of 786.6 mg/L before ethanol dosage. The filter removal efficiency during the filter run was 46%, whereas the removal efficiency prior to the filter run was 53%.

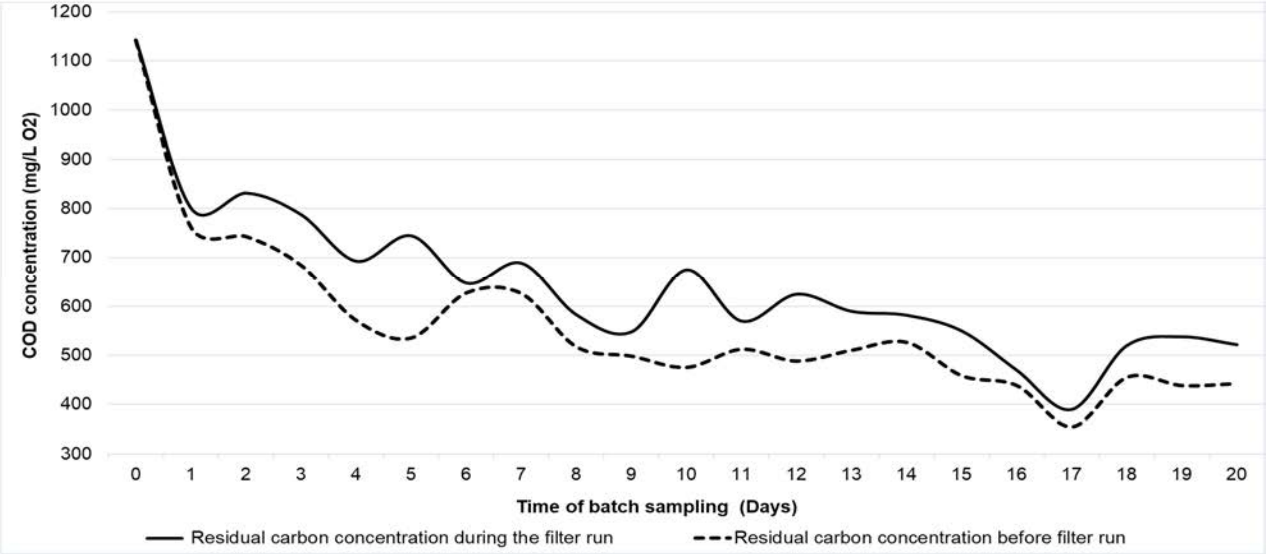


Figure 4.21 Residual carbon trend measured as COD during and before filter run in the filter that used ethanol as a carbon source.

4.10 Total suspended solids (TSS)

This section presents total suspended solids (TSS) data from tested raw water and filter filtrate with and without a carbon source. Annexure J provides detailed tables on TSS removal efficiency in the filter with and without a carbon supply.

4.10.1 TSS at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N

Figure 4.22 below represents the TSS removal efficiency in the filter with and without a carbon source. The TSS of raw river water ranged from 17 mg/L to 39 mg/L, with a TSS average of 26.95 mg/L. The filter with a carbon source removed 87% of the TSS, while the filter without a carbon source removed 90% of the TSS.

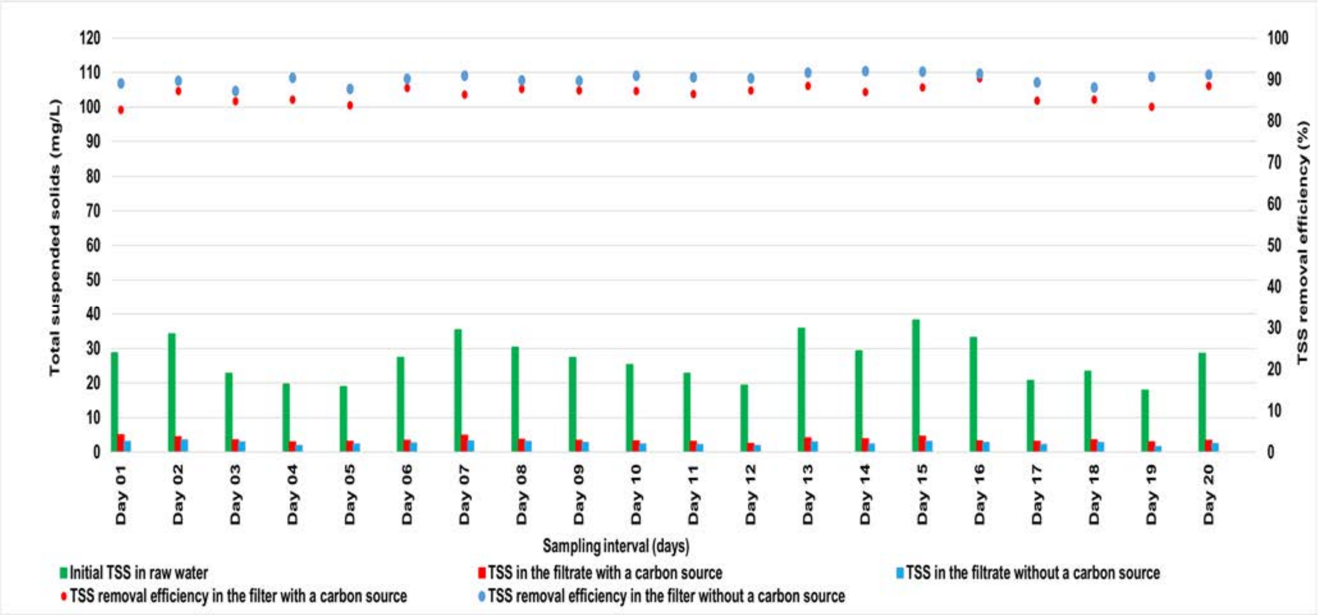


Figure 4.22 Total suspended solids removal efficiency using a filter with and without a source of Carbon.

4.10.2 TSS at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Figure 4.23 below shows the efficiency of TSS removal in the filter with and without a carbon supply. The TSS was within the range of 8 mg/L to 118 mg/L with an average TSS of 33.74 mg/L. The filter with a carbon source had a TSS removal rate of 70%, whereas the filter without a carbon source had an 82% TSS removal efficiency.

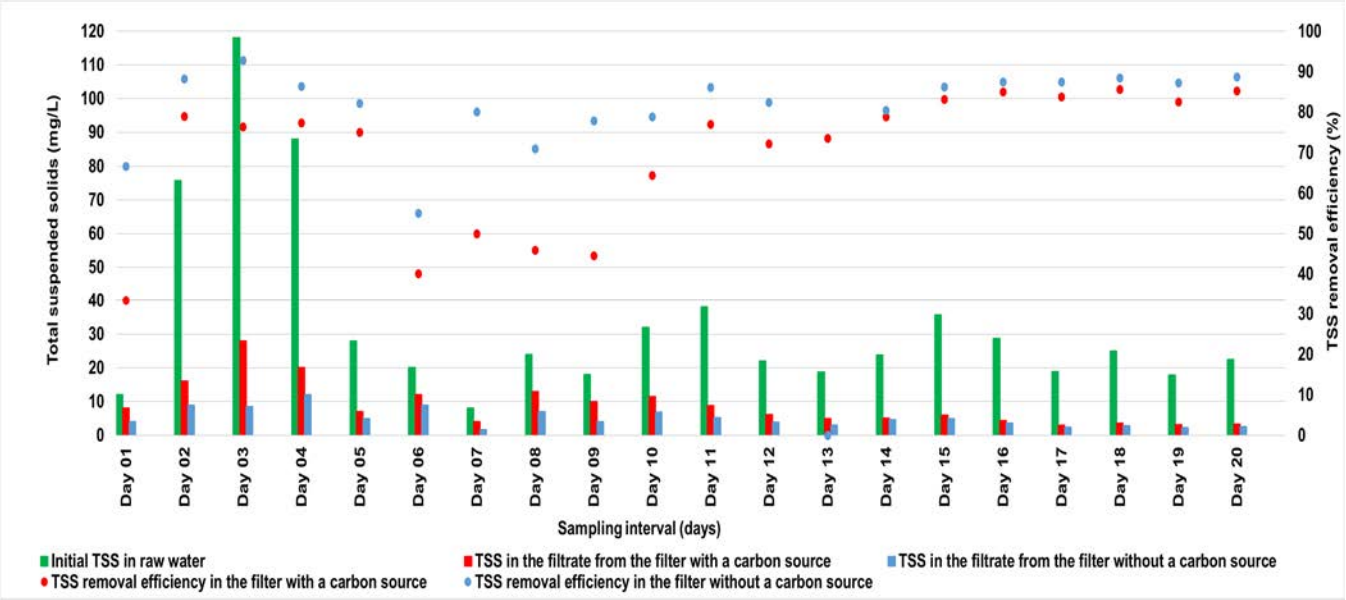


Figure 4.23 Total suspended solids removal efficiency using a filter with and without a source of carbon.

4.10.3 TSS at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figure 4.24 below represents the TSS removal efficiency in the filter with and without a carbon source. The TSS of raw river water ranged from 14 mg/L to 34 mg/L, with a TSS average of 22.88 mg/L. The filter with a carbon source removed 79% of the TSS, while the filter without a carbon source removed 84% of the TSS.

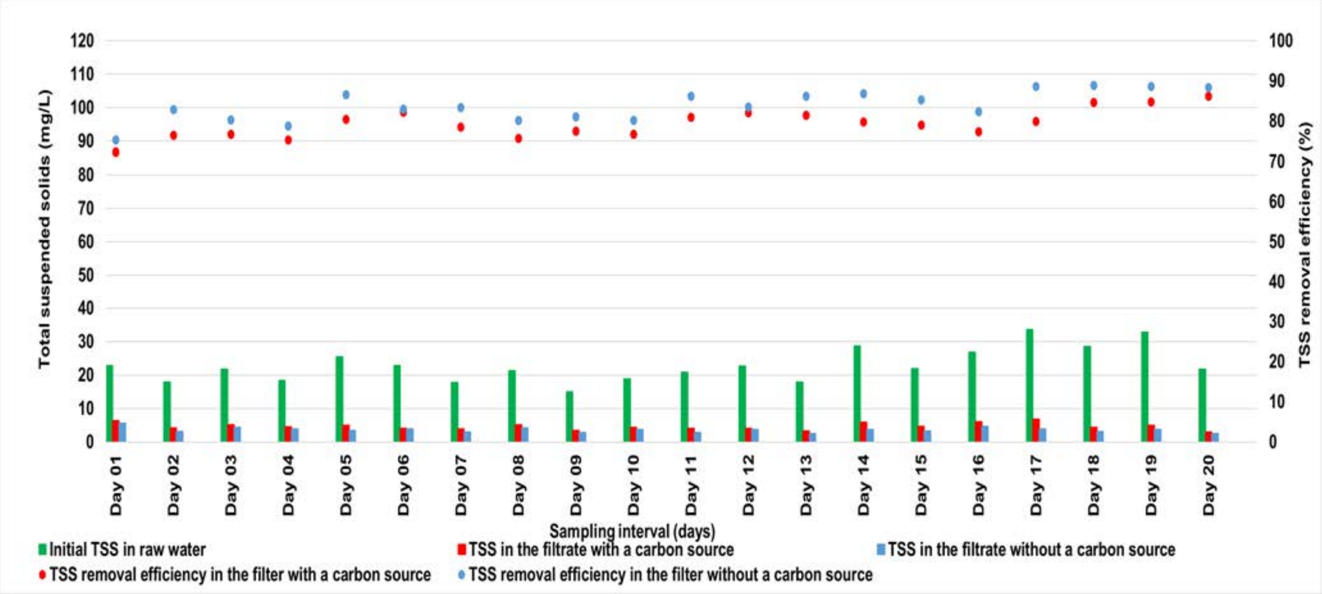


Figure 4.24 Total suspended solids removal efficiency using a filter with and without a source of carbon.

4.11 Turbidity

This section presents the turbidity data acquired by testing the raw water and filtrate in both the filter with and without a source of carbon during sampling. Annexure K contains detailed tables on the reduction of turbidity with depth in the filter with and without a carbon source.

4.11.1 Turbidity concentration at C/N ratio of 1.05 and inflow nitrate concentration of 15mg/L-N

Figure 4.25 below shows turbidity removal in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply. The initial raw river water had a turbidity concentration of 377.1 NTU in both filters. The average turbidity in the filtrate at various depths ranged within 38.0 NTU to 142.0 NTU in a VRF_{wt}. At 270 mm depth, the average turbidity removal efficiency was 76%, while at 750 mm and 1000 mm depths, the average turbidity removal efficiency was 82%. The total turbidity removal efficiency was 80%. The turbidity concentration in the filtrate at various depths ranging within 4.0

NTU to 101.0 NTU in the VRF$_{wo}$. At 270 mm depth, the average turbidity removal efficiency was 87%, while at 750 mm and 1000 mm depths, the average turbidity removal efficiency was 91%. The total turbidity removal efficiency was 90%.

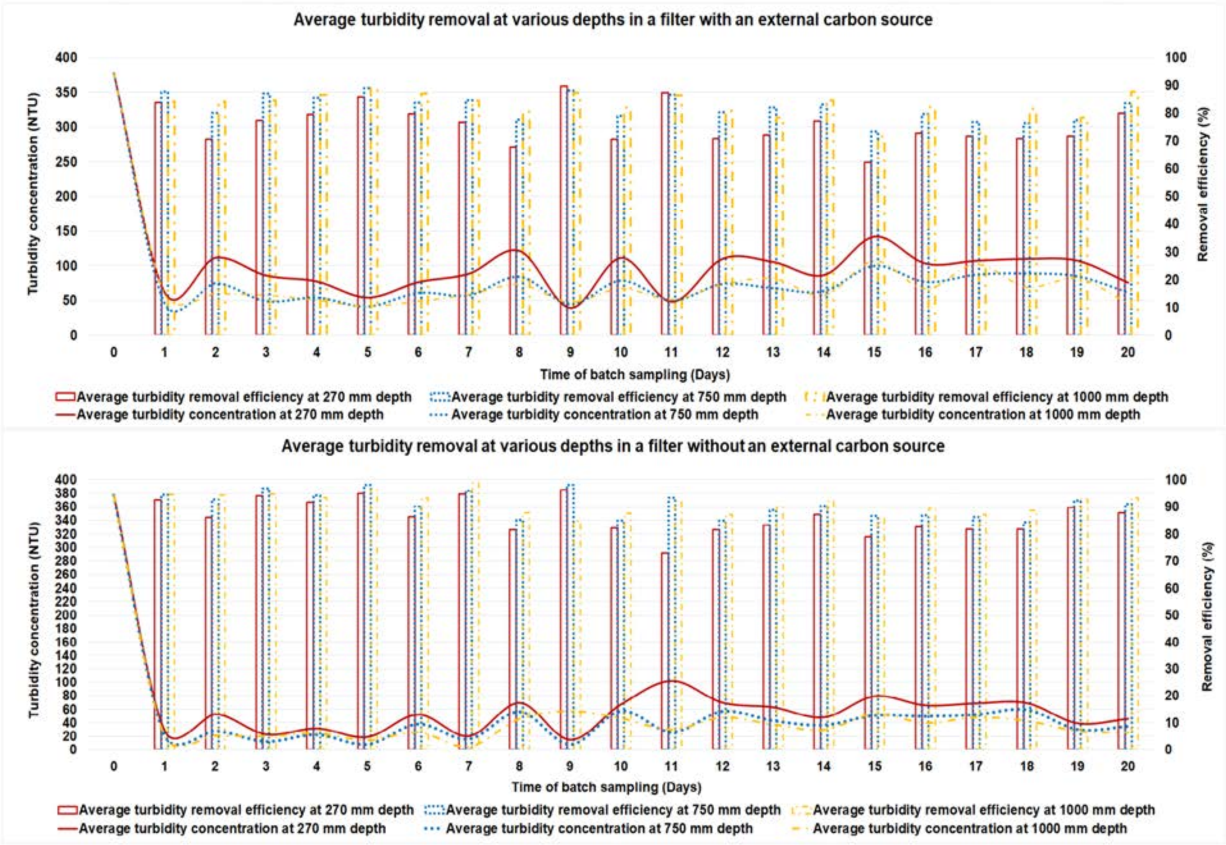


Figure 4.25 Overall average turbidity removal with filter depth in a filter with and without a source of carbon at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

4.11.2 Turbidity concentration at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Turbidity removal in the filter with (VRF$_{wt}$) and without (VRF$_{wo}$) a carbon supply is shown in Figure 4.26 below. In both filters, the initial raw river water had a turbidity concentration of 286.37 NTU. The average turbidity concentration in the VRF$_{wt}$ at various depths ranged within 13.0 NTU to 112.0 NTU. At 270 mm, the average turbidity removal efficiency was 75%, while at 750 mm, the average turbidity removal efficiency was 81%, and at 1000 mm, the average turbidity removal efficiency was 82%. The overall turbidity removal efficiency was 79%. Turbidity concentration in the VRF$_{wo}$ at various depths ranged within 7.0 NTU to 51.0 NTU. A turbidity removal efficiency of 88% was recorded at a depth of 270 mm, a 90% removal efficiency at a depth of 750 mm, and a

91% removal efficiency at a depth of 1000 mm. The total turbidity removal efficiency in the filter was 90%.

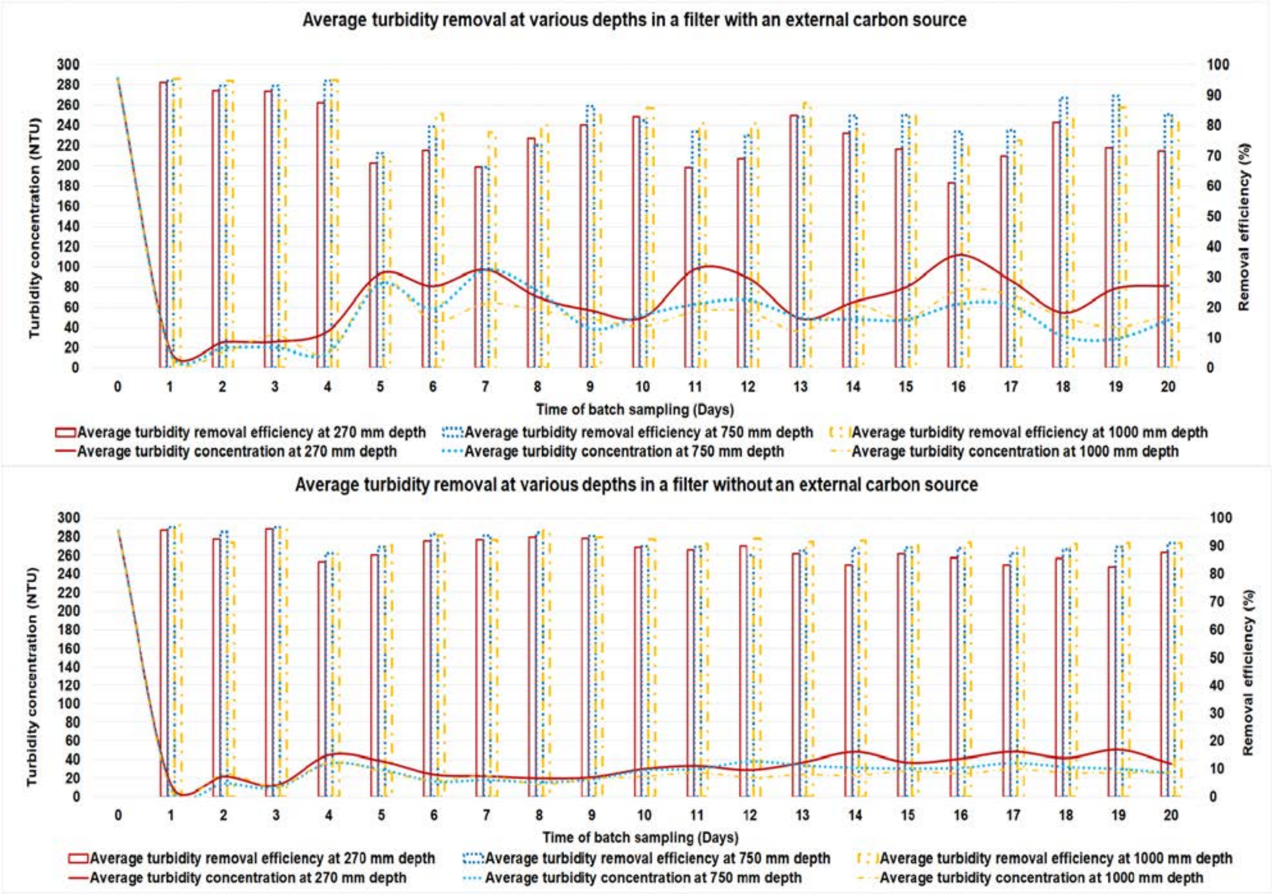


Figure 4.26 Overall average turbidity removal with filter depth in a filter with and without a source of carbon at a C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

4.11.3 Turbidity concentration at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figures 4.27 below shows turbidity removal in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply. The initial raw river water had an average turbidity concentration of 505.75 NTU in both filters. The average turbidity concentration at various depths ranged within 21.0 NTU to 149.0 NTU in the VRF_{wt}. At 270 mm, the average turbidity removal efficiency was 81%, while at 750 mm and 1000 mm, the average turbidity removal efficiency was 89%. The total turbidity removal efficiency in the filter was 86%. The average turbidity concentration in the VRF_{wo} at various depths ranged within 21.0 NTU to 130.0 NTU. At a depth of 270 mm, the average turbidity removal efficiency was 85%, while at a depth of 750 mm, the average turbidity removal efficiency was 91%, and at a depth of 1000 mm, the average turbidity removal efficiency was 90%. The total turbidity removal efficiency was 89%.

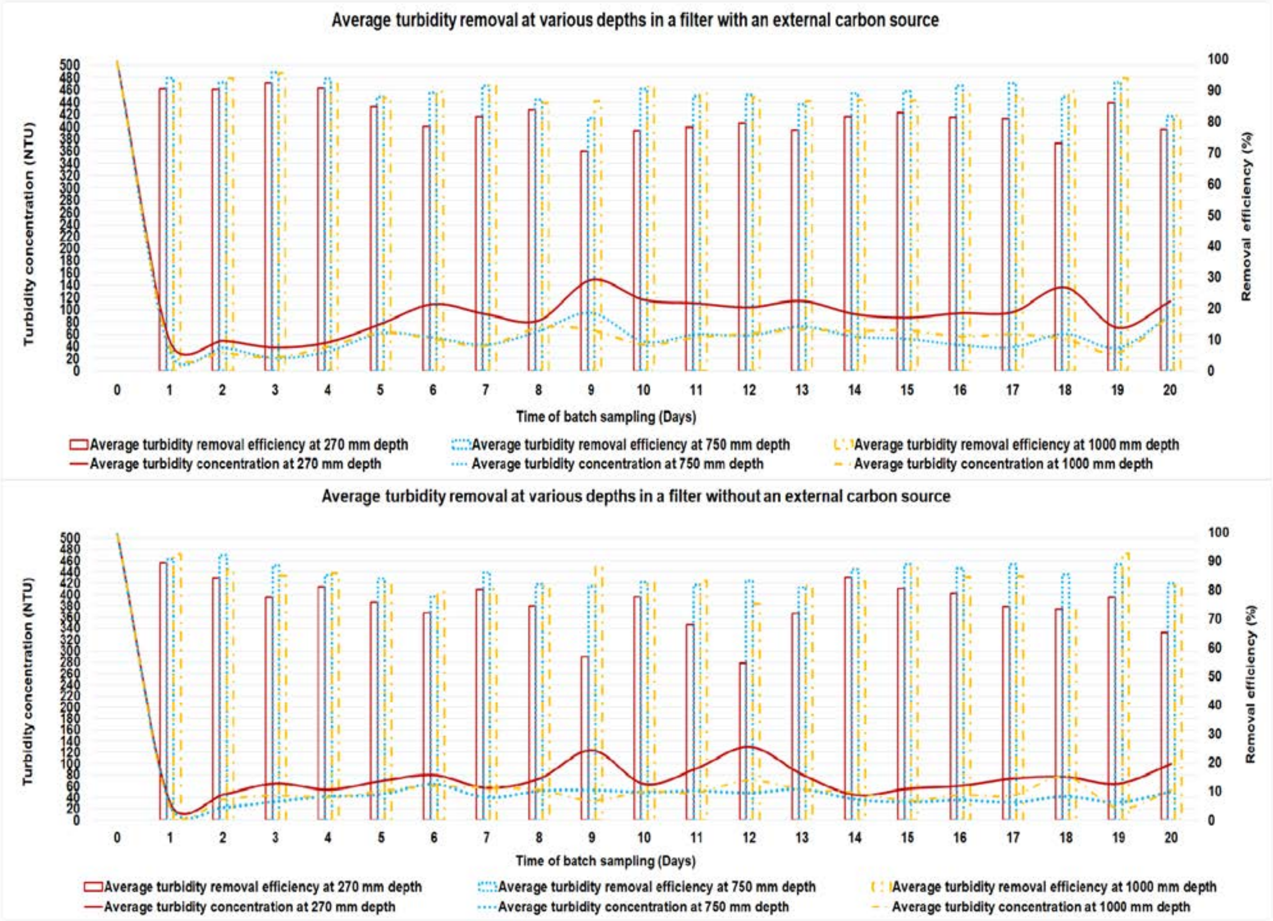


Figure 4.27 Overall average turbidity removal with filter depth in a filter with and without a source of carbon at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

4.12 Nitrite (NO_2^-)

This section presents the nitrite findings obtained by testing the raw water and filtrate in both the filters with and without a source of carbon during sampling. Annexure L includes detailed tables and graphical representation of nitrite removal with depth in the filter with and without a carbon supply.

4.12.1 Nitrite concentration at C/N ratio of 1.05 and inflow nitrate concentration of 15mg/L-N

Figure 4.28 below shows nitrite variations in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply. The initial raw river water had an average nitrite concentration of 0.09 mg/L-N in both filters. The average filtrate nitrite concentration with depth in the VRF_{wt} was within the range of 0 to 0.04 mg/L-N. At 270 mm depth, the average nitrite drop was 97%, while at 750 mm and 1000 mm depths, a slight 98% average nitrite decrease was detected. The total nitrite removal efficiency in the filter was 98%. The average filtrate nitrite concentration with depth ranged within 0.01 mg/L-N to 0.16 mg/L-N in the VRF_{wo}. At 270 mm, the average nitrite drop was 93%, while at 750 mm and 1000 mm, the average nitrite decrease was 92%. The total nitrite removal efficiency in the filter was 92%.

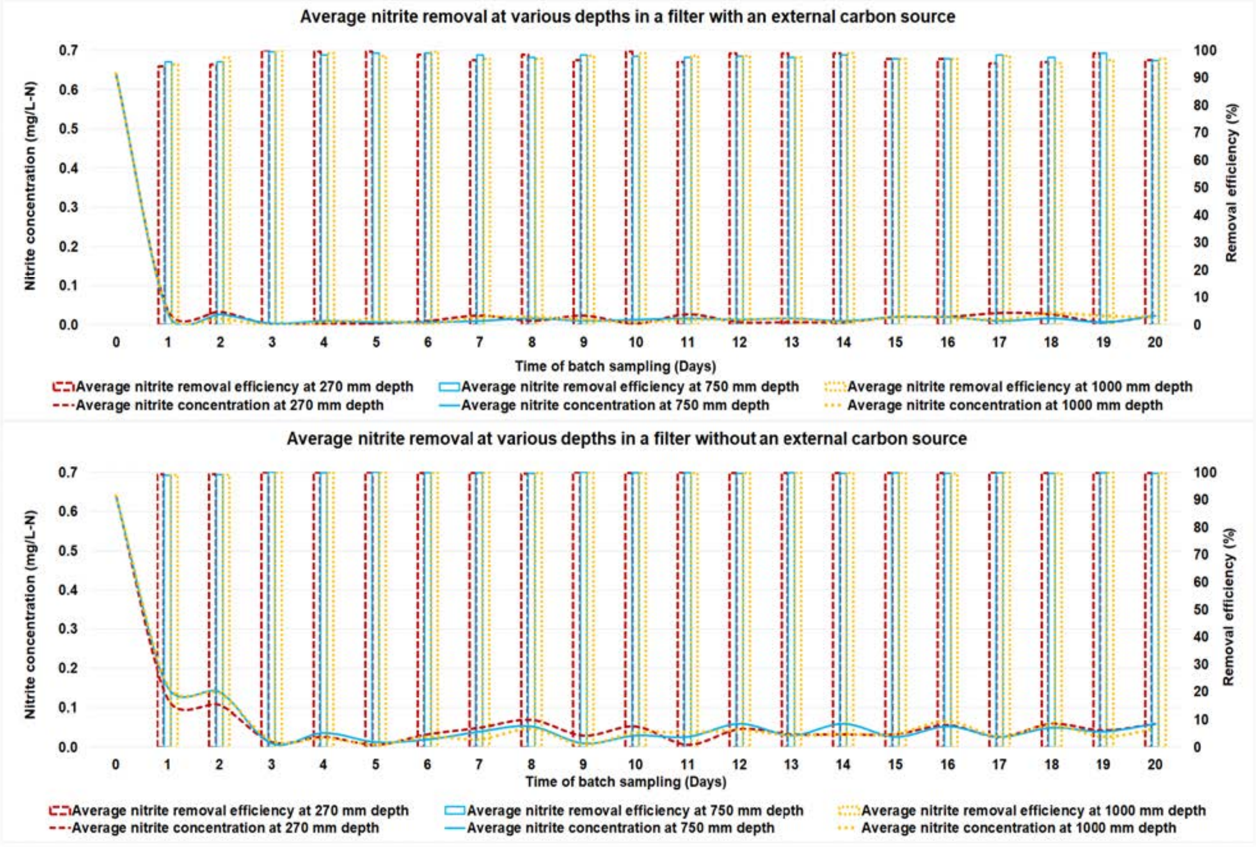


Figure 4.28 Average nitrite removal at varied depth in the filter with and without a carbon source at inflow nitrate concentration of 15 mg/L-N and C/N ratio of 1.05.

Figure 4.29 below shows the nitrite concentration in the filtrate during and before running the filters with and without a carbon source. The nitrite concentration in raw river water ranged within

0.03 mg/L-N to 0.2 mg/L-N, with an average nitrite concentration of 0.09 mg/L-N. The filter with a carbon source reduced nitrite by 93% during the filter run and by 99% before the filter run, while the filter without a carbon source reduced nitrite by 88% during the filter run and by 95% before the filter was run.

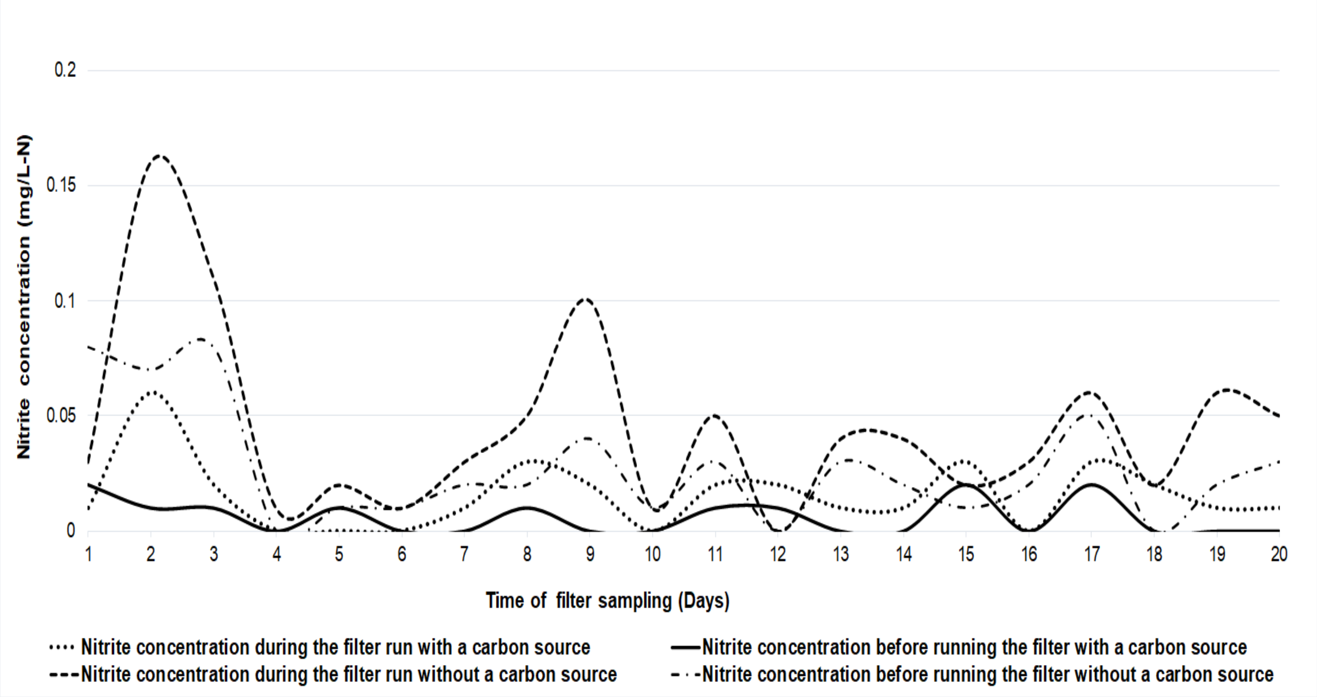


Figure 4.29 Nitrite concentration during and before the filter run in the filter with and without a carbon source at a C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

4.12.2 Nitrite concentration at C/N ratio of 1.08 and inflow nitrate concentration of 25mg/L-N

Figure 4.30 below shows nitrite variations in the filter with (VRF_{wt}) and without (VRF_{wt}) a carbon supply, respectively. The initial raw river water had an average nitrite concentration of 0.11 mg/L-N in both filters. The average filtrate nitrite concentration with depth ranged within 0.02 mg/L-N to 2.1 mg/L-N in the VRF_{wt}. An average nitrite reduction of 85% was recorded at a depth of 1000 mm, whereas average nitrite decreases of 81% and 82% were reported at depths of 270 mm and 750 mm, respectively.

The overall nitrite removal efficiency in the filter was 82%. The average filtrate nitrite concentration with depth ranged within 0.01 mg/L-N to 2.1 mg/L-N in the VRF_{wo}. A 77% average drop in nitrite was predominantly recorded at a depth of 1000 mm, whereas a 75 and 74% decrease in nitrite was mostly detected at depths of 270 mm and 750 mm, respectively. The total nitrite removal efficiency in the filter was 75%.

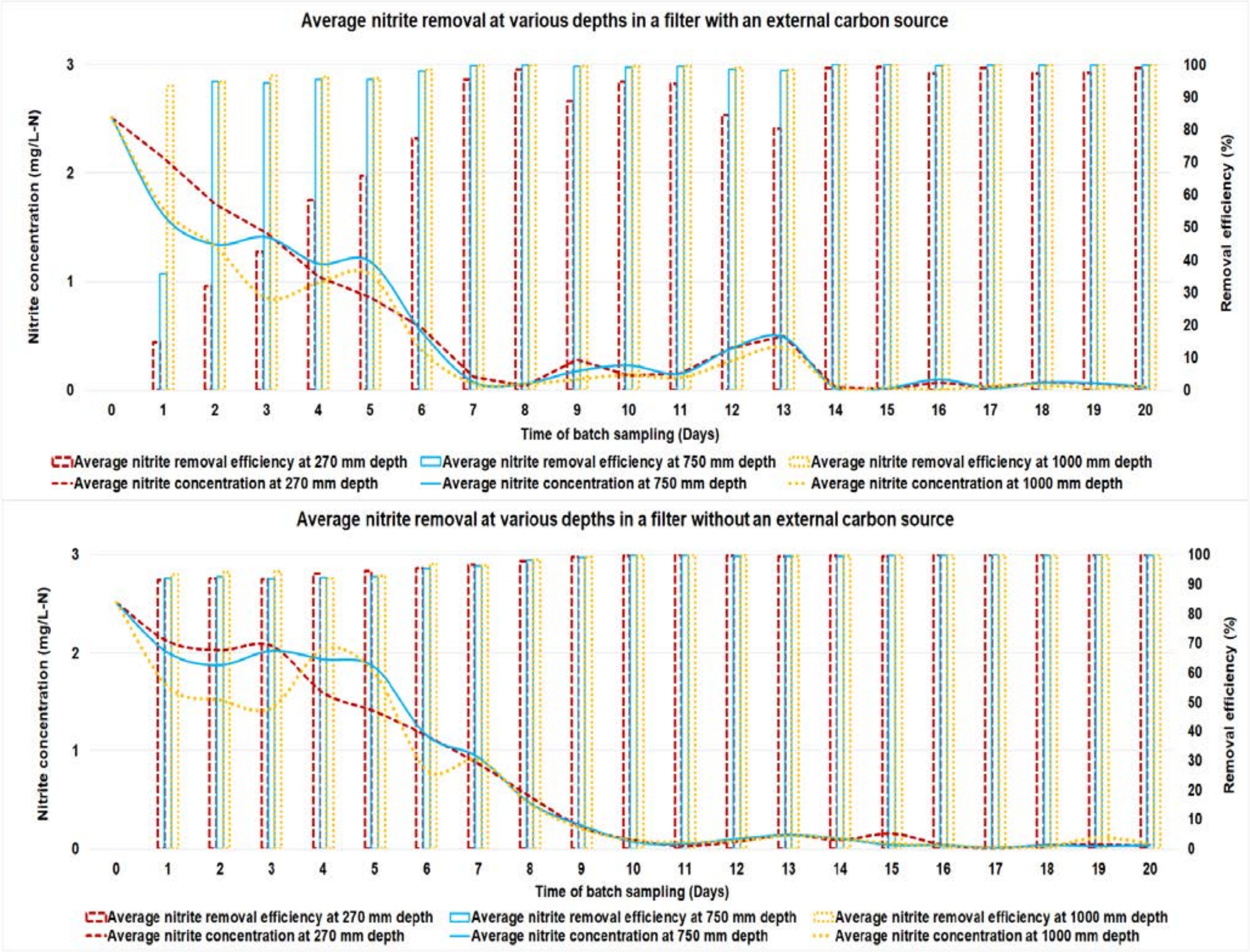


Figure 4.30 Average nitrite removal at varied depths in the filter with and without a carbon source at inflow nitrate concentration of 25 mg/L-N and C/N ratio of 1.08.

Figure 4.31 below represents the nitrite concentration in the filtrate while the filter was operating (during the filter run) and the period prior to running the filter (before running the filter). The nitrite concentration in raw river water ranged within 0 to 0.25 mg/L-N, with an average nitrite concentration of 0.11 mg/L-N.

The filter with a carbon source reduced nitrite by 76% during the filter run and by 87% before the filter run, while the filter without a Carbon source reduced nitrite by 71% during the filter run and by 84% before the filter was run.

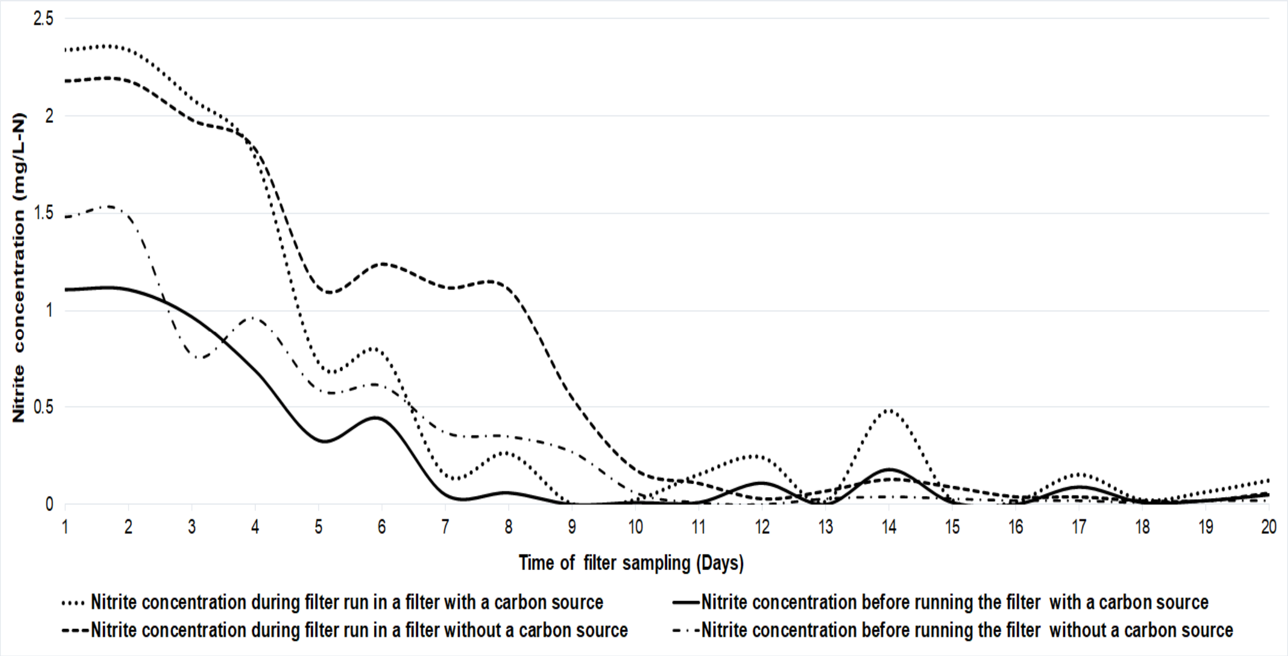


Figure 4.31 Nitrite concentration during and before the filter run in the filter with and without a carbon source at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

4.12.3 Nitrite concentration at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N

Figure 4.32 below shows nitrite variations in the filter with (VRF_{wt}) and without (VRF_{wt}) a carbon supply. The initial raw river water had an average nitrite concentration of 0.05 mg/L-N in both filters. The average filtrate nitrite concentration with depth ranged within 0.04 mg/L-N to 4 mg/L-N in the VRF_{wt}. The average nitrite reduction was 79% at 1000 mm, whereas the average nitrite decline was 81% and 80% at 270 mm and 750 mm, respectively.

The total nitrite removal efficiency in the filter was 80%. The average filtrate nitrite concentration with depth ranged within 0.01 mg/L-N to 1.4 mg/L-N in the VRF_{wo}. At depths of 270 mm and 750 mm, the average nitrite reduction was 97%, while at 1000 mm, the average nitrite decrease was 96%. The total nitrite removal efficiency in the filter was 97%.

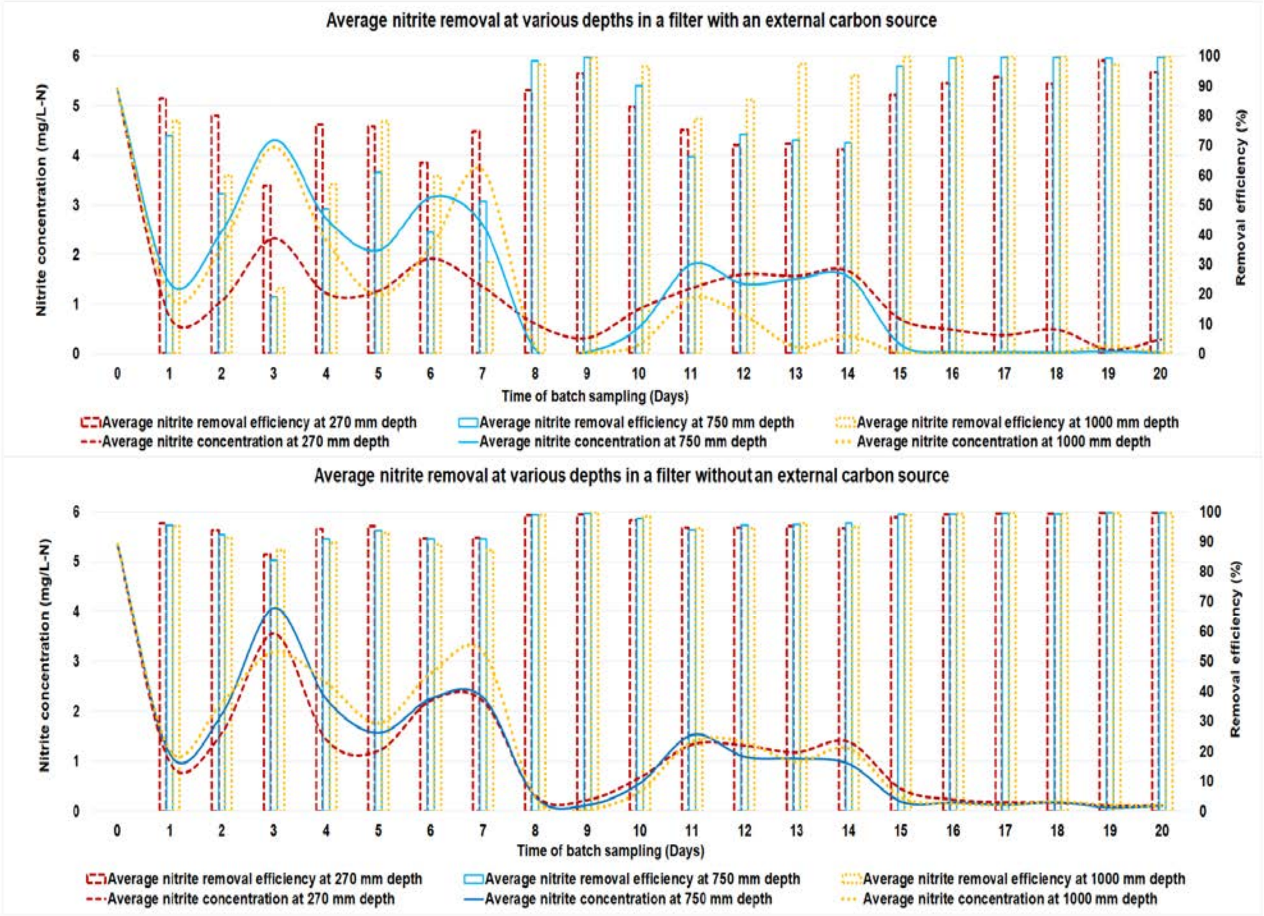


Figure 4.32 Average nitrite removal at varied depths in the filter with and without a carbon source inflow nitrate concentration of 50 mg/L-N and C/N ratio of 1.1.

Figure 4.33 below shows the nitrite concentration in the filtrate during and before running the filters with and without a carbon source. The nitrite concentration in raw river water ranged within 0.02 mg/L-N to 0.14 mg/L-N, with an average nitrite concentration of 0.05 mg/L-N. The filter with a carbon source reduced nitrite by 84% during the filter run and by 94% before the filter run, whereas the filter without a carbon source reduced nitrite by 97% during the filter run and by 99% before the filter run.

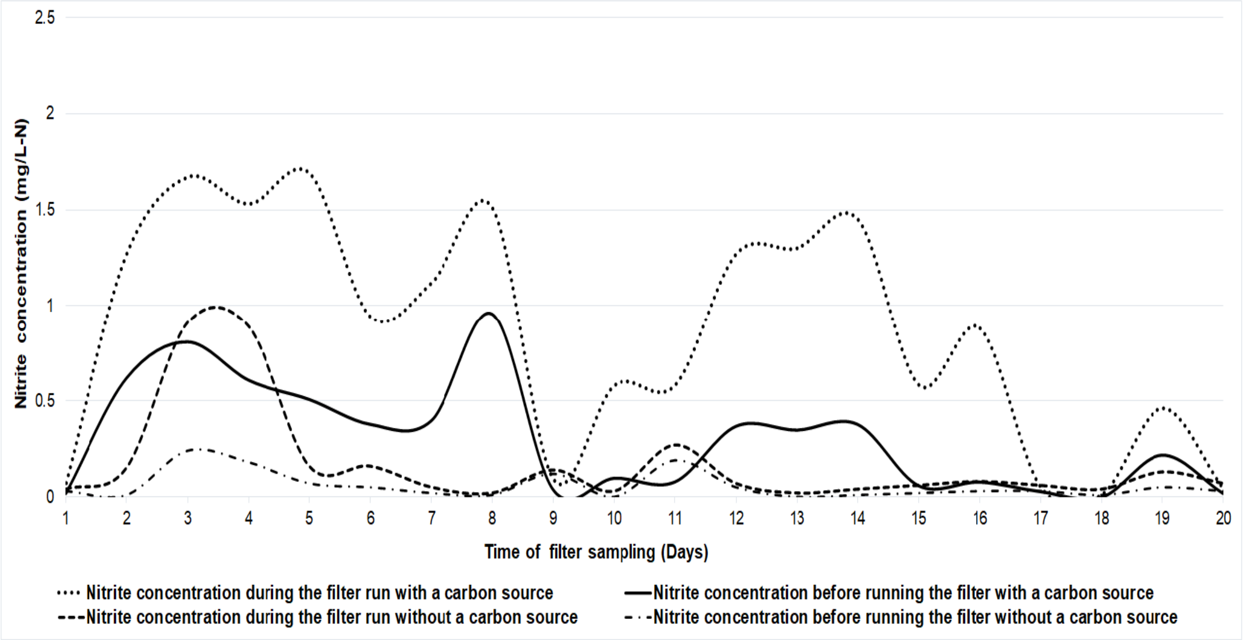


Figure 4.33 Nitrite concentration during and before the filter run in the filter with and without a carbon source at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

4.13 Nitrate (NO_3^-)

This section presents nitrate findings acquired from testing raw water and filtrate in both the filter with and without a carbon source during sampling. Annexure M includes detailed tables on nitrate removal with depth in the filter with and without a carbon supply.

4.13.1 C/N ratio of 1.05 and inflow nitrate concentration at 15 mg/L-N

Figure 4.34 below shows the average nitrate removal at various depths in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply. The initial raw river water had an average nitrate concentration of 10.52 mg/L-N and a spiked concentration of 15.13 mg/L-N in both filters. During the VRF_{wt} operation the average nitrate concentration in the filtrate ranged within 0.15 mg/L-N to 4.5 mg/L-N. At depths of 250 mm and 750 mm, the average nitrate removal was 89%, while at 1000 mm, the average nitrate removal was 86%. In the VRF_{wo}, the average nitrate concentration of the filtrate at various depths was within the range of 1.1 mg/L-N to 8.2 mg/L-N. At depths of 250 mm and 750 mm, average nitrate removal was 70%, whereas at 1000 mm, average nitrate removal was 64%.

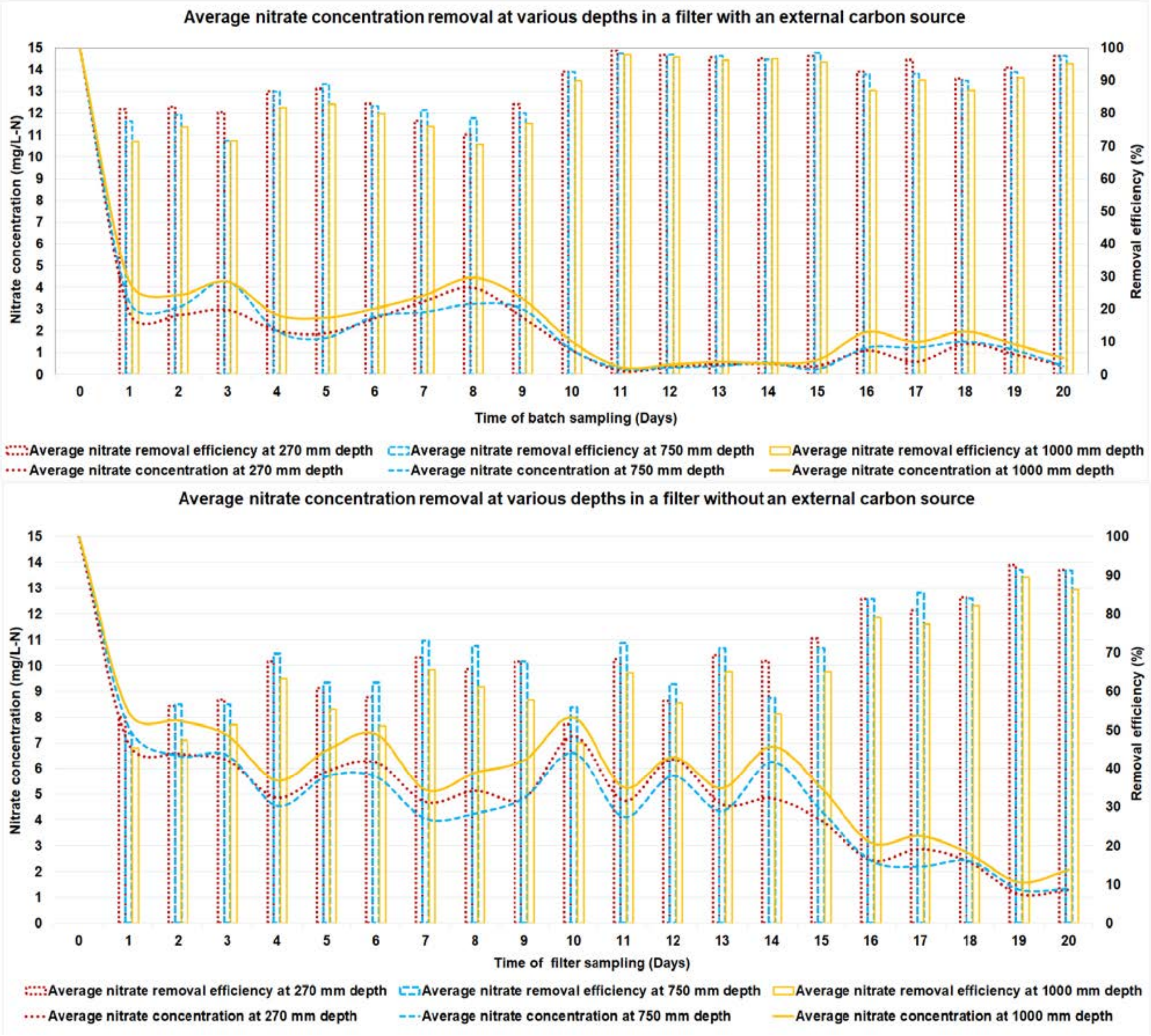


Figure 4.34 Average nitrate removal at various depths in the filter with and without a carbon source, at a C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

Figure 4.35 below shows the overall performance of nitrate removal in filters with and without a carbon supply. Overall nitrate removal efficiency in the filter with and without a carbon supply was 88% and 68%, respectively.

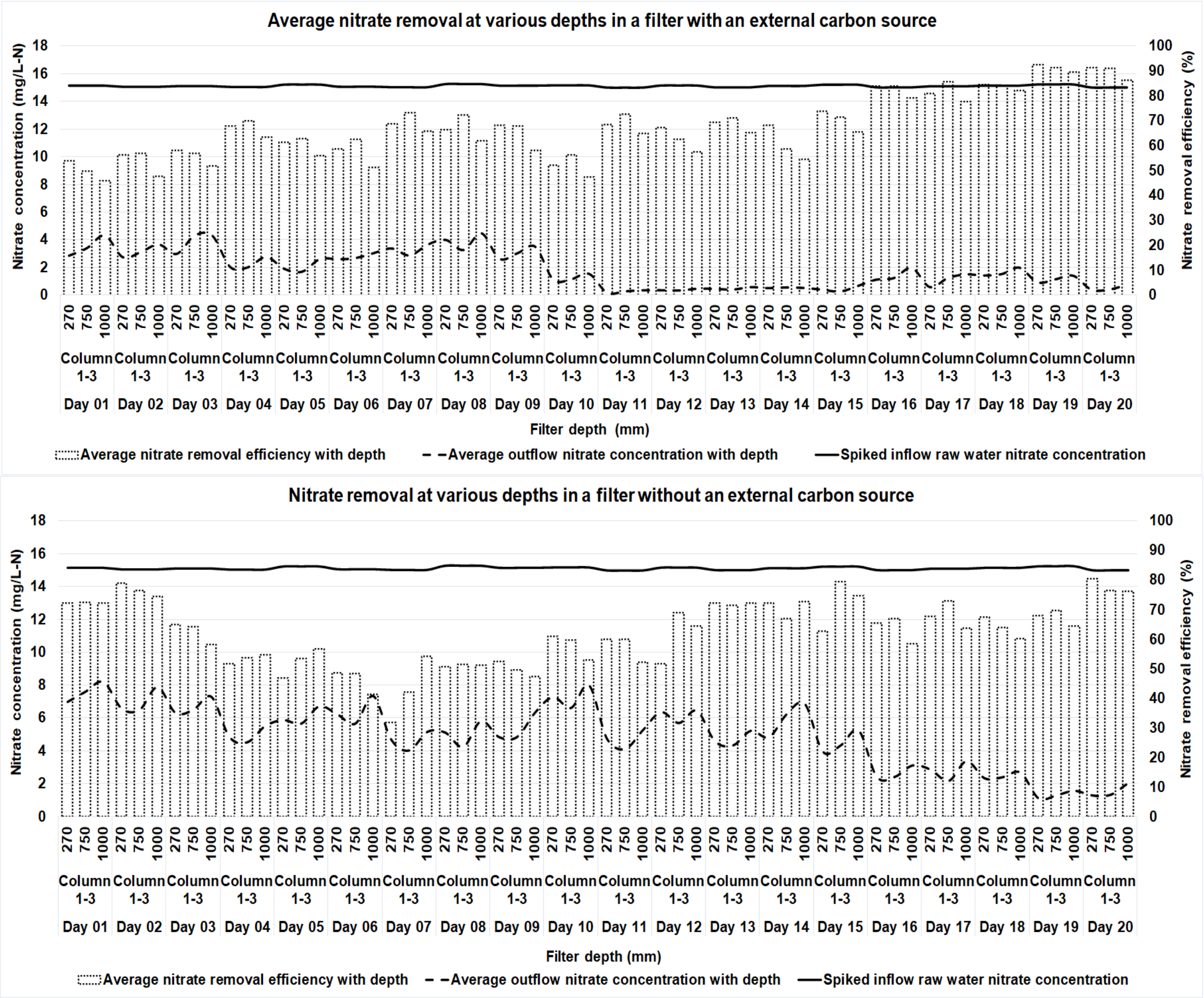


Figure 4.35 Overall average nitrate removal in a filter with and without a source of carbon at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

Figure 4.36 below represents the nitrate concentration in the filtrate during and before running the filters with and without a carbon source. The nitrate concentration in raw river water ranged from 8.0 mg/L-N to 13.3 mg/L-N, with an average nitrate concentration of 10.52 mg/L-N.

The filter with a carbon source reduced nitrate by 88% during the filter run and by 94% before the filter run, while the filter without a carbon source reduced nitrate by 66% during the filter run and by 76% before the filter run.

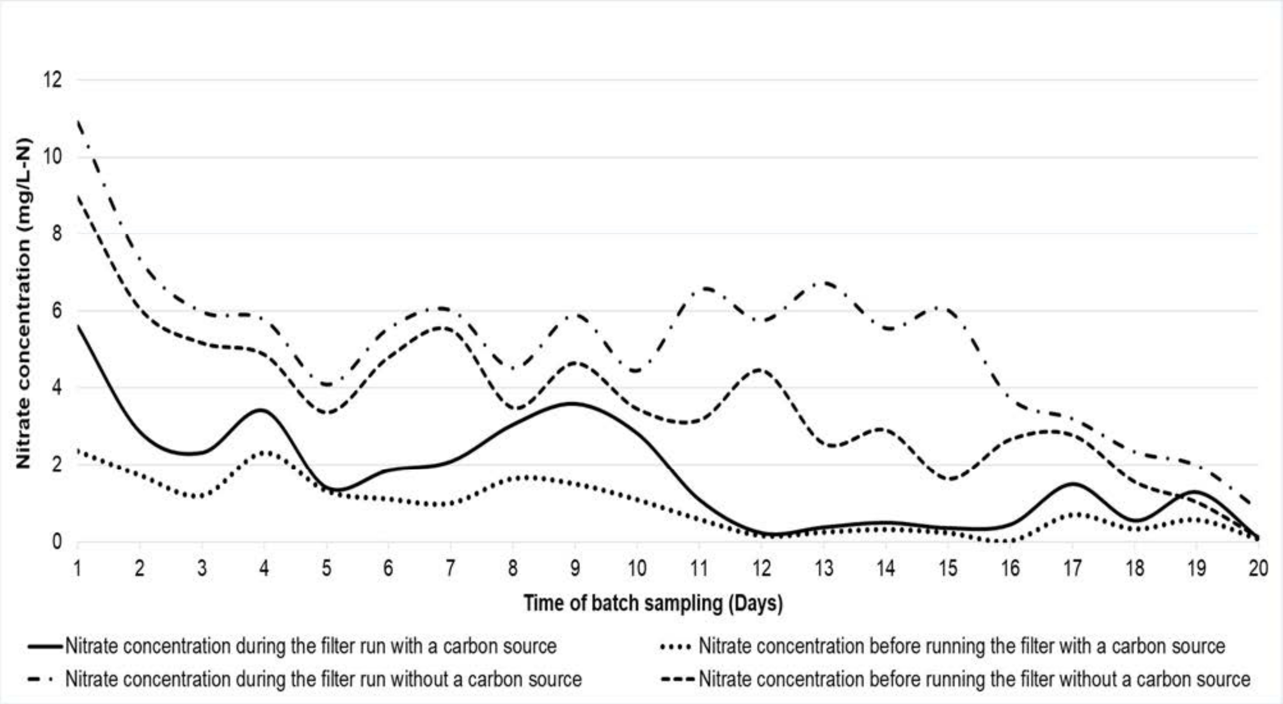


Figure 4.36 Nitrate concentration during and before the filter run in the filter with and without a carbon source at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N.

4.13.2 C/N ratio of 1.08 and inflow nitrate concentration at 25 mg/L-N

Figure 4.37 shows the average nitrate removal at various depths in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply. The initial raw river water in both filters had an average nitrate concentration of 12.61 mg/L-N and a spiked concentration of 25.33 mg/L-N. During the VRF_{wt} operation the average nitrate concentration in the filtrate ranged within 1.7 mg/L-N to 16 mg/L-N. At depths of 250 mm and 750 mm, the average nitrate removal was 72%, whereas at 1000 mm, the average nitrate removal was 66%. In the VRF_{wo}, the average nitrate concentration in the filtrate ranged within 4.9 mg/L-N to 17.5 mg/L-N. A 61% average removal of nitrate was recorded at a depth of 250 mm, 59% at a depth of 750 mm, and 56% at a depth of 1000 mm.

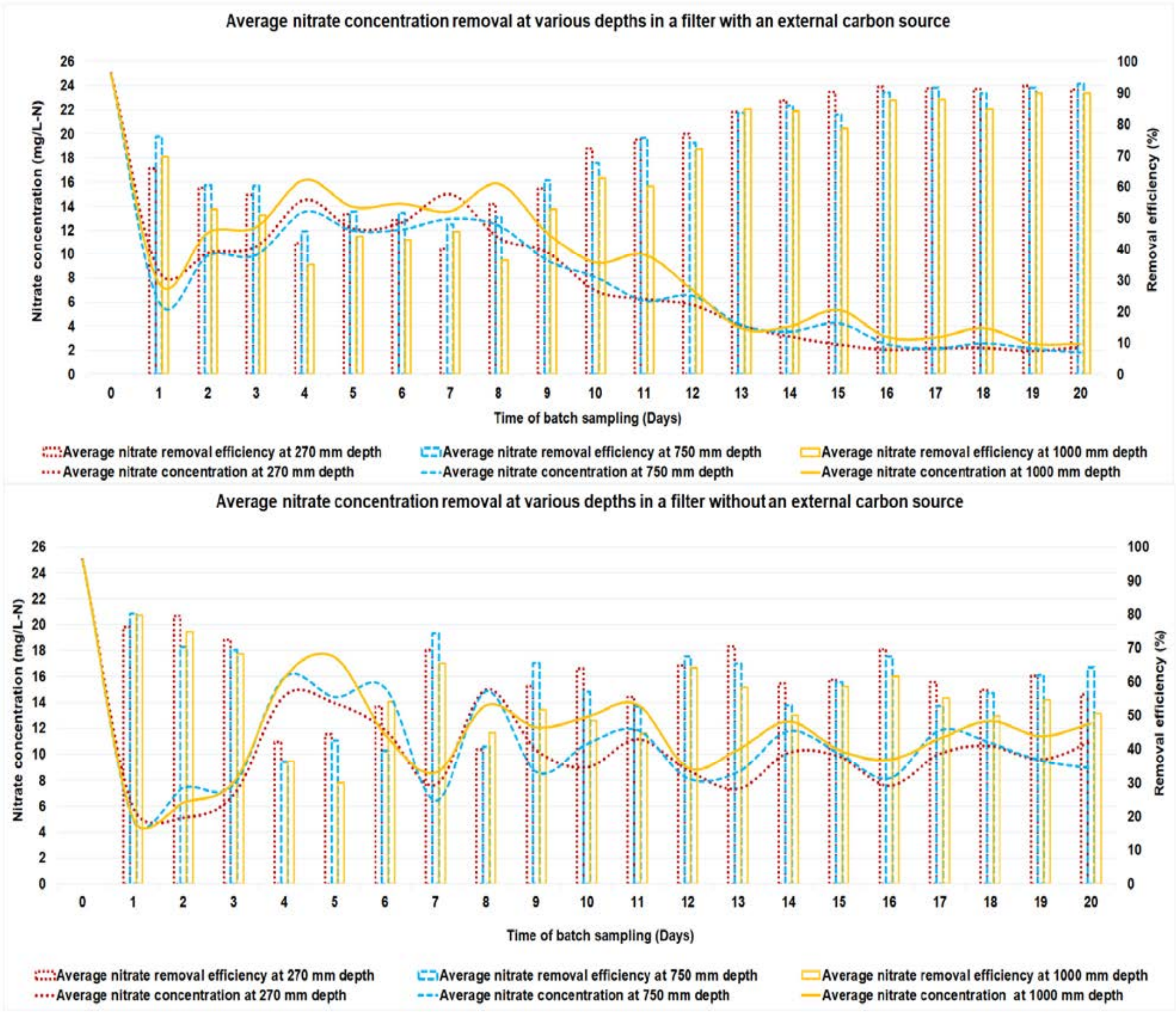


Figure 4.37 Average nitrate removal at varied depth in the filter with and without a carbon source at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

Figure 4.38 below shows the overall performance of nitrate removal in filters with and without a carbon source. The total nitrate removal efficiency of the filter with and without a carbon supply was 70% and 59%, respectively.

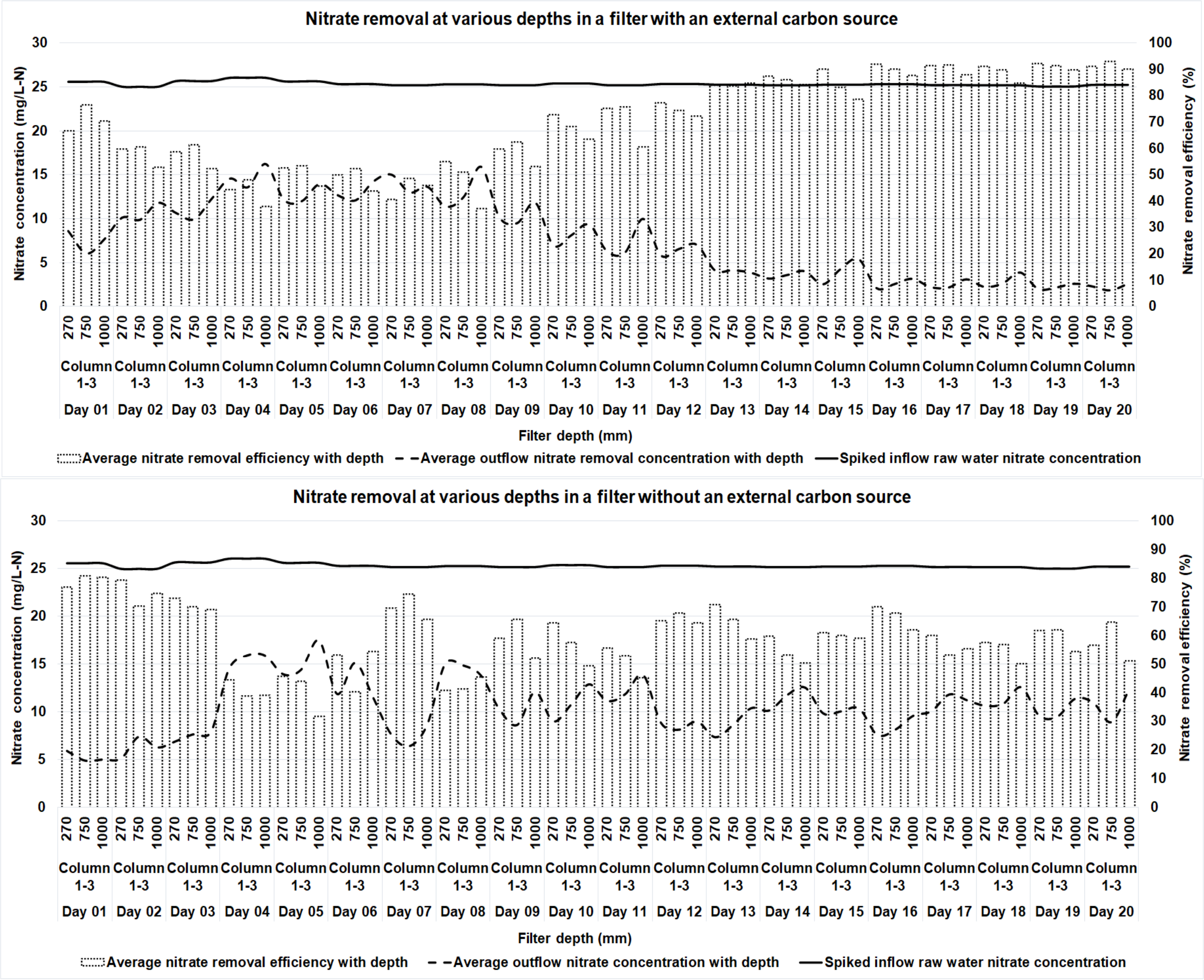


Figure 4.38 Overall average nitrate removal in a filter with and without a source of carbon at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

Figure 4.39 shows the nitrate concentration in the filtrate during and before running the filters with and without a carbon source. The nitrate concentration in raw river water ranged from 6.0 mg/L-N to 20.0 mg/L-N, with an average nitrate concentration of 12.61 mg/L-N. The filter with a carbon source reduced nitrate by 69% during the filter run and by 77% before the filter run, whereas the filter without a carbon source reduced nitrate by 64% during the filter run and by 74% before the filter run.

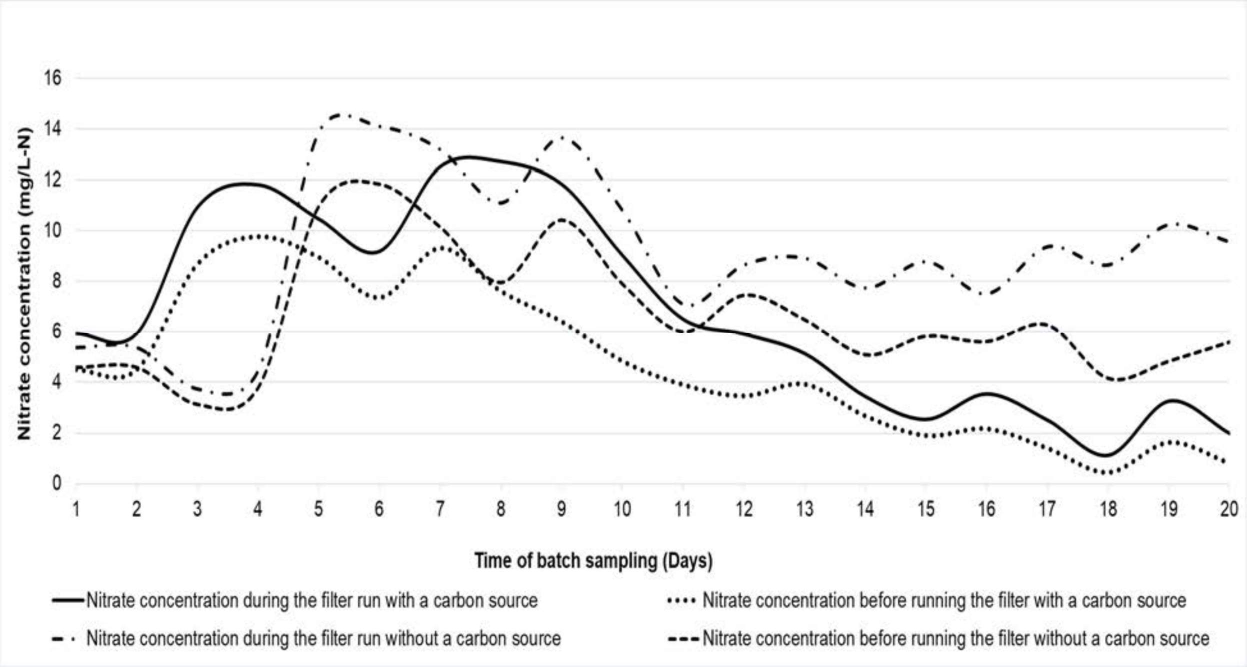


Figure 4.39 Nitrate concentration during and before the filter run in the filter with and without a carbon source at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N.

4.13.3 C/N ratio of 1.1 and inflow nitrate concentration at 50 mg/L-N

Figure 4.40 below represents the average nitrate removal in the filter with (VRF_{wt}) and without (VRF_{wo}) a carbon supply at various depths. In both filters, the initial raw river water had an average nitrate concentration of 3.2 mg/L-N and a spiked concentration of 50.22 mg/L-N. The VRF_{wt} indicates that the nitrate concentration in the filtrate ranged within 3.25 mg/L-N to 17.2 mg/L-N.

At a depth of 270 mm, nitrate removal efficiency was 84%, at 750 mm depth removal efficiency was 83%, and at 1000 mm depth removal efficiency was 82%. In the VRF_{wo}, the average nitrate concentration in the filtrate ranged from 9.8 mg/L-N to 34.3 mg/L-N.

The average removal of nitrate was 63% at a depth of 250 mm, 64% at a depth of 750 mm, and 61% at a depth of 1000 mm.

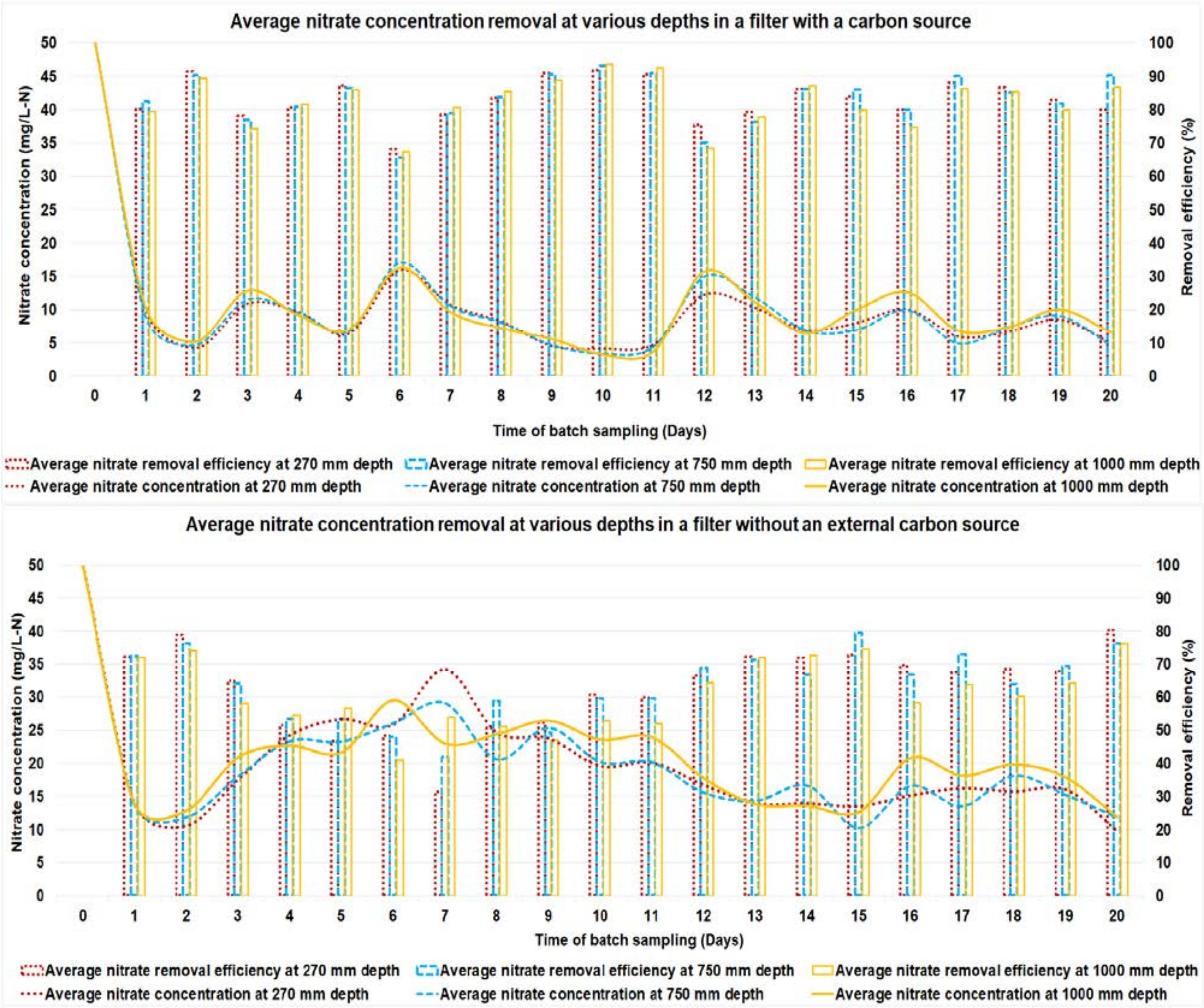


Figure 4.40 Average nitrate removal at varied depth in the filter with and without a carbon source at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

Figures 4.41 below represent the total nitrate removal performance of the filters with and without a carbon source. The total nitrate removal efficiency of the filter with and without a carbon source was 83% and 63%, respectively.

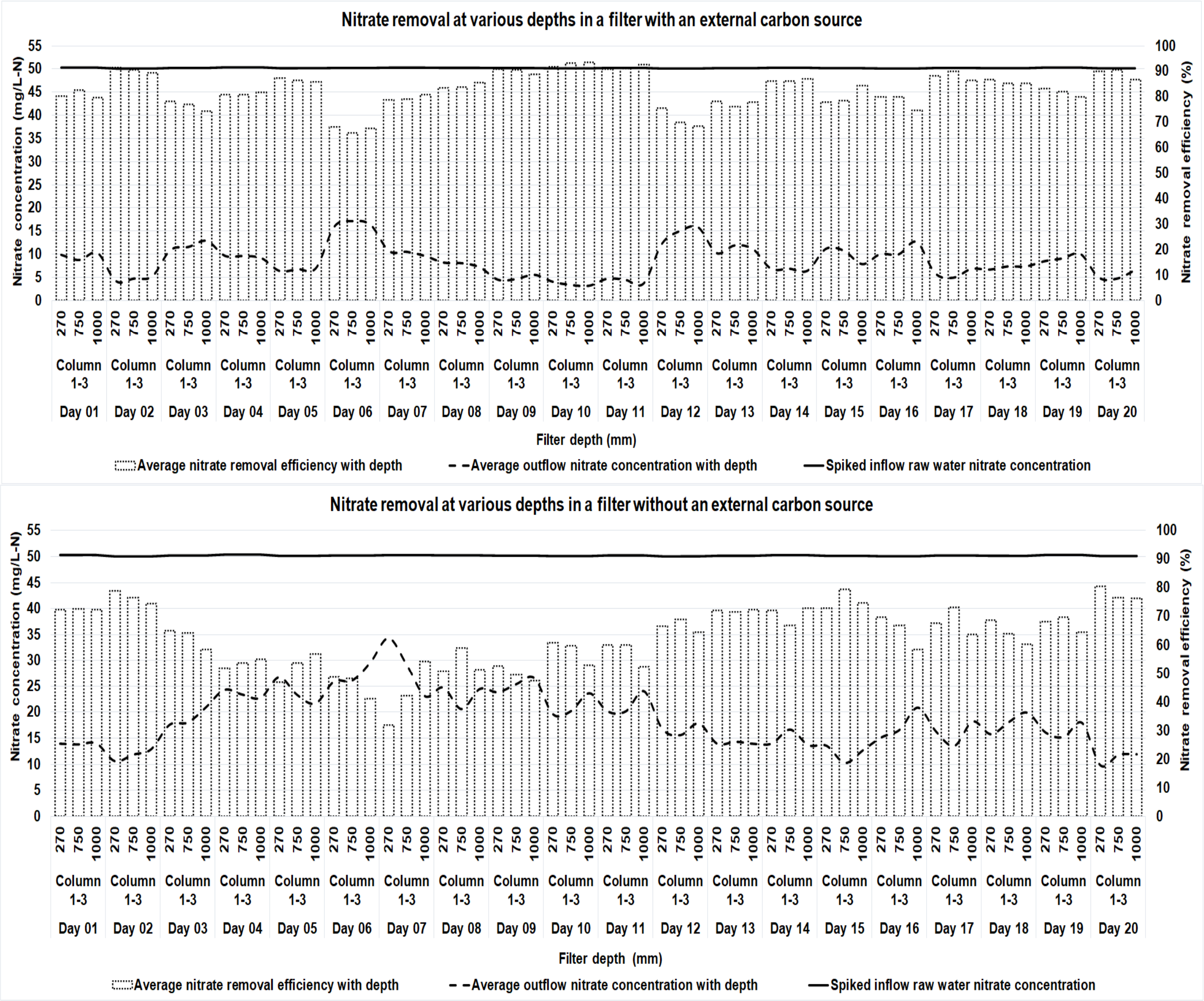


Figure 4.41 Overall average nitrate removal in a filter with and without a source of carbon at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

Figure 4.42 below represents the nitrate concentration in the filtrate during and before running the filters with and without a carbon source. Raw river water had a nitrate content ranging from 3.4 mg/L-N to 20.0 mg/L-N, with an average nitrate value of 13.32 mg/L-N.

The filter with a carbon source reduced nitrate by 85% during the filter run and by 92% before the filter run, whereas the filter without a carbon source reduced nitrate by 67% during the filter run and by 80% before the filter was run.

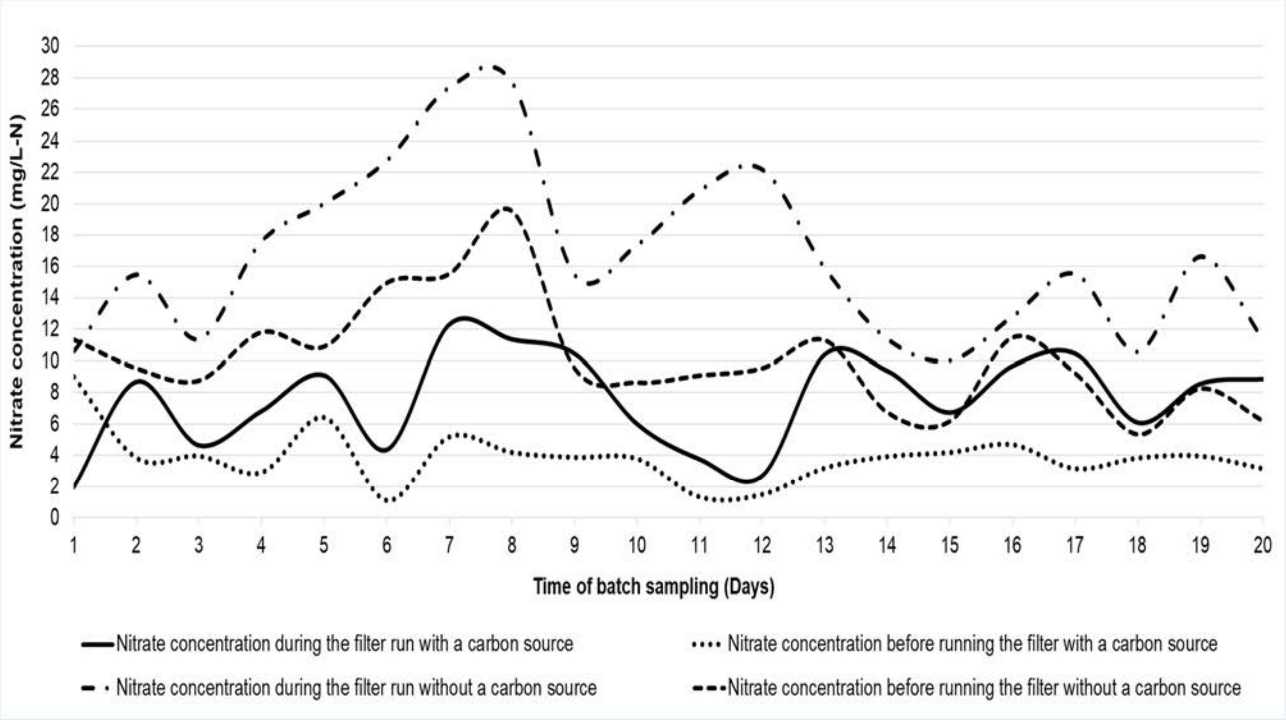


Figure 4.42 Nitrate concentration during and before the filter run in the filter with and without a carbon source at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

4.14 Validation of the Results

Validation of results obtained in both the filter with and without a source of carbon during sampling is presented in this section. The validation was limited to pH, turbidity, dissolved oxygen, temperature, COD, nitrate, and nitrate. Annexure N contains detailed results validation tables and sample calculations.

4.14.1 Nitrate validation at C/N ratio of 1.05 and inflow nitrate concentration of 15 mg/L-N

Table 4.4 below represents nitrate results validation in both the filter with and without a carbon source when the C/N ratio was 1.05.

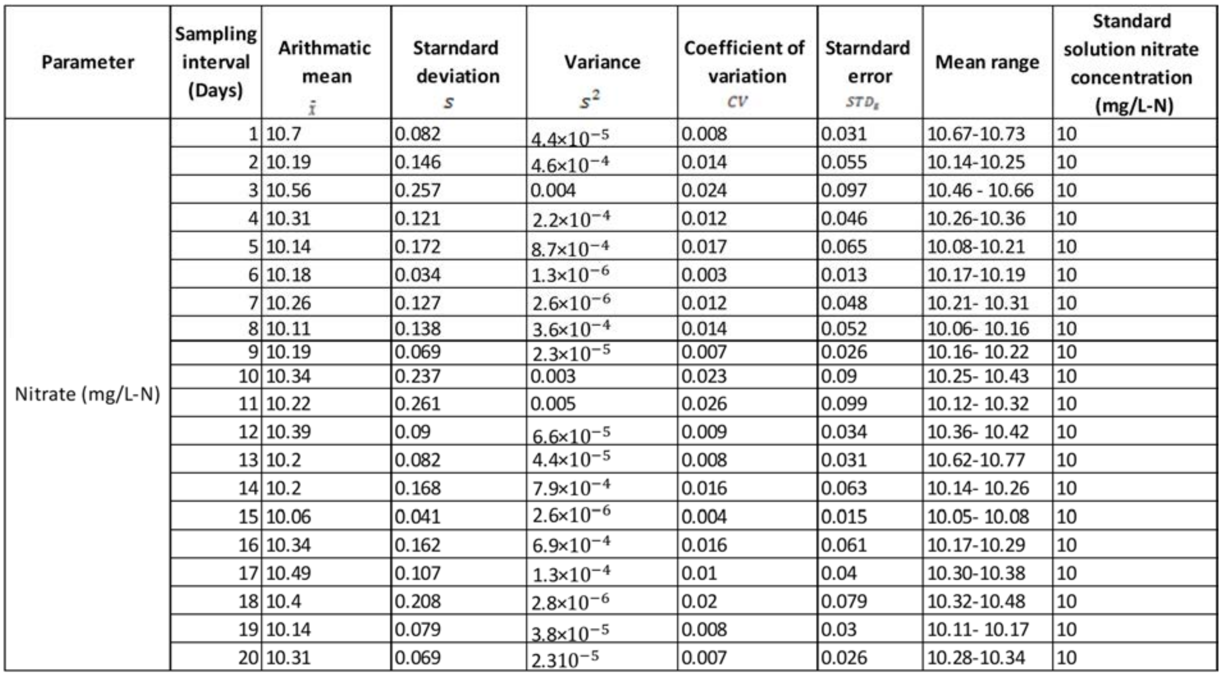
Table 4.4 Results validation for nitrate concentration in the filter with and without a carbon source using C/N ratio of 1.05.

Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error STD_E	Mean range	Standard solution nitrate concentration (mg/L-N)
Nitrate (mg/L-N)	1	10.3	0.1	1.0×10^{-4}	0.01	0.038	10.26-10.34	10
	2	10.18	0.092	7.0×10^{-5}	0.009	0.035	10.15-10.22	10
	3	10.14	0.12	2.1×10^{-4}	0.012	0.045	10.09 - 10.19	10
	4	10.16	0.053	8.2×10^{-6}	0.005	0.02	10.14-10.18	10
	5	10.09	0.113	1.4×10^{-4}	0.011	0.043	10.05-10.13	10
	6	10.13	0.076	3.3×10^{-5}	0.007	0.029	10.10-10.16	10
	7	10.07	0.104	1.2×10^{-4}	0.01	0.039	10.03- 10.11	10
	8	9.98	0.036	1.6×10^{-6}	0.004	0.013	9.97- 9.99	10
	9	10.08	0.023	2.6×10^{-7}	0.002	0.009	10.07- 10.09	10
	10	10.33	0.125	3.8×10^{-9}	0.012	0.047	10.28- 10.38	10
	11	10.1	0.008	2.5×10^{-4}	0.001	0.003	10.09- 10.10	10
	12	10.07	0.017	8.7×10^{-8}	0.002	0.006	10.06- 10.08	10
	13	10.39	0.121	2.2×10^{-4}	0.012	0.046	10.34-10.44	10
	14	10.03	0.071	2.5×10^{-5}	0.007	0.027	10.00- 10.06	10
	15	10.23	0.076	3.3×10^{-5}	0.007	0.029	10.03- 10.09	10
	16	9.93	0.263	0.005	0.026	0.099	9.83-10.03	10
	17	10.4	0.1	1.0×10^{-4}	0.01	0.038	10.36-10.44	10
	18	10.16	0.053	8.2×10^{-6}	0.005	0.02	10.14-10.18	10
	19	10.09	0.018	1.1×10^{-7}	0.002	0.007	10.08- 10.09	10
	20	10.37	0.111	1.5×10^{-4}	0.011	0.042	10.33-10.41	10

4.14.2 Nitrate validation at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Table 4.5 below represents nitrate results validation in both the filter with and without a carbon source when the C/N ratio was 1.08.

Table 4.5 Results validation for nitrate concentration in the filter with and without a carbon source using C/N ratio of 1.08.

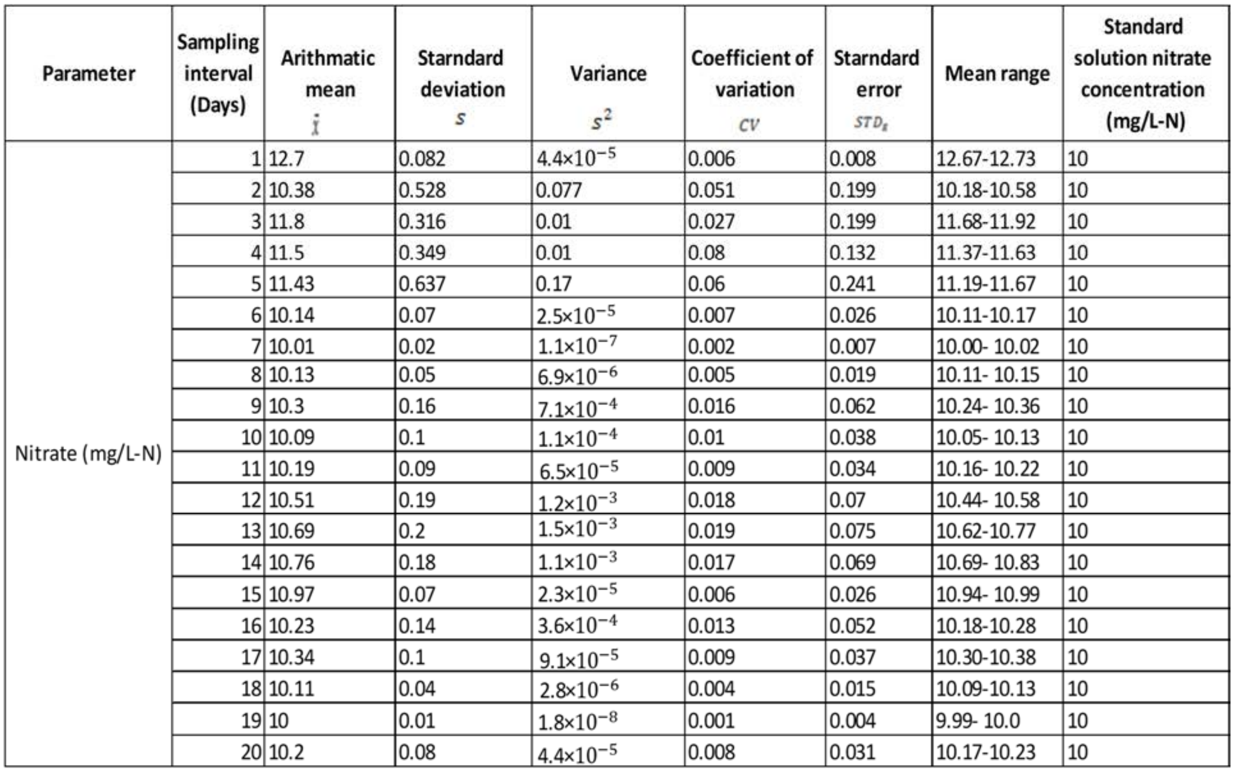


Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error STD_E	Mean range	Standard solution nitrate concentration (mg/L-N)
Nitrate (mg/L-N)	1	10.7	0.082	4.4×10^{-5}	0.008	0.031	10.67-10.73	10
	2	10.19	0.146	4.6×10^{-4}	0.014	0.055	10.14-10.25	10
	3	10.56	0.257	0.004	0.024	0.097	10.46 - 10.66	10
	4	10.31	0.121	2.2×10^{-4}	0.012	0.046	10.26-10.36	10
	5	10.14	0.172	8.7×10^{-4}	0.017	0.065	10.08-10.21	10
	6	10.18	0.034	1.3×10^{-6}	0.003	0.013	10.17-10.19	10
	7	10.26	0.127	2.6×10^{-6}	0.012	0.048	10.21- 10.31	10
	8	10.11	0.138	3.6×10^{-4}	0.014	0.052	10.06- 10.16	10
	9	10.19	0.069	2.3×10^{-5}	0.007	0.026	10.16- 10.22	10
	10	10.34	0.237	0.003	0.023	0.09	10.25- 10.43	10
	11	10.22	0.261	0.005	0.026	0.099	10.12- 10.32	10
	12	10.39	0.09	6.6×10^{-5}	0.009	0.034	10.36- 10.42	10
	13	10.2	0.082	4.4×10^{-5}	0.008	0.031	10.62-10.77	10
	14	10.2	0.168	7.9×10^{-4}	0.016	0.063	10.14- 10.26	10
	15	10.06	0.041	2.6×10^{-6}	0.004	0.015	10.05- 10.08	10
	16	10.34	0.162	6.9×10^{-4}	0.016	0.061	10.17-10.29	10
	17	10.49	0.107	1.3×10^{-4}	0.01	0.04	10.30-10.38	10
	18	10.4	0.208	2.8×10^{-6}	0.02	0.079	10.32-10.48	10
	19	10.14	0.079	3.8×10^{-5}	0.008	0.03	10.11- 10.17	10
	20	10.31	0.069	2.310^{-5}	0.007	0.026	10.28-10.34	10

4.14.3 Nitrate validation at C/N ratio of 1.08 and inflow nitrate concentration of 25 mg/L-N

Table 4.6 below represents nitrate results validation in both the filter with and without a carbon source when the C/N ratio was 1.1.

Table 4.6 Results validation for nitrate concentration in the filter with and without a carbon source using C/N ratio of 1.1.



Parameter	Sampling interval (Days)	Arithmatic mean $\dot{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error STD_E	Mean range	Standard solution nitrate concentration (mg/L-N)
Nitrate (mg/L-N)	1	12.7	0.082	4.4×10^{-5}	0.006	0.008	12.67-12.73	10
	2	10.38	0.528	0.077	0.051	0.199	10.18-10.58	10
	3	11.8	0.316	0.01	0.027	0.199	11.68-11.92	10
	4	11.5	0.349	0.01	0.08	0.132	11.37-11.63	10
	5	11.43	0.637	0.17	0.06	0.241	11.19-11.67	10
	6	10.14	0.07	2.5×10^{-5}	0.007	0.026	10.11-10.17	10
	7	10.01	0.02	1.1×10^{-7}	0.002	0.007	10.00- 10.02	10
	8	10.13	0.05	6.9×10^{-6}	0.005	0.019	10.11- 10.15	10
	9	10.3	0.16	7.1×10^{-4}	0.016	0.062	10.24- 10.36	10
	10	10.09	0.1	1.1×10^{-4}	0.01	0.038	10.05- 10.13	10
	11	10.19	0.09	6.5×10^{-5}	0.009	0.034	10.16- 10.22	10
	12	10.51	0.19	1.2×10^{-3}	0.018	0.07	10.44- 10.58	10
	13	10.69	0.2	1.5×10^{-3}	0.019	0.075	10.62-10.77	10
	14	10.76	0.18	1.1×10^{-3}	0.017	0.069	10.69- 10.83	10
	15	10.97	0.07	2.3×10^{-5}	0.006	0.026	10.94- 10.99	10
	16	10.23	0.14	3.6×10^{-4}	0.013	0.052	10.18-10.28	10
	17	10.34	0.1	9.1×10^{-5}	0.009	0.037	10.30-10.38	10
	18	10.11	0.04	2.8×10^{-6}	0.004	0.015	10.09-10.13	10
	19	10	0.01	1.8×10^{-8}	0.001	0.004	9.99- 10.0	10
	20	10.2	0.08	4.4×10^{-5}	0.008	0.031	10.17-10.23	10

4.15 Statistical Analysis

A two-way analysis of variance (ANOVA) was used to test the null hypothesis that the measured parameters which include pH, dissolved Oxygen (DO), nitrite (NO_2^-) and temperature have a significant influence on the removal of nitrate (NO_3^-) in the vertical roughing filter with or without an external carbon source at varied nitrate concentrations and C/N ratios. The ANOVA between subject's findings are presented in Table 4.7 below while the results on individual parameter influences on nitrate removal using multiple comparison post-hoc test are presented in Tables 4.8 and 4.9 below.

Table 4.7 ANOVA between subject's results in the filter with and without a carbon source at varied nitrate concentrations.

Vertical roughing filter without a carbon source (VRFwo)							
Inflow nitrate concentration (mg/L-N)	C/N ratio	Degree of freedom (df)	Mean square (MS)	F-Statistic (F)	Mean square error	Probability value (P-value)	F-Critical (F-Crit)
15	-	4	1679.06	1986.062	0.845	<0.001	2.492
25	-	4	1416.59	466.094	3.039	<0.001	2.492
50	-	4	2144.27	369.078	5.81	<0.001	2.492
Vertical roughing filter with a carbon source (VRFwt)							
15	1.05	4	1858.61	3872.413	0.48	<0.001	2.492
25	1.08	4	1567.27	273.311	5.734	<0.001	2.492
50	1.1	4	1879.52	737.204	2.55	<0.001	2.492

Table 4.8 Post-hoc comparison test in a filter without a carbon source (VRF_{wo}) at inflow nitrate concentration of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N.

Multiple Comparisons							
	(I) Measured parameter in the filter without a carbon source (VRFwo) at inflow nitrate concentration of 15 mg/L-N	(J) Measured parameter in the filter without a carbon source (VRFwo) at inflow nitrate concentrtion of 15 mg/L-N	Mean Difference (I-J)	Stamdard Error	Probability value (P-value)	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Nitrate	pH	-2.3050*	0.29076	0.000	-3.1175	-1.4925
		Dissolved oxygen	-0.5325	0.29076	0.363	-1.3450	0.2800
		Nitrite	4.8305*	0.29076	0.000	4.0180	5.6430
		Temperature	-19.1190*	0.29076	0.000	-19.9315	-18.3065
	At inflow nitrate concentration of 25 mg/L-N	At inflow nitrate concentration of 25 mg/L-N					
Tukey HSD	Nitrate	pH	3.2165*	0.55130	0.000	1.6760	4.7570
		Dissolved oxygen	5.5615*	0.55130	0.000	4.0210	7.1020
		Nitrite	9.8285*	0.55130	0.000	8.2880	11.3690
		Temperature	-12.3775*	0.55130	0.000	-13.9180	-10.8370
	At inflow nitrate concentration of 50 mg/L-N	At inflow nitrate concentration of 50 mg/L-N					
Tukey HSD	Nitrate	pH	11.4375*	0.76222	0.000	9.3076	13.5674
		Dissolved oxygen	13.1390*	0.76222	0.000	11.0091	15.2689
		Nitrite	18.5865*	0.76222	0.000	16.4566	20.7164
		Temperature	-6.7345*	0.76222	0.000	-8.8644	-4.6046
Based on observed means. The error term is Mean Square (Error): =0.845 at 15 mg/L-N =3.039 at 25 mg/L-N =5.810 at 50 mg/L-N *The mean difference is significant at the 0.05 level.							

Table 4.9 Post-hoc comparison test in a filter with a carbon source (VRF_{wt}) at inflow nitrate concentration of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N.

Multiple Comparisons							
	(I) Measured parameter in the filter with a carbon source (VRFwt) at inflow nitrate concentration of 15 mg/L-N and C/N ratio of 1.05	(J) Measured parameter in the filter with a carbon source (VRFwt) at inflow nitrate concentration of 15 mg/L-N and C/N ratio of 1.05	Mean Difference (I-J)	Starndard Error	Probability value (P-value)	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Nitrate	pH	-5.0970*	0.21908	0.000	-5.7092	-4.4848
		Dissolved oxygen	-1.6805*	0.21908	0.000	-2.2927	-1.0683
		Nitrite	1.8200*	0.21908	0.000	1.2078	2.4322
		Temperature	-22.0285*	0.21908	0.000	-22.6407	-21.4163
	At inflow nitrate concentration of 25 mg/L-N and C/N ratio of 1.08	At inflow nitrate concentration of 25 mg/L-N and C/N ratio of 1.08					
Tukey HSD	Nitrate	pH	0.7445*	0.75725	0.862	-1.3715	2.8605
		Dissolved oxygen	5.6460*	0.75725	0.000	3.5300	7.7620
		Nitrite	7.2230*	0.75725	0.000	5.1070	9.3390
		Temperature	-15.1430*	0.75725	0.000	-17.2590	-13.0270
	At inflow nitrate concentration of 50 mg/L-N and C/N ratio of 1.1	At inflow nitrate concentration of 50 mg/L-N and C/N ratio of 1.1					
Tukey HSD	Nitrate	pH	1.1515*	0.50493	0.163	-0.2594	2.5624
		Dissolved oxygen	5.4370*	0.50493	0.000	4.0261	6.8479
		Nitrite	7.3525*	0.50493	0.000	5.9416	8.7634
		Temperature	-17.1165*	0.50493	0.000	-18.5274	-15.7056

Based on observed means.
The error term is Mean Square (Error):
= 0.480 at 15 mg/L-N
= 5.734 at 25 mg/L-N
= 2.550 at 50 mg/L-N
*The mean difference is significant at the 0.05 level.

4.16 The Predictive Nitrate Removal Model in a Vertical Roughing Filter

This section presents the nitrate model that best describes the removal of nitrate in a vertical roughing filter. The general approach to developing the kinetic removal rate equation have been developed over the past years, as described in the literature review section 2.10. In this research, a predictive nitrate removal rate model was established empirically from analysis of obtained test results from the laboratory. The filter with an external carbon source (VRF_{wt}) and the filter without an external carbon source (VRF_{wo}) were each evaluated at inflow nitrate concentrations of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N, in order to obtain the best data plot that will best describe the removal of nitrate in a vertical roughing filter.

The model development related the inlet and outlet nitrate concentrations as a function of physiochemical parameters such as flow rate, dissolved oxygen concentration, pH, C/N ratio and temperature. The removal of nitrate in an upward vertical roughing filter process by heterogeneous microorganisms was evaluated based on the reaction rate verses the outflow nitrate concentration as presented in Figure 4.43 below. Figure 4.44 below illustrates a log-log plot of the experimental data to obtain a reaction rate order (n) while corresponding zero kinetic reaction rate constant (k_0) was estimated by a regression analysis of outflow nitrate concentration (C_e), with respect to time of sampling as presented in Figure 4.45 below. The removal of nitrate in the vertical roughing filter was evaluated based on the change in concentration of nitrate across the filters, divided by the hydraulic retention time. The approach used was also based on the assumption that the rate of reaction was proportional to the n^{th} power of the nitrate concentration. The predictive nitrate removal in a vertical roughing filter is described by a zero-order kinetic rate model, as described by Equation 4.3 to 4.7. The regression analysis data and zero order kinetic coefficients on all results obtained are listed in Table 4.10 below. Annexure O provides detailed tables on the analysis and laboratory results data for the predictive nitrate removal rate model development.

$$\frac{dC_{NO_3-}}{dt} = \frac{Q(C_{i-}C_e)}{V_r} = -k_0 \times C^n_{NO_3-} \qquad (4.3)$$

Where:

$\frac{dC_{NO_3^-}}{dt}$= Kinetic nitrate reaction rate (mg/L/day)

$dC_{NO_3^-}$= Change in nitrate across the roughing filter (mg/L)

$C_{NO_3^-}$= Nitrate concentration (mg/L)

Q= Flow rate through the roughing filter (L/day)

C_i= Concentration of nitrate inflow (mg/L)

C_e= Concentration of nitrate in the filtrate (mg/L)

V_r= Volume of roughing filter (L)

k_0= Zero order reaction rate constant (mg/L/day)

n= Reaction rate order

by substituting n = 0 (zero order) that was evaluated from taking the average of the regression slops values in Figure 4.44 below.

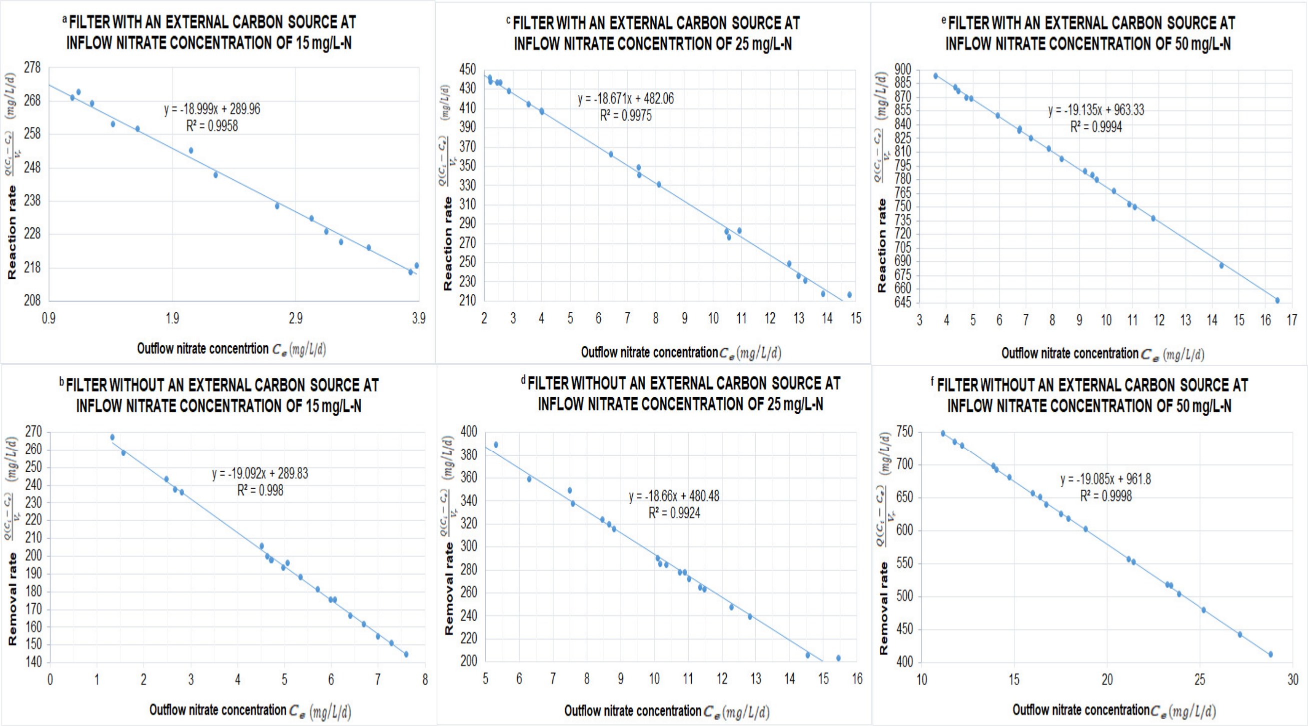
$$\frac{dC_{NO_3^-}}{dt} = \frac{Q(C_i - C_e)}{V_r} = -k_0 \times C^0_{NO_3^-} \tag{4.4}$$

by substituting k = 0.244 mg/L/day) that was evaluated from taking the average of the regression slopes values in Figure 4.45 below.

$$\frac{dC_{NO_3^-}}{dt} = \frac{Q(C_i - C_e)}{V_r} = -0.244 \tag{4.5}$$

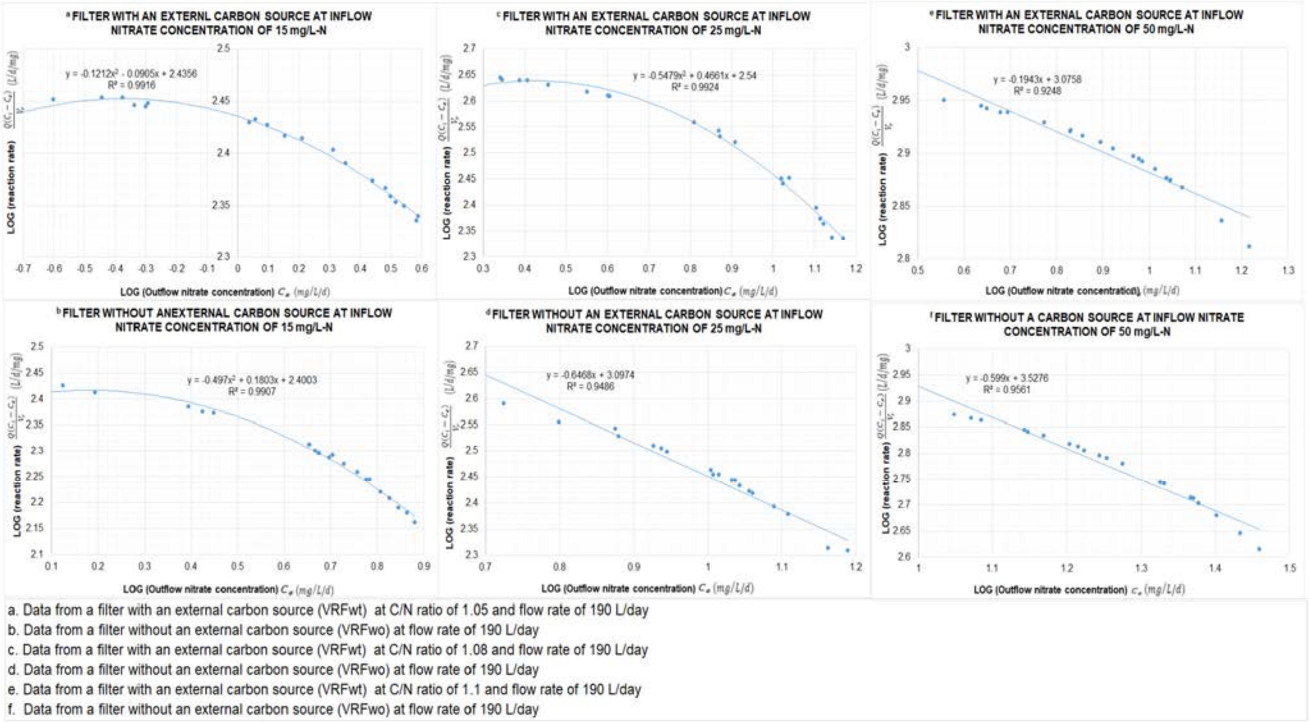
$$V_r = \frac{Q(C_i - C_e)}{-0.244} \tag{4.6}$$

$$C_e = \frac{QC_i - 0.244V_r}{Q} \tag{4.7}$$



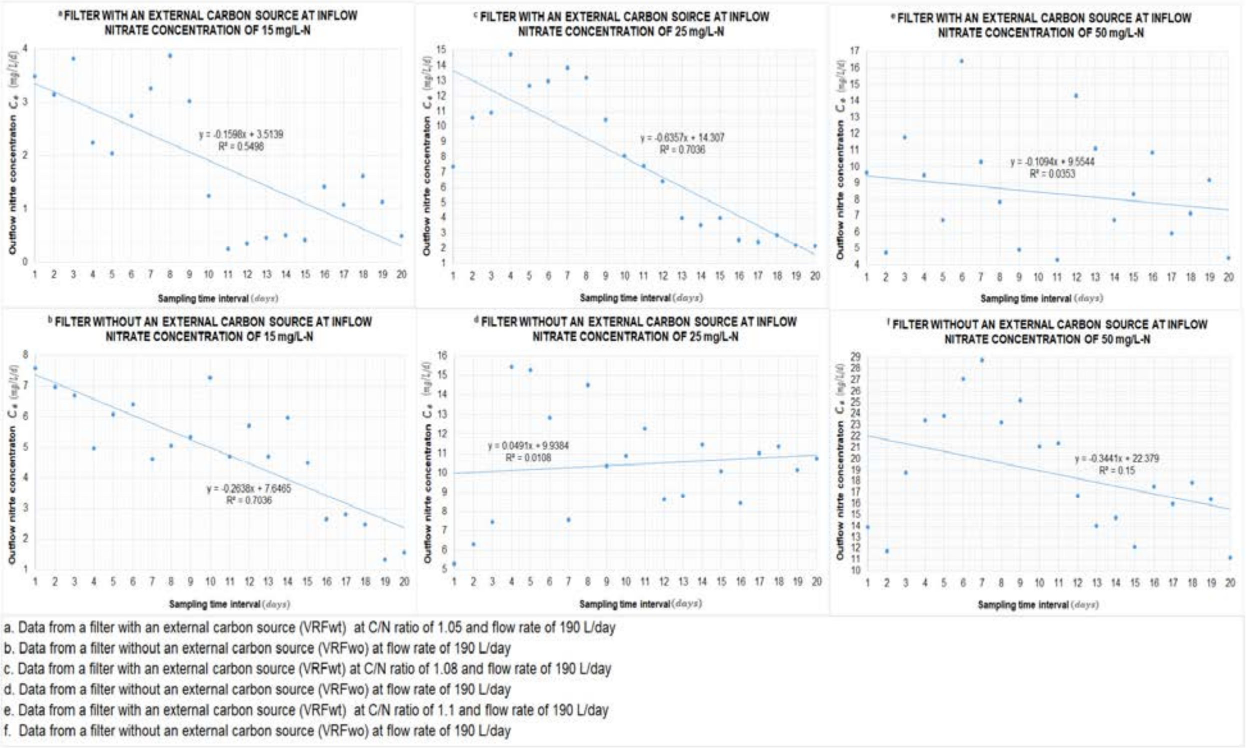
a. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.05 and flow rate of 190 L/day
b. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day
c. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.08 and flow rate of 190 L/day
d. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day
e. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.1 and flow rate of 190 L/day
f. Data from a filter without an external carbon source (VRFwo) at and flow rate of 190 L/day

Figure 4.43 Kinetic reaction rate ($\frac{Q(C_i - C_e)}{V_r}$) for the removal of nitrate with respect to outflow nitrate concentration (C_e) in the filter with and without a carbon source.



a. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.05 and flow rate of 190 L/day
b. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day
c. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.08 and flow rate of 190 L/day
d. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day
e. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.1 and flow rate of 190 L/day
f. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day

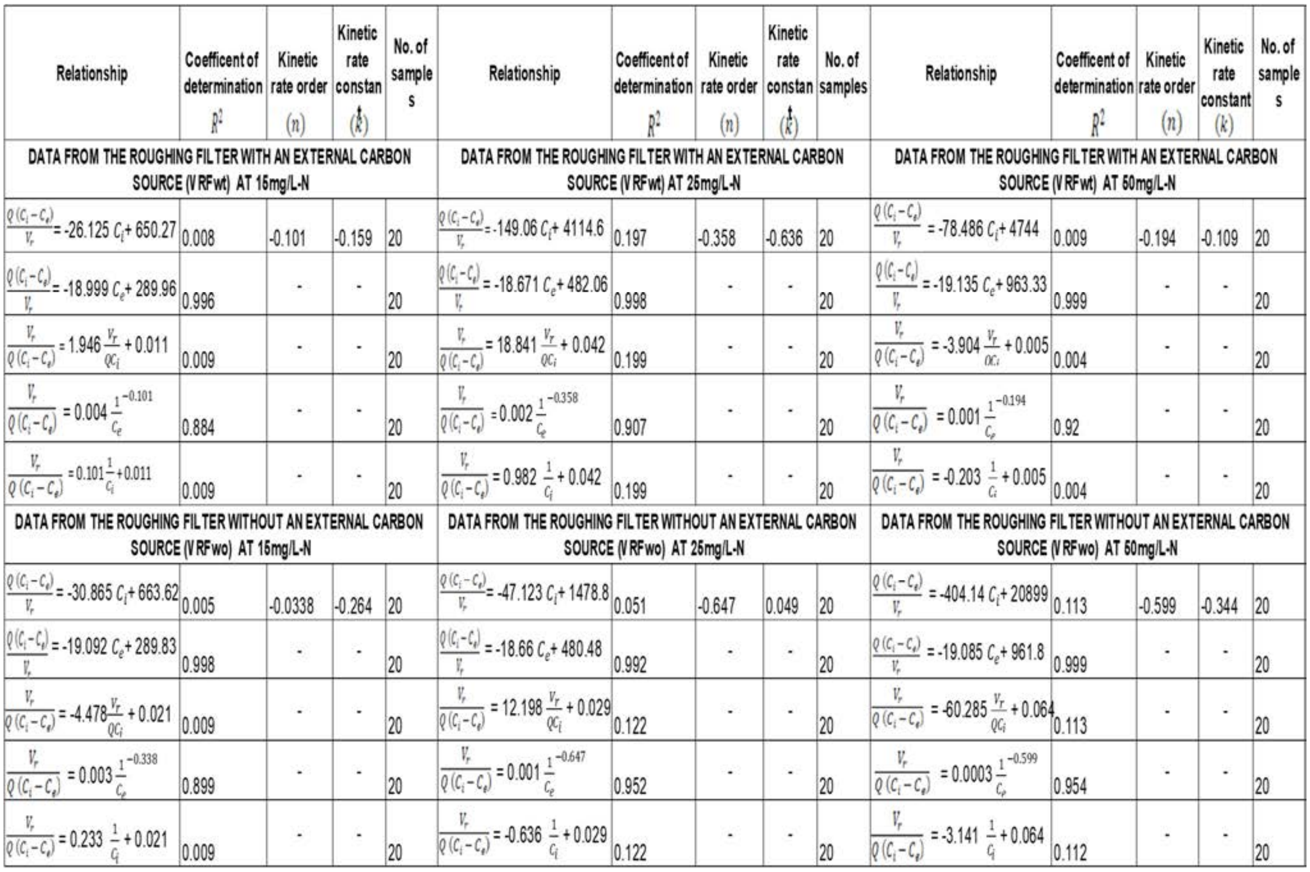
Figure 4.44 Kinetic reaction rate order (n) analysis for an upward vertical roughing filter.



a. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.05 and flow rate of 190 L/day
b. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day
c. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.08 and flow rate of 190 L/day
d. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day
e. Data from a filter with an external carbon source (VRFwt) at C/N ratio of 1.1 and flow rate of 190 L/day
f. Data from a filter without an external carbon source (VRFwo) at flow rate of 190 L/day

Figure 4.45 Nitrate concentration as a function of time showing the zero-order reaction rate constant (k_0).

Table 4.10 Regression analysis data and zero order kinetic coefficients from the roughing filter with and without a carbon source.



Relationship	Coefficent of determination R^2	Kinetic rate order (n)	Kinetic rate constan (k)	No. of samples	Relationship	Coefficent of determination R^2	Kinetic rate order (n)	Kinetic rate constan (k)	No. of samples	Relationship	Coefficent of determination R^2	Kinetic rate order (n)	Kinetic rate constant (k)	No. of samples
DATA FROM THE ROUGHING FILTER WITH AN EXTERNAL CARBON SOURCE (VRFwt) AT 15mg/L-N					DATA FROM THE ROUGHING FILTER WITH AN EXTERNAL CARBON SOURCE (VRFwt) AT 25mg/L-N					DATA FROM THE ROUGHING FILTER WITH AN EXTERNAL CARBON SOURCE (VRFwt) AT 50mg/L-N				
$\frac{Q(C_i-C_e)}{V_r} = -26.125\,C_i + 650.27$	0.008	-0.101	-0.159	20	$\frac{Q(C_i-C_e)}{V_r} = -149.06\,C_i + 4114.6$	0.197	-0.358	-0.636	20	$\frac{Q(C_i-C_e)}{V_r} = -78.486\,C_i + 4744$	0.009	-0.194	-0.109	20
$\frac{Q(C_i-C_e)}{V_r} = -18.999\,C_e + 289.96$	0.996	-	-	20	$\frac{Q(C_i-C_e)}{V_r} = -18.671\,C_e + 482.06$	0.998	-	-	20	$\frac{Q(C_i-C_e)}{V_r} = -19.135\,C_e + 963.33$	0.999	-	-	20
$\frac{V_r}{Q(C_i-C_e)} = 1.946\,\frac{V_r}{QC_i} + 0.011$	0.009	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 18.841\,\frac{V_r}{QC_i} + 0.042$	0.199	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = -3.904\,\frac{V_r}{QC_i} + 0.005$	0.004	-	-	20
$\frac{V_r}{Q(C_i-C_e)} = 0.004\,\frac{1}{C_e}^{-0.101}$	0.884	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 0.002\,\frac{1}{C_e}^{-0.358}$	0.907	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 0.001\,\frac{1}{C_e}^{-0.194}$	0.92	-	-	20
$\frac{V_r}{Q(C_i-C_e)} = 0.101\frac{1}{C_i} + 0.011$	0.009	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 0.982\,\frac{1}{C_i} + 0.042$	0.199	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = -0.203\,\frac{1}{C_i} + 0.005$	0.004	-	-	20
DATA FROM THE ROUGHING FILTER WITHOUT AN EXTERNAL CARBON SOURCE (VRFwo) AT 15mg/L-N					DATA FROM THE ROUGHING FILTER WITHOUT AN EXTERNAL CARBON SOURCE (VRFwo) AT 25mg/L-N					DATA FROM THE ROUGHING FILTER WITHOUT AN EXTERNAL CARBON SOURCE (VRFwo) AT 50mg/L-N				
$\frac{Q(C_i-C_e)}{V_r} = -30.865\,C_i + 663.62$	0.005	-0.0338	-0.264	20	$\frac{Q(C_i-C_e)}{V_r} = -47.123\,C_i + 1478.8$	0.051	-0.647	0.049	20	$\frac{Q(C_i-C_e)}{V_r} = -404.14\,C_i + 20899$	0.113	-0.599	-0.344	20
$\frac{Q(C_i-C_e)}{V_r} = -19.092\,C_e + 289.83$	0.998	-	-	20	$\frac{Q(C_i-C_e)}{V_r} = -18.66\,C_e + 480.48$	0.992	-	-	20	$\frac{Q(C_i-C_e)}{V_r} = -19.085\,C_e + 961.8$	0.999	-	-	20
$\frac{V_r}{Q(C_i-C_e)} = -4.478\frac{V_r}{QC_i} + 0.021$	0.009	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 12.198\,\frac{V_r}{QC_i} + 0.029$	0.122	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = -60.285\,\frac{V_r}{QC_i} + 0.064$	0.113	-	-	20
$\frac{V_r}{Q(C_i-C_e)} = 0.003\,\frac{1}{C_e}^{-0.338}$	0.899	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 0.001\,\frac{1}{C_e}^{-0.647}$	0.952	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = 0.0003\,\frac{1}{C_e}^{-0.599}$	0.954	-	-	20
$\frac{V_r}{Q(C_i-C_e)} = 0.233\,\frac{1}{C_i} + 0.021$	0.009	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = -0.636\,\frac{1}{C_i} + 0.029$	0.122	-	-	20	$\frac{V_r}{Q(C_i-C_e)} = -3.141\,\frac{1}{C_i} + 0.064$	0.112	-	-	20

Chapter 5 Discussions

This section discusses and evaluates the findings presented in Chapter 4. The treatment performance of nitrate in surface water using a conventional upward vertical roughing filter with and without a carbon supply is discussed, as well as the relationship between physicochemical parameters in a vertical roughing filter. Furthermore, it presents a discussion on a suitable carbon: Nitrogen (C/N) ratio in a vertical roughing filter for optimum nitrate removal; on suitable optimal time and depth for removal of nitrate removal in a vertical roughing filter; and on the impact of biomass growth on filter operation and treated water quality in terms of residual Carbon in order to meet water quality standards. A suitable kinetic nitrate rate model for predicting the removal of nitrate in a vertical roughing filter is also proposed.

5.1 Treatment Performance of the Vertical Roughing Filter in Series (VRFs)

Various parameters were evaluated in order to assess if they have an effect on nitrate removal in a VRF system. The raw water from the 20 L feed tank represented the inflow to the filter columns and was so termed as the 'inflow'. Similarly, the final filtrate from the outlets of each sampling point was termed as 'outflow'. This terminology has been used throughout Chapter 5 to facilitate interpretation.

5.1.1 Physiochemical parameter characterisation of untreated and roughing filter treated river water

Initially, untreated, and roughing filter-treated river water samples were sent to the Bemlab Laboratory for chemical analysis on nitrate and COD. The water samples were taken from the roughing filter that used a source of carbon (VRF_{wt}). The same water samples were also tested at the CPUT laboratory. Table 5.1 below presents the results from the CPUT laboratory while Annexure B provides results from the Bemlab Laboratory.

The average nitrate concentration of the raw water was 16.06 mg/L-N while the average COD was 117.07 mg/L-O_2. Since the source river flows through an industrial area, this nitrate concentration above the maximum limit guideline set by WHO (2011) and SANS (2015) (16.06 mg/L-N > 11 mg/L-N) could be attributed to waste disposal and surface runoff into the river.

The average nitrate concentration was found to be within the normal average nitrate levels in surface and ground water of 0 to 18 mg/L-N, as stated by WHO (2011). However, this nitrate concentration was above the maximum limit guideline value of 11mg/L-N set by WHO and the

South African National Standards (SANS, 241). Thus, nitrate removal from the raw water was required. The raw river water was also spiked with potassium nitrate to increase the initial concentration. Increasing the nitrate concentration allowed a wider range of evaluation of nitrate removal efficiency of an up-ward vertical roughing filter (UVRF). The results showed that the UVRF was successful in reducing high nitrate concentration in raw river water to values below the guideline value of 11 mg/L-N.

Table 5.1 COD and nitrate laboratory results performed on raw river water before filtering (Inflow)and river water after filtering (Outflow).

Tested date	Test	Units	CPUT LABORATORY		
			Unspiked raw water sample	KNO_3 & Ethanol spiked inflow raw water sample	KNO_3 & Ethanol Spiked outflow water sample
18-09-2020	Nitrate	(mg/L- N)	15.9	25.4	5.32
	COD	(mg/L O_2)	128	1258	760
29-10-2020	Nitrate	(mg/L- N)	14.55	25.19	3.09
	COD	(mg/L O_2)	112.5	979	598
17-12-2020	Nitrate	(mg/L- N)	17.73	25.19	10
	COD	(mg/L O_2)	110.72	1037	688

5.2 Roughing Filter Flow Rate

As presented in Figure 4.3 above, the initial flow rate in the vertical roughing filter without a carbon source (VRF_{wo}) was 0.133 L/m and decreased to 0.113 L/m at the end of the filter operation. In the vertical roughing filter with a carbon source, the flow rate dropped from 0.133 L/m to 0.096 L/m (VRF_{wt}). A decline in flow rate was more significant in the filter dosed with an external carbon source (VRF_{wt}) at 27 %, compared to the 15 % drop noticed in a filter without a carbon source VRF_{wo}. The decline in filtration rate was caused by filter maturity and was significant as the biological layer matured. Studies by Eljamal *et al.* (2006) and Eljamal *et al.*(2007) also reported the same phenomenon on bacteria growth and microbial build-up that results in resistance in flow through columns when sawdust and bamboo chip were used as an organic carbon source.

As a result, this implies that the filter with an external carbon source provided favourable conditions for heterotrophic bacterial growth, resulting in the rapid development of the biological layer on the gravel medium. The fast biological layer formation on the gravel media will eventually cause the filter to clog and limit the flow of water through the filter media, lowering the daily water production. In this case, the filter would need to be flushed out with clean water in order to deprive the microorganism nutrients from rapidly growing and developing the biological layer. Furthermore, sloughing of the biological layer was observed when the microorganisms were deprived nutrients in order to reduce the rapid biological layer growth and also as the flow rate varied. The presence of the slough lead to some physical aesthetic changes in the filtrate such colour, increase in turbidity, total suspended solids (TSS) and undesirable odour.

The biological filter media ripening increases the removal efficiency of nitrate in roughing filters, because the filter media becomes stickier (Collins *et al.*1994). The organic layer typically requires 20-30 days to mature in a new filter, depending on the inflow water quality and operating temperature (Mahlangu, 2011). However, due to intermittent operation of the filter during this research, maturity was evident at 30-35 days from the start of the filter operation. A start of a drastic drop-in flow rate was evident during the 30–35-day period. The filters were operated for 12 hrs during the day and thereafter rested for 12 hrs.

5.3 Changes in pH and Dissolved Oxygen

There was a decrease in pH towards the top at 1 m depth. The pH decrease could be caused by the acid formation from the nitrification process that mostly produces acid at the top zone of the filter column; that is highly exposed to oxygen. Eljamal *et al.* (2020) also reported that a decrease in pH is caused by the nitrification process as the bacteria use the alkalinity as a source of carbon. There was also a pH rise towards the bottom of the filter and predominantly at a depth of 0.25 m to 0.75 m in both filters, where less oxygen was exposed. The increase in pH can result during denitrification when carbon dioxide and oxygen hydroxide (OH^-) are produced as nitrate is reduced to gaseous nitrogen. These products can combine to create carbonate (CO_3^2) and bicarbonate (HCO_3-) (Wang *et al.,* 1995). However, because denitrification occurs best at a pH range of 7.0-8.5, the fluctuation in pH could still favour denitrification (Wang et al., 1995). pH levels less than 6.0 and greater than 8.5 could have resulted in a severe reduction in denitrification activities or a decreased microorganism growth rate, resulting in an unfavourable environment for denitrification. Overall, the pH levels were within the permissible South African and WHO guideline limits of 5.0-9.7 (SANS, 2015; WHO, 2011).

Dissolved oxygen concentration can be influenced by a number of factors such as water temperature, salinity, organic matter, and atmospheric pressure. However, only temperature was measured in this research. The filters were operated at temperatures varying between 18℃ to 28℃. Depending on the level of pollution, DO in river water can usually range between 0-18 mg/L (Mutsvangwa & Matope, 2017). High %age decrease in DO towards the bottom of the filter (270 mm and 750 mm) suggested anoxic conditions whereby denitrification occurs when oxygen levels are depleted and nitrate becomes the primary oxygen source for microorganisms, whereas a low %age decrease in DO towards the top zone of the filter (1000 mm) with excess oxygen suggests a favourable condition for the nitrification process.

5.4 Residual Ethanol Measured as Chemical Oxygen Demand (COD)

The results of residual carbon trend measured as COD, during the filter run and before running the filter at varied C/N ratios, is presented in section 4.9. The average residual ethanol measured as COD in the filter with an external carbon source (VRF_{wt}) during the filter run was 85 mg/L, 632 mg/L and 618 mg/L. The corresponding removal efficiency was 75, 43, and 46 % at C/N ratio of 1.05,1.08 and 1.1, respectively. The average residual ethanol measured as COD before running the filter was 41 mg/L, 561 mg/L and 533 mg/L and the removal efficiency was 88, 49 and 53 % at a C/N ratio of 1.05,1.08 and 1.1, respectively.

The results obtained prior to running the filter revealed a greater COD removal efficiency than the removal efficiency during the filter run. The COD removal fluctuated with time, as the sampling interval increased. The same trend was observed from the nitrate samples taken before running the filter, as previously shown in Figures 4.36, 4.39 and 4.42. This demonstrated that the period before running the filter provided effective time for the microorganisms to further respond during denitrification. However, it was observed that the residual COD concentration during the filter run and before running the filter was still above the South African water quality guidelines of < 5 mg/L. This high level of COD concentrations can be toxic to human health. Therefore, there is a crucial need to explore post-treatment techniques for removing residual carbon in vertical roughing filters.

5.5 Changes in Turbidity and Total Suspended Solids

The initial turbidity of raw water varied within 1 NTU and 11 NTU, while the average turbidity concentration of the raw water after a clay spike was within the range of 280 NTU to 510 NTU. The average turbidity concentration in the filtrate from a vertical roughing filter with ethanol as an external carbon source (VRF_{wt}) was 82.95 NTU, 56.64 NTU and 55.84 NTU, while the average turbidity concentration in the filter without a carbon source (VRF_{wo}) was 51.8 NTU, 34.36 NTU, and 34.42 NTU at filter depths of 0.27 m, 0.75 m, and 1.0 m, respectively.

The average turbidity removal efficiency in a vertical roughing filter with ethanol as an external carbon source (VRF_{wt}) was 77, 84 and 84 % and the average turbidity removal in the filter without a carbon source (VRF_{wo}) was 87, 91, and 91 % at filter depths of 0.27 m, 0.75 m, and 1.0 m, respectively. Both filters showed a high turbidity efficiency removal. Turbidity removal was effective as the water moved through the filter media towards the top of the filter column; predominantly at the depth of 1.0 m, as presented in the results section 4.11. Furthermore, turbidity removal efficiency in column 1 (13 mm gravel filter media), column 2 (9 mm gravel filter media) and column 3 (6 mm gravel filter media) was 73%, 84% and 87 % respectively in the VRF_{wt}, whereas turbidity efficiency removal in the VRF_{wo} was 82%, 91% and 95 % respectively. However, the overall turbidity removal efficiency was profound in the roughing filter without ethanol as an external carbon source (VRF_{wo}) at 1m depth. Turbidity in both filters did not satisfy the WHO (2011) and SANS (2015) guidelines for operational risk (≤1 NTU) and aesthetic risk (≤5 NTU), hence additional treatment is required to reduce turbidity in the filtrate.

The initial average Total Suspended Solids (TSS) in the raw water was in the range of 23 mg/L to 34 mg/L. At an average inflow concentration of 34 mg/L, 23 mg/L and 27 mg/L, the average TSS removal efficiency in a vertical roughing filter with ethanol as an external carbon source (VRF_{wt}) was 87, 70 and 79 %, while the average TSS removal in the filter without a carbon source (VRF_{wo}) was 90, 82, and 84 % during nitrate inflow concentrations of 15 mg/L, 25 mg/L and 50 mg/L, respectively. Both filters showed a potential in TSS removal from raw water. However, TSS removal was mostly effective in the $VRF_{wo,}$ as presented in Figures 4.31 to 4.33. TSS high removal in both filters could be attributable to the filters being operated at laminar flow conditions (flow rates within 0.03 m/h -0.1 m/h), because significant solids removal efficiencies are only achieved under laminar flow conditions that favour sedimentation, which is the predominant process in roughing filtration (Wegelin, 1996). The successive decrease in the filter medium size further also reduces the concentration of suspended solids. The removal efficiency of TSS increased as the operating time increased. The accumulation of solid matter over time as a result of deep penetration into the filter medium can result in less void space in the media, allowing fewer solid particles to pass through. The bulk of the solids was mostly deposited in the filter media located at the entrance next to the filter bottom. Although reduced void space in the filter medium can increase TSS removal, filter clogging can also occur. Therefore, periodic back flushing with turbulent flow was used to clean the filters.

5.6 Nitrate (NO_3-) and Nitrite (NO_2-) Removal in a Vertical Roughing Filter

Nitrate removal occurs during biological denitrification when heterotrophic bacteria breathe anaerobically (anoxic condition) using nitrate $\mathrm{NO_3}^-$ instead of using oxygen as an electron-acceptor, resulting in a gradual reduction of nitrate to Nitrogen gas N_2 and the process is enhanced by an external carbon source (Yang *et al.*, 2012). The organic carbon is used as an electron donor for the heterotrophic bacteria.

As a result of the process, the average nitrate removal efficiency in a vertical roughing filter with ethanol as an external carbon source (VRF_{wt}) was 88%, 70%, and 83% at C/N ratios of 1.05, 1.08, and 1.1, respectively, while the average nitrate removal in the filter without a carbon source (VRF_{wo}) was 68%, 59%, and 63% at inflow nitrate concentration of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N, respectively. Both filters indicated the removal of nitrate to be most profound towards the bottom of the filter, where there was a reduction of dissolved oxygen, predominantly at depths of 0.25 m to 0.75 m, as previously illustrated in the results section 4.13. A study by Eljamal *et al.* (2020) also reported that biological reduction of nitrate to nitrogen gas could not occur under aerobic conditions but only when oxygen levels are depleted.

However, the overall nitrate removal efficiency was profound in the roughing filter with ethanol as an external carbon source (VRF_{wt}) at a C/N ratio of 1.05. Similarly, a study by Matějů et al. (1992) compared weight ration of the substrate to nitrogen for methanol, ethanol, and acetic acid, as carbon sources for denitrification of drinking water, in which ethanol was shown to be the most favourable and effective at a C:N ratio of 1.05. This is due to carbon being the limiting factor in denitrification since heterotrophic bacteria require organic carbon as an electron donor and as a source of carbon.

Moreover, the average nitrate concentration in the filtrate with a carbon source was 1.84, 7.63 and 8.45 mg/L-N at C/N ratios of 1.05, 1.08, and 1.1, respectively, while the average nitrate concentration in a filter without a carbon source was 4.88, 10.45 and 18.77 mg/L-N at inflow nitrate concentrations of 15 mg/L-N, 25 mg/L and 50 mg/L-N, respectively. The nitrate concentration in the filtrate was below the WHO (2011) and SANS (2015) recommended guideline value of ≤11 mg/L-N for potable use. However, the filtrate results from the (VRF_{wo}) at inflow nitrate concentration of 50 mg/L-N still indicated a nitrate concentration above the recommended guideline.

Despite the fact that the pH range was favourable for denitrification, the failure to obtain a nitrate concentration value below the recommendation in the VRF_{wo} could be attributed to the elevated DO associated with low microbial activity. Optimum denitrification happens under anoxic conditions when there is depletion of oxygen thus, nitrate becomes the main oxygen source for heterotrophic bacteria. The process occurs when DO concentration is less than 0.5 mg/L, preferably less than 0.2 mg/L (Jorgensen & Sorensen, 1988). A high DO average concentration of 5.63 mg/L was recorded in the VRF_{wo} which was higher than the recommended value.

The filter was only used intermittently, it was operated for 12 hrs during the day and was non-operational (switched off) during the night for 12 hrs. To avoid overheating the pumps, the filter system was not run continuously. However, the nitrate removal efficiency in both filters was found to be greater in the period preceding the filter run (before running the filter) compared to the removal efficiency findings during the filter run; as previously demonstrated in Figures 4.36, 4.39 and 4.42 .

The average nitrate removal efficiency in a vertical roughing filter, with ethanol as an external carbon source (VRF_{wt}) was 94%, 77%, and 92% at C/N ratios of 1.05, 1.08, and 1, respectively, while the average nitrate removal in the filter without a Carbon source (VRF_{wo}) was 76%, 80%, and 74% at inflow nitrate concentrations of 15 mg/L-N, 25 mg/L and 50 mg/L-N, respectively. It was therefore found that the period before running the filter resulted in a higher nitrate removal efficiency. This suggested that the period when the filter was switched off (during the 12 hrs) provided an effective length of time (contact time) for the heterotrophic bacteria to biologically reduce the nitrate (NO_3^-) to nitrogen gas (N_2), during the denitrification process. If pumping is employed, Wegelin (1986) recommended 8 to 16 hours of filter operation each day. Nonetheless, Wegelin (1986) demonstrated that running a continuous filter operation 24 hours a day improves performance and provides a consistent flow pattern. However, in such an ideal situation, a full gravity flow is required.

Similarly, a study by Abu-Ghararah (1994) achieved high nitrate removal efficiencies of 98% to 99%, when using an anoxic up-flow packed reactor at a hydraulic retention time greater or equal to nine hours (≥ 9 hrs). Since the filter was run intermittently yet microorganisms also require a constant water flow for nutrients, an effective resting duration in a vertical roughing filter when operated intermittently needs to be investigated. However, a prolonged rest duration may also reduce the possibility of biological layer development (Baumgartner *et al.,* 2007).

Similarly, nitrite NO_2^- concentration was also investigated at various depth in both filters. The removal efficiency in a vertical roughing filter, with ethanol as an external carbon source (VRF_{wt}) was 98%, 82%, and 80% at C/N ratios of 1.05, 1.08, and 1.1 respectively, while the average nitrite removal in the filter without a carbon source (VRF_{wo}) was 92%, 75%, and 97% at inflow nitrate concentration of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N, respectively. Both filters indicated a high removal of nitrite, however, nitrite removal efficiency was most profound towards the top zone of the filter where there was a higher exposure to free Oxygen. Therefore, at this zone, nitrification was most predominant at depths of 0.75 m to 1 m as previously illustrated in the results section 4.12.

Nitrification is a two-step process in which ammonia in the raw water is oxidised to nitrite, followed by oxidation of the nitrite to nitrate. These reactions are coupled and proceed rapidly to nitrate form, hence the low nitrite concentration at any given time. However, the overall nitrite removal efficiency was profound in the roughing filter with ethanol as an external carbon source (VRF_{wt}) at C/N ratio of 1.05. The average nitrite concentration in the filtrate was well below the SANS (2015) maximum nitrite concentration guidelines of ≤ 0.9 mg/L, although the average nitrite concentration of 1.1 mg/L during the C/N ratio of 1.1 in the VRF_{wt} was still found to be above the maximum guideline.

5.7 Statistical Analysis

Using a two-way analysis of variance (ANOVA), the measured parameters that include pH, dissolved Oxygen (DO) concentration, nitrite (NO_2^-) concentration, nitrate (NO_3^-) concentration, temperature and C/N ratio were tested on the null hypothesis that all the parameters have a significant influence on the removal of nitrate (NO_3^-) in the vertical roughing filter, with or without an external carbon source at varied nitrate concentrations and C/N ratios. A p-test was performed to confirm the parameters' influence on nitrate removal, and the resulting p-values were compared to the significant level of 0.05. Individual parameter influences on nitrate removal were compared using a multiple comparison post-hoc test. The findings of the between subjects ANOVA in Table 4.8 above indicated that the measured parameters had a substantial influence on nitrate removal, with a p-value of 0.001, thus, $p < 0.05$ in both filters.

A post-hoc comparison test was performed to verify each parameter's relationship to nitrate removal. The multiple comparison post hoc test indicated that pH, nitrate concentration, and temperature have significant influence ($p < 0.001$ at inflow nitrate concentration of 15 mg/L-N) in a VRF_{wo}, while dissolved oxygen (DO) resulted in no influence (p = 0.363 at 15 mg/L-N), as shown in Table 4.9. The findings suggest that there was less microbial activity in the filter, which resulted in low oxygen demand. However, there was a significant influence on all of the parameters in a VRF_{wo} at p-values ($p < 0.001$) at inflow nitrate concentration of 25 mg/L-N) and ($p < 0.001$ at inflow nitrate concentration of 50 mg/L-N), as shown in Table 4.9.

At inflow nitrate concentration of 15 mg/L-N and a C/N ratio of 1.05 in a VRF_{wt}, all parameters showed a significant influence ($p < 0.001$), as shown in Table 4.10. However, only DO, nitrite, and temperature were shown to have a significant impact ($p < 0.001$) at inflow nitrate concentration of 25 mg/L-N with a C/N ratio of 1.08, and also at inflow nitrate concentration of 50 mg/L-N, with a C/N ratio of 1.1. The pH showed no influence (p = 0.862) at inflow nitrate concentration of 25 mg/L-N, with a C/N ratio of 1.08 and also (p = 0.163) at inflow nitrate concentration of 50 mg/L-N, with a C/N ratio of 1.1, as presented in Tables 4.10. Overall, the findings showed that not all of the measured parameters had an influence on nitrate removal in the filter with and without an external carbon source.

5.8 The Predictive Nitrate Removal Model

The removal of nitrate in an upward vertical roughing filter process by heterogeneous microorganisms was evaluated, based on the change in concentration of nitrate across the filters $(C_i - C_e)$ divided by the hydraulic retention time $\frac{V_r}{Q}$. Also, the approach used to develop the equation was based on the assumption that the kinetic rate of the reaction was proportional to the nth power (reaction rate order) of the concentration, where (k) is the reaction rate constant and $C_{NO_3{}^-}$ is the nitrate concentration. The regression analysis plots of inflow nitrate concentration (C_i) and total organic loading rate (QS_i/V), with respect to the reaction rate, resulted in a weak linear fit, whereas the regression analysis plot of the reaction rate $\frac{Q\,(C_i - C_e)}{V_r}$ with respect to outflow nitrate concentration (C_e) resulted in a best fit linear distribution trend with an average coefficient of determination (R^2) of 0.998. The major feature of these graphs is the reduction in the reaction rate with increase in the outflow nitrate concentration, as shown in Figure 4.43 in the results section.

The approach used to develop the equation was based on the assumption that the kinetic rate of the reaction was proportional to the nth power (reaction rate order) of the nitrate concentration. The reaction rate order (n) determined how the concentration of nitrate affected the removal rate, and it was found that it followed zero order removal rate kinetics. The zero-order reaction kinetics were found to be independent of the inflow nitrate concentration (C_i). However, they were highly influenced by the outflow nitrate concentration (C_e). The plot of outflow nitrate concentration versus time (see Figure 4.45) determined the reaction rate constant (k), which illustrated how the nitrate concentration decreased over time. Since the temperature was not controlled in the filters, the reaction constant varied within the range of 0 to - 0.7 during the reaction. As a result, a small average rate constant of 2.44 mg/L/day was obtained, which indicated a slow reaction in nitrate removal. Therefore, Equation 4.5 provided the necessary information for kinetic coefficients in the treatment of nitrate in raw water, using a vertical roughing filter.

Chapter 6 Summary of research findings, conclusions, and recommendations

6.1 Introduction

This chapter presents a recap of the study. It incorporates findings from the existing literature on a vertical roughing filter with an external carbon source for removing nitrate in raw water. The literature review assisted in providing a wider view and better understanding of the nitrogen cycle, nitrate chemistry, sources and problems associated with nitrate, nitrate prevalence, other nitrate removal techniques and their limitations and the current status of roughing filters, with regard to the removal of nitrate. That, in turn led to the development of the research experiment and the construction of two laboratory roughing filter models. The findings from this study are linked to the conclusion and are presented in this chapter. The recommendations provide suggestion for future research, which emerged because of the findings from this study. The study's contribution to the body of knowledge and limitations are also highlighted in this chapter.

6.2 Review of the Aim and Objectives

The principal aim of this study was to provide an answer to this main research question:

"What is the effectiveness of a vertical roughing filter with an external organic carbon source in removing nitrate in raw water for potable use?" To provide answers to the issues surrounding the question, the study identified the following specific objectives:

- To investigate the design parameters, process capabilities and nitrate concentration for optimal nitrate removal, using a conventional vertical roughing filter with and without a carbon source.
- To determine the optimum time and depth for removal of nitrate in a vertical roughing filter.
- To investigate the optimum carbon: nitrogen (C/N) ratio for optimum nitrate removal and the relationship between physicochemical parameters in a vertical roughing filter.
- To investigate the effect of the biomass growth on filter operation and the quality of treated water with regard to residual carbon, to meet water quality standards.
- To develop a model to predict removal of nitrate in a vertical roughing filter, using an external organic carbon source.

To achieve these objectives, the study conducted a thorough review of the existing literature in order to get an understanding of previous efforts on the subject of the research. This thesis examined the use of an upward vertical roughing filter with ethanol as an external carbon source in removing nitrate in raw water for potable use. In acknowledging the importance of considering other physicochemical characteristics that can affect the removal of nitrate and the quality of treated effluent water, tests on Dissolved oxygen (DO), nitrite, pH, Chemical oxygen demand (COD), temperature, turbidity, and Total Suspended Solids (TSS) were also conducted. In addressing the objectives of this study, a laboratory experimental investigation was performed, and analysis was employed. Therefore, the findings derived from the methodological procedures employed to achieve the study objectives are summarized in the next section of this chapter.

6.2.1 The design parameters, process capabilities and nitrate concentration for optimal nitrate removal using a conventional vertical roughing filter, with and without a carbon source

The first specific objective of the research investigated the design parameters, process capabilities and nitrate concentration for optimal nitrate removal, using a conventional vertical roughing filter with and without a carbon source. The literature review in chapter two discovered that optimum treatment in roughing filters is generally achieved when using multiple numbers of individual compartments in series, thus, resembling the hydraulic behaviour of a plug-flow system. Therefore, a roughing filter of 3 stages is expected to perform better than a roughing filter of 2 stages. The literature revealed that the vertical roughing filter direction of flow makes it favourable for nitrate removal as denitrification is stated to be the only process capable of reducing nitrate concentration during downward percolation.

Moreover, for high removal efficiency of nitrate to occur due to a biological denitrification process, two distinct zones have to be established: anoxic and aerobic zones. Denitrification usually takes place at the zone near the base of the filter where there is low oxygen. Anoxic conditions are experienced as low dissolved oxygen in the presence of nitrate, while aerobic conditions occur with higher levels of oxygen. Biological, chemical and adsorption processes are supported by low filtration rates used in roughing filtration. As a result, roughing filters can slightly improve the quality of bacteriological water, apart from solid water separation. Furthermore, chapter 3 presented the filter design principles and set-up to support chemical and biological processes to effectively take place during filtration, which include:

- Hydraulic loading rates within the ranges of 0.03 m/h to 0.1 m/h.

- Three translucent polyvinyl chloride (PVC) columns were connected in series, with each having a total length of 1000 mm and internal and external diameters of 110 mm and 170 mm, respectively.
- Successive filter media (gravel) gradations were packed in series as column 1 (13 mm), column 2 (9 mm), and column 3 (6 mm).
- Monitoring points were available along each column at 270 mm, 750 mm, and 1000 mm from the bottom inlet.
- Ethanol (C_2H_5OH) was used as an organic carbon source to enhance the vitality of the denitrification process in removing nitrate from water.

6.2.2 The optimum time and depth for removal of nitrate in a vertical roughing filter

The second objective of the study was to determine the optimum time and depth for removal of nitrate in a vertical roughing filter. The literature identified longer filter depths as usually being associated with improved efficiencies in cumulative removal. However, vertical roughing filters have a comparatively small filter depth and, due to structural limitations, are restricted to 1 m for each compartment. Therefore, in this study each filter comprised a total depth of 3 m for the three filter columns connected in series. In each column, sampling points were established at heights of 0.27 m, 0.75 m, and 1 m from the bottom inlet. This provided the ability to evaluate the effect depth in the removal of nitrate. The results indicated the removal of nitrate to be most profound towards the bottom of the filter where there was a depletion of dissolved oxygen, predominantly at depths of 0.25 m to 0.75 m in the filter with and without a carbon source. The literature showed that optimum denitrification occurs under anoxic condition when there is depletion of oxygen. Thus, nitrate becomes the main oxygen source for heterotrophic bacteria. The process occurs when the DO concentration is less than 0.5 mg/L and preferably less than 0.2 mg/L.

Since the filter was only used intermittently, it was operated for 12 hrs during the day and was non-operational (shut off) during the night, for 12 hrs. The filter system was not continuously operated in order not to overheat the pumps. Some studies recommended avoiding long pause periods (>48 hrs) as this might kill the biological layer due to nutrient depletion. The samples were taken both while it was operating (during the filter run) and before the filter was run. Each time a new test run was performed, the head of water that was maintained in the columns was flushed out. The sampling frequency was once a week and was increased gradually to a frequency of three as the filter matured with time. The results showed nitrate removal efficiency in both filters to be greater in the period preceding the filter run (before running the filter) compared to the removal efficiency findings during the filter run. This was attributed to the period when the filter was switched off (during the 12 hrs), as this provided an effective length of time (contact time) for the heterotrophic bacteria to biologically reduce the nitrate (NO_3) to nitrogen gas (N_2) during the denitrification process. The literature recommended 8 – 16 hrs per day of filter operation if pumping is used. It was further discovered that a continuous filter operation that runs 24 hrs a day increases performance and provides a consistent flow pattern. However, in such an ideal condition, a full gravity flow is necessary. Similarly, studies from the literature achieved high nitrate removal efficiencies of 98 to 99 % when using an anoxic up-flow packed vector at a hydraulic retention time greater or equal to nine hrs (≥ 9 hrs).

6.2.3 The optimum Carbon: Nitrogen (C/ N) ratio for optimum nitrate removal and the relationship between physicochemical parameters in a vertical roughing filter

The third objective of this study was to investigate the optimum Carbon: Nitrogen (C/N) ratio for optimum nitrate removal and the relationship between physicochemical parameters in a vertical roughing filter. The literature identified biological denitrification as an effective technology for total nitrate removal in water, and the process is enhanced by an external carbon source. The type of carbon source utilised can strongly affect the rate of denitrification. Moreover, the literature identified several common carbon compounds that can be utilised as energy sources such as ethanol, glucose, sucrose, acetic acid, sugar, methanol and acetone. Most of the reviewed literature recommends ethanol as a safe organic carbon source and its use as a carbon source in water treatment has shown effective success over years. This is due to its degradable nature and the absence of toxic effects. Ethanol is also affordable and has no limits of usage set on it in treatment of raw water for potable use. Ethanol is, therefore, suitable as a replacement for other carbon sources in the denitrification process. Therefore, ethanol was used as a carbon source in this research. The C/N ratio established from the reviewed literature were 1.05,1.08 and 1.1, while the targeted nitrate concentrations selected were 15 mg/L-N, 25 mg/L-N and 50 mg/L-N, respectively. The selected range chosen was some areas in South Africa where high nitrate concentrations above 100 mg/L-NO_3 equivalent to 23 mg/L-N in raw water are found. The results revealed a C/N ratio that can effectively remove nitrate in raw water to be 1.05. On the other hand, the measured parameters that include pH, dissolved oxygen (DO) concentration, nitrite (NO_2^-) concentration, nitrate (NO_3^-) concentration, temperature and C/N ratio were tested using a two-way analysis of variance (ANOVA), on the null hypothesis that all the parameters have a significant influence on the removal of nitrate (NO_3^-) in the vertical roughing filter with or without an external carbon source at varied nitrate concentrations and C/N ratios. Overall, it was discovered that not all of the measured parameters had an influence on nitrate removal in both the filter with and without an external carbon source.

6.2.4 The effect of biomass growth on filter operation and the quality of treated water with regards to residual carbon, to meet water quality standards

The fourth objective was to investigate the effect of the biomass growth on filter operation and the quality of treated water with regards to residual carbon, to meet the water quality standards. The literature revealed that a biological denitrification process in a vertical roughing filter takes place during a fixed film growth process in which the bacteria develop on the gravel media layer. Some studies in the literature stated that the organic layer typically required 20-30 days to mature in a new filter, depending on the inflow water quality condition. However, due to operating the filters intermittently in this research, it was found that maturity was evident at 30-35 days. To investigate the biomass growth effect on filter performance, daily flow rate variations in the filter with and without a carbon source were monitored throughout the course of the test period. Based on the results of data analysis, a decline in flow rate was more significant in the filter dosed with an external carbon source (VRF_{wt}) at 27 %, compared to a 15 % drop noticed in a VRF_{wo}. The decline in filtration rate was attributed to the filter maturity and was significant as the biological layer matured.

The rate of biofilm development in a filter with and without the use of a carbon source was examined through testing the quality of the filtrate on nitrate removal and also a decrease in the initial flow rate through the filter. Therefore, a COD test was conducted primarily to measure and compare the ethanol concentration inflow with the concentration obtained in the filtrate, in order to assess organic removal performance and the quality of the filtered water with regards to the presence of residual carbon. The results revealed that there was an effective decrease in COD when the filter was switched off, compared to the COD results obtained during the filter run. This suggested that the period the water remained in the filter columns allowed sufficient time for the microorganisms to continue to react during denitrification. However, it was observed that the residual COD concentration during the filter run, and filter flushing was still above the South African water quality guidelines of < 5 mg/L. This high level of COD concentrations can be toxic to human health. Therefore, there is a crucial need to explore post-treatment techniques for removing residual carbon in vertical roughing filters.

6.2.5 A model to predict removal of nitrate in a vertical roughing filter, using an external organic carbon source

The fifth objective of this research was to develop a model to predict removal of nitrate in a vertical roughing filter, using an external organic carbon source. In order to achieve this objective, a literature review was conducted on several models that were used to describe the overall kinetics of biological reactors, such as the first order model, the zero-order model, the Monod Model, the Stover-Kincannon Model, and the Efficiency Loss Model. Thereafter, a predictive nitrate removal rate model was established empirically from analysis of obtained test results from the laboratory.

A regression analysis was carried out on the datasets from the filter with and without a carbon source, in order to evaluate a relationship that most closely fits the data between the kinetic reaction rate $\left(\frac{Q\,(C_i - C_e)}{V_r}\right)$ for the removal of nitrate and the variables that include inflow nitrate concentration (C_i), outflow nitrate concentration (C_e) and total organic loading rate (QC_i/V). The filter with an external carbon source (VRF$_{wt}$) and the filter without an external carbon source (VRF$_{wo}$) were each evaluated at inflow nitrate concentrations of 15 mg/L-N, 25 mg/L-N and 50 mg/L-N, in order to obtain the best data plot that would best describe the removal of nitrate in a vertical roughing filter.

The model development related the inflow (C_i) and outflow (C_e) nitrate concentrations as a function of physiochemical parameters such as flow rate, dissolved oxygen concentration, pH, C/N ratio and temperature. The removal of nitrate in an upward vertical roughing filter process by heterogeneous microorganisms was evaluated, based on the kinetic reaction rate $\left(\frac{Q\,(C_i - C_e)}{V_r}\right)$ versus the outflow nitrate concentration (C_e). A log-log plot of the experimental data was used to obtain a reaction rate order (n) while corresponding zero kinetic reaction rate constant (k_0) was estimated by performing a regression analysis of outflow nitrate concentration (C_e), with respect to the time of sampling. The removal of nitrate in the vertical roughing filter was evaluated, based on the change in concentration of nitrate across the filters $(C_i - C_e)$ divided by the hydraulic retention time $\frac{V_r}{Q}$. The approach used was also based on the assumption that the rate of reaction was proportional to the n^{th} power of the nitrate concentration. The predictive nitrate removal in the vertical roughing filter was described using a zero-order kinetic rate model.

The regression analysis plots of inflow nitrate concentration (C_i) and the total organic loading rate (QS_i/V) with respect to the reaction rate, resulted in a weak linear fit, whereas the regression analysis plot of the reaction rate $\frac{Q\,(C_i - C_e)}{V_r}$ with respect to outflow nitrate concentration (C_e) resulted in a best fit linear distribution trend with an average coefficient of determination (R^2) of 0.998. The reaction rate order (n) determined how the concentration of nitrate affected the removal rate, and it was found that it followed zero order removal rate kinetics. The zero-order reaction kinetics were found to be independent of the inflow nitrate concentration (C_i), but were highly influenced by the outflow nitrate concentration (C_e). On the other hand, the reaction rate constant (k) illustrated how the nitrate concentration decreased over time. Since the temperature was not controlled in the filters, the reaction constant varied within the range of 0 to -0.7 during the reaction. As a result, a small average rate constant of 2.44 mg/L/day was obtained, which indicated a slow reaction in nitrate removal. Therefore, the zero-order kinetic rate model provided the necessary information for kinetic coefficients in the treatment of nitrate in raw water, using a vertical roughing filter.

6.2.6 Concluding remarks

This thesis has satisfied the aim and the set objectives specified in the introduction of this thesis. The study has:

- Investigated the design parameters and process capabilities for effective nitrate removal when using a conventional vertical roughing filter with and without a carbon source.
- Determined the optimum time and depth for effective removal of nitrate in a vertical roughing filter.
- Investigated the optimum carbon: nitrogen (C/N) ratio for optimum nitrate removal and the relationship between physicochemical parameters in a vertical roughing filter.
- Investigated the effect of the biomass growth on filter operation and the quality of treated water with regards to the residual carbon to meet the water quality standards.
- Developed a predictive nitrate removal model in a vertical roughing filter using an external carbon source.

6.3 Summary of the Research

This research was set out to investigate nitrate removal in raw water for potable use, using a vertical roughing filter with an external organic source of carbon. In pursuit of the study focus, a review on the nitrogen cycle, nitrate chemistry, sources and problems associated with nitrate, nitrate prevalence, other nitrate removal techniques and their limitations and the current status of roughing filters with regard to the removal of nitrate were highlighted. The types of filters and their functions under different conditions were discussed. Moreover, several studies have explored the feasibility and efficacy of various filter types such as bio-filters, roughing filters, slow sand filters and rapid sand filters for extracting dissolved nutrients, coliforms, suspended solids, iron and manganese and high turbidity in water through biological denitrification. However, the primary focus was on roughing filters as they have shown to slightly improve the quality of bacteriological water apart from their most widely spread use of reducing suspended solids in highly turbid waters. A gap was identified in the literature of limited data on vertical roughing filter efficiency, mainly on nitrate removal in raw water for potable use. Roughing filters commonly comprise horizontal and vertical flow directions. However, horizontal roughing filters have shown to respond less to filtration rate adjustments, thus, limiting effective denitrification. Conversely, denitrification is stated to be the only process capable of reducing nitrate concentration during downward percolation; not horizontally. Therefore, this study adopted a vertical roughing filter due to the direction of flow that makes it favourable for nitrate removal.

Furthermore, nitrate (NO_3^-) pollution in surface water was brought into focus as part of the primary inorganic forms of nitrogen. It was revealed that the activities generated from humans, animals, agriculture, and industries contribute greatly to surface and groundwater sources pollution in an attempt to provide sustainable food security and economic development. The discussions in the review section have shown that there are harmful effects on humans, animals and the environment that are associated with high nitrate contamination (≥11 mg/L-N) in water. These effects are found to be deadly and cause several health problems in adults and babies such as diarrhoea, diabetes and methemoglobinemia. Moreover, the increase in nitrate concentration has been identified in rivers and streams to promote the rapid growth of algal blooms. Many distinct places such as West and Central America, China, India, Namibia, and Botswana have exceeded the World Health Organisation (WHO) maximum nitrate contamination level of 50 mg/L-NO_3^-. This also includes South Africa, with areas such as Moretele District in the Northwest Province and Kudumane District in the Free State Province experienced high nitrate concentrations of 173 mg/L-NO_3^- and 130 mg/L-NO_3^- respectively. However, to date, nitrate levels have been measured in South Africa, but only through a limited number of repeated analyses for contamination point sources, with entirely predictable results.

Water with high nitrate levels has been recommended for treatment to meet the regulated nitrate maximum concentration level (MCL). A number of technologies including reverse osmosis (RO), electrodialysis, chemical denitrification, membrane bioreactor, nanofiltration, autotrophic denitrification and biological denitrification have been identified as treatment alternatives for high nitrate contamination in water. However, these chemical and physical methods have shown to result in drawbacks that include the production of high strength residual brine and low efficiency. Nonetheless, biological denitrification has proved to be an effective technology for nitrate removal and the process can be enhanced by adding an external carbon source. Several studies have shown methanol, ethanol, and acetic acid to be practically effective organic carbon sources for nitrate removal, due to their degradable and simple nature. However, it was revealed that methanol is associated with toxic effects at high concentration due to excess residual carbon detected in the effluent water, thus, limiting its usage at only low concentrations. Conversely, ethanol was stated as a safe organic carbon source as its use in water treatment has shown effective success over the years. Therefore, ethanol was used in this study.

Subsequently, the nitrate reaction rate kinetics applied in the modelling of nitrate, both in surface and groundwater environments was discussed. It was found that several removal kinetics have been used to predict the efficiency of nitrate removal in water using filtration systems. However, there is currently no standardised way to report rouging filter performance in nitrate removal in order to facilitate the end user selection among the different roughing filter types. Therefore, to address the issue, a predictive nitrate removal rate model was developed empirically from analysis of laboratory test results. The zero-order kinetic reaction rate model was considered an appropriate model for nitrate removal in a vertical roughing filter in this research, since it assumes an anoxic system that is conducive for denitrification; and also, since the zero-order kinetic model is considered appropriate in modelling high inflow nitrate concentrations greater than 1 mg/L.

Arising from the literature review, a conceptual illustration of the use of an external carbon source in roughing filters was formulated and also forms the basis for the research design, to conceptualise what is happening in the roughing filter with a carbon source. Result validation was conducted by testing the raw water samples after instrument calibration, instrument verification and error calculation. The instrument was verified with the standard solution following each data set test on the raw water. When the result was not within the error range, the previous tests were rejected, and the calibration and verification were performed again. Furthermore, a statical analysis was performed using a two-way analysis of variance (ANOVA) on the measured parameters that include pH, dissolved Oxygen (DO) concentration, nitrite (NO_2^-) concentration, nitrate (NO_3^-) concentration, temperature, and C/N ratio. The parameters were tested on the null hypothesis that all the parameters have a significant influence on the removal of nitrate (NO_3^-) in the vertical roughing filter, with or without an external Carbon source at varied nitrate concentrations and C/N ratios. A p-test was performed to confirm the parameters' influence on nitrate removal, and the resulting p-values were compared to the significant level of 0.05. Individual parameter influences on nitrate removal using a multiple comparison post-hoc test. The findings of the between subjects ANOVA indicated that the measured parameters had a substantial influence on nitrate removal, with a p-value of 0.001, thus, $p < 0.05$ in both filters. Subsequently, a post-hoc comparison test was performed to verify each parameter's relationship to nitrate removal. The multiple comparison post hoc test indicated that not all of the measured parameters had an influence on nitrate removal in the filter, both with and without an external carbon source.

6.4 Conclusions

A vertical roughing filter that uses ethanol as an external carbon source (VRF_{wt}) has a higher potential for removing nitrate in raw water. The nitrate concentration in the filtrate when using a vertical roughing filter with ethanol as an external carbon source (VRF_{wt}) was 1.84 mg/L-N, 7.63 mg/L-N and 8.45 mg/L-N, which resulted in an average nitrate removal efficiency of 88, 70, and 83% at C/N ratios of 1.05, 1.08, and 1.1, respectively. As a result, the nitrate concentration levels in the filtrate were lower than the WHO and SANS recommended guidelines of ≤ 11mg/L-N, indicating that the technology can limit nitrate in raw water. Overall, the study indicated that there is a higher potential in the use of a vertical roughing filter enhanced with an external carbon source for removal of nitrates in raw water, through heterotrophic denitrification. As a result of the filter media clogging, the flow rate was observed to decrease over time throughout the experiment. A reduction in flow rate in the VRF_{wo} was from 0.133 L/m to 0.113 L/m, while the flow rate in VRF_{wt} reduced from 0.133 L/m to 0.096 L/m. The decline was significant in the filter with an external carbon source (VRF_{wt}) at 27 % compared to a 15 % drop that was noticed in a filter without a carbon source VRF_{wo} as the biological layer was reaching complete development. The rapid biological filter layer development can cause the filter to clog, hence, lowering the daily water production. Thus, the filter would need to be flushed out with clean water in order to starve the microorganisms of nutrients, thereby reducing the rapid growth of the biological layer.

The low DO levels towards the bottom of the filter columns promoted heterotrophic denitrification which favoured nitrate removal. DO concentration in the filtrate reduced due to the nitrification process that takes place during aerobic oxidation, which was most profound towards the upper zone of the filter. Statiscally, it was found that DO does not have an influence on nitrate removal ($p = 0.363$) at inflow nitrate concentrations of 15 mg/L-N, when using a vertical roughing filter without a carbon source (VRF_{wo}); whereas the measured parameters that include temperature, nitrate, and pH influenced nitrate removal. However, pH did not have any influence (p = 0.163 at 25 mg/L-N, C/N ratios of 1.08) and (p = 0.862 at 50 mg/L-N, C/N ratio of 1.1) when using a vertical roughing filter with a carbon source (VRF_{wt}); whereas the measured parameters that include temperature, nitrate and DO showed an influence in nitrate removal.

Also, pH increased towards the filter bottom at depths of 0.25 m to 0.75 m in both the filter with and the filter without a carbon source during the denitrification that takes place in anoxic conditions, carbon dioxide and oxygen hydroxide (OH^-) are produced as nitrate is reduced to gaseous nitrogen. A decrease in pH results in a top zone that is exposed to oxygen, thus, providing a conducive environment for the nitrification process that results in high acid production. There was a higher removal efficiency in the residual ethanol measured as COD in the filter with an external carbon source (VRF_{wt}) before running the filter compared to the removal efficiency during the filter run. The average COD in the filter with an external Carbon source (VRF_{wt}) during the filter run was 85 mg/L, 632 mg/L and 618 mg/L whereas the average residual ethanol measured as COD before running the filter was 41 mg/L, 561 mg/L and 533 mg/L at a C/N ratio of 1.05, 1.08 and 1.1, respectively. However, the COD concentration was still above the South African water quality guidelines of < 5 mg/L. The high residual carbon concentration in the filtrate is the major challenge with regard to the use of an external carbon source and can pose a health risk and major problems in the water distribution system thus, additional treatment is required to lower the high concentration.

The removal of nitrate in an upward vertical roughing filter process by heterogeneous microorganisms can be evaluated by using the nitrate reaction rate as a function of the outflow nitrate concentration (C_e). The nitrate reaction rate kinetics were found to be independent of the inflow nitrate concentration (C_i). However, they were highly influenced by the outflow nitrate concentration (C_e). The zero-order reaction rate model proved to be the best fit model to describe nitrate removal rate in an upward vertical roughing filter, when treating raw river water. The zero-order model presented a relationship that most closely fits the regression analysis, with a resulting average coefficient of determination (R^2) of 0.998. The average reaction rate constant and reaction rate order were evaluated as 0.244 mg/L/day and 0.373. This zero-order model can also be used to determine the volume (V) required to decrease the inflow nitrate concentration to outflow nitrate concentration; or to determine the outflow nitrate concentration for a given volume and inflow nitrate concentration.

6.5 Recommendations

Based on the findings from this research, the following recommendations are be made to provide guidance in the use of a vertical roughing filter, with an external carbon source in removing nitrate in raw water.

- It is recommended that if run intermittently; the roughing filter should be allowed a minimum of 30 days to mature, prior to sampling.
- In order to provide more contact time for microorganism activity in the filter, thus improving the removal efficiency of the filter; it is recommended that low hydraulic loading rates within the range of 0.03 m/h to 0.1 m/h should be used.
- Although there was a decrease in the residual COD concentration in the outflow, it is worth noting that this residual concentration was still above the South African water quality guidelines of < 5 mg/L. This high level of COD concentrations can be toxic to human health. Therefore, post-treatment is recommended in order to reduce the high concentrations.
- Since the filter was operated intermittently, it is recommended that a head of water (50 mm to 100 mm) should be left maintained in the filter columns, in order to sustain the microorganisms when the filter is not in operation.
- The rapid biological filter layer development can cause the filter to clog, hence, lowering the daily water demand. It is therefore recommended that the filter should be flushed out with clean water in order to starve the microorganisms of nutrients, thereby reducing the rapid growth of the biological layer.

6.6 Contribution to the Body of Knowledge

The aim of this research was to investigate nitrate removal in raw water for potable use using a vertical roughing filter with an external organic source. This research adds to the existing nitrate removal technologies in water. Special emphasis was placed on the reduction of high nitrate levels in raw water for potable use. This technology will increase access to water sources that were initially rendered unsuitable to many water utilities, thereby increasing their water supply. Importantly, the lack of nitrate in potable water would minimize water-related diseases induced by the use of high nitrate-rich water. This technology can improve the economies of scale of water utilities in South Africa and other less developed countries, when operated at a full-scale design level. Another major contribution from the study is a predictive nitrate removal rate model that was established empirically from analysis of obtained test results from the laboratory. The model development reported the inlet and outlet nitrate concentrations as a function of physiochemical parameters such as flow rate, dissolved oxygen concentration, pH, C/N ratio and temperature. The removal of nitrate in an upward vertical roughing filter process by heterogeneous microorganisms was evaluated based on the reaction rate versus the outflow nitrate concentration. Again, the reaction rate order (n) and reaction rate constant (k) determined from the nitrate removal kinetic model can help in assessing the total nitrate removal rate and efficiency in a vertical roughing filter, without the need to operate the filter, thus saving time and money. Therefore, this research has contributed to the existing knowledge by presenting a technology and a kinetic nitrate removal model that will provide an effective and economic water treatment technology within the Civil Engineering, Water and Environmental Engineering sector under Water and Wastewater Treatment disciplines; primarily focusing on improving water quality.

6.7 Limitations of the Research

Regardless of the industry, clean potable water is the most crucial component in the production process. The research carried out in this study is significant and the findings from the study are useful to many industries such as the health care industries, dairy industries, municipalities, the mining industry, food and beverage industries and agricultural industries. However, the research is not without limitations. The research was only focused on investigating the removal of nitrate in raw water, using a vertical roughing filter with ethanol as an external carbon source. The sample water that was used in the research was from surface water and the source was Kuils River, located in the Western Cape Province. This therefore is a limitation since the results may only be valid for surface water but not ground water. The research only focused at the filtration rate, filter depth and media size as the main design parameters for the vertical roughing filter. Other variables that can affect the removal of nitrate and the quality of treated effluent water include, carbon:nitrogen ratio (C/N), process capabilities, residual carbon and biomass were also considered. Physicochemical characteristics of water tested in the research included dissolved oxygen (DO), nitrate, nitrite, pH, Chemical Oxygen Demand (COD), temperature, turbidity, and Total Suspended Solids (TSS). The study did not analyse phosphates, total and soluble Kjeldahl Nitrogen (TKN) parameters, major cations, and anions, metals, and organics, including biodegradable Organic Carbon (BDOC) and Bacterial Regrowth Potential (BRP). However, it is acknowledged that there was time, administrative and financial constraints. Despite this, the study's significance remains, since the constraints do not divert the researcher from the study's aim, but rather provide scope for future research.

6.8 Suggestions for Further Research

As stated in the findings and limitations of this study outlined in the preceding sections, it is critical to identify potential areas for future research efforts to expand and modify the findings in this research, which are:

- Investigations on nitrate removal from raw water need to be carried out, using a downward flow vertical roughing filter type with various external carbon sources, to establish differentials in the effectiveness of nitrate removal in raw water, using an upward flow roughing filter type.
- Running the vertical roughing filter intermittently demonstrated a delay in the filter approaching maturity (biological layer formation) for optimum performance. Therefore, the use of a continuous flow in a vertical roughing filter (a full gravity flow) to remove nitrate from raw water requires additional investigation.
- Since the survival of microorganisms is dependent on the continuous flow of water supply for nutrients, there is a need to investigate the effective hydraulic residence time in a vertical roughing filter when operated intermittently, to determine how long the raw water must be in contact with the media to insure optimal denitrification.
- Research efforts should also be directed towards exploring post-treatment techniques for removing high concentrations of residual carbon in vertical roughing filters.
- Another area to investigate is microorganism concentration in a vertical roughing filter in order to establish its relationship to nitrate removal. This variable will be incorporated into further developing the kinetic removal rate model in a vertical roughing filter, for nitrate removal.

6.9 Concluding Summary

The aim of the research was to investigate nitrate removal in raw water for potable use, using a vertical roughing filter with an external organic source, which has been achieved through a successful identification of the highlighted objectives in the preceding sections. The study established that a vertical roughing filter that uses ethanol as an external carbon source (VRF_{wt}) has a higher potential for removing nitrate in raw water at a C/N ratio of 1.05. It further established the relationship between physicochemical parameters in a vertical roughing filter on nitrate removal; and the nature and strength of the relationships were statically analysed. The overall conclusion drawn from the foregoing is that, not all of the measured parameters had an influence on nitrate removal in the filter with and without an external carbon source. Furthermore, the study has made a significant contribution to roughing filters and water treatment technologies literature in nitrate removal in raw water, by developing a kinetic removal rate model for nitrate removal in a vertical roughing filter, which many of the previous researchers in this area have not investigated thoroughly enough. The research, whilst completed at this stage, has opened up opportunities for further research in many other areas. The findings in this study can be further extended and modified to accomplish the ultimate goal of promoting and improving roughing filters in removing nitrate in raw water.

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Appendices

Appendix A. Potassium nitrate and Carbon dosage calculations

The tables below represent the detailed dosage calculations for potassium nitrate and ethanol as a carbon source.

Table A.1 Ethanol dosage calculation at C/N ratio of 1:05

Item	Ethanol detailed dosage calculations
1	Ethanol molecular equation is given by C_2H_5OH and therefore has a molar mass of 46 g/mol.
2	The Carbon equivalent in the C_2H_5OH equation is 24 g/mol. The amount of Carbon in ethanol is therefore 24/46 x 100 % = 52.17 %.
3	The concentration of nitrate to be used in the equation is 15 mg/L and the C/N ratio established from the literature review is 1.05.
4	Nitrate (NO_3^-) and Nitrogen (N) ratio 14 + (3x16)/14 = 4.430
5	The C / N ratio is therefore 1.05 which gives 1.05 x 4.43 = 4.65 ethanol.
6	The Carbon concentration is 15 mg/L x 4.65 = 69.975 mg/L of Carbon.
7	Concentration of ethanol is given by 69.975 mg/L divided by %age of Carbon in ethanol = 69.975/0.522 = 134.052 mg/L of ethanol.
8	Required ethanol volume = ethanol concentration / ethanol density = 134.052 mg/L divided by 789 mg/mL = 0.169 ml/L
9	The capacity of the feed tank is 20 L, hence the required dose = 20L x 0.169 ml/L = 3.38 ml of Carbon as ethanol.

Table A.2 Potassium nitrate dosage calculation for 15 mg/L- N targeted concentration

Item	Potassium nitrate detailed dosage calculations
1	Potassium nitrate molecular equation is given by KNO_3 and therefore has a molecular mass of 101g/mol
2	Fractional composition of nitrate = molecular weight of NO_3 divide by molecular weight of KNO_3 $=62/101 = 0.614\, g/mol$. This means that NO_3 makes 61.3 % in the KNO_3.
3	The targeted nitrate concentration required into the UVRF is dependent on the filter volume, all dosages were performed in the 20L feed tank.
4	The required mass of potassium nitrate was determined from the equation given by: $C_s = \frac{M_{KNO_3} \times x_{NO_3}}{V}$ $\frac{C_s \times V}{x_{NO_3}} = M_{KNO_3}$ Where: C_s= Concentration of a substance (mg/L) M_{KNO_3}= Mass of potassium nitrate (g) x_{NO_3}= Fractional composition of nitrate (g/mol) V= Volume of water (L) $\frac{0.066 \times 20}{0.614} = 2.149g$
5	The potassium nitrate dosage required is 2.149g

Table A.3 Ethanol dosage calculation at C/N ratio of 1:08

Item	Ethanol detailed dosage calculations
1	Ethanol molecular equation is given by C_2H_5OH and therefore has a molar mass of 46 g/mol.
2	The Carbon equivalent in the C_2H_5OH equation is 24 g/mol. The amount of Carbon in ethanol is therefore 24/46 x 100 % = 52.17 %.
3	The concentration of nitrate to be used in the equation is 25 mg/L and the C/N ratio established from the literature review is 1.08.
4	Nitrate (NO_3^-) and Nitrogen (N) ratio 14 + (3x16)/14 = 4.430
5	The C / N ratio is therefore 1.08 which gives 1.08x 4.430 = 4.784 ethanol.
6	The Carbon concentration is 25 mg/L x 4.784 = 119.6 mg/L of Carbon.
7	Concentration of ethanol is given by 119.6 mg/L divided by %age of Carbon in ethanol = 119.6/0.522 = 229.119 mg/L of ethanol.
8	Required ethanol volume = ethanol concentration / ethanol density = 229.119 mg/L divided by 789 mg/mL = 0.290 ml/L
9	The capacity of the feed tank is 20 L, hence the required dose = 20L x 0.290 ml/L = 5.8 ml of Carbon as ethanol.

Table A.4 Potassium nitrate dosage calculation for 25 mg/L- N targeted concentration

Item	Potassium nitrate detailed dosage calculations
1	Potassium nitrate molecular equation is given by KNO_3 and therefore has a molecular mass of 101g/mol
2	Fractional composition of nitrate = molecular weight of NO_3 divide by molecular weight of KNO_3 $=62/101 = 0.614\, g/mol$. This means that NO_3 makes 61.3 % in the KNO_3.
3	The targeted nitrate concentration required into the UVRF is dependent on the filter volume, all dosages were performed in the 20L feed tank.
4	The required mass of potassium nitrate was determined from the equation given by: $C_s = \frac{M_{KNO_3} \times x_{NO_3}}{V}$ $\frac{C_s \times V}{x_{NO_3}} = M_{KNO_3}$ Where: C_s= Concentration of a substance (mg/L) M_{KNO_3}= Mass of potassium nitrate (g) x_{NO_3}= Fractional composition of nitrate (g/mol) V= Volume of water (L) $\frac{0.11 \times 20}{0.614} = 3.583g$
5	The potassium nitrate dosage required is 3.583 g

Appendix B. Kuils river raw water quality

The tables below represent the initial results of the raw water collected from Kuils River. The results were recorded before each raw water batch was filtered. The water quality parameters were limited to pH, turbidity, dissolved Oxygen, temperature, COD, TSS, nitrate and nitrate. The raw water samples were tested before and after ethanol dosage, potassium nitrate and clay spike. Due to the intermittent running of the filter, filtrate samples were also tested each time before running the filter.

B.1. Initial raw water at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table B.1 represents the initial raw water from twenty tested sample batches in which a C/N ratio of 1.05 was used. Potassium nitrate *was* also used to spike the initial raw water nitrate concentration to attain a concentration of 15 mg/L-N.

Table B.5 Kuils River raw water quality results

RAW WATER SAMPLE 1					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	10.4	39.4	54	-	66.7
Nitrate (mg/L- N)	2.36	8.95	12.27	-	15.16
Nitrite (mg/L NO_2)	0.06	0.28	0.14	-	1.85
Nitrite (mg/L- N)	0.02	0.08	0.04	-	0.56
pH	5.69	6.73	7.09	-	-
COD(mg/L O_2)	25	-	110	-	380
DO (mg/L)	2.14	4.17	4.31	-	-
Temperature ℃	23	22.9	23.7	-	-
Turbidity (NTU)	-	-	3.43	419	-
TSS (mg/L)	-	-	28.7	-	-

RAW WATER SAMPLE 2					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	7.6	26.6	45	-	66.32
Nitrate (mg/L- N)	1.73	6.05	10.23	-	15.07
Nitrite (mg/L NO_2)	0.04	0.23	0.11	-	1.97
Nitrite (mg/L- N)	0.01	0.07	0.03	-	0.45
pH	6.91	7.11	7.12	-	-
COD(mg/L O_2)	36	-	102	-	418
DO (mg/L)	2.19	4.97	6.08	-	-
Temperature ℃	23.8	23.9	22.9	-	-
Turbidity (NTU)	-	-	5.1	426	-
TSS (mg/L)	-	-	34.2	-	-

RAW WATER SAMPLE 3					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	5.3	22.7	39	-	66.54
Nitrate (mg/L- N)	1.2	5.16	8.86	-	15.12
Nitrite (mg/L NO_2)	0.05	0.25	0.25	-	1.92
Nitrite (mg/L- N)	0.01	0.08	0.08	-	0.58
pH	6.4	6.75	7.45	-	-
COD(mg/L O_2)	58	-	95	-	340
DO (mg/L)	1.23	4.82	6.39	-	-
Temperature ℃	24.2	24.3	23.7	-	-
Turbidity (NTU)	-	-	1.76	225	-
TSS (mg/L)	-	-	22.7	-	-

RAW WATER SAMPLE 4					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	10.2	21.4	42	-	66.25
Nitrate (mg/L- N)	2.32	4.86	9.55	-	15.06
Nitrite (mg/L NO_2)	0	0.01	0.31	-	2.08
Nitrite (mg/L- N)	0	0	0.09	-	0.47
pH	6.68	6.28	7.27	-	-
COD(mg/L O_2)	35	-	112	-	405
DO (mg/L)	1.92	4.61	6.88	-	-
Temperature ℃	22.4	22.7	22.8	-	-
Turbidity (NTU)	-	-	4.42	298	-
TSS (mg/L)	-	-	19.64	-	-

RAW WATER SAMPLE 5					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	5.8	14.8	56	-	67.04
Nitrate (mg/L- N)	1.32	3.36	12.73	-	15.24
Nitrite (mg/L NO_2)	0.02	0.11	0.28	-	2.1
Nitrite (mg/L- N)	0.01	0.03	0.08	-	0.64
pH	5.93	6.01	7.49	-	-
COD(mg/L O_2)	52	-	98	-	360
DO (mg/L)	1.89	3.15	6.09	-	-
Temperature ℃	23.9	23.8	23.7	-	-
Turbidity (NTU)	-	-	1.83	377	-
TSS (mg/L)	-	-	18.96	-	-

RAW WATER SAMPLE 6					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate, clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	4.9	21.1	48	-	66.34
Nitrate (mg/L- N)	1.11	4.79	10.91	-	15.08
Nitrite (mg/L NO_2)	0	0.02	0.17	-	2.34
Nitrite (mg/L- N)	0	0.01	0.05	-	0.71
pH	6.67	7.01	7.2	-	-
COD(mg/L O_2)	32	-	85	-	385
DO (mg/L)	2.21	3.02	5.98	-	-
Temperature ℃	22.6	22.8	24.5	-	-
Turbidity (NTU)	-	-	2.98	335	-
TSS (mg/L)	-	-	27.4	-	-

RAW WATER SAMPLE 7					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	4.4	24.2	50	-	66.17
Nitrate (mg/L- N)	1	5.5	11.36	-	15.04
Nitrite (mg/L NO_2)	0.02	0.08	0.22	-	2.28
Nitrite (mg/L- N)	0.01	0.05	0.07	-	0.69
pH	6.2	6.78	7.45	-	-
COD(mg/L O_2)	48	-	108	-	392
DO (mg/L)	2.8	3.8	4.22	-	-
Temperature ℃	23.4	23.5	23.9	-	-
Turbidity (NTU)	-	-	3.82	403	-
TSS (mg/L)	-	-	35.4	-	-

RAW WATER SAMPLE 8					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	7.2	15.3	38	-	67.21
Nitrate (mg/L- N)	1.64	3.48	8.64	-	15.28
Nitrite (mg/L NO_2)	0.03	0.1	0.31	-	2.5
Nitrite (mg/L- N)	0.01	0.02	0.09	-	0.76
pH	6.03	6.92	7.36	-	-
COD(mg/L O_2)	37	-	75	-	295
DO (mg/L)	1.94	3.03	6.12	-	-
Temperature ℃	22.8	22.7	23.4	-	-
Turbidity (NTU)	-	-	4.81	431	-
TSS (mg/L)	-	-	30.3	-	-

RAW WATER SAMPLE 9					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	6.6	20.4	42	-	66.82
Nitrate (mg/L- N)	1.5	4.64	9.55	-	15.16
Nitrite (mg/L NO_2)	0.01	0.13	0.35	-	2.8
Nitrite (mg/L- N)	0	0.04	0.11	-	0.85
pH	6.95	7.02	7.49	-	-
COD (mg/L O_2)	33	-	92	-	325
DO (mg/L)	2.01	3.92	4.93	-	-
Temperature ℃	23.3	23.5	23.3	-	-
Turbidity (NTU)	-	-	2.9	395	-
TSS (mg/L)	-	-	27.3	-	-

RAW WATER SAMPLE 10					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	4.8	15.2	37	-	66.8
Nitrate (mg/L- N)	1.09	3.45	8.41	-	15.18
Nitrite (mg/L NO_2)	0	0.02	0.21	-	2.18
Nitrite (mg/L- N)	0	0.01	0.06	-	0.66
pH	5.98	6.72	6.63	-	-
COD(mg/L O_2)	46	-	68	-	355
DO (mg/L)	2.8	4.51	5.5	-	-
Temperature ℃	22.8	22.7	22.9	-	-
Turbidity (NTU)	-	-	1.92	411	-
TSS (mg/L)	-	-	25.3	-	-

RAW WATER SAMPLE 11					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	2.56	13.9	35.2	-	66.04
Nitrate (mg/L- N)	0.58	3.16	8	-	15.01
Nitrite (mg/L NO_2)	0.03	0.09	0.48	-	2.25
Nitrite (mg/L- N)	0.01	0.03	0.15	-	0.51
pH	6.79	6.88	7.41	-	-
COD(mg/L O_2)	55	-	45	-	280
DO (mg/L)	1.98	4.22	4.88	-	-
Temperature ℃	22.4	22.6	22.7	-	-
Turbidity (NTU)	-	-	1.59	304	-
TSS (mg/L)	-	-	22.7	-	-

RAW WATER SAMPLE 12					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	0.7	19.6	58.4	-	66.73
Nitrate (mg/L- N)	0.16	4.45	13.27	-	15.17
Nitrite (mg/L NO_2)	0.02	0	0.33	-	2.3
Nitrite (mg/L- N)	0.01	0	0.1	-	0.69
pH	5.47	6.33	6.92	-	-
COD(mg/L O_2)	62	-	78	-	310
DO (mg/L)	2.08	3.7	6.13	-	-
Temperature ℃	23.6	23.8	23.4	-	-
Turbidity (NTU)	-	-	5.32	462	-
TSS (mg/L)	-	-	19.4	-	-

RAW WATER SAMPLE 13					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	1.1	11.2	64	-	66.11
Nitrate (mg/L- N)	0.25	2.55	14.5	-	15.03
Nitrite (mg/L NO_2)	0.02	0.09	0.32	-	2.32
Nitrite (mg/L- N)	0.01	0.03	0.09	-	0.7
pH	6.81	7.03	7.59	-	-
COD	43	-	58	-	365
DO (mg/L)	2.3	3.41	7.15	-	-
Temperature ℃	23.4	23.6	22.4	-	-
Turbidity (NTU)	-	-	3.94	398	-
TSS (mg/L)	-	-	35.8	-	-

RAW WATER SAMPLE 14					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	1.4	12.8	39.7	-	66.62
Nitrate (mg/L- N)	0.32	2.91	9.02	-	15.14
Nitrite (mg/L NO_2)	0.01	0.07	0.22	-	2.13
Nitrite (mg/L- N)	0	0.02	0.07	-	0.64
pH	5.89	6.88	7.27	-	-
COD(mg/L O_2)	36	-	80	-	290
DO (mg/L)	2.17	4.9	6.86	-	-
Temperature ℃	22.4	22.7	23.6	-	-
Turbidity (NTU)	-	-	4.4	345	-
TSS (mg/L)	-	-	29.3	-	-

RAW WATER SAMPLE 15					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	1	7.2	58	-	67.03
Nitrate (mg/L- N)	0.23	1.63	13.18	-	15.23
Nitrite (mg/L NO_2)	0.05	0.03	0.44	-	2.2
Nitrite (mg/L- N)	0.02	0.01	0.13	-	0.66
pH	5.66	6.82	7.06	-	-
COD(mg/L O_2)	30	-	96	-	415
DO (mg/L)	2.71	4.04	7.06	-	-
Temperature ℃	23.5	23.7	22.9	-	-
Turbidity (NTU)	-	-	2.4	382	-
TSS (mg/L)	-	-	38.2	-	-

RAW WATER SAMPLE 16					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	0.08	11.7	41	-	66.13
Nitrate (mg/L -N)	0.02	2.66	9.32	-	15.03
Nitrite (mg/L NO_2)	0	0.06	0.21	-	1.97
Nitrite (mg/L -N)	0	0.02	0.06	-	0.57
pH	5.3	5.73	6.22	-	-
COD (mg/L O_2)	68	-	110	-	308
DO (mg/L)	2.07	4.16	5.92	-	-
Temperature ℃	22.2	22.4	23.8	-	-
Turbidity (NTU)	-	-	6.7	427	-
TSS (mg/L)	-	-	33.1	-	-

RAW WATER SAMPLE 17					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	3.1	12.2	50	-	66.5
Nitrate (mg/L- N)	0.7	2.77	11.36	-	15.11
Nitrite (mg/L NO_2)	0.05	0.15	0.32	-	2.65
Nitrite (mg/L- N)	0.02	0.05	0.09	-	0.6
pH	6.15	6.71	6.57	-	-
COD	32	-	90	-	403
DO (mg/L)	2.38	3.79	6.25	-	-
Temperature ℃	23.3	23.4	23.1	-	-
Turbidity (NTU)	-	-	4.06	310	-
TSS (mg/L)	-	-	20.7	-	-

RAW WATER SAMPLE 18					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	1.45	6.8	36	-	66.72
Nitrate (mg/L- N)	0.33	1.55	8.18	-	15.16
Nitrite (mg/L NO_2)	0.02	0.01	0.57	-	2.48
Nitrite (mg/L- N)	0	0	0.17	-	0.75
pH	4.06	5.7	7.48	-	-
COD (mg/L O_2)	57	-	62	-	298
DO (mg/L)	2.97	4.03	7.33	-	-
Temperature ℃	24.2	24.5	22.6	-	-
Turbidity (NTU)	-	-	5.79	405	-
TSS (mg/L)	-	-	23.4	-	-

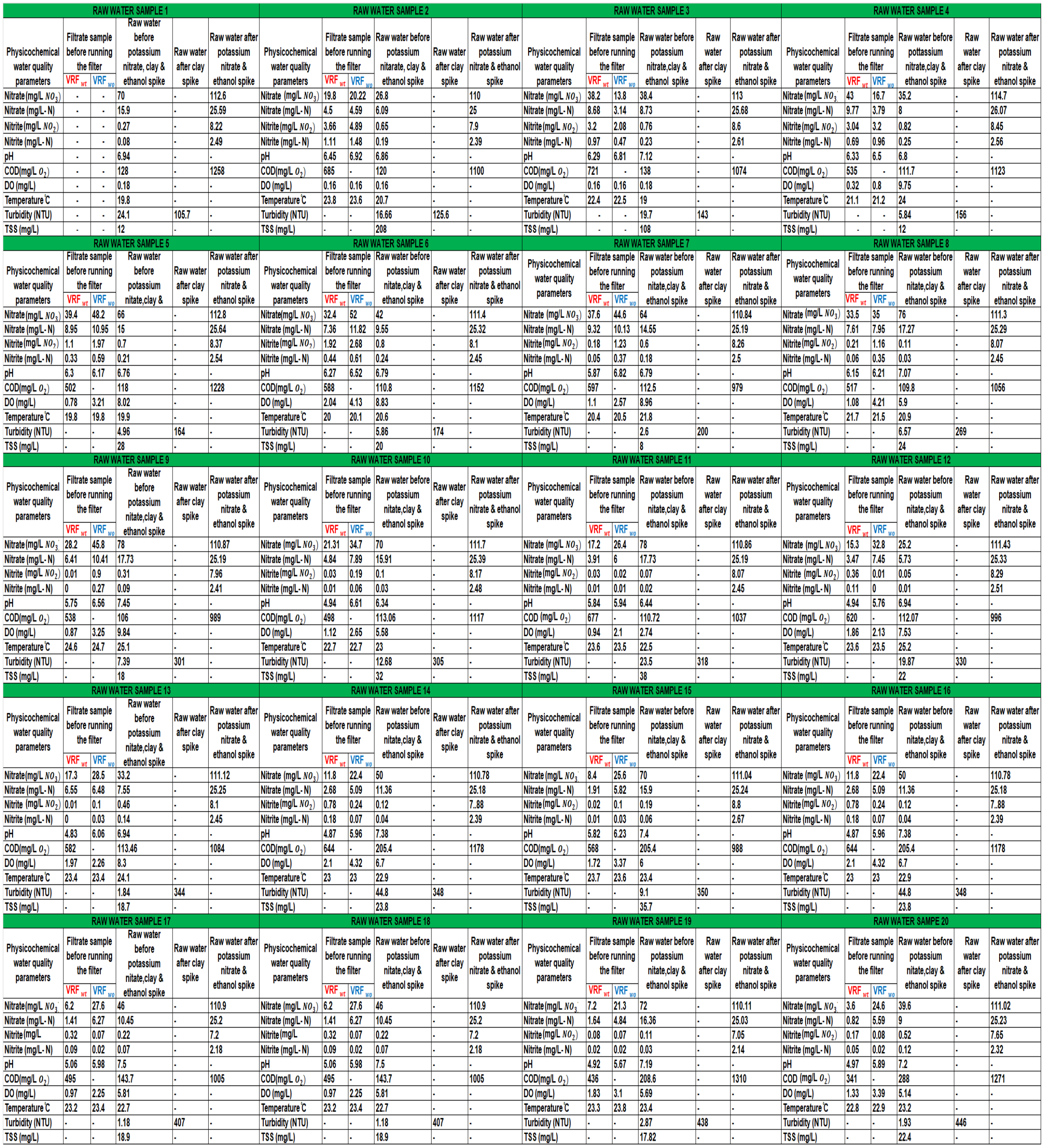
RAW WATER SAMPLE 19					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	1.45	6.8	36	-	66.72
Nitrate (mg/L- N)	0.33	1.55	8.18	-	15.16
Nitrite (mg/L NO_2)	0.02	0.01	0.57	-	2.48
Nitrite (mg/L- N)	0	0	0.17	-	0.75
pH	4.06	5.7	7.48	-	-
COD(mg/L O_2)	57	-	62	-	298
DO (mg/L)	2.97	4.03	7.33	-	-
Temperature ℃	24.2	24.5	22.6	-	-
Turbidity (NTU)	-	-	5.79	405	-
TSS (mg/L)	-	-	23.4	-	-

RAW WATER SAMPLE 20					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	0.25	0.44	51	-	66.09
Nitrate (mg/L- N)	0.06	0.1	11.59	-	15.02
Nitrite (mg/L NO_2)	0.01	0.1	0.41	-	2.02
Nitrite (mg/L- N)	0	0.03	0.12	-	0.61
pH	5.73	6.26	7.16	-	-
COD (mg/L O_2)	37	-	98	-	386
DO (mg/L)	2.61	4.17	6.84	-	-
Temperature ℃	23.4	23.6	23.5	-	-
Turbidity (NTU)	-	-	5.66	388	-
TSS (mg/L)	-	-	28.6	-	-

B.2. Initial raw water at C/N ratio of 1.08 and nitrate concentration of 25mg/L-N

Table B.2 represents the initial raw water from twenty tested sample batches in which a C/N ratio of 1.08 was used. Potassium nitrate was also used to spike the initial raw water nitrate concentration to attain a concentration of 25 mg/L-N.

Table B.6 Kuils River raw water quality results



RAW WATER SAMPLE 1					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitrate, clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	-	-	70	-	112.6
Nitrate (mg/L- N)	-	-	15.9	-	25.59
Nitrite (mg/L NO_2)	-	-	0.27	-	8.22
Nitrite (mg/L- N)	-	-	0.08	-	2.49
pH	-	-	6.94	-	-
COD(mg/L O_2)	-	-	128	-	1258
DO (mg/L)	-	-	0.18	-	-
Temperature ℃	-	-	19.8	-	-
Turbidity (NTU)	-	-	24.1	105.7	-
TSS (mg/L)	-	-	12	-	-

RAW WATER SAMPLE 2					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitarate, clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	19.8	20.22	26.8	-	110
Nitrate (mg/L- N)	4.5	4.59	6.09	-	25
Nitrite (mg/L NO_2)	3.66	4.89	0.65	-	7.9
Nitrite (mg/L- N)	1.11	1.48	0.19	-	2.39
pH	6.45	6.92	6.86	-	-
COD(mg/L O_2)	685	-	120	-	1100
DO (mg/L)	0.16	0.16	0.16	-	-
Temperature ℃	23.8	23.6	20.7	-	-
Turbidity (NTU)	-	-	16.66	125.6	-
TSS (mg/L)	-	-	208	-	-

RAW WATER SAMPLE 3					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitrate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	38.2	13.8	38.4	-	113
Nitrate (mg/L- N)	8.68	3.14	8.73	-	25.68
Nitrite (mg/L NO_2)	3.2	2.08	0.76	-	8.6
Nitrite (mg/L- N)	0.97	0.47	0.23	-	2.61
pH	6.29	6.81	7.12	-	-
COD(mg/L O_2)	721	-	138	-	1074
DO (mg/L)	0.16	0.16	0.18	-	-
Temperature ℃	22.4	22.5	19	-	-
Turbidity (NTU)	-	-	19.7	143	-
TSS (mg/L)	-	-	108	-	-

RAW WATER SAMPLE 4					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before pottassium nitrate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3	43	16.7	35.2	-	114.7
Nitrate (mg/L- N)	9.77	3.79	8	-	26.07
Nitrite (mg/L NO_2)	3.04	3.2	0.82	-	8.45
Nitrite (mg/L- N)	0.69	0.96	0.25	-	2.56
pH	6.33	6.5	6.8	-	-
COD(mg/L O_2)	535	-	111.7	-	1123
DO (mg/L)	0.32	0.8	9.75	-	-
Temperature ℃	21.1	21.2	24	-	-
Turbidity (NTU)	-	-	5.84	156	-
TSS (mg/L)	-	-	12	-	-

RAW WATER SAMPLE 5					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay &	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	39.4	48.2	66	-	112.8
Nitrate (mg/L- N)	8.95	10.95	15	-	25.64
Nitrite (mg/L NO_2)	1.1	1.97	0.7	-	8.37
Nitrite (mg/L- N)	0.33	0.59	0.21	-	2.54
pH	6.3	6.17	6.76	-	-
COD(mg/L O_2)	502	-	118	-	1228
DO (mg/L)	0.78	3.21	8.02	-	-
Temperature ℃	19.8	19.8	19.9	-	-
Turbidity (NTU)	-	-	4.96	164	-
TSS (mg/L)	-	-	28	-	-

RAW WATER SAMPLE 6					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	32.4	52	42	-	111.4
Nitrate (mg/L- N)	7.36	11.82	9.55	-	25.32
Nitrite (mg/L NO_2)	1.92	2.68	0.8	-	8.1
Nitrite (mg/L- N)	0.44	0.61	0.24	-	2.45
pH	6.27	6.52	6.79	-	-
COD(mg/L O_2)	588	-	110.8	-	1152
DO (mg/L)	2.04	4.13	8.83	-	-
Temperature ℃	20	20.1	20.6	-	-
Turbidity (NTU)	-	-	5.86	174	-
TSS (mg/L)	-	-	20	-	-

RAW WATER SAMPLE 7					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	37.6	44.6	64	-	110.84
Nitrate (mg/L- N)	9.32	10.13	14.55	-	25.19
Nitrite (mg/L NO_2)	0.18	1.23	0.6	-	8.26
Nitrite (mg/L- N)	0.05	0.37	0.18	-	2.5
pH	5.87	6.82	6.79	-	-
COD(mg/L O_2)	597	-	112.5	-	979
DO (mg/L)	1.1	2.57	8.96	-	-
Temperature ℃	20.4	20.5	21.8	-	-
Turbidity (NTU)	-	-	2.6	200	-
TSS (mg/L)	-	-	8	-	-

RAW WATER SAMPLE 8					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	33.5	35	76	-	111.3
Nitrate (mg/L- N)	7.61	7.95	17.27	-	25.29
Nitrite (mg/L NO_2)	0.21	1.16	0.11	-	8.07
Nitrite (mg/L- N)	0.06	0.35	0.03	-	2.45
pH	6.15	6.21	7.07	-	-
COD(mg/L O_2)	517	-	109.8	-	1056
DO (mg/L)	1.08	4.21	5.9	-	-
Temperature ℃	21.7	21.5	20.9	-	-
Turbidity (NTU)	-	-	6.57	269	-
TSS (mg/L)	-	-	24	-	-

RAW WATER SAMPLE 9					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3	28.2	45.8	78	-	110.87
Nitrate (mg/L- N)	6.41	10.41	17.73	-	25.19
Nitrite (mg/L NO_2)	0.01	0.9	0.31	-	7.96
Nitrite (mg/L- N)	0	0.27	0.09	-	2.41
pH	5.75	6.56	7.45	-	-
COD(mg/L O_2)	538	-	106	-	989
DO (mg/L)	0.87	3.25	9.84	-	-
Temperature ℃	24.6	24.7	25.1	-	-
Turbidity (NTU)	-	-	7.39	301	-
TSS (mg/L)	-	-	18	-	-

RAW WATER SAMPLE 10					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	21.31	34.7	70	-	111.7
Nitrate (mg/L- N)	4.84	7.89	15.91	-	25.39
Nitrite (mg/L NO_2)	0.03	0.19	0.1	-	8.17
Nitrite (mg/L- N)	0.01	0.06	0.03	-	2.48
pH	4.94	6.61	6.34	-	-
COD(mg/L O_2)	498	-	113.06	-	1117
DO (mg/L)	1.12	2.65	5.58	-	-
Temperature ℃	22.7	22.7	23	-	-
Turbidity (NTU)	-	-	12.68	305	-
TSS (mg/L)	-	-	32	-	-

RAW WATER SAMPLE 11					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	17.2	26.4	78	-	110.86
Nitrate (mg/L- N)	3.91	6	17.73	-	25.19
Nitrite (mg/L NO_2)	0.03	0.02	0.07	-	8.07
Nitrite (mg/L- N)	0.01	0.01	0.02	-	2.45
pH	5.84	5.94	6.44	-	-
COD (mg/L O_2)	677	-	110.72	-	1037
DO (mg/L)	0.94	2.1	2.74	-	-
Temperature ℃	23.6	23.5	22.5	-	-
Turbidity (NTU)	-	-	23.5	318	-
TSS (mg/L)	-	-	38	-	-

RAW WATER SAMPLE 12					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	15.3	32.8	25.2	-	111.43
Nitrate (mg/L- N)	3.47	7.45	5.73	-	25.33
Nitrite (mg/L NO_2)	0.36	0.01	0.05	-	8.29
Nitrite (mg/L- N)	0.11	0	0.01	-	2.51
pH	4.94	5.76	6.94	-	-
COD (mg/L O_2)	620	-	112.07	-	996
DO (mg/L)	1.86	2.13	7.53	-	-
Temperature ℃	23.6	23.5	25.2	-	-
Turbidity (NTU)	-	-	19.87	330	-
TSS (mg/L)	-	-	22	-	-

RAW WATER SAMPLE 13					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	17.3	28.5	33.2	-	111.12
Nitrate (mg/L- N)	6.55	6.48	7.55	-	25.25
Nitrite (mg/L NO_2)	0.01	0.1	0.46	-	8.1
Nitrite (mg/L- N)	0	0.03	0.14	-	2.45
pH	4.83	6.06	6.94	-	-
COD(mg/L O_2)	582	-	113.46	-	1084
DO (mg/L)	1.97	2.26	8.3	-	-
Temperature ℃	23.4	23.4	24.1	-	-
Turbidity (NTU)	-	-	1.84	344	-
TSS (mg/L)	-	-	18.7	-	-

RAW WATER SAMPLE 14					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	11.8	22.4	50	-	110.78
Nitrate (mg/L- N)	2.68	5.09	11.36	-	25.18
Nitrite (mg/L NO_2)	0.78	0.24	0.12	-	7..88
Nitrite (mg/L- N)	0.18	0.07	0.04	-	2.39
pH	4.87	5.96	7.38	-	-
COD(mg/L O_2)	644	-	205.4	-	1178
DO (mg/L)	2.1	4.32	6.7	-	-
Temperature ℃	23	23	22.9	-	-
Turbidity (NTU)	-	-	44.8	348	-
TSS (mg/L)	-	-	23.8	-	-

RAW WATER SAMPLE 15					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3	8.4	25.6	70	-	111.04
Nitrate (mg/L- N)	1.91	5.82	15.9	-	25.24
Nitrite (mg/L NO_2)	0.02	0.1	0.19	-	8.8
Nitrite (mg/L- N)	0.01	0.03	0.06	-	2.67
pH	5.82	6.23	7.4	-	-
COD(mg/L O_2)	568	-	205.4	-	988
DO (mg/L)	1.72	3.37	6	-	-
Temperature ℃	23.7	23.6	23.4	-	-
Turbidity (NTU)	-	-	9.1	350	-
TSS (mg/L)	-	-	35.7	-	-

RAW WATER SAMPLE 16					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	11.8	22.4	50	-	110.78
Nitrate (mg/L- N)	2.68	5.09	11.36	-	25.18
Nitrite (mg/L NO_2)	0.78	0.24	0.12	-	7..88
Nitrite (mg/L- N)	0.18	0.07	0.04	-	2.39
pH	4.87	5.96	7.38	-	-
COD(mg/L O_2)	644	-	205.4	-	1178
DO (mg/L)	2.1	4.32	6.7	-	-
Temperature ℃	23	23	22.9	-	-
Turbidity (NTU)	-	-	44.8	348	-
TSS (mg/L)	-	-	23.8	-	-

RAW WATER SAMPLE 17					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3	6.2	27.6	46	-	110.9
Nitrate (mg/L- N)	1.41	6.27	10.45	-	25.2
Nitrite (mg/L	0.32	0.07	0.22	-	7.2
Nitrite (mg/L- N)	0.09	0.02	0.07	-	2.18
pH	5.06	5.98	7.5	-	-
COD(mg/L O_2)	495	-	143.7	-	1005
DO (mg/L)	0.97	2.25	5.81	-	-
Temperature ℃	23.2	23.4	22.7	-	-
Turbidity (NTU)	-	-	1.18	407	-
TSS (mg/L)	-	-	18.9	-	-

RAW WATER SAMPLE 18					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	6.2	27.6	46	-	110.9
Nitrate (mg/L- N)	1.41	6.27	10.45	-	25.2
Nitrite (mg/L	0.32	0.07	0.22	-	7.2
Nitrite (mg/L- N)	0.09	0.02	0.07	-	2.18
pH	5.06	5.98	7.5	-	-
COD(mg/L O_2)	495	-	143.7	-	1005
DO (mg/L)	0.97	2.25	5.81	-	-
Temperature ℃	23.2	23.4	22.7	-	-
Turbidity (NTU)	-	-	1.18	407	-
TSS (mg/L)	-	-	18.9	-	-

RAW WATER SAMPLE 19					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3	7.2	21.3	72	-	110.11
Nitrate (mg/L- N)	1.64	4.84	16.36	-	25.03
Nitrite (mg/L NO_2)	0.08	0.07	0.11	-	7.05
Nitrite (mg/L- N)	0.02	0.02	0.03	-	2.14
pH	4.92	5.67	7.19	-	-
COD(mg/L O_2)	436	-	208.6	-	1310
DO (mg/L)	1.83	3.1	5.69	-	-
Temperature ℃	23.3	23.8	23.4	-	-
Turbidity (NTU)	-	-	2.87	438	-
TSS (mg/L)	-	-	17.82	-	-

RAW WATER SAMPE 20					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3	3.6	24.6	39.6	-	111.02
Nitrate (mg/L- N)	0.82	5.59	9	-	25.23
Nitrite (mg/L NO_2)	0.17	0.08	0.52	-	7.65
Nitrite (mg/L- N)	0.05	0.02	0.12	-	2.32
pH	4.97	5.89	7.2	-	-
COD (mg/L O_2)	341	-	288		1271
DO (mg/L)	1.33	3.39	5.14	-	-
Temperature ℃	22.8	22.9	23.2	-	-
Turbidity (NTU)	-	-	1.93	446	-
TSS (mg/L)	-	-	22.4	-	-

B.3. Initial raw water at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table B.3 represents the initial raw water from twenty tested sample batches in which a C/N ratio of 1.1 was used. Potassium nitrate was also used to spike the initial raw water nitrate concentration to attain a concentration of 50 mg/L-N.

Table B.7 Kuils River raw water quality result

RAW WATER SAMPLE 1					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	39.6	50	54	-	221.4
Nitrate (mg/L-N)	9	11.36	12.27	-	50.32
Nitrite (mg/L NO_2)	0.08	0.1	0.35	-	18.71
Nitrite (mg/L-N)	0.02	0.03	0.14	-	5.67
pH	6.36	7.07	6.98	-	-
COD(mg/L O_2)	762	-	864	-	1106
DO (mg/L)	2.23	3.55	8.3	-	-
Temperature °C	25.8	25.8	25.8	-	-
Turbidity (NTU)	-	-	4.64	296	-
TSS (mg/L)	-	-	22.8	-	-

RAW WATER SAMPLE 2					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	16.8	42	15.2	-	220.8
Nitrate (mg/L-N)	3.82	9.55	3.45	-	50.32
Nitrite (mg/L NO_2)	2.06	0.02	0.1	-	19.11
Nitrite (mg/L-N)	0.62	0.01	0.03	-	5.79
pH	5.96	6.42	6.9	-	-
COD(mg/L O_2)	743	-	785	-	1350
DO (mg/L)	1.89	3.04	6.21	-	-
Temperature °C	26.6	26.6	27	-	-
Turbidity (NTU)	-	-	1.39	303	-
TSS (mg/L)	-	-	17.84	-	-

RAW WATER SAMPLE 3					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	17.4	38.6	60	-	221.06
Nitrate (mg/L-N)	3.95	8.77	13.64	-	50.24
Nitrite (mg/L NO_2)	2.68	0.79	0.24	`	18.71
Nitrite (mg/L-N)	0.81	0.24	0.07	-	5.67
pH	5.33	6.73	7.22	-	-
COD (mg/L O_2)	684	-	912	-	1084
DO (mg/L)	1.93	3.13	8.45	-	-
Temperature °C	25.9	25.9	26.6	-	-
Turbidity (NTU)	-	-	2.28	318	-
TSS (mg/L)	-	-	21.8	-	-

RAW WATER SAMPLE 4					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	12.7	52	86	-	221.7
Nitrate (mg/L-N)	2.89	11.82	19.55	-	50.39
Nitrite (mg/L NO_2)	2.29	0.58	0.38	-	17.69
Nitrite (mg/L-N)	0.69	0.18	0.12	-	5.36
pH	6.62	7.07	7.05	-	-
COD (mg/L O_2)	571	-	822	-	1196
DO (mg/L)	1.73	4.06	7.26	-	-
Temperature °C	25.6	25.5	25.5	-	-
Turbidity (NTU)	-	-	0.57	336	-
TSS (mg/L)	-	-	18.4	-	-

RAW WATER SAMPLE 5					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	28.2	48	72	-	220.8
Nitrate (mg/L-N)	6.41	10.91	16.36	-	50.18
Nitrite (mg/L NO_2)	1.68	0.23	0.12	-	18.55
Nitrite (mg/L-N)	0.51	0.07	0.04	-	5.62
pH	5.42	6.63	7.38	-	-
COD(mg/L O_2)	535	-	738	-	1245
DO (mg/L)	1.58	3.27	8.65	-	-
Temperature °C	24.7	24.5	24.8	-	-
Turbidity (NTU)	-	-	2.89	354	-
TSS (mg/L)	-	-	25.4	-	-

RAW WATER SAMPLE 6					
Filtrate sample before running the filter	Water sample before filter flushing		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	4.8	65.8	36.4	-	221.06
Nitrate (mg/L-N)	1.09	14.95	8.27	-	50.24
Nitrite (mg/L NO_2)	1.27	0.16	0.1	-	18.68
Nitrite (mg/L-N)	0.38	0.05	0.03	-	5.66
pH	5.42	6.53	7.18	-	-
COD(mg/L O_2)	657	-	698	-	1155
DO (mg/L)	1.88	3.25	6.74	-	-
Temperature °C	23.4	23.8	24.7	-	-
Turbidity (NTU)	-	-	2.28	356	-
TSS (mg/L)	-	-	22.8	-	-

RAW WATER SAMPLE 7					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	22.8	68.3	19.6	-	221.36
Nitrate (mg/L-N)	5.18	15.52	4.45	-	50.31
Nitrite (mg/L NO_2)	1.32	0.07	0.09	-	19.7
Nitrite (mg/L-N)	0.4	0.02	0.03	-	5.97
pH	5.54	6.41	7.2	-	-
COD(mg/L O_2)	626	-	903	-	1128
DO (mg/L)	1.25	3.52	6.16	-	-
Temperature °C	24.8	25	25	-	-
Turbidity (NTU)	-	-	1.4	384	-
TSS (mg/L)	-	-	17.8	-	-

RAW WATER SAMPLE 8					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	18.4	86	30.8	-	221.14
Nitrate (mg/L-N)	4.18	19.55	7	-	50.26
Nitrite (mg/L NO_2)	3.18	0.02	0.11	-	16.37
Nitrite (mg/L-N)	0.96	0.18	0.03	-	4.96
pH	5.35	6.5	7.23	-	-
COD (mg/L O_2)	587	-	685	-	1100
DO (mg/L)	2.27	3.81	6.02	-	-
Temperature °C	24.4	24.6	25.3	-	-
Turbidity (NTU)	-	-	3.42	404	-
TSS (mg/L)	-	-	21.31	-	-

RAW WATER SAMPLE 9					
Filtrate sample before running the filter	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	17	42	86	-	220.92
Nitrate (mg/L-N)	3.86	9.55	19.55	-	50.21
Nitrite (mg/L NO_2)	0.19	0.41	0.08	-	18.78
Nitrite (mg/L-N)	0.04	0.12	0.02	-	5.69
pH	5.4	6.99	6.86	-	-
COD(mg/L O_2)	498	-	775	-	1058
DO (mg/L)	1.65	3.23	5.61	-	-
Temperature °C	25.6	25.5	25.5	-	-
Turbidity (NTU)	-	-	0.75	434	-
TSS (mg/L)	-	-	14.97	-	-

RAW WATER SAMPLE 10					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	16.6	38	72	-	220.6
Nitrate (mg/L-N)	3.77	8.64	16.36	-	50.14
Nitrite (mg/L NO_2)	0.33	0.01	0.05	-	17.89
Nitrite (mg/L-N)	0.1	0	0.02	-	5.42
pH	5.5	6.3	7.3	-	-
COD(mg/L O_2)	475	-	848	-	1175
DO (mg/L)	1.58	3.11	6.2	-	-
Temperature °C	25.6	25.7	24.9	-	-
Turbidity (NTU)	-	-	1.78	476	-
TSS (mg/L)	-	-	18.9	-	-

RAW WATER SAMPLE 11					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	5.8	40	58	-	221.12
Nitrate (mg/L-N)	1.31	9.09	13.18	-	50.25
Nitrite (mg/L NO_2)	0.25	0.65	0.1	-	18.15
Nitrite (mg/L-N)	0.08	0.19	0.03	-	5.5
pH	4.7	5.99	6.97	-	-
COD (mg/L O_2)	652	-	786	-	1140
DO (mg/L)	1.64	2.97	6.46	-	-
Temperature °C	25.5	25.4	25.62	-	-
Turbidity (NTU)	-	-	1.78	519	-
TSS (mg/L)	-	-	20.83	-	-

RAW WATER SAMPLE 12					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	6.5	42	70	-	220.42
Nitrate (mg/L-N)	1.48	9.55	15.91	-	50.09
Nitrite (mg/L	1.21	0.18	0.18	-	18.08
Nitrite (mg/L-N)	0.37	0.05	0.05	-	5.48
pH	5.61	6.13	6.68	-	-
COD(mg/L O_2)	488	-	720	-	1215
DO (mg/L)	1.77	3.58	6.97	-	-
Temperature °C	23.9	23.7	24.1	-	-
Turbidity (NTU)	-	-	1.96	544	-
TSS (mg/L)	-	-	22.67	-	-

RAW WATER SAMPLE 13					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	14	49.8	42	-	220.83
Nitrate (mg/L-N)	3.18	11.32	9.55	-	50.19
Nitrite (mg/L NO_2)	1.14	0.01	0.07	-	15.35
Nitrite (mg/L-N)	0.35	0	0.02	-	4.65
pH	4.48	5.9	6.71	-	-
COD(mg/L O_2)	510	-	825	-	1150
DO (mg/L)	1.04	3.96	5.63	-	-
Temperature °C	23.9	24	24.1	-	-
Turbidity (NTU)	-	-	1.33	550	-
TSS (mg/L)	-	-	17.87	-	-

RAW WATER SAMPLE 14					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	17.2	29.7	50	-	221.3
Nitrate (mg/L-N)	3.91	6.75	11.36	-	50.29
Nitrite (mg/L NO_2)	1.27	0.04	0.1	-	15.41
Nitrite (mg/L-N)	0.38	0.01	0.03	-	4.67
pH	5.48	6.24	7.08	-	-
COD(mg/L O_2)	556.2	-	937	-	1207
DO (mg/L)	1.88	3.69	4.82	-	-
Temperature °C	24.4	24.5	24.5	-	-
Turbidity (NTU)	-	-	3.09	582	-
TSS (mg/L)	-	-	28.7	-	-

RAW WATER SAMPLE 15					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	18.4	27.4	76	-	220.77
Nitrate (mg/L-N)	4.18	6.2	17.27	-	50.18
Nitrite (mg/L NO_2)	0.21	0.07	0.12	-	16.99
Nitrite (mg/L-N)	0.06	0.29	0.04	-	5.15
pH	5.49	6.17	7.21	-	-
COD(mg/L O_2)	458	-	755	-	1085
DO (mg/L)	1.34	4.43	6.35	-	-
Temperature °C	24.8	24.8	24.7	-	-
Turbidity (NTU)	-	-	1	632	-
TSS (mg/L)	-	-	21.96	-	-

RAW WATER SAMPLE 16					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	20.6	41.4	56	-	220.47
Nitrate (mg/L-N)	4.68	9.41	12.73	-	50.11
Nitrite (mg/L NO_2)	0.25	0.1	0.15	-	16.27
Nitrite (mg/L-N)	0.08	0.03	0.05	-	4.93
pH	5.16	6.89	6.7	-	-
COD(mg/L O_2)	438	-	728	-	1180
DO (mg/L)	1.89	3.91	5.83	-	-
Temperature °C	24.7	24.8	25	-	-
Turbidity (NTU)	-	-	1.27	645	-
TSS (mg/L)	-	-	26.8	-	-

RAW WATER SAMPLE 17					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate(mg/L NO_3)	13.8	40.6	48	-	221.04
Nitrate (mg/L-N)	3.14	9.23	10.91	-	50.24
Nitrite (mg/L NO_2)	0.09	0.09	0.11	-	15.61
Nitrite (mg/L-N)	0.03	0.16	0.03	-	4.73
pH	5.71	6.14	7.18	-	-
COD(mg/L O_2)	410	-	800	-	1050
DO (mg/L)	2.17	4.16	6.1	-	-
Temperature °C	24.3	24.4	24.7	-	-
Turbidity (NTU)	-	-	1.96	694	-
TSS (mg/L)	-	-	33.6	-	-

RAW WATER SAMPLE 18					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	16.8	23.6	76	-	220.85
Nitrate (mg/L-N)	3.82	5.36	17.27	-	50.19
Nitrite (mg/L NO_2)	0.01	0.04	0.17	-	18.35
Nitrite (mg/L-N)	0	0.23	0.05	-	5.56
pH	5.92	6.13	7.14	-	-
COD(mg/L O_2)	455	-	750	-	1100
DO (mg/L)	2.17	3.84	4.38	-	-
Temperature °C	22.8	22.8	22.9	-	-
Turbidity (NTU)	-	-	1.78	698	-
TSS (mg/L)	-	-	28.6	-	-

RAW WATER SAMPLE 19					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	17.4	36.4	86	-	221.46
Nitrate (mg/L-N)	3.95	8.27	19.55	-	50.33
Nitrite (mg/L NO_2)	0.73	0.18	0.18	-	15.44
Nitrite (mg/L-N)	0.04	0.27	0.05	-	4.68
pH	5.92	6.33	7.01	-	-
COD (mg/L O_2)	438	-	685	-	1030
DO (mg/L)	1.78	3.95	5.67	-	-
Temperature °C	23.3	23.3	23	-	-
Turbidity (NTU)	-	-	1.86	713	-
TSS (mg/L)	-	-	32.8	-	-

RAW WATER SAMPLE 20					
Physicochemical water quality parameters	Filtrate sample before running the filter		Raw water before potassium nitate,clay & ethanol spike	Raw water after clay spike	Raw water after potassium nitrate & ethanol spike
	VRF_{wt}	VRF_{wo}			
Nitrate (mg/L NO_3)	13.8	27.4	78	-	220.68
Nitrate (mg/L-N)	3.14	6.23	17.73	-	50.15
Nitrite (mg/L NO_2)	0.06	0.1	0.16	-	18.55
Nitrite (mg/L-N)	0.05	0.22	0.05	-	5.62
pH	5.17	6.26	7.14	-	-
COD (mg/L O_2)	442	-	715	-	1085
DO (mg/L)	2.1	4.02	4.81	-	-
Temperature °C	23	23	23.3	-	-
Turbidity (NTU)	-	-	1.45	877	-
TSS (mg/L)	-	-	21.8	-	-

Table B.8 COD and nitrate results performed on raw river water before filtering (Inflow)and river water after filtering (Outflow).

Tested date	Test	Units	EXTERNAL LABORATORY		
			Unspiked raw water sample	KNO3 & Ethanol spiked inflow raw water sample	KNO3 & Ethanol Spiked outflow water sample
18-09-2020	Nitrate	(mg/L- N)	2.7	-	<0.18
	COD	(mg/LO_2)	31	-	600
29-10-2020	Nitrate	(mg/L- N)	-	11.3	<0.18
	COD	(mg/LO_2)	-	64	604
17-12-2020	Nitrate	(mg/L- N)	-	<0.18	<0.18
	COD	(mg/LO_2)	-	1070	710

Appendix C. Particle size distribution for the filter media

C.1. Particle distribution tables

The Tables C.1 to C.3 below represent the detailed calculations for the particle distribution for the aggregates used as filter media while Table C.4 shows the retained average mass of each media size on the respective sieves.

Table C.9. Particle distribution table for the 13 mm aggregates

Sieve Number	Diameter (mm)	Mass of basin (g)	Mass of basin & Soil (g)	Mass retained (g)	Mass retained (%)	Cumulative mass retained (%)	Soil Passing (%)
0.53 in	13.20	628.4	1236.2	607.8	60.8	59.8	39.3
3/8 in	9.51	628.4	820.8	192.4	19.2	79.0	20.0
0.265 in	6.73	628.4	756.7	128.3	12.8	91.9	7.2
No. 4	4.75	628.4	684.8	56.4	5.6	97.5	1.6
No. 8	2.36	628.4	639.6	11.2	1.1	98.6	0.4
No. 16	1.18	628.4	628.5	0.1	0	98.6	0.4
No. 30	0.60	628.4	628.7	0.3	0	98.8	0.3
No. 40	0.43	628.4	629.5	1.1	0.1	98.9	0.2
No. 50	0.30	628.4	629.0	0.6	0.1	98.9	0.1
No. 100	0.15	628.4	628.7	0.3	0	99.0	0.1
No. 200	0.075	628.4	628.6	0.2	0	99.0	0.1
Pan				0.9	0.1	99.1	0
Total				**999.6**	**100.0**		

Table C.10. Particle distribution table for the 9 mm aggregates

Sieve Number	Diameter (mm)	Mass of basin (g)	Mass of basin & Soil (g)	Mass retained (g)	Mass retained (%)	Cumulative mass retained (%)	Soil Passing (%)
0.53 in	13.20	628.4	635.7	7.3	0.7	0.7	99.0
3/8 in	9.51	628.4	1271.8	643.4	64.3	65.0	34.6
0.265 in	6.73	628.4	793.4	165	16.5	81.5	18.1
No. 4	4.75	628.4	764.6	136.2	13.6	95.2	4.5
No. 8	2.36	628.4	665.8	37.4	3.7	98.9	0.8
No.16	1.18	628.4	631.6	3.2	0.3	99.2	0.5
No. 30	0.60	628.4	628.7	0.3	0.0	99.3	0.4
No. 40	0.43	628.4	629.4	1	0.1	99.4	0.3
No. 50	0.30	628.4	628.7	0.3	0.0	99.4	0.3
No.100	0.15	628.4	630.2	1.8	0.2	99.6	0.1
No. 200	0.075	628.4	629.4	1	0.1	99.7	0
Pan				0.1	0	99.7	0
Total				**997**	**99.7**		

Table C.11. Particle distribution table for the 6 mm aggregates

Sieve size	Diameter (mm)	Mass of basin (g)	Mass of basin & Soil (g)	Mass retained (g)	Mass retained (%)	Cumulative mass retained (%)	Soil Passing (%)
0.53 in	13.20	628.4	628.4	0	0	0	99.8
3/8 in	9.51	628.4	752	123.6	12.4	12.4	87.4
0.265 in	6.73	628.4	1308.3	679.9	68.0	80.4	19.4
No. 4	4.75	628.4	764.2	135.8	13.6	93.9	5.8
No. 8	2.36	628.4	678.9	50.5	5.1	99.0	0.8
No.16	1.18	628.4	630.5	2.1	0.2	99.2	0.6
No. 30	0.60	628.4	629	0.6	0.1	99.3	0.5
No. 40	0.43	628.4	630.5	2.1	0.2	99.5	0.3
No. 50	0.30	628.4	629.3	0.9	0.1	99.6	0.2
No. 100	0.15	628.4	629.5	1.1	0.1	99.7	0.1
No. 200	0.075	628.4	629.2	0.8	0.1	99.7	0
Pan				0.1	0	99.8	0
Total				**997.5**	**99.8**		

Table C.12. Particle size distribution for UVRF filter media

Sieve size (mm)	Average mass retained (g)		
	13 mm gravel	**9 mm gravel**	**6 mm gravel**
13.2	607.8	7.3	0
9.5	192.4	643.4	123.6
6.7	128.3	165	679.9
4.75	56.4	136.2	135.8
2.36	11.2	37.4	50.5
1.18	0.1	3.2	2.1
0.6	0.3	0.3	0.6
0.425	1.1	1	2.1
0.3	0.6	0.3	0.9
0.15	0.3	1.8	1.1
0.075	0.2	1	0.8
Pan	0.9	0.1	0.1
Total	**999.6**	**997.0**	**997.5**

C.2. Particle distribution plots

The figures below represent the plots for the particle distribution on each filter media size.

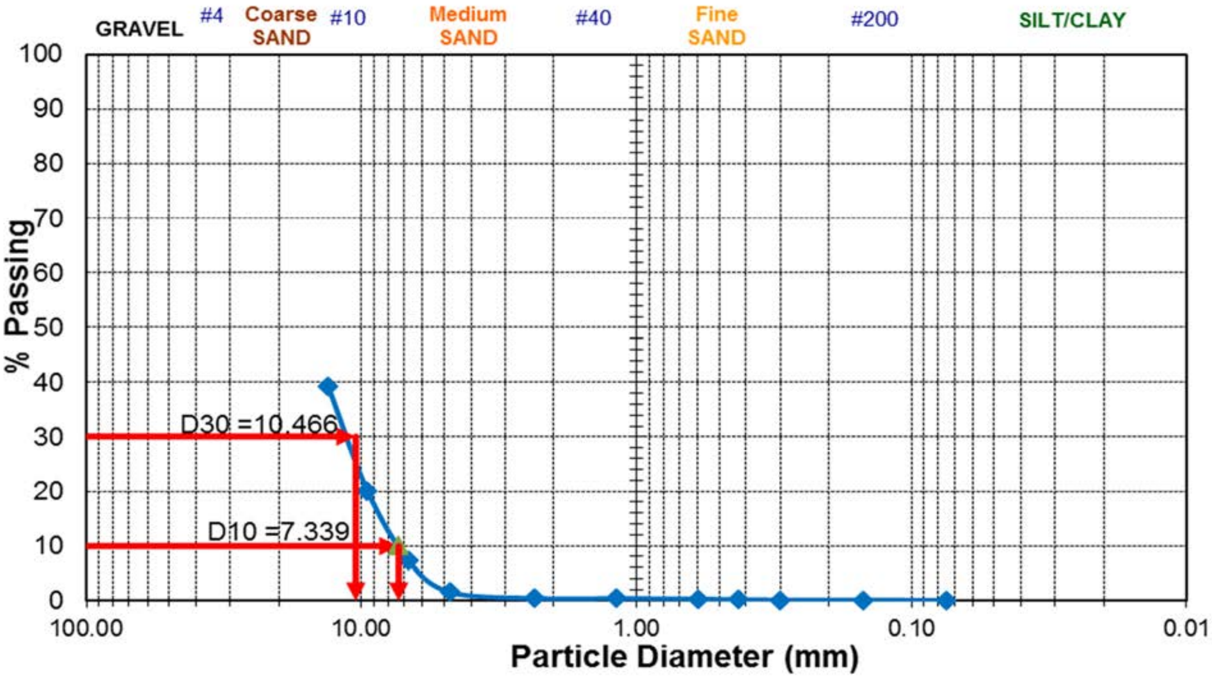


Figure C.1 13 mm filter media particle distribution plot

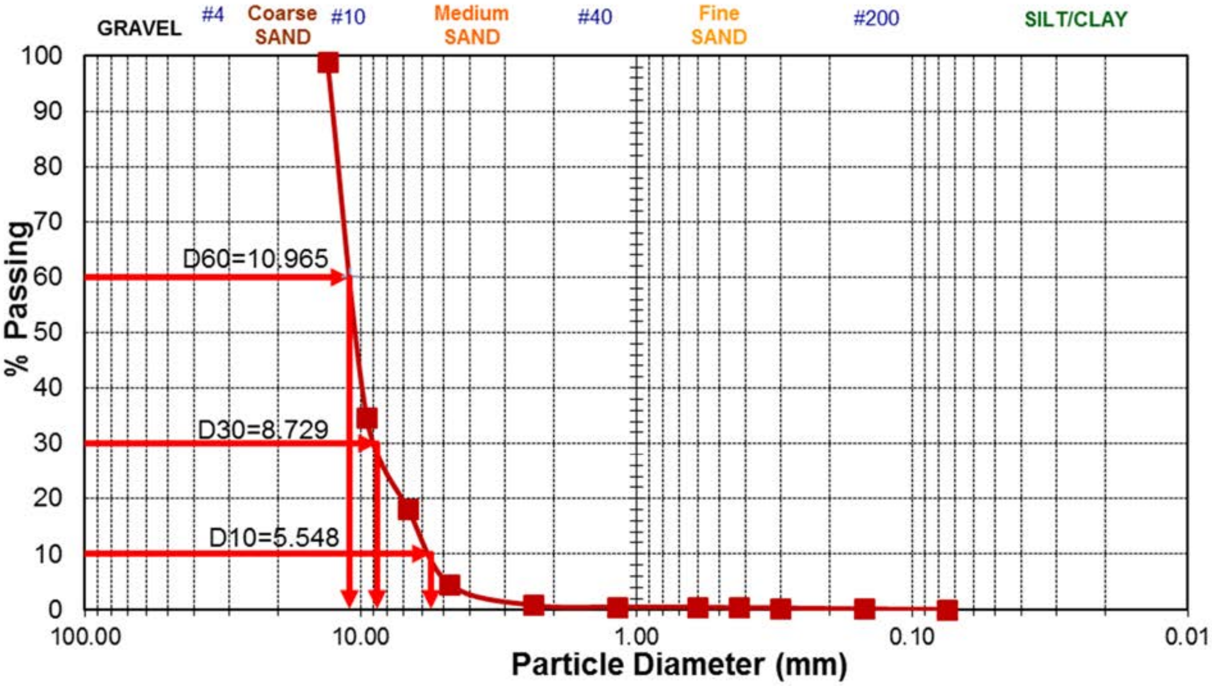


Figure C.2 9 mm filter media particle distribution plot

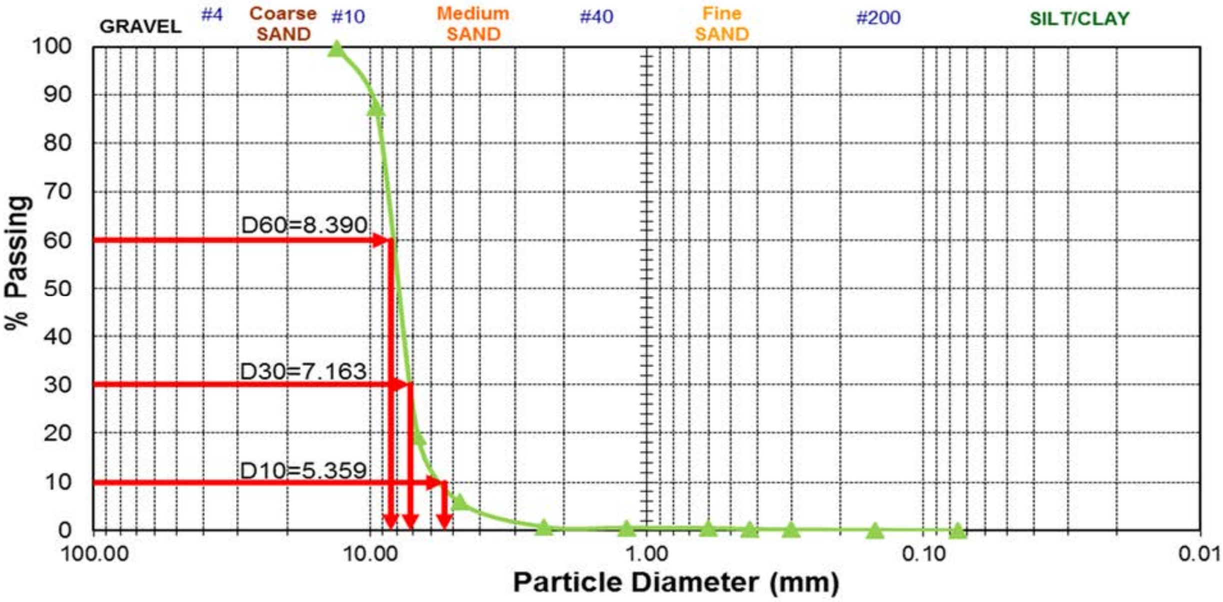


Figure C.3. 6 mm filter media particle distribution plot

Appendix D. Filter media permeability coefficient calculation

The permeability coefficient (K) for each filter media size was determined by a constant head permeability test as illustrated in section 3.3.3.2, Figure 3.17. The calculation for the permeability coefficient were determined using Equation D.1. as presented below. A permeability coefficient sample calculation for a 13mm media size is also represented below.

$$K = \frac{QL}{tAh} \tag{D.1}$$

Q_1= 793.9 ml, Q_2= 1697.9 ml, Q_3= 3961.2 ml, Q_4= 6812.8 ml

t_1= 60 sec, t_2= 120 sec, t_3= 240 sec, t_4= 360 sec

h_1= 6.5 cm, h_2= 16.4 cm, h_3= 13.0 cm. h_4= 9.4 cm

L= 7 cm

d= 11 cm

A= 95.033 cm^2

K= ?

$$K_1 = \frac{793.9 \times 7}{60 \times 95.033 \times 6.5}$$

$$K_1 = 0.149\ cm/sec$$

$$K_2 = \frac{1697.9 \times 7}{120 \times 95.033 \times 16.4}$$

$$K_2 = 0.064\ cm/sec$$

$$K_3 = \frac{3961.2 \times 7}{240 \times 95.033 \times 13.0}$$

$$K_3 = 0.094\ cm/sec$$

$$K_4 = \frac{6812.8 \times 7}{360 \times 95.033 \times 9.4}$$

$$K_4 = 0.148\ cm/sec$$

$$K_T = \frac{K_1 + K_2 + K_3 + K_4}{4}$$

$$K_T = \frac{0.149 + 0.064 + 0.094 + 0.148}{4}$$

$$\mathrm{K_T} = 0.114\ \mathrm{cm/sec}$$

Appendix E. Filter flow rate & design

E.1. Initial design flow rate

The flow rate at which the pumps were operated in order to control the flow in the roughing filters are presented in this section. The filter flow rate was evaluated at standard filtration rates within the ranges of 0.03 m/h - 0.1 m/h and as characterized by laminar flow which occurs in small numbers of Reynolds (Equation E.2). The sample calculation for the flow rate is as represented below using Equation E.1.

$$V_f = \frac{Q}{A} \tag{E.1}$$

Filtration rate V_f (m/h) = 0.03 m/h-0.1 m/h for vertical roughing filters.

∴ Take V_f as 0.03 m/h

Filter bed area A (m^2) = $A = \pi dh$

$A = \pi \times 0.11 \times 0.85$

$A = 0.294m^2$

Filter volume $V(m^3) = V = \pi r^2 L$

$V = \pi \times 0.055^2 \times 1$

$V = 9.5 \times 10^{-3} m^3$(Filter column capacity)

Total filter capacity for 3 columns V_T

$V_T = 3(9.5 \times 10^{-3})$

$V_T = 0.029\ m^3$

Total filter capacity when media packed V_P

$V_P = 3\ (3.3 \times 10^{-3})$

$V_p = 9.9\ m^3$

Flow rate $Q(m^3/h) = Q = A \times V_f$

V_f = 0.03 m/h

$Q = 0.294 \times 0.03 m/h$

$Q = 0.009\ \mathrm{m^3/h}$

1 m^3/h= 16. 667 l/min

$Q = 0.15\ \mathrm{l/min}$

$$R_e = \frac{\mathrm{V} \times d_c}{v} \tag{E.2}$$

$V_f = \ 0.03\ m/h$

$V_f\ = 8.333 \times 10^{-6}\ m/s$

$d_c = 0.11m$
v= 1.004×10^{-6} $m^{2/}$/s at 20°C
Re= ?

$$R_e = \frac{8.3 \times 10^{-6} \times 0.11}{1.004 \times 10^{-6}}$$
$\mathrm{R}_e = 0.909$
$\mathrm{R}_e < 10 = Laminar\ flow$
$0.9 < 10$
$\therefore The\ flow\ is\ laminar$

E.2. Daily flow rate during filter operation

During the filter run the change in flow rate through the vertical roughing filters was monitored daily and determined by taking the flow rates over a significant portion of the fluid cycle. Each filter was provided with an empty 1 L measuring cylinder at the beginning of each cycle. The daily flow rate was determined using Equation E.3 as shown by the sample calculation below and the results on the monitored flow rates are represented by Table E.1.

$$Q = \frac{V_s \times 60sec}{1\min(t_1 - t_0)} \qquad \text{(E.3)}$$

Take day 10 in the filter with a Carbon source
V_s= 1 L
t_0= 0
t_1= 7:41 min
= 461 sec
Q= ?
$$Q = \frac{1 \times 60}{1\min(461 - 0)}$$
$Q = 0.130\ L/m$

Take day 10 in the filter without Carbon source
V_s= 1 L
t_0= 0
t_1= 7:33 min
= 453 sec
Q= ?
$$Q = \frac{1 \times 60}{1\min(453 - 0)}$$
$Q = 0.132\ L/m$

Table E.13 Monitored daily flow rates from the filter with and without a Carbon source

Time of filter operation (days)	Collecting cylinder volume (L)	Roughhing filter with a carbon source (VRFwt) collection time (min)	Roughhing filter with a carbon source (VRFwt) Flow rate (L/m)	Roughhing filter without a carbon source (VRFwo) collection time (min)	Roughhing filter without a carbon source (VRFwo) Flow rate (L/m)
1	1L	7:36	0.132	7:31	0.133
2	1L	7:34	0.132	7:33	0.132
3	1L	7:33	0.133	7:29	0.134
4	1L	7:34	0.132	7:30	0.133
5	1L	7:32	0.133	7:34	0.132
6	1L	7:33	0.133	7:31	0.133
7	1L	7:35	0.132	7:29	0.134
8	1L	7:38	0.131	7:32	0.133
9	1L	7:36	0.132	7:35	0.132
10	1L	7:41	0.13	7:33	0.132
11	1L	7:35	0.132	7:28	0.134
12	1L	7:38	0.131	7:31	0.133
13	1L	7:41	0.13	7:34	0.132
14	1L	7:36	0.132	7:30	0.133
15	1L	7:43	0.13	7:32	0.133
16	1L	7:41	0.13	7:35	0.132
17	1L	7:37	0.131	7:31	0.133
18	1L	7:40	0.13	7:29	0.134
19	1L	7:39	0.131	7:34	0.132
20	1L	7:41	0.13	7:32	0.133
21	1L	7:35	0.132	7:29	0.134
22	1L	7:40	0.13	7:28	0.134
23	1L	7:48	0.128	7:31	0.133
24	1L	7:51	0.127	7:33	0.132
25	1L	7:48	0.128	7:34	0.132
26	1L	7:55	0.126	7:32	0.133
27	1L	7:49	0.128	7:33	0.132
28	1L	7:45	0.129	7:31	0.133
29	1L	7:48	0.128	7:39	0.131
30	1L	8:08	0.123	7:47	0.128
31	1L	8:02	0.124	7:41	0.13
32	1L	7:58	0.123	7:44	0.129
33	1L	7:56	0.126	7:35	0.132
34	1L	8:08	0.123	7:30	0.133
35	1L	7:54	0.127	7:41	0.129
36	1L	7:51	0.127	7:34	0.132
37	1L	7:58	0.126	7:45	0.129
38	1L	8:09	0.123	7:54	0.127
39	1L	8:03	0.124	7:51	0.127
40	1L	8:25	0.119	8:00	0.125
41	1L	8:45	0.114	8:23	0.119
42	1L	8:38	0.116	8:25	0.119
43	1L	8:35	0.117	8:20	0.12
44	1L	8:44	0.114	8:21	0.12
45	1L	8:51	0.113	8:38	0.116
46	1L	9:03	0.11	8:42	0.115
47	1L	9:08	0.109	8:45	0.114
48	1L	9:08	0.109	8:40	0.115
49	1L	8:58	0.112	8:48	0.114
50	1L	9:05	0.11	8:52	0.113
51	1L	9:03	0.11	8:49	0.113
52	1L	8:58	0.112	8:45	0.114
53	1L	8:58	0.112	8:48	0.114
54	1L	9:02	0.11	8:48	0.114
55	1L	9:05	0.11	8:50	0.113
56	1L	9:08	0.109	8:47	0.114
57	1L	9:08	0.109	8:52	0.113
58	1L	9:05	0.11	8:49	0.113
59	1L	9:07	0.109	8:55	0.112
60	1L	9:05	0.11	8:53	0.113

61	1L	9:10	0.109	8:55	0.112
62	1L	9:03	0.11	8:50	0.113
63	1L	9:03	0.11	8:52	0.113
64	1L	9:05	0.11	8:54	0.112
65	1L	9:02	0.11	8:54	0.112
66	1L	9:07	0.109	8:55	0.112
67	1L	9:07	0.109	8:51	0.113
68	1L	9:05	0.11	8:48	0.114
69	1L	9:04	0.11	8:44	0.114
70	1L	9:01	0.111	8:40	0.115
71	1L	9:04	0.11	8:39	0.116
72	1L	9:04	0.11	8:35	0.117
73	1L	9:08	0.109	8:32	0.117
74	1L	9:11	0.109	8:50	0.113
75	1L	9:09	0.109	8:44	0.114
76	1L	9:10	0.109	8:50	0.113
77	1L	9:05	0.11	8:39	0.116
78	1L	9:03	0.11	8:41	0.115
79	1L	9:05	0.11	8:31	0.117
80	1L	9:07	0.109	8:28	0.118
81	1L	9:05	0.11	8:32	0.117
82	1L	9:08	0.109	8:38	0.116
83	1L	9:11	0.109	8:40	0.115
84	1L	9:12	0.109	8:31	0.117
85	1L	9:09	0.109	8:27	0.118
86	1L	9:07	0.109	8:32	0.117
87	1L	9:10	0.109	8:35	0.117
88	1L	9:09	0.109	8:35	0.117
89	1L	9:11	0.109	8:38	0.116
90	1L	9:11	0.109	8:32	0.117
91	1L	9:08	0.109	8:35	0.117
92	1L	9:10	0.109	8:38	0.116
93	1L	9:08	0.109	8:40	0.115
94	1L	9:12	0.109	8:44	0.114
95	1L	9:11	0.109	8:42	0.115
96	1L	9:14	0.108	8:47	0.114
97	1L	9:12	0.109	8:45	0.114
98	1L	9:10	0.109	8:43	0.115
99	1L	9:12	0.109	8:48	0.114
100	1L	9:14	0.108	8:46	0.114
101	1L	9:10	0.109	8:40	0.115
102	1L	9:08	0.109	8:38	0.116
103	1L	9:11	0.109	8:42	0.115
104	1L	9:10	0.109	8:39	0.116
105	1L	9:12	0.109	8:41	0.115
106	1L	9:14	0.108	8:44	0.114
107	1L	9:15	0.108	8:45	0.114
108	1L	9:21	0.107	8:48	0.114
109	1L	9:18	0.108	8:44	0.114
110	1L	9:25	0.106	8:46	0.114
111	1L	9:27	0.106	8:51	0.113
112	1L	9:23	0.107	8:55	0.112
113	1L	9:27	0.106	8:53	0.113
114	1L	9:22	0.107	8:49	0.113
115	1L	9:29	0.105	8:52	0.113
116	1L	9:33	0.105	8:55	0.112
117	1L	9:28	0.106	8:51	0.112
118	1L	9:35	0.104	8:54	0.113
119	1L	9:32	0.105	8:48	0.114
120	1L	9:36	0.104	8:52	0.113

121	1L	9:38	0.104	8:55	0.112
122	1L	9:43	0.103	8:49	0.113
123	1L	9:48	0.102	8:51	0.113
124	1L	9:45	0.103	8:53	0.113
125	1L	9:48	0.102	8:57	0.112
126	1L	9:44	0.103	8:55	0.112
127	1L	9:40	0.103	8:55	0.112
128	1L	9:43	0.103	8:52	0.113
129	1L	9:45	0.103	8:49	0.113
130	1L	9:42	0.103	8:49	0.113
131	1L	9:39	0.104	8:53	0.113
132	1L	9:37	0.104	8:50	0.113
133	1L	9:41	0.103	8:48	0.114
134	1L	9:45	0.103	8:44	0.114
135	1L	9:40	0.103	8:38	0.116
136	1L	9:44	0.103	8:32	0.117
137	1L	9:47	0.102	8:40	0.115
138	1L	9:49	0.102	8:42	0.115
139	1L	9:52	0.101	8:39	0.116
140	1L	9:50	0.102	8:28	0.118
141	1L	9:48	0.102	8:38	0.116
142	1L	9:55	0.101	8:35	0.117
143	1L	9:53	0.101	8:40	0.115
144	1L	9:53	0.101	8:38	0.116
145	1L	9:51	0.102	8:35	0.117
146	1L	9:49	0.102	8:28	0.118
147	1L	9:48	0.102	8:32	0.117
148	1L	9:50	0.102	8:35	0.117
149	1L	9:56	0.101	8:38	0.116
150	1L	9:58	0.1	8:38	0.116
151	1L	9:57	0.101	8:29	0.116
152	1L	9:55	0.101	8:32	0.117
153	1L	9:58	0.1	8:36	0.117
154	1L	9:58	0.1	8:38	0.116
155	1L	9:55	0.101	8:35	0.117
156	1L	9:53	0.101	8:40	0.115
157	1L	9:47	0.102	8:42	0.115
158	1L	9:51	0.102	8:45	0.114
159	1L	9:48	0.102	8:43	0.115
160	1L	9:50	0.102	8:40	0.115
161	1L	9:53	0.101	8:38	0.116
162	1L	9:55	0.101	8:42	0.115
163	1L	9:40	0.103	8:44	0.115
164	1L	9:48	0.102	8:47	0.114
165	1L	9:52	0.101	8:45	0.114
166	1L	9:57	0.101	8:43	0.115
167	1L	9:58	0.1	8:40	0.115
168	1L	9:53	0.101	8:44	0.115
169	1L	9:50	0.102	8:38	0.116
170	1L	9:48	0.102	8:38	0.116
171	1L	9:43	0.103	8:32	0.117
172	1L	9:45	0.103	8:35	0.117
173	1L	9:48	0.102	8:32	0.117
174	1L	9:45	0.103	8:30	0.118
175	1L	9:49	0.102	8:33	0.117
176	1L	9:52	0.101	8:35	0.117
177	1L	9:55	0.101	8:32	0.117
178	1L	9:53	0.101	8:36	0.116
179	1L	9:50	0.102	8:38	0.116
180	1L	9:54	0.101	8:41	0.115

181	1L	9:57	0.101	8:43	0.115
182	1L	9:59	0.1	8:40	0.115
183	1L	10:05	0.099	8:42	0.115
184	1L	10:08	0.099	8:44	0.115
185	1L	10:12	0.098	8:47	0.114
186	1L	10:10	0.098	8:45	0.114
187	1L	10:14	0.098	8:48	0.114
188	1L	10:17	0.097	8:52	0.113
189	1L	10:15	0.098	8:50	0.113
190	1L	10:18	0.097	8:54	0.112
191	1L	10:20	0.097	8:57	0.112
192	1L	10:22	0.096	8:55	0.112
193	1L	10:19	0.097	8:58	0.112
194	1L	10:21	0.097	8:57	0.112
195	1L	10:20	0.097	8:55	0.112
196	1L	10:22	0.096	8:52	0.113
197	1L	10:19	0.097	8:50	0.113
198	1L	10:17	0.097	8:48	0.114
199	1L	10:15	0.098	8:52	0.113
200	1L	10:18	0.097	8:54	0.113
201	1L	10:20	0.097	8:56	0.112
202	1L	10:23	0.096	8:53	0.113
203	1L	10:25	0.096	8:55	0.112
204	1L	10:27	0.096	8:57	0.112
205	1L	10:31	0.095	8:54	0.113
206	1L	10:28	0.096	8:50	0.113
207	1L	10:25	0.096	8:47	0.114
208	1L	10:27	0.096	8:52	0.113
209	1L	10:30	0.095	8:55	0.112
210	1L	10:28	0.096	8:53	0.113

Appendix F. pH at varied filter depths

The tables below represent the daily pH variation with depth in the filter with and without a Carbon source during the filter operation.

F.1. pH concentration at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table F.14 Daily pH variations with depth in the filter with a Carbon source.

Filter with a carbon source										
Sampling interval (Day)	Initial raw water pH	Filter column depths (mm)	Column 1 pH with depth	Column 1 change in pH (%)	Column 2 pH with depth	Column 2 change in pH (%)	Column 3 pH with depth	Column 3 change in pH (%)	Average pH with depth	Avarage change in pH (%)
1	7.09	270	7.33	3	7.2	2	7.13	1	7.22	2
		750	7.27	3	7.18	1	7.15	1	7.20	2
		1000	7.22	2	7.18	1	7.09	0	7.16	1
Day 1 filter average			**7.27**	**3**	**7.19**	**1**	**7.12**	**0**	**7.19**	**1**
2	7.12	270	7.41	4	7.08	1	6.88	3	7.12	3
		750	7.2	1	7.05	1	6.82	4	7.02	2
		1000	7.16	1	6.94	3	6.79	5	6.96	3
Day 2 filter average			**7.26**	**2**	**7.02**	**1**	**6.83**	**4**	**7.04**	**2**
3	7.45	270	7.13	4	6.89	8	6.86	8	6.96	7
		750	7.18	4	6.84	8	6.88	8	6.97	6
		1000	6.99	6	6.89	8	6.9	7	6.93	7
Day 3 filter average			**7.10**	**5**	**6.87**	**7.7**	**6.88**	**8**	**6.95**	**7**
4	7.27	270	7.21	1	6.92	5	6.77	7	6.97	4
		750	7.12	2	6.88	5	6.85	6	6.95	4
		1000	7.07	3	6.81	6	6.83	6	6.90	5
Day 4 filter average			**7.13**	**2**	**6.87**	**6**	**6.82**	**6**	**6.94**	**5**
5	7.49	270	7.23	3	6.77	10	6.67	11	6.89	8
		750	6.98	7	6.73	10	6.67	11	6.79	9
		1000	6.9	8	6.69	11	6.72	10	6.77	10
Day 5 filter average			**7.04**	**6**	**6.73**	**10**	**6.69**	**11**	**6.82**	**9**
6	7.2	270	7.18	0.3	6.92	4	6.81	5	6.97	3
		750	7.11	1	6.9	4	6.8	6	6.94	4
		1000	7.06	2	6.84	5	6.85	5	6.92	4
Day 6 filter average			**7.12**	**1**	**6.89**	**4**	**6.82**	**5**	**6.94**	**4**
7	7.45	270	7.58	2	6.96	7	6.88	8	7.14	5
		750	7.22	3	6.89	8	6.88	8	7.00	6
		1000	7.1	5	6.86	8	6.98	6	6.98	6
Day 7 filter average			**7.30**	**3**	**6.90**	**7**	**6.91**	**7**	**7.04**	**6**
8	7.36	270	7.4	-1	7.07	4	6.86	7	7.11	3
		750	7.18	2	7.02	5	6.82	7	7.01	5
		1000	7.12	3	6.9	6	6.85	7	6.96	5
Day 8 filter average			**7.23**	**2**	**7.00**	**5**	**6.84**	**7**	**7.02**	**5**
9	7.49	270	7.55	1	6.98	7	6.86	8.4	7.13	5
		750	7.22	4	6.94	7	6.84	9	7.00	7
		1000	7.08	5	6.89	8	6.81	9	6.93	8
Day 9 filter average			**7.28**	**3**	**6.94**	**7**	**6.84**	**9**	**7.02**	**6**
10	6.63	270	7.42	12	7.14	8	6.85	3	7.14	8
		750	7.31	10	7.09	7	6.78	2	7.06	6
		1000	7.23	9	6.9	4	6.82	3	6.98	5
Day 10 filter average			**7.32**	**10**	**7.04**	**6**	**6.82**	**3**	**7.06**	**6**
11	7.41	270	7.62	3	7.02	5	6.96	6	7.20	5
		750	7.22	3	6.99	6	6.98	6	7.06	5
		1000	7.12	4	6.94	6	6.96	6	7.01	5
Day 11 filter average			**7.32**	**3**	**6.98**	**6**	**6.97**	**6**	**7.09**	**5**
12	6.92	270	7.5	8	7.24	5	6.87	1	7.20	5
		750	7.39	7	7.16	3	6.94	0.3	7.16	4
		1000	7.32	6	6.9	0.3	6.82	1	7.01	3
Day 12 filter average			**7.40**	**7**	**7.10**	**3**	**6.88**	**1**	**7.13**	**4**
13	7.59	270	7.59	0	6.93	9	6.72	11	7.08	7
		750	7.26	4	6.81	10	6.78	11	6.95	8
		1000	7.11	6	6.74	11	6.85	10	6.90	9
Day 13 filter average			**7.32**	**4**	**6.83**	**10**	**6.78**	**11**	**6.98**	**8**
14	7.27	270	7.48	3	7.07	3	6.69	8	7.08	5
		750	7.29	0.3	6.8	6	6.65	9	6.91	5
		1000	7.17	1	6.72	8	6.78	7	6.89	5
Day 14 filter average			**7.31**	**2**	**6.86**	**6**	**6.71**	**8**	**6.96**	**5**
15	7.06	270	7.02	1	6.52	8	6.41	9	6.65	6
		750	6.68	5	6.49	8	6.41	9	6.53	8
		1000	6.62	6	6.44	8.8	6.47	8	6.51	8
Day 15 filter average			**6.77**	**4**	**6.48**	**8**	**6.43**	**9**	**6.56**	**7**
16	6.22	270	7.15	15	6.77	9	6.52	5	6.81	10
		750	7.11	14	6.65	7	6.97	12	6.91	11
		1000	7.04	13	6.56	5	6.4	3	6.67	7
Day 16 a filter verage			**7.10**	**14**	**6.66**	**7**	**6.63**	**7**	**6.80**	**9**
17	6.57	270	7.01	7	6.63	1	6.46	2	6.70	3
		750	6.74	3	6.51	1	6.45	2	6.57	2
		1000	6.74	3	6.46	2	6.55	0.3	6.58	2
Day 17 filter average			**6.83**	**4**	**6.53**	**1**	**6.49**	**1**	**6.62**	**2**
18	7.48	270	7.19	4	6.93	7	6.75	10	6.96	7
		750	7.07	5	6.82	9	6.72	10	6.87	8
		1000	6.98	7	6.77	9	6.69	11	6.81	9
Day 18 filter average			**7.08**	**5**	**6.84**	**9**	**6.72**	**10**	**6.88**	**8**
19	7.05	270	7.02	0.4	6.64	6	6.54	7	6.73	4
		750	6.78	4	6.61	6	6.51	8	6.63	6
		1000	6.67	5	6.58	7	6.52	8	6.59	7
Day 19 filter average			6.82	**3**	6.61	**6**	6.52	**7**	6.65	6
20	7.16	270	7.36	3	7.04	2	6.82	5	7.07	3
		750	7.21	0.7	6.9	4	6.67	7	6.93	4
		1000	7.1	1	6.88	4	6.71	6	6.90	4
Week 20 filter average			**7.22**	**1**	**6.94**	**3**	**6.73**	**6**	**6.97**	**3**
Total Average	**7.16**	270	**7.32**	**4**	**6.94**	**5**	**6.77**	**6**	**7.01**	**5**
		750	**7.13**	**4**	**6.86**	**6**	**6.78**	**7**	**6.92**	**6**
		1000	**7.04**	**5**	**6.79**	**6**	**6.77**	**6**	**6.87**	**6**
			7.16	**4**	**6.86**	**6**	**6.77**	**6**	**6.93**	**5**

Table F.15 Daily pH variations with depth in the filter without a Carbon source.

Filter without a carbon source										
Sampling interval (Day)	Initial raw water pH	Filter column depths (mm)	Column 1 pH with depth	Column 1 change in pH (%)	Column 2 pH with depth	Column 2 change in pH (%)	Column 3 pH with depth	Column 3 change in pH (%)	Average pH with depth	Avarage change in pH (%)
1	7.09	270	7.38	4	7.28	3	7.36	4	7.34	4
		750	7.27	3	7.21	2	7.36	4	7.28	3
		1000	7.32	3	7.34	4	7.44	5	7.37	4
Day 1 filter average			7.32	3	7.28	3	7.39	4	7.33	3
2	7.12	270	7.33	3	7.25	2	7.2	1	7.26	2
		750	7.3	3	7.22	1	7.23	2	7.25	2
		1000	7.27	2	7.19	1	7.35	3	7.27	2
Day 2 filter average			7.30	3	7.22	1	7.26	2	7.26	2
3	7.45	270	7.05	5	7.05	5	7.05	5	7.05	5
		750	7.1	5	7.09	5	7.07	5	7.09	5
		1000	7.04	6	7.08	5	7.18	4	7.10	5
Day 3 filter average			7.06	5	7.07	5.1	7.10	5	7.08	5
4	7.27	270	7.11	2	7.03	3	7.13	2	7.09	2
		750	7.08	3	7.09	2	7.13	2	7.10	2
		1000	7.05	3	7.1	2	7.15	2	7.10	2
Day 4 filter average			7.08	3	7.07	3	7.14	2	7.10	2
5	7.49	270	7.59	1	7.17	4	7.12	5	7.29	4
		750	7.3	3	7.18	4	7.15	5	7.21	4
		1000	7.23	3	7.15	5	7.21	4	7.20	4
Day 5 filter average			7.37	2	7.17	4	7.16	4	7.23	4
6	7.2	270	7.33	1.8	7.22	0.3	7.13	1	7.23	1
		750	7.28	1	7.18	0.3	7.11	1	7.19	1
		1000	7.25	1	7.16	1	7.15	1	7.19	1
Day 6 filter average			7.29	1	7.19	0	7.13	1	7.20	1
7	7.45	270	7.62	2	7.13	4	7.1	5	7.28	4
		750	7.32	2	7.09	5	7.1	5	7.17	4
		1000	7.19	3	7.07	5	7.06	5	7.11	5
Day 7 filter average			7.38	3	7.10	5	7.09	5	7.19	4
8	7.36	270	7.55	3	7.44	1	7.33	0.4	7.44	1
		750	7.52	2	7.42	1	7.28	1	7.41	1
		1000	7.48	2	7.39	0.4	7.25	1	7.37	1
Day 8 filter average			7.52	2	7.42	1	7.29	1	7.41	1
9	7.49	270	6.87	8	7.28	3	7.19	4.0	7.11	5
		750	7.66	2	7.25	3	7.19	4	7.37	3
		1000	7.36	2	7.23	3	7.33	2	7.31	2
Day 9 filter average			7.30	4	7.25	3	7.24	3	7.26	4
10	6.63	270	7.56	14	7.45	12	7.37	11	7.46	13
		750	7.52	13	7.4	12	7.35	11	7.42	12
		1000	7.48	13	7.42	12	7.38	11	7.43	12
Day 10 filter average			7.52	13	7.42	12	7.37	11	7.44	12
11	7.41	270	7.56	2	7.13	4	7.13	4	7.27	3
		750	7.28	2	7.13	4	7.14	4	7.18	3
		1000	7.15	4	7.09	4	7.18	3	7.14	4
Day 11 filter average			7.33	2	7.12	4	7.15	4	7.20	3
12	6.92	270	7.62	10	7.35	6	7.21	4	7.39	7
		750	7.58	10	7.3	5	7.17	4	7.35	6
		1000	7.44	8	7.25	5	7.11	3	7.27	5
Day 12 filter average			7.55	9	7.30	5	7.16	4	7.34	6
13	7.59	270	7.37	3	7.2	5	7.12	6	7.23	5
		750	7.24	5	7.2	5	7.07	7	7.17	6
		1000	7.2	5	7.17	6	7.07	7	7.15	6
Day 13 filter average			7.27	4	7.19	5	7.09	7	7.18	5
14	7.27	270	7.52	3	7.3	0.4	7.19	1	7.34	2
		750	7.4	1.8	7.27	0	7.13	2	7.27	1
		1000	7.35	1	7.22	1	7.1	2	7.22	1
Day 14 filter average			7.42	2	7.26	0	7.14	2	7.28	1
15	7.06	270	7.1	1	6.79	4	6.89	2	6.93	2
		750	6.85	3	6.85	3	6.89	2	6.86	3
		1000	6.81	4	6.87	2.7	6.95	2	6.88	3
Day 15 filter average			6.92	2	6.84	3	6.91	2	6.89	3
16	6.22	270	7.28	17	7.09	14	6.77	9	7.05	13
		750	7.22	16	6.93	11	6.47	4	6.87	11
		1000	7.16	15	6.78	9	6.95	12	6.96	12
Day 16 a filter verage			7.22	16	6.93	11	6.73	8	6.96	12
17	6.57	270	7.07	8	6.84	4	6.86	4	6.92	5
		750	6.9	5	6.86	4	6.86	4	6.87	5
		1000	6.82	4	6.85	4	6.91	5	6.86	4
Day 17 filter average			6.93	5	6.85	4	6.88	5	6.89	5
18	7.48	270	7.28	3	7.19	4	7.09	5	7.19	4
		750	7.25	3	7.15	4	7.07	5	7.16	4
		1000	7.22	3	7.12	5	7.04	6	7.13	5
Day 18 filter average			7.25	3	7.15	4	7.07	6	7.16	4
19	7.05	270	7.1	-0.7	6.85	3	6.89	2	6.95	1
		750	6.88	2	6.87	3	6.9	2	6.88	2
		1000	6.86	3	6.86	3	6.94	2	6.89	2
Day 19 filter average			6.95	1	6.86	3	6.91	2	6.91	2
20	7.16	270	7.52	5	7.4	3	7.22	1	7.38	3
		750	7.47	4.3	7.33	2	7.18	0.3	7.33	2
		1000	7.45	4	7.26	1	7.13	0.4	7.28	2
Week 20 filter average			7.48	4	7.33	2	7.18	1	7.33	2
Total Average	7.16	270	7.34	5	7.17	4	7.12	4	7.21	4
		750	7.27	4	7.15	4	7.09	4	7.17	4
		1000	7.21	4	7.13	4	7.14	4	7.16	4
			7.27	5	7.15	4	7.12	4	7.18	4

F.2. pH concentration at C/N ratio of 1.08 and nitrate concentration of 25mg/L-N

Table F.16 Daily pH variations with depth in the filter with a Carbon source.

Filter with a carbon source										
Sampling interval (Days)	**Initial raw water pH**	**Filter column depths (mm)**	**Column 1 pH with depth**	**Column 1 change in pH (%)**	**Column 2 pH with depth**	**Column 2 change in pH (%)**	**Column 3 pH with depth**	**Column 3 change in pH (%)**	**Average pH with depth**	**Avarage change in pH (%)**
1	6.94	270	7.08	2	7.34	6	7.43	7	7.28	5
		750	7.1	2	7.38	6	7.44	7	7.31	5
		1000	7.21	4	7.43	7	7.51	8	7.38	6
Day 1 filter average			**7.13**	**3**	**7.38**	**6**	**7.46**	**7**	**7.32**	**6**
2	6.86	270	7.06	3	7.27	6	7.36	7	7.23	5
		750	7.26	6	7.31	7	7.38	8	7.32	7
		1000	7.21	5	7.35	7	7.41	8	7.32	7
Day 2 filter average			**7.18**	**5**	**7.31**	**7**	**7.38**	**8**	**7.29**	**6**
3	7.12	270	6.65	7	7.01	2	7.17	1	6.94	3
		750	6.87	4	7.11	0.1	7.21	1	7.06	2
		1000	6.98	2	7.14	0.3	7.18	1	7.10	1
Day 3 filter average			**6.83**	**4**	**7.09**	**1**	**7.19**	**1**	**7.04**	**2**
4	6.8	270	7.31	8	7.46	10	7.5	10	7.42	9
		750	7.39	9	7.48	10	7.5	10	7.46	10
		1000	7.45	10	7.5	10	7.48	10	7.48	10
Day 4 filter average			**7.38**	**9**	**7.48**	**10**	**7.49**	**10**	**7.45**	**10**
5	6.76	270	6.79	0.4	7.02	4	7	4	6.94	3
		750	6.94	3	7.05	4	6.9	2	6.96	3
		1000	7.03	4	7.02	4	6.93	3	6.99	3
Day 5 filter average			**6.92**	**2**	**7.03**	**4**	**6.94**	**3**	**6.96**	**3**
6	6.82	270	6.82	0	7.21	6	7.18	5	7.07	4
		750	7.1	4	7.21	6	7.17	5	7.16	5
		1000	7.19	5	7.22	6	7.11	4	7.17	5
Day 6 filter average			**7.04**	**3**	**7.21**	**6**	**7.15**	**5**	**7.13**	**5**
7	6.79	270	7.25	7	7.12	5	6.93	2	7.10	5
		750	7.21	6	7.02	3	6.97	3	7.07	4
		1000	7.19	6	6.95	2	6.78	0.1	6.97	3
Day 7 filter average			**7.22**	**6**	**7.03**	**4**	**6.89**	**2**	**7.05**	**4**
8	7.07	270	6.94	2	7.06	0.1	6.87	3	6.96	2
		750	7.13	1	7.07	0	7.01	1	7.07	1
		1000	7.08	0.1	6.99	1	7	1	7.02	1
Day 8 filter average			**7.05**	**1**	**7.04**	**0.4**	**6.96**	**2**	**7.02**	**1**
9	7.45	270	6.64	11	6.81	9	6.31	15	6.59	12
		750	6.8	9	6.66	11	6.23	16	6.56	12
		1000	6.95	7	6.37	14	6.14	18	6.49	13
Day 9 filter average			**6.80**	**9**	**6.61**	**11**	**6.23**	**16**	**6.55**	**12**
10	6.34	270	6.42	1	6.53	3	6.31	0.5	6.42	2
		750	6.54	3	6.5	3	6.1	4	6.38	3
		1000	6.51	3	6.06	4	5.74	9	6.10	6
Day 10 filter average			**6.49**	**2**	**6.36**	**3**	**6.05**	**5**	**6.30**	**3**
11	6.44	270	6.45	0.2	6.62	3	6.59	2	6.55	2
		750	6.58	2	6.67	4	6.6	2	6.62	3
		1000	6.6	2	6.62	3	6.54	2	6.59	2
Day 11 filter average			**6.54**	**2**	**6.64**	**3**	**6.58**	**2**	**6.59**	**2**
12	6.94	270	6.79	2	6.91	0.4	6.68	4	6.79	2
		750	6.98	1	6.85	1	6.58	5	6.80	2
		1000	6.96	0.3	6.75	3	6.41	8	6.71	4
Day 12 filter average			**6.91**	**1**	**6.84**	**1**	**6.56**	**6**	**6.77**	**3**
13	6.94	270	6.65	4	6.76	3	6.59	5	6.67	4
		750	6.76	3	6.76	3	6.55	6	6.69	4
		1000	6.76	3	6.64	4	6.46	7	6.62	5
Day 13 filter average			**6.72**	**3**	**6.72**	**3**	**6.53**	**6**	**6.66**	**4**
14	7.38	270	7.18	3	7.35	0.4	7.01	5	7.18	3
		750	7.25	2	7.24	2	7.02	5	7.17	3
		1000	7.36	0.3	7.03	5	7.02	5	7.14	3
Day 14 filter average			**7.26**	**2**	**7.21**	**2**	**7.02**	**5**	**7.16**	**3**
15	7.4	270	7.46	1	6.92	6	6.82	8	7.07	5
		750	7.1	4	6.89	7	6.77	9	6.92	6
		1000	7.02	5	6.92	6	6.84	8	6.93	6
Day 15 filter average			**7.19**	**3**	**6.91**	**7**	**6.81**	**8**	**6.97**	**6**
16	6.52	270	6.42	2	6.57	1	6.36	2	6.45	2
		750	6.54	0.3	6.55	0.5	6.24	4	6.44	2
		1000	6.62	2	6.51	0.2	5.86	10	6.33	4
Day 16 a filter verage			**6.53**	**1**	**6.54**	**0.5**	**6.15**	**6**	**6.41**	**2**
17	7.5	270	7.66	2	7.11	5	6.87	8	7.21	5
		750	7.2	4	7.02	6	6.85	9	7.02	6
		1000	7.2	4	6.94	7	6.86	9	7.00	7
Day 17 filter average			**7.35**	**3**	**7.02**	**6**	**6.86**	**9**	**7.08**	**6**
18	6.44	270	6.4	1	6.56	2	6.26	3	6.41	2
		750	6.52	1	6.63	3	6.38	1	6.51	2
		1000	6.49	1	6.21	4	5.22	19	5.97	8
Day 18 filter average			**6.47**	**1**	**6.47**	**3**	**5.95**	**8**	**6.30**	**4**
19	7.19	270	7.06	2	6.77	6	6.64	8	6.82	5
		750	6.98	3	6.4	11	6.51	9	6.63	8
		1000	6.65	8	6.28	13	6.12	15	6.35	12
Day 19 filter average			**6.90**	**4**	**6.48**	**10**	**6.42**	**11**	**6.60**	**8**
20	7.2	270	7.53	5	7.17	0.4	6.93	4	7.21	3
		750	7.25	1	7.02	3	6.9	4	7.06	2
		1000	7.25	1	6.98	3	6.9	4	7.04	3
Day 20 filter average			**7.34**	**2**	**7.06**	**2**	**6.91**	**4**	**7.10**	**3**
Total Average	6.95	270	**6.93**	**3**	**6.98**	**4**	**6.84**	**5**	**6.92**	**4**
		750	**6.98**	**3**	**6.94**	**4**	**6.82**	**6**	**6.91**	**4**
		1000	**6.99**	**4**	**6.85**	**5**	**6.68**	**7**	**6.84**	**5**
			6.96	**3**	**6.92**	**4**	**6.78**	**6**	**6.89**	**5**

Table F.17 Daily pH variations with depth in the filter without a Carbon source.

Filter without a carbon source										
Sampling interval (Days)	**Initial raw water pH**	**Filter column depths (mm)**	**Column 1 pH with depth**	**Column 1 change in pH (%)**	**Column 2 pH with depth**	**Column 2 change in pH (%)**	**Column 3 pH with depth**	**Column 3 change in pH (%)**	**Average pH with depth**	**Avarage change in pH (%)**
1	6.94	270	7.54	9	7.56	9	7.63	10	7.58	9
		750	7.54	9	7.64	10	7.62	10	7.60	10
		1000	7.52	8	7.65	10	7.62	10	7.60	9
Day 1 filter average			**7.53**	**9**	**7.62**	**10**	**7.62**	**10**	**7.59**	**9**
2	6.86	270	7.22	5	7.76	13	7.94	16	7.64	11
		750	7.61	11	7.88	15	7.94	16	7.81	14
		1000	7.72	13	7.92	15	7.97	16	7.87	15
Day 2 filter average			**7.52**	**10**	**7.85**	**14**	**7.95**	**16**	**7.77**	**13**
3	7.12	270	7.16	1	7.38	4	7.45	5	7.33	3
		750	7.36	3	7.4	4	7.45	5	7.40	4
		1000	7.38	4	7.42	4	7.51	5	7.44	4
Day 3 filter average			**7.30**	**3**	**7.40**	**4**	**7.47**	**5**	**7.39**	**4**
4	6.8	270	6.78	0.3	7.3	7	7.49	10	7.19	6
		750	7.04	4	7.4	9	7.5	10	7.31	8
		1000	7.19	6	7.46	10	7.51	10	7.39	9
Day 4 filter average			**7.00**	**3**	**7.39**	**9**	**7.50**	**10**	**7.30**	**7**
5	6.76	270	6.73	0.4	7.09	5	7.23	7	7.02	4
		750	7.02	4	7.22	7	7.26	7	7.17	6
		1000	7.05	4	7.15	6	7.2	7	7.13	6
Day 5 filter average			**6.93**	**3**	**7.15**	**6**	**7.23**	**7**	**7.11**	**5**
6	6.82	270	6.74	1	7.17	5	7.25	6	7.05	4
		750	7.02	3	7.17	5	7.27	7	7.15	5
		1000	7.11	4	7.2	6	7.31	7	7.21	6
Day 6 filter average			**6.96**	**3**	**7.18**	**5**	**7.28**	**7**	**7.14**	**5**
7	6.79	270	6.89	1	7.22	6	7.39	9	7.17	6
		750	7.1	5	7.31	8	7.41	9	7.27	7
		1000	7.13	5	7.36	8	7.43	9	7.31	8
Day 7 filter average			**7.04**	**4**	**7.30**	**7**	**7.41**	**9**	**7.25**	**7**
8	7.07	270	7.21	2	7.13	1	7.1	0.4	7.15	1
		750	7.09	0.3	7.14	1	7.04	0.4	7.09	1
		1000	7.16	1	7.03	1	7.15	1	7.11	1
Day 8 filter average			**7.15**	**1**	**7.10**	**1**	**7.10**	**1**	**7.12**	**1**
9	7.45	270	7.29	2	7.7	3	7.58	2	7.52	2
		750	7.65	3	7.64	3	7.56	1	7.62	2
		1000	7.61	2	7.57	2	7.6	2	7.59	2
Day 9 filter average			**7.52**	**2**	**7.64**	**3**	**7.58**	**2**	**7.58**	**2**
10	6.34	270	6.44	2	6.76	7	6.84	8	6.68	5
		750	6.59	4	6.8	7	6.87	8	6.75	7
		1000	6.67	5	6.84	8	6.93	9	6.81	7
Day 10 filter average			**6.57**	**4**	**6.80**	**7**	**6.88**	**9**	**6.75**	**6**
11	6.44	270	6.67	4	6.87	7	6.92	7	6.82	6
		750	6.77	5	6.89	7	6.92	7	6.86	7
		1000	6.82	6	6.95	8	7.01	9	6.93	8
Day 11 filter average			**6.75**	**5**	**6.90**	**7**	**6.95**	**8**	**6.87**	**7**
12	6.94	270	7.05	2	7.23	4	7.27	5	7.18	4
		750	7.23	4	7.31	5	7.24	4	7.26	5
		1000	7.23	4	7.27	5	7.24	4	7.25	4
Day 12 filter average			**7.17**	**3**	**7.27**	**5**	**7.25**	**4**	**7.23**	**4**
13	6.94	270	6.85	1	7.35	6	7.62	10	7.27	6
		750	7.18	3	7.53	9	7.58	9	7.43	7
		1000	7.26	5	7.55	9	7.61	10	7.47	8
Day 13 filter average			**7.10**	**3**	**7.48**	**8**	**7.60**	**10**	**7.39**	**7**
14	7.38	270	7.41	0.4	7.1	4	7.07	4	7.19	3
		750	7.14	3	7.09	4	7.1	4	7.11	4
		1000	7.08	4	7.09	4	7.09	4	7.09	4
Day 14 filter average			**7.21**	**3**	**7.09**	**4**	**7.09**	**4**	**7.13**	**3**
15	7.4	270	7.56	2	7.29	1	7.23	2	7.36	2
		750	7.3	1	7.25	2	7.27	2	7.27	2
		1000	7.25	2	7.25	2	7.36	1	7.29	2
Day 15 filter average			**7.37**	**2**	**7.26**	**2**	**7.29**	**2**	**7.31**	**2**
16	6.52	270	6.91	6	7.03	8	7.1	9	7.01	8
		750	6.9	6	7.06	8	7.12	9	7.03	8
		1000	6.97	7	7.09	9	7.2	10	7.09	9
Day 16 a filter verage			**6.93**	**6**	**7.06**	**8**	**7.14**	**10**	**7.04**	**8**
17	7.5	270	7.53	0.4	7.13	5	7.2	4	7.29	3
		750	7.23	4	7.07	6	7.2	4	7.17	4
		1000	7.16	5	7.18	4	7.25	3	7.20	4
Day 17 filter average			**7.31**	**3**	**7.13**	**5**	**7.22**	**4**	**7.22**	**4**
18	6.44	270	6.55	2	7.06	10	7.07	10	6.89	7
		750	6.83	6	7.11	10	7.08	10	7.01	9
		1000	6.96	8	7.12	11	7.18	11	7.09	10
Day 18 filter average			**6.78**	**5**	**7.10**	**10**	**7.11**	**10**	**7.00**	**9**
19	7.19	270	6.88	4	7.22	0.4	7.2	0.1	7.10	2
		750	7.14	1	7.38	3	7.18	0.1	7.23	1
		1000	7.19	0	7.27	1	7.12	1	7.19	1
Day 19 filter average			**7.07**	**2**	**7.29**	**1**	**7.17**	**0.4**	**7.18**	**1**
20	7.2	270	7.63	6	7.29	1	7.35	2	7.42	3.1
		750	7.34	2	7.33	2	7.38	3	7.35	2
		1000	7.27	1	7.35	2	7.43	3	7.35	2
Day 20 filter average			**7.41**	**3**	**7.32**	**2**	**7.39**	**3**	**7.37**	**2**
Total Average	**6.95**	270	**7.05**	**3**	**7.23**	**5**	**7.30**	**6**	**7.19**	**5**
		750	**7.15**	**4**	**7.28**	**6**	**7.30**	**6**	**7.24**	**6**
		1000	**7.19**	**5**	**7.29**	**6**	**7.34**	**7**	**7.27**	**6**
			7.13	**4**	**7.27**	**6**	**7.31**	**6**	**7.24**	**5**

F.3. pH concentration at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table F.18 Daily pH variations with depth in the filter with a Carbon source.

Filter with a carbon source										
Sampling interval (Day)	**Initial raw water pH**	**Filter column depths (mm)**	**Column 1 pH with depth**	**Column 1 change in pH (%)**	**Column 2 pH with depth**	**Column 2 change in pH (%)**	**Column 3 pH with depth**	**Column 3 change in pH (%)**	**Average pH with depth**	**Avarage change in pH (%)**
1	6.98	270	7.36	5	7.38	6	7.26	4	7.33	5
		750	7.38	6	7.44	7	7.31	5	7.38	6
		1000	6.89	1	6.83	2	7.06	1	6.93	2
Day 1 filter average			**7.21**	**4**	**7.22**	**5**	**7.21**	**3**	**7.21**	**4**
2	6.9	270	7.06	2	7.11	3	7.18	4	7.12	3
		750	7.25	5	7.2	4	7.11	3	7.19	4
		1000	7.2	4	7.14	3	7.15	4	7.16	4
Day 2 filter average			**7.17**	**4**	**7.15**	**4**	**7.15**	**4**	**7.16**	**4**
3	7.22	270	7.3	1	7.16	1	7.14	1	7.20	1
		750	7.45	3	7.23	0.1	7.13	1	7.27	2
		1000	7.33	2	7.2	0.3	7.09	2	7.21	1
Day 3 filter average			**7.36**	**2**	**7.20**	**0.4**	**7.12**	**1**	**7.23**	**1**
4	7.05	270	7.2	2	7.39	5	7.12	1	7.24	3
		750	7.48	6	7.36	4	7.1	1	7.31	4
		1000	7.39	5	7.3	4	7.26	3.0	7.32	4
Day 4 filter average			7.36	**4**	7.35	**4**	7.16	**2**	7.29	**3**
5	7.38	270	7.43	1	7.64	4	7.46	1	7.51	2
		750	7.71	4	7.59	3	7.37	0.1	7.56	2
		1000	7.73	5	7.63	3	7.23	2	7.53	3
Day 5 filter average			**7.62**	**3**	**7.62**	**3**	**7.35**	**1**	**7.53**	**3**
6	7.18	270	7.54	5	7.56	5	7.35	2	7.48	4
		750	7.75	8	7.54	5	7.31	2	7.53	5
		1000	7.54	5	7.46	4	7.25	1	7.42	3
Day 6 filter average			**7.61**	**6**	**7.52**	**5**	**7.30**	**2**	**7.48**	**4**
7	7.2	270	7.26	1	7.45	3	7.33	2	7.35	2
		750	7.59	5	7.37	2	7.08	2	7.35	3
		1000	7.59	5	7.24	1	6.99	3	7.27	3
Day 7 filter average			**7.48**	**4**	**7.35**	**2**	**7.13**	**2**	**7.32**	**3**
8	7.23	270	7.07	2	7.25	0.3	7.18	1	7.17	1
		750	7.43	3	7.31	1	7.09	2	7.28	2
		1000	7.56	5	7.34	2	7.05	2	7.32	3
Day 8 filter average			**7.35**	**3**	**7.30**	**1**	**7.11**	**2**	**7.25**	**2**
9	6.86	270	6.99	2	7.41	8	7.12	4	7.17	5
		750	7.21	5	7.25	6	6.75	2	7.07	4
		1000	7.36	7	6.7	2	6.67	3	6.91	4
Day 9 filter average			**7.19**	**5**	**7.12**	**5**	**6.85**	**3**	**7.05**	**4**
10	7.3	270	7.17	2	7.22	1	7.11	3	7.17	2
		750	7.34	1	7.28	0.3	7.08	3	7.23	1
		1000	7.5	3	7.36	1	7.13	2	7.33	2
Day 10 filter average			**7.34**	**2**	**7.29**	**1**	**7.11**	**3**	**7.24**	**2**
11	6.97	270	7.37	6	7.22	4	7.11	2	7.23	4
		750	7.34	5	7.28	4	7.18	3	7.27	4
		1000	7.5	8	7.36	6	7.13	2	7.33	5
Day 11 filter average			**7.40**	**6**	**7.29**	**5**	**7.14**	**2**	**7.28**	**4**
12	6.68	270	6.74	1	7.41	11	7.24	8	7.13	7
		750	7.23	8	7.36	10	7.35	10	7.31	9
		1000	7.36	10	7.28	9	7.2	8	7.28	9
Day 12 filter average			**7.11**	**6**	**7.35**	**10**	**7.26**	**9**	**7.24**	**8**
13	6.71	270	7.1	6	7.54	12	7.35	10	7.33	9
		750	7.24	8	7.5	12	7.25	8	7.33	9
		1000	7.36	10	7.38	10	7.32	9	7.35	10
Day 13 filter average			**7.23**	**8**	**7.47**	**11**	**7.31**	**9**	**7.34**	**9**
14	7.08	270	7.17	1	7.62	8	7.48	6	7.42	5
		750	7.33	4	7.66	8	7.32	3	7.44	5
		1000	7.51	6	7.61	7	7.21	2	7.44	5
Day 14 filter average			**7.34**	**4**	**7.63**	**8**	**7.34**	**4**	**7.43**	**5**
15	7.21	270	7.25	1	7.48	4	7.08	2	7.27	2
		750	7.33	2	7.41	3	6.93	4	7.22	3
		1000	7.41	3	7.34	2	7.25	1	7.33	2
Day 15 filter average			**7.33**	**2**	**7.41**	**3**	**7.09**	**2**	**7.28**	**2**
16	6.7	270	7.36	10	7.73	15	7.46	11	7.52	12
		750	7.55	13	7.65	14	7.53	12	7.58	13
		1000	7.75	16	7.51	12	7.45	11	7.57	13
Day 16 a filter verage			**7.55**	**13**	**7.63**	**14**	**7.48**	**12**	**7.55**	**13**
17	7.18	270	7.46	4	7.7	7	7.39	3	7.52	5
		750	7.52	5	7.54	5	7.41	3	7.49	4
		1000	7.63	6	7.41	3	7.35	2	7.46	4
Day 17 filter average			**7.54**	**5**	**7.55**	**5**	**7.38**	**3**	**7.49**	**4**
18	7.14	270	7.63	7	7.86	10	7.55	6	7.68	8
		750	7.68	8	7.82	10	7.41	4	7.64	7
		1000	7.74	8	7.64	7	7.34	3	7.57	6
Day 18 filter average			**7.68**	**8**	**7.77**	**9**	**7.43**	**4**	**7.63**	**7**
19	7.01	270	7.01	0	6.92	1	7.15	2	7.03	1
		750	6.88	2	6.94	1	6.94	1	6.92	1
		1000	7.12	2	7.18	2	7.2	3	7.17	2
Day 19 filter average			**7.00**	**1**	**7.01**	**2**	**7.10**	**2**	**7.04**	**2**
20	7.14	270	7.37	3	7.19	1	7.2	1	7.25	2
		750	7.23	1	7.08	1	6.7	6	7.00	3
		1000	7.18	1	6.86	4	6.59	8	6.88	4
Week 20 filter average			**7.26**	**2**	**7.04**	**2**	**6.83**	**5**	**7.04**	**3**
Total Average	**7.06**	270	**7.24**	**3**	**7.41**	**5**	**7.26**	**4**	**7.31**	**4**
		750	**7.40**	**5**	**7.39**	**5**	**7.17**	**4**	**7.32**	**5**
		1000	**7.43**	**6**	**7.29**	**4**	**7.15**	**4**	**7.29**	**4**
			7.36	**5**	**7.36**	**5**	**7.19**	**4**	**7.30**	**4**

Table F.19 Daily pH variations with depth in the filter without a Carbon source.

Filter without a carbon source										
Sampling interval (Day)	**Initial raw water pH**	**Filter column depths (mm)**	**Column 1 pH with depth**	**Column 1 change in pH (%)**	**Column 2 pH with depth**	**Column 2 change in pH (%)**	**Column 3 pH with depth**	**Column 3 change in pH (%)**	**Average pH with depth**	**Avarage change in pH (%)**
1	6.98	270	7.54	8	7.61	9	7.53	8	7.56	8
		750	7.51	8	7.39	6	7.44	7	7.45	7
		1000	7.18	3	7.28	4	7.3	5	7.25	4
Day 1 filter average			**7.41**	**6**	**7.43**	**6**	**7.42**	**6**	**7.42**	**6**
2	6.9	270	7.41	7	7.58	10	7.61	10	7.53	9
		750	7.53	9	7.62	10	7.62	10	7.59	10
		1000	7.59	10	7.13	3	7.67	11	7.46	8
Day 2 filter average			**7.51**	**9**	**7.44**	**8**	**7.63**	**11**	**7.53**	**9**
3	7.22	270	7.44	3	7.46	3	7.48	4	7.46	3
		750	7.55	5	7.54	4	7.53	4	7.54	4
		1000	7.29	1	7.3	1	7.36	2	7.32	1
Day 3 filter average			**7.43**	**3**	**7.43**	**3**	**7.46**	**3**	**7.44**	**3**
4	7.05	270	7.39	5	7.48	6	7.49	6	7.45	6
		750	7.52	7	7.54	7	7.52	7	7.53	7
		1000	7.36	4	7.36	4	7.62	8	7.45	6
Day 4 filter average			7.42	**5**	7.46	**6**	7.54	**7**	7.48	6
5	7.38	270	7.32	1	7.58	3	7.53	2	7.48	2
		750	7.5	2	7.66	4	7.63	3	7.60	3
		1000	7.54	2	7.4	0.3	7.66	4	7.53	2
Day 5 filter average			**7.45**	**2**	**7.55**	**2**	**7.61**	**3**	**7.54**	**2**
6	7.18	270	7.19	0.1	7.47	4	7.53	5	7.40	3
		750	7.33	2	7.43	3	7.55	5	7.44	4
		1000	7.47	4	7.52	5	7.61	6	7.53	5
Day 6 filter average			**7.33**	**2**	**7.47**	**4**	**7.56**	**5**	**7.46**	**4**
7	7.2	270	7.38	3	7.4	3	7.43	3	7.40	3
		750	7.43	3	7.37	2	7.39	3	7.40	3
		1000	7.46	4	7.44	3	7.55	5	7.48	4
Day 7 filter average			**7.42**	**3**	**7.40**	**3**	**7.46**	**4**	**7.43**	**3**
8	7.23	270	7.23	0	7.3	1	7.27	1	7.27	1
		750	7.27	1	7.33	1	7.23	0	7.28	1
		1000	7.28	1	7.34	2	7.35	2	7.32	1
Day 8 filter average			**7.26**	**0**	**7.32**	**1**	**7.28**	**1**	**7.29**	**1**
9	6.86	270	7.15	4	7.13	4	7.2	5	7.16	4
		750	7.07	3	7.18	5	7.21	5	7.15	4
		1000	7.11	4	7.19	5	7.32	7	7.21	5
Day 9 filter average			**7.11**	**4**	**7.17**	**4**	**7.24**	**6**	**7.17**	**5**
10	7.3	270	7.25	1	7.32	0.3	7.35	1	7.31	1
		750	7.23	1	7.36	1	7.31	0.1	7.30	1
		1000	7.27	0.4	7.34	1	7.42	2	7.34	1
Day 10 filter average			**7.25**	**1**	**7.34**	**1**	**7.36**	**1**	**7.32**	**1**
11	6.97	270	7.25	4	7.32	5	7.35	5	7.31	5
		750	7.23	4	7.36	6	7.31	5	7.30	5
		1000	7.27	4	7.34	5	7.42	6	7.34	5
Day 11 filter average			**7.25**	**4**	**7.34**	**5**	**7.36**	**6**	**7.32**	**5**
12	6.68	270	6.79	2	7.07	6	7.17	7	7.01	5
		750	6.91	3	7.1	6	7.17	7	7.06	6
		1000	7.01	5	7.17	7	7.25	9	7.14	7
Day 12 filter average			**6.90**	**3**	**7.11**	**6**	**7.20**	**8**	**7.07**	**6**
13	6.71	270	7.2	7	7.3	9	7.29	9	7.26	8
		750	7.3	9	7.29	9	7.28	8	7.29	9
		1000	7.3	9	7.3	9	7.33	9	7.31	9
Day 13 filter average			**7.27**	**8**	**7.30**	**9**	**7.30**	**9**	**7.29**	**9**
14	7.08	270	7.23	2	7.29	3	7.38	4	7.30	3
		750	7.29	3	7.3	3	7.36	4	7.32	3
		1000	7.29	3	7.38	4	7.4	5	7.36	4
Day 14 filter average			**7.27**	**3**	**7.32**	**3**	**7.38**	**4**	**7.32**	**3**
15	7.21	270	7.22	0.1	7.25	1	7.28	1	7.25	1
		750	7.15	1	7.25	1	7.27	1	7.22	1
		1000	7.21	0	7.28	1	7.33	2	7.27	1
Day 15 filter average			**7.19**	**0.3**	**7.26**	**1**	**7.29**	**1**	**7.25**	**1**
16	6.7	270	7.26	8	7.25	8	7.29	9	7.27	8
		750	7.16	7	7.27	9	7.3	9	7.24	8
		1000	7.21	8	7.3	9	7.36	10	7.29	9
Day 16 a filter verage			**7.21**	**8**	**7.27**	**9**	**7.32**	**9**	**7.27**	**8**
17	7.18	270	7.38	3	7.22	1	7.25	1	7.28	1
		750	7.21	0.4	7.25	1	7.25	1	7.24	1
		1000	7.2	0.3	7.24	1	7.3	2	7.25	1
Day 17 filter average			**7.26**	**1**	**7.24**	**1**	**7.27**	**1**	**7.26**	**1**
18	7.14	270	7.35	3	7.13	0.1	7.14	0	7.21	1
		750	7.05	1	7.13	0.1	7.15	0.1	7.11	1
		1000	7.07	1	7.14	0	7.23	1	7.15	1
Day 18 filter average			**7.16**	**2**	**7.13**	**0.1**	**7.17**	**0.5**	**7.15**	**1**
19	7.01	270	7.52	7	7.43	6	7.3	4	7.42	6
		750	7.78	11	7.39	5	7.29	4	7.49	7
		1000	7.56	8	7.34	5	7.35	5	7.42	6
Day 19 filter average			7.62	**9**	7.39	**5**	7.31	**4**	**7.44**	6
20	7.14	270	7.43	4	7.1	1	7.12	0.3	7.22	1.6
		750	7.12	0.3	7.1	1	7.09	1	7.10	1
		1000	7.13	0.1	7.16	0.3	7.14	0	7.14	0.1
Week 20 filter average			**7.23**	**1**	**7.12**	**0.5**	**7.12**	**0.3**	**7.15**	**1**
Total Average	**7.06**	270	**7.30**	**4**	**7.33**	**4**	**7.35**	**4**	**7.33**	**4**
		750	**7.31**	**4**	**7.34**	**4**	**7.35**	**4**	**7.33**	**4**
		1000	**7.29**	**4**	**7.30**	**3**	**7.40**	**5**	**7.33**	**4**
			7.30	**4**	**7.33**	**4**	**7.36**	**4**	**7.33**	**4**

Appendix G. Temperature at varied filter depths

The tables below represent the daily temperature variation with depth in the filter with and without a Carbon source during the filter operation.

G.1. Temperature concentration at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table G.20 Daily temperature variations with depth in the filter with a Carbon source.

Filter with a carbon source										
Sampling interval (Day)	**Initial raw water temperature (̊C)**	**Filter column depths (mm)**	**Column 1 temperature at depth**	**Column 1 change in temperature (̊C)**	**Column 2 temperature at depth**	**Column 2 change in temperature(̊C)**	**Column 3 temperature at depth**	**Column 3 change in temperature(̊C)**	**Average temperature at depth**	**Avarage change in temperature(%)**
1	23.7	270	24.5	3	24.4	3	24.2	2	24.37	3
		750	24.4	3.0	24.4	3	24.2	2	24.33	3
		1000	24.3	2.5	24.3	3	24.2	2.1	24.27	2
Day 1 filter average			**24.40**	**3.0**	**24.37**	**3**	**24.20**	**2**	**24.32**	**3**
2	22.9	270	23.9	4	23.7	3	23.6	3	23.73	3.6
		750	23.8	4	23.5	3	23.5	3	23.60	3.1
		1000	23.8	4	23.6	3	23.7	3	23.70	3.5
Day 2 filter average			**23.83**	**4.1**	**23.60**	**3.1**	**23.60**	**3.1**	**23.68**	**3.4**
3	23.7	270	25	5	24.8	5	24.5	3	24.77	4.5
		750	24.9	5	24.8	5	24.7	4	24.80	4.6
		1000	24.9	5	24.6	4	24.8	5	24.77	4.5
Day 3 filter average			**24.93**	**5.2**	**24.73**	**4.4**	**24.67**	**4.1**	**24.78**	**4.5**
4	22.8	270	23.8	4	23.9	5	23.5	3	23.73	4
		750	24.2	6	23.7	4	23.7	4	23.87	5
		1000	24.3	7	23.6	4	23.6	4	23.83	5
Day 4 filter average			**24.10**	**6**	**23.73**	**4**	**23.60**	**4**	**23.81**	**4**
5	23.7	270	24.6	4	24.6	4	24.6	4	24.60	4
		750	24.6	4	24.6	4	24.7	4	24.63	4
		1000	24.7	4	24.6	4	24.7	4	24.67	4
Day 5 filter average			**24.63**	**4**	**24.60**	**4**	**24.67**	**4**	**24.63**	**4**
6	24.5	270	22.9	6.5	23.5	4.1	23.7	3	23.37	4.6
		750	23.4	4.5	23.8	2.9	23.6	4	23.60	3.7
		1000	23.5	4	23.7	3.3	23.7	3	23.63	3.5
Day 6 filter average			**23.27**	**5**	**23.67**	**3.4**	**23.67**	**3**	**23.53**	**3.9**
7	23.9	270	24.9	4	24.7	3	24.5	3	24.70	3
		750	24.7	3	24.7	3	24.7	3	24.70	3
		1000	24.7	3	24.7	3	24.8	4	24.73	3
Day 7 filter average			**24.77**	**4**	**24.70**	**3**	**24.67**	**3**	**24.71**	**3**
8	23.4	270	22.8	3	23.5	0.4	23.3	0.4	23.20	1
		750	22.7	3	23.4	0	23.4	0	23.17	1
		1000	23.4	0	23.3	0.4	23.3	0.4	23.33	0.3
Day 8 filter average			**22.97**	**2**	**23.40**	**0**	**23.33**	**0**	**23.23**	**1**
9	23.3	270	24.3	4	24.3	4	24.3	4	24.30	4
		750	24.2	4	24.2	4	24.3	4	24.23	4
		1000	24.2	4	24.3	4	24.2	4	24.23	4
Day 9 filter average			**24.23**	**4**	**24.27**	**4**	**24.27**	**4**	**24.26**	**4**
10	22.9	270	23.2	1	23.5	3	23.6	3	23.43	2
		750	23.5	3	23.5	3	23.6	3	23.53	3
		1000	23.6	3	23.6	3	23.5	3	23.57	3
Day 10 filter average			**23.43**	**2**	**23.53**	**3**	**23.57**	**3**	**23.51**	**3**
11	22.7	270	23.4	3.1	23.2	2.2	23.1	1.8	23.23	2.3
		750	23.4	3.1	23.3	2.6	23.1	1.8	23.27	2.5
		1000	23.2	2.2	23.1	1.8	23	1.3	23.10	1.8
Day 11 filter average			**23.33**	**2.8**	**23.20**	**2.2**	**23.07**	**1.6**	**23.20**	**2.2**
12	23.4	270	23.4	0	23.2	1	23.1	1	23.23	1
		750	23.4	0	23.3	0.4	23.1	1	23.27	1
		1000	23.2	1	23.1	1	23	2	23.10	1
Day 12 filter average			**23.33**	**0**	**23.20**	**1**	**23.07**	**1**	**23.20**	**1**
13	22.4	270	23.2	4	23	3	23	3	23.07	3
		750	23.2	4	23.2	4	23.3	4	23.23	4
		1000	23.2	4	23.2	4	23.2	4	23.20	4
Day 13 filter average			**23.20**	**4**	**23.13**	**3**	**23.17**	**3**	**23.17**	**3**
14	23.6	270	23.5	0.4	23.6	0	23.3	1	23.47	1
		750	23.7	0.4	23.7	0.4	23.2	2	23.53	1
		1000	23.6	0	23.4	0.8	23.4	0.8	23.47	1
Day 14 filter average			**23.60**	**0**	**23.57**	**0**	**23.30**	**1**	**23.49**	**1**
15	22.9	270	23.7	3	23.5	3	23.5	3	23.57	3
		750	23.7	3	23.5	3	23.6	3	23.60	3
		1000	23.6	3	23.6	3	23.6	3	23.60	3
Day 15 filter average			**23.67**	**3**	**23.53**	**3**	**23.57**	**3**	**23.59**	**3**
16	23.8	270	24.3	2	24.4	3	24.3	2	24.33	2
		750	24.5	3	24.3	2	24.5	3	24.43	3
		1000	24.5	3	24.3	2	24.3	2	24.37	2
Day 16 filter average			**24.43**	**3**	**24.33**	**2**	**24.37**	**2**	**24.38**	**2**
17	23.1	270	23.7	3	23.6	2	23.6	2	23.63	2
		750	23.7	3	23.8	3	23.7	3	23.73	3
		1000	23.7	3	23.7	3	23.7	3	23.70	3
Day 17 filter average			**23.70**	**3**	**23.70**	**3**	**23.67**	**2**	**23.69**	**3**
18	22.6	270	24.8	10	24.5	8	23.4	4	24.23	7.2
		750	24.2	7	24.3	8	23.3	3	23.93	5.9
		1000	24.3	8	23.5	4	23.4	4	23.73	5.0
Day 18 filter average			**24.43**	**8.1**	**24.10**	**6.6**	**23.37**	**3.4**	**23.97**	**6.0**
19	22.9	270	23.8	4	23.6	3	23.6	3	23.67	3
		750	23.7	3	23.4	2	23.5	3	23.53	3
		1000	23.7	3	23.6	3	23.6	3	23.63	3
Day 19 filter average			**23.73**	**4**	**23.53**	**3**	**23.57**	**3**	**23.61**	**3**
20	23.5	270	24.2	3	24.7	5	24.5	4	24.47	4
		750	24.5	4	24.6	5	24.6	5	24.57	5
		1000	24.6	5	24.6	5	24.5	4	24.57	5
Day 20 filter average			**24.43**	**4**	**24.63**	**5**	**24.53**	**4**	**24.53**	**4**
Total Average	**23.29**	270	**23.90**	**4**	**23.91**	**3**	**23.76**	**3**	**23.86**	**3**
		750	**23.92**	**4**	**23.90**	**3**	**23.82**	**3**	**23.88**	**3**
		1000	**23.95**	**3**	**23.82**	**3**	**23.81**	**3**	**23.86**	**3**
			23.92	**3**	**23.88**	**3**	**23.80**	**3**	**23.86**	**3**

Table G.21 Daily temperature variations with depth in the filter without a Carbon source

Filter without a carbon source										
Sampling interval (Day)	**Initial raw water temperature (̊C)**	**Filter column depths (mm)**	**Column 1 temperature at depth**	**Column 1 change in temperature (̊C)**	**Column 2 temperature at depth**	**Column 2 change in temperature(̊C)**	**Column 3 temperature at depth**	**Column 3 change in temperature (̊C)**	**Average temperature at depth**	**Avarage change in temperature(%)**
1	23.7	270	24	1	26	10	26.1	10	25.37	7
		750	24.3	2.5	26.1	10	26.4	11	25.60	8
		1000	24.4	3.0	26.2	11	25.9	9.3	25.50	8
Day 1 filter average			**24.23**	**2.3**	**26.10**	**10**	**26.13**	**10**	**25.49**	**8**
2	22.9	270	23.5	3	23.7	3	23.7	3	23.63	3.2
		750	23.4	2	23.7	3	23.7	3	23.60	3.1
		1000	23.5	3	23.6	3	23.7	3	23.60	3.1
Day 2 filter average			**23.47**	**2.5**	**23.67**	**3.3**	**23.70**	**3.5**	**23.61**	**3.1**
3	23.7	270	24.8	5	24.7	4	24.6	4	24.70	4.2
		750	24.7	4	24.7	4	24.7	4	24.70	4.2
		1000	24.7	4	24.7	4	24.8	5	24.73	4.4
Day 3 filter average			**24.73**	**4.4**	**24.70**	**4.2**	**24.70**	**4.2**	**24.71**	**4.3**
4	22.8	270	23.9	5	23.7	4	23.8	4	23.80	4
		750	23.7	4	23.9	5	23.7	4	23.77	4
		1000	23.8	4	23.8	4	23.7	4	23.77	4
Day 4 filter average			**23.80**	**4**	**23.80**	**4**	**23.73**	**4**	**23.78**	**4**
5	23.7	270	24.4	3	24.6	4	24.6	4	24.53	4
		750	24.6	4	24.7	4	24.7	4	24.67	4
		1000	24.7	4	24.6	4	24.8	5	24.70	4
Day 5 filter average			**24.57**	**4**	**24.63**	**4**	**24.70**	**4**	**24.63**	**4**
6	24.5	270	23.5	4.1	23.7	3.3	23.7	3	23.63	3.5
		750	23.6	3.7	23.8	2.9	23.7	3	23.70	3.3
		1000	23.6	4	23.8	2.9	23.8	3	23.73	3.1
Day 6 filter average			**23.57**	**4**	**23.77**	**3.0**	**23.73**	**3**	**23.69**	**3.3**
7	23.9	270	24.8	4	24.8	4	24.9	4	24.83	4
		750	24.7	3	24.9	4	25	5	24.87	4
		1000	24.7	3	24.9	4	25.1	5	24.90	4
Day 7 filter average			**24.73**	**3**	**24.87**	**4**	**25.00**	**5**	**24.87**	**4**
8	23.4	270	23.6	1	23.7	1	23.7	1	23.67	1
		750	23.5	0.4	23.6	1	23.5	0.4	23.53	1
		1000	23.5	0.4	23.6	1	23.5	0.4	23.53	1
Day 8 filter average			**23.53**	**1**	**23.63**	**1**	**23.57**	**1**	**23.58**	**1**
9	23.3	270	24.3	4	24.2	-4	24.3	4.3	24.27	2
		750	24.1	3	24.2	4	24.3	4	24.20	4
		1000	24.2	4	24.2	4	24.4	5	24.27	4
Day 9 filter average			**24.20**	**4**	**24.20**	**1**	**24.33**	**4**	**24.24**	**3**
10	22.9	270	23.7	3	23.7	3	23.6	3	23.67	3
		750	23.6	3	23.5	3	23.7	3	23.60	3
		1000	23.6	3	23.6	3	23.6	3	23.60	3
Day 10 filter average			**23.63**	**3**	**23.60**	**3**	**23.63**	**3**	**23.62**	**3**
11	22.7	270	23.3	2.6	23.2	2.2	23.1	1.8	23.20	2.2
		750	23.2	2.2	23.2	2.2	23.2	2.2	23.20	2.2
		1000	23.1	1.8	23.2	2.2	23	1.3	23.10	1.8
Day 11 filter average			**23.20**	**2.2**	**23.20**	**2.2**	**23.10**	**1.8**	**23.17**	**2.1**
12	23.4	270	23.3	0.4	23.2	1	23.1	1	23.20	1
		750	23.2	1	23.2	1	23.2	1	23.20	1
		1000	23.1	1	23.2	1	23	2	23.10	1
Day 12 filter average			**23.20**	**1**	**23.20**	**1**	**23.10**	**1**	**23.17**	**1**
13	22.4	270	23.2	4	23.2	4	23.2	4	23.20	4
		750	23.2	4	23.2	4	23.2	4	23.20	4
		1000	23.2	4	23.3	4	23.2	4	23.23	4
Day 13 filter average			**23.20**	**4**	**23.23**	**4**	**23.20**	**4**	**23.21**	**4**
14	23.6	270	23.4	1	23.4	0.8	23.6	0	23.47	1
		750	23.6	0	23.4	0.8	23.6	0	23.53	0.3
		1000	23.6	0	23.5	0.4	23.7	0.4	23.60	0
Day 14 filter average			**23.53**	**0**	**23.43**	**1**	**23.63**	**0**	**23.53**	**0**
15	22.9	270	23.4	2	23.4	2	23.5	3	23.43	2
		750	23.5	3	23.6	3	23.6	3	23.57	3
		1000	23.6	3	23.7	3	23.7	3	23.67	3
Day 15 filter average			**23.50**	**3**	**23.57**	**3**	**23.60**	**3**	**23.56**	**3**
16	23.8	270	24.6	3	24.6	3	24.6	3	24.60	3
		750	24.5	3	24.6	3	24.5	3	24.53	3
		1000	24.5	3	24.4	3	24.6	3	24.50	3
Day 16 filter average			**24.53**	**3**	**24.53**	**3**	**24.57**	**3**	**24.54**	**3**
17	23.1	270	23.5	2	23.6	2	23.7	3	23.60	2
		750	23.6	2	23.7	3	23.7	3	23.67	2
		1000	23.6	2	23.8	3	23.7	3	23.70	3
Day 17 filter average			**23.57**	**2**	**23.70**	**3**	**23.70**	**3**	**23.66**	**2**
18	22.6	270	24.7	9	24.5	8	24.7	9	24.63	9.0
		750	24.6	9	24.6	9	24.5	8	24.57	8.7
		1000	24.7	9	24.6	9	24.7	9	24.67	9.1
Day 18 filter average			**24.67**	**9.1**	**24.57**	**8.7**	**24.63**	**9.0**	**24.62**	**8.9**
19	22.9	270	23.7	3	23.7	3	23.7	3	23.70	3
		750	23.6	3	23.7	3	23.7	3	23.67	3
		1000	23.7	3	23.7	3	23.8	4	23.73	4
Day 19 filter average			**23.67**	**3**	**23.70**	**3**	**23.73**	**4**	**23.70**	**3**
20	23.5	270	24.7	5	24.4	4	24.6	5	24.57	5
		750	24.5	4	24.5	4	24.5	4	24.50	4
		1000	24.5	4	24.6	5	24.6	5	24.57	5
Day 20 filter average			**24.57**	**5**	**24.50**	**4**	**24.57**	**5**	**24.54**	**4**
Total Average	**23.29**	270	**23.92**	**3**	**24.00**	**3**	**24.04**	**4**	**23.99**	**3**
		750	**23.89**	**3**	**24.04**	**4**	**24.06**	**4**	**23.99**	**4**
		1000	**23.92**	**3**	**24.05**	**4**	**24.07**	**4**	**24.01**	**4**
			23.91	**3**	**24.03**	**4**	**24.05**	**4**	**24.00**	**3**

G.2. Temperature concentration at C/N ratio of 1.08 and nitrate concentration of 25 mg/L-N

Table G.22 Daily temperature variations with depth in the filter with a Carbon source

Filter with a carbon source										
Sampling interval (Day)	**Initial raw water temperature (̊C)**	**Filter column depths (mm)**	**Column 1 temperature with depth(̊C)**	**Column 1 change in temperature (%)**	**Column 2 temperature with depth(̊C)**	**Column 2 change in temperature(%)**	**Column 3 temperature with depth(̊C)**	**Column 3 change in temperature (%)**	**Average temperature at depth (̊C)**	**Avarage change in temperature(%)**
1	19.8	270	19.6	1	19.6	1	19.6	1	19.60	1
		750	18.9	5	19.6	1	19.6	1	19.37	2
		1000	19.7	1	19.7	1	19.5	2	19.63	1
Day 1 average			**19.40**	**2**	**19.63**	**1**	**19.57**	**1**	**19.53**	**1**
2	20.7	270	20.7	0	20.7	0	20.7	0	20.70	0
		750	20.8	0.5	20.7	0	20.7	0	20.73	0.2
		1000	20.8	0.5	20.6	0.5	20.7	0	20.70	0.3
Day 2 average			**20.77**	**0.3**	**20.67**	**0.2**	**20.70**	**0**	**20.71**	**0.2**
3	19	270	19.3	2	19.1	1	19.2	1	19.20	1
		750	19.3	2	19.2	1	19.2	1	19.23	1
		1000	19.2	1	19.2	1	19.2	1	19.20	1
Day 3 average			**19.27**	**1**	**19.17**	**1**	**19.20**	**1**	**19.21**	**1**
4	24	270	22.1	8	22	8	22	8	22.03	8
		750	22.1	8	22.1	8	22	8	22.07	8
		1000	22	8	22	8	22.1	8	22.03	8
Day 4 average			**22.07**	**8**	**22.03**	**8**	**22.03**	**8**	**22.04**	**8**
5	19.9	270	21.3	7	21.3	7	21.3	7	21.30	7
		750	21.3	7	21.3	7	21.3	7	21.30	7
		1000	21.3	7	21.3	7	21.3	7	21.30	7
Day 5 average			**21.30**	**7**	**21.30**	**7**	**21.30**	**7**	**21.30**	**7**
6	20.6	270	22.1	7	22	7	21.9	6	22.00	7
		750	22	7	22	7	21.9	6	21.97	7
		1000	22	7	21.9	6	22	7	21.97	7
Day 6 average			**22.03**	**7**	**21.97**	**7**	**21.93**	**6**	**21.98**	**7**
7	21.8	270	19.6	10	17.4	20	19	13	18.67	14
		750	18.7	14	15.5	29	17.8	18	17.33	20
		1000	18.3	16	19	13	18.8	14	18.70	14
Day 7 average			**18.87**	**13**	**17.30**	**21**	**18.53**	**15**	**18.23**	**16**
8	20.9	270	23	10	23.2	11	23.3	11	23.17	11
		750	23.2	11	23.3	11	23.4	12	23.30	11
		1000	23.3	11	23.6	13	23.6	13	23.50	12
Day 8 average			**23.17**	**11**	**23.37**	**12**	**23.43**	**12**	**23.32**	**12**
9	25.1	270	23.3	7	23.5	6	23.5	6	23.43	7
		750	23.2	8	23.6	6	23.6	6	23.47	7
		1000	23.4	7	23.7	6	23.7	6	23.60	6
Day 9 average			**23.30**	**7**	**23.60**	**6**	**23.60**	**6**	**23.50**	**6**
10	23	270	24.3	6	24.3	6	24.3	6	24.30	6
		750	24.4	6	24.3	6	24.4	6	24.37	6
		1000	24.3	6	24.5	7	24.4	6	24.40	6
Day 10 average			**24.33**	**6**	**24.37**	**6**	**24.37**	**6**	**24.36**	**6**
11	22.5	270	24.2	8	24.2	8	24	7	24.13	7
		750	24.2	8	24.3	8	24.3	8	24.27	8
		1000	23	2	24.2	8	24.4	8	23.87	6
Day11 average			**23.80**	**6**	**24.23**	**8**	**24.23**	**8**	**24.09**	**7**
12	25.2	270	25.8	2	25.7	2	25.6	2	25.70	2
		750	25.8	2	25.7	2	25.7	2	25.73	2
		1000	25.8	2	25.6	2	25.4	1	25.60	2
Day 12 average			**25.80**	**2**	**25.67**	**2**	**25.57**	**1**	**25.68**	**2**
13	24.1	270	24.9	3	24.8	3	24.6	2	24.77	3
		750	24.9	3	24.8	3	24.9	3	24.87	3
		1000	24.9	3	24.8	3	24.9	3	24.87	3
Day 13 average			**24.90**	**3**	**24.80**	**3**	**24.80**	**3**	**24.83**	**3**
14	22.9	270	24.5	7	24.5	7	24.4	7	24.47	7
		750	24.5	7	24.5	7	24.4	7	24.47	7
		1000	24.5	7	24.4	7	23.3	2	24.07	5
Day 14 average			**24.50**	**7**	**24.47**	**7**	**24.03**	**5**	**24.33**	**6**
15	23.4	270	24.3	4	24.3	4	24.3	4	24.30	4
		750	24.3	4	24.3	4	24.4	4	24.33	4
		1000	24.3	4	24.4	4	24.3	4	24.33	4
Day 15 average			**24.30**	**4**	**24.33**	**4**	**24.33**	**4**	**24.32**	**4**
16	23.5	270	22	6	21.9	7	22	6	21.97	7
		750	21.9	7	21.9	7	21.8	7	21.87	7
		1000	21.9	7	21.9	7	20.4	13	21.40	9
Day 16 average			**21.93**	**7**	**21.90**	**7**	**21.40**	**9**	**21.74**	**7**
17	22.7	270	24.6	8	24.5	8	24.4	7	24.50	8
		750	24.6	8	24.5	8	24.4	7	24.50	8
		1000	24.5	8	24.4	7	24.5	8	24.47	8
Day 17 average			**24.57**	**8**	**24.47**	**8**	**24.43**	**8**	**24.49**	**8**
18	21.9	270	23.2	6	23.2	6	23.2	6	23.20	6
		750	23.2	6	23.3	6	23.3	6	23.27	6
		1000	23.3	6	23.5	7	23.6	8	23.47	7
Day 18 average			**23.23**	**6**	**23.33**	**7**	**23.37**	**7**	**23.31**	**6**
19	23.4	270	24.2	3	24.6	5	24.4	4	24.40	4
		750	24.6	5	23.8	2	24.4	4	24.27	4
		1000	24.6	5	23.5	0	24.5	5	24.20	3
Day 19 average			**24.47**	**5**	**23.97**	**2**	**24.43**	**4**	**24.29**	**4**
20	23.2	270	24.4	5	24.3	5	24.2	4	24.30	5
		750	24.2	4	24.3	5	24.1	4	24.20	4
		1000	24.3	5	24.2	4	24.2	4	24.23	4
Day 20 average			**24.30**	**5**	**24.27**	**5**	**24.17**	**4**	**24.24**	**5**
Total Average	**22.38**	270	**22.87**	**6**	**22.76**	**6**	**22.80**	**5**	**22.81**	**6**
		750	**22.81**	**6**	**22.65**	**6**	**22.78**	**6**	**22.75**	**6**
		1000	**22.77**	**6**	**22.82**	**6**	**22.74**	**6**	**22.78**	**6**
			22.82	**6**	**22.74**	**6**	**22.77**	**6**	**22.78**	**6**

Table G.23 Daily temperature variations with depth in the filter with a Carbon source

Filter without a carbon source										
Sampling interval (Day)	**Initial raw water temperature (°C)**	**Filter column depths (mm)**	**Column 1 temperature with depth (°C)**	**Column 1 change in temperature (%)**	**Column 2 temperature with depth (°C)**	**Column 2 change in temperature(%)**	**Column 3 temperature with depth (°C)**	**Column 3 change in temperature (%)**	**Average temperature at depth (°C)**	**Avarage change in temperature(%)**
1	19.8	270	19.4	2	19.4	2	19.6	1	19.47	2
		750	19.5	2	19.4	2	19.5	2	19.47	2
		1000	19.6	1	19.5	2	19.4	2	19.50	2
Day 1 average			**19.50**	**2**	**19.43**	**2**	**19.50**	**2**	**19.48**	**2**
2	20.7	270	20.6	0.5	20.5	1	20.7	0	20.60	0.5
		750	20.6	0.5	20.6	0.5	20.6	0.5	20.60	0.5
		1000	20.7	0.0	20.6	0.5	20.6	0.5	20.63	0.3
Day 2 average			**20.63**	**0.3**	**20.57**	**0.6**	**20.63**	**0.3**	**20.61**	**0.4**
3	19	270	19	0.0	19.1	0.5	19.1	0.5	19.07	0.4
		750	19	0.0	19	0	19.1	0.5	19.03	0.2
		1000	19.1	0.5	19.1	0.5	19.1	0.5	19.10	0.5
Day 3 average			**19.03**	**0.2**	**19.07**	**0.4**	**19.10**	**0.5**	**19.07**	**0.4**
4	24	270	22.2	8	22.1	8	22.1	8	22.13	8
		750	22.2	8	22.1	8	22.1	8	22.13	8
		1000	22.1	8	22.1	8	22.1	8	22.10	8
Day 4 average			**22.17**	**8**	**22.10**	**8**	**22.10**	**8**	**22.12**	**8**
5	19.9	270	22.2	12	22.1	11	22.1	11	22.13	11
		750	22.2	12	22.1	11	22.1	11	22.13	11
		1000	22.1	11	22.1	11	22.1	11	22.10	11
Day 5 average			**22.17**	**11**	**22.10**	**11**	**22.10**	**11**	**22.12**	**11**
6	20.6	270	21.9	6	21.9	6	21.8	6	21.87	6
		750	21.9	6	21.9	6	21.8	6	21.87	6
		1000	21.9	6	21.9	6	21.8	6	21.87	6
Day 6 average			**21.90**	**6**	**21.90**	**6**	**21.80**	**6**	**21.87**	**6**
7	21.8	270	19.8	9	19.8	9	17.9	18	19.17	12
		750	19.8	9	18.9	13	19.5	11	19.40	11
		1000	19.5	11	18.8	14	19.7	10	19.33	11
Day 7 average			**19.70**	**10**	**19.17**	**12**	**19.03**	**13**	**19.30**	**11**
8	20.9	270	23.4	12	23.5	12	23.5	12	23.47	12
		750	23.4	12	23.6	13	23.4	12	23.47	12
		1000	23.6	13	23.7	13	23.5	12	23.60	13
Day 8 average			**23.47**	**12**	**23.60**	**13**	**23.47**	**12**	**23.51**	**12**
9	25.1	270	23.7	6	23.6	6	23.6	6	23.63	6
		750	23.8	5	23.7	6	23.6	6	23.70	6
		1000	23.9	5	23.7	6	23.7	6	23.77	5
Day 9 average			**23.80**	**5**	**23.67**	**6**	**23.63**	**6**	**23.70**	**6**
10	23	270	24.5	7	24.5	7	24.5	7	24.50	7
		750	24.5	7	24.5	7	24.4	6	24.47	6
		1000	24.6	7	24.5	7	24.5	7	24.53	7
Day 10 average			**24.53**	**7**	**24.50**	**7**	**24.47**	**6**	**24.50**	**7**
11	22.5	270	24.2	8	24.1	7	24.3	8	24.20	8
		750	24.2	8	24.2	8	24.4	8	24.27	8
		1000	24.4	8	24.6	9	24.5	9	24.50	9
Day11 average			**24.27**	**8**	**24.30**	**8**	**24.40**	**8**	**24.32**	**8**
12	25.2	270	25.6	2	25.5	1	25.5	1	25.53	1
		750	25.6	2	25.6	2	25.6	2	25.60	2
		1000	25.6	2	25.6	2	25.5	1	25.57	1
Day 12 average			**25.60**	**2**	**25.57**	**1**	**25.53**	**1**	**25.57**	**1**
13	24.1	270	24.6	2	24.6	2	24.5	2	24.57	2
		750	24.6	2	24.8	3	24.9	3	24.77	3
		1000	24.8	3	24.9	3	24.7	2	24.80	3
Day 13 average			**24.67**	**2**	**24.77**	**3**	**24.70**	**2**	**24.71**	**3**
14	22.9	270	24.4	7	24.4	7	24.3	6	24.37	6
		750	24.4	7	24.3	6	24.5	7	24.40	7
		1000	24.4	7	24.4	7	24.6	7	24.47	7
Day 14 average			**24.40**	**7**	**24.37**	**6**	**24.47**	**7**	**24.41**	**7**
15	23.4	270	24.4	4	24.3	4	24.4	4	24.37	4
		750	24.3	4	24.4	4	24.4	4	24.37	4
		1000	24.3	4	24.3	4	24.4	4	24.33	4
Day 15 average			**24.33**	**4**	**24.33**	**4**	**24.40**	**4**	**24.36**	**4**
16	23.5	270	21.9	7	21.9	7	22.1	6	21.97	7
		750	21.8	7	21.9	7	22	6	21.90	7
		1000	22	6	22	6	22.1	6	22.03	6
Day 16 average			**21.90**	**7**	**21.93**	**7**	**22.07**	**6**	**21.97**	**7**
17	22.7	270	24.4	7	24.2	7	24.3	7	24.30	7
		750	24.2	7	24.3	7	24.4	7	24.30	7
		1000	24.4	7	24.5	8	24.4	7	24.43	8
Day 17 average			**24.33**	**7**	**24.33**	**7**	**24.37**	**7**	**24.34**	**7**
18	21.9	270	21.9	0.0	21.9	0	22.1	0.9	21.97	0.3
		750	21.8	0.5	21.9	0	22	0.5	21.90	0.3
		1000	22	0.5	22	0.5	22.1	0.9	22.03	0.6
Day 18 average			**21.90**	**0.3**	**21.93**	**0.2**	**22.07**	**0.8**	**21.97**	**0.4**
19	23.4	270	24.1	3	23.8	2	23.6	1	23.83	2
		750	24.3	4	23.8	2	24.2	3	24.10	3
		1000	23.9	2	23.8	2	24.3	4	24.00	3
Day 19 average			**24.10**	**3**	**23.80**	**2**	**24.03**	**3**	**23.98**	**2**
20	23.2	270	24.7	6	24.7	6	24.8	7	24.73	7
		750	24.6	6	24.7	6	24.7	6	24.67	6
		1000	24.7	6	24.7	6	24.8	7	24.73	7
Day 20 average			**24.67**	**6**	**24.70**	**6**	**24.77**	**7**	**24.71**	**7**
Total Average	**22.38**	270	**22.85**	**5**	**22.80**	**5**	**22.74**	**6**	**22.79**	**5**
		750	**22.84**	**5**	**22.79**	**6**	**22.86**	**6**	**22.83**	**5**
		1000	**22.88**	**5**	**22.84**	**6**	**22.90**	**6**	**22.87**	**6**
			22.85	**5**	**22.81**	**6**	**22.83**	**6**	**22.83**	**5**

G.3. Temperature concentration at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table G.24 Daily temperature variations with depth in the filter with a Carbon source

Filter with a carbon source										
Sampling interval (Day)	**Initial raw water temperature (°C)**	**Filter column depths (mm)**	**Column 1 temperature at depth**	**Column 1 change in temperature (°C)**	**Column 2 temperature at depth**	**Column 2 change in temperature (°C)**	**Column 3 temperature at depth**	**Column 3 change in temperature (°c)**	**Average temperature at depth**	**Avarage change in temperature(%)**
1	25.8	270	26.3	2	26.3	2	26.3	2	26.30	2
		750	26.2	2	26.2	2	26.4	2	26.27	2
		1000	26.2	2	26.3	2	26.3	2	26.27	2
Day 1 filter average			**26.23**	**1.7**	**26.27**	**2**	**26.33**	**2**	**26.28**	**2**
2	27	270	27.9	3	27.7	3	27.5	2	27.70	2.6
		750	27.9	3	27.7	3	27.7	3	27.77	2.8
		1000	27.9	3	27.8	3	27.7	3	27.80	3.0
Day 2 filter average			**27.90**	**3.3**	**27.73**	**2.7**	**27.63**	**2.3**	**27.76**	**2.8**
3	26.6	270	27.2	2	27.2	2	27	2	27.13	2.0
		750	27.2	2	27.2	2	26.8	1	27.07	1.8
		1000	27.2	2	27.2	2	27.1	2	27.17	2.1
Day 3 filter average			**27.20**	**2.3**	**27.20**	**2.3**	**26.97**	**1.4**	**27.12**	**2.0**
4	25.5	270	26.6	4	26.5	4	26.5	4	26.53	4
		750	26.6	4	26.6	4	26.5	4	26.57	4
		1000	26.5	4	26.4	4	26.5	4	26.47	4
Day 4 filter average			**26.57**	**4**	**26.50**	**4**	**26.50**	**4**	**26.52**	**4**
5	24.8	270	26.1	5	26	5	25.9	4	26.00	5
		750	26.1	5	26	5	26	5	26.03	5
		1000	26.1	5	26.1	5	26	5	26.07	5
Day 5 filter average			**26.10**	**5**	**26.03**	**5**	**25.97**	**5**	**26.03**	**5**
6	24.7	270	25	1	24.9	1	24.8	0.4	24.90	0.8
		750	25	1	24.9	1	24.7	0	24.87	0.7
		1000	24.9	1	24.8	0.4	24.5	1	24.73	0.7
Day 6 filter average			**24.97**	**1**	**24.87**	**0.7**	**24.67**	**0.4**	**24.83**	**0.7**
7	25	270	26	4	25.9	4	26	4	25.97	4
		750	26.1	4	26	4	25.9	4	26.00	4
		1000	26.1	4	26	4	26	4	26.03	4
Day 7 filter average			**26.07**	**4**	**25.97**	**4**	**25.97**	**4**	**26.00**	**4**
8	25.3	270	25.9	2	25.7	2	25.7	2	25.77	2
		750	25.8	2	25.9	2	25.8	2	25.83	2
		1000	25.9	2	25.8	2	25.8	2	25.83	2
Day 8 filter average			**25.87**	**2**	**25.80**	**2**	**25.77**	**2**	**25.81**	**2**
9	25.5	270	25.9	2	25.9	2	25.8	1	25.87	1
		750	25.8	1	25.9	2	25.8	1	25.83	1
		1000	25.9	2	25.9	2	25.7	1	25.83	1
Day 9 filter average			**25.87**	**1**	**25.90**	**2**	**25.77**	**1**	**25.84**	**1**
10	24.9	270	25.3	2	25.4	2	25.5	2	25.40	2
		750	25.3	2	25.4	2	25.4	2	25.37	2
		1000	25.4	2	25.4	2	25.4	2	25.40	2
Day 10 filter average			**25.33**	**2**	**25.40**	**2**	**25.43**	**2**	**25.39**	**2**
11	25.62	270	25.6	0.1	25.6	0.1	25.6	0.1	25.60	0.1
		750	25.6	0.1	25.5	0.5	25.6	0.1	25.57	0.2
		1000	25.5	0.5	25.6	0.1	25.6	0.1	25.57	0.2
Day 11 filter average			**25.57**	**0.2**	**25.57**	**0.2**	**25.60**	**0.1**	**25.58**	**0.2**
12	24.1	270	25.1	4	25	4	25	4	25.03	4
		750	24.8	3	25	4	25	4	24.93	3
		1000	25	4	24.9	3	25	4	24.97	4
Day 12 filter average			**24.97**	**4**	**24.97**	**4**	**25.00**	**4**	**24.98**	**4**
13	24.1	270	25.1	4	25.1	4	25.1	4	25.10	4
		750	25.1	4	25	4	25.1	4	25.07	4
		1000	25.1	4	25.1	4	25.1	4	25.10	4
Day 13 filter average			**25.10**	**4**	**25.07**	**4**	**25.10**	**4**	**25.09**	**4**
14	24.5	270	25.7	5	25.6	4	25.5	4	25.60	4
		750	25.5	4	25.5	4	25.6	4	25.53	4
		1000	25.6	4	25.6	4	25.6	4	25.60	4
Day 14 filter average			**25.60**	**4**	**25.57**	**4**	**25.57**	**4**	**25.58**	**4**
15	24.7	270	25.7	4	25.4	3	25.6	4	25.57	4
		750	25.7	4	25.7	4	25.6	4	25.67	4
		1000	25.7	4	25.7	4	25.7	4	25.70	4
Day 15 filter average			**25.70**	**4**	**25.60**	**4**	**25.63**	**4**	**25.64**	**4**
16	25	270	26.2	5	26.1	4	26	4	26.10	4
		750	26.2	5	26.1	4	26.1	4	26.13	5
		1000	26.1	4	25.8	3	26.1	4	26.00	4
Day 16 filter average			**26.17**	**5**	**26.00**	**4**	**26.07**	**4**	**26.08**	**4**
17	24.7	270	25.6	4	25.6	4	25.3	2	25.50	3
		750	25.6	4	25.6	4	25.3	2	25.50	3
		1000	25.6	4	25.2	2	25.4	3	25.40	3
Day 17 filter average			**25.60**	**4**	**25.47**	**3**	**25.33**	**3**	**25.47**	**3**
18	22.9	270	23.9	4	23.7	3	23.7	3	23.77	4
		750	23.7	3	23.7	3	23.8	4	23.73	4
		1000	23.6	3	23.7	3	23.8	4	23.70	3
Day 18 filter average			**23.73**	**3.6**	**23.70**	**3.5**	**23.77**	**3.8**	**23.73**	**3.6**
19	23	270	24.1	5	24	4	24	4	24.03	4
		750	24.1	5	23.9	4	24.1	5	24.03	4
		1000	24.2	5	24	4	24.2	5	24.13	5
Day 19 filter average			**24.13**	**5**	**23.97**	**4**	**24.10**	**5**	**24.07**	**5**
20	23.3	270	23.9	3	23.7	2	23.6	1	23.73	2
		750	23.7	2	23.6	1	23.5	1	23.60	1
		1000	23.7	2	23.6	1	23.5	1	23.60	1
Day 20 filter average			**23.77**	**2**	**23.63**	**1**	**23.53**	**1**	**23.64**	**1**
Total Average	**24.85**	270	**25.66**	**3**	**25.57**	**3**	**25.52**	**3**	**25.58**	**3**
		750	**25.60**	**3**	**25.57**	**3**	**25.54**	**3**	**25.57**	**3**
		1000	**25.61**	**3**	**25.55**	**3**	**25.55**	**3**	**25.57**	**3**
			25.62	**3**	**25.56**	**3**	**25.54**	**3**	**25.57**	**3**

Table G.25 Daily temperature variations with depth in the filter without a Carbon source

Filter without a carbon source										
Sampling interval (Day)	Initial raw water temperature (C)	Filter column depths (mm)	Column 1 temperature at depth	Column 1 change in temperature (C)	Column 2 temperature at depth	Column 2 change in temperature(C)	Column 3 temperature at depth	Column 3 change in temperature (C)	Average temperature at depth	Avarage change in temperature(%)
1	25.8	270	25.8	0	26	1	26.1	1	25.97	1
		750	25.9	0.4	26.1	1	26.4	2	26.13	1
		1000	25.9	0.4	26.2	2	25.9	0.4	26.00	1
Day 1 filter average			**25.87**	**0.3**	**26.10**	**1**	**26.13**	**1**	**26.03**	**1**
2	27	270	27.9	3	27.7	3	27.7	3	27.77	2.8
		750	27.7	3	27.7	3	27.8	3	27.73	2.7
		1000	27.6	2	27.8	3	27.8	3	27.73	2.7
Day 2 filter average			**27.73**	**2.7**	**27.73**	**2.7**	**27.77**	**2.8**	**27.74**	**2.8**
3	26.6	270	27.1	2	27	2	27	2	27.03	1.6
		750	27.1	2	27.1	2	27.1	2	27.10	1.9
		1000	27.1	2	27.1	2	27.1	2	27.10	1.9
Day 3 filter average			**27.10**	**1.9**	**27.07**	**1.8**	**27.07**	**1.8**	**27.08**	**1.8**
4	25.5	270	26.3	3	26.2	3	26.2	3	26.23	3
		750	26.4	4	26.3	3	26.5	4	26.40	4
		1000	26.3	3	26.5	4	26.5	4	26.43	4
Day 4 filter average			**26.33**	**3**	**26.33**	**3**	**26.40**	**4**	**26.36**	**3**
5	24.8	270	25.6	3	25.6	3	25.7	4	25.63	3
		750	25.5	3	25.7	4	25.8	4	25.67	3
		1000	25.7	4	25.9	4	25.8	4	25.80	4
Day 5 filter average			**25.60**	**3**	**25.73**	**4**	**25.77**	**4**	**25.70**	**4**
6	24.7	270	24.8	0.4	24.6	0.4	24.7	0	24.70	0.3
		750	24.8	0.4	24.8	0.4	24.7	0	24.77	0.3
		1000	24.9	1	24.8	0.4	24.7	0	24.80	0.4
Day 6 filter average			**24.83**	**1**	**24.73**	**0.4**	**24.70**	**0**	**24.76**	**0.3**
7	25	270	25.8	3	25.8	3	25.8	3	25.80	3
		750	26	4	25.9	4	26	4	25.97	4
		1000	26	4	26.1	4	26	4	26.03	4
Day 7 filter average			**25.93**	**4**	**25.93**	**4**	**25.93**	**4**	**25.93**	**4**
8	25.3	270	25.6	1	25.5	1	25.7	2	25.60	1
		750	25.7	2	25.7	2	25.6	1	25.67	1
		1000	25.8	2	25.8	2	25.5	1	25.70	2
Day 8 filter average			**25.70**	**2**	**25.67**	**1**	**25.60**	**1**	**25.66**	**1**
9	25.5	270	25.8	1	25.5	0	25.6	0.4	25.63	1
		750	25.8	1	25.8	1	25.7	1	25.77	1
		1000	25.7	1	25.8	1	25.7	1	25.73	1
Day 9 filter average			**25.77**	**1**	**25.70**	**1**	**25.67**	**1**	**25.71**	**1**
10	24.9	270	25.5	2	25.5	2	25.6	3	25.53	3
		750	25.4	2	25.5	2	25.5	2	25.47	2
		1000	25.5	2	25.6	3	25.5	2	25.53	3
Day 10 filter average			**25.47**	**2**	**25.53**	**3**	**25.53**	**3**	**25.51**	**2**
11	25.62	270	25.7	0.3	25.5	0.5	25.7	0.3	25.63	0.4
		750	25.6	0.1	25.7	0.3	25.6	0.1	25.63	0.2
		1000	25.6	0.1	25.7	0.3	25.6	0.1	25.63	0.2
Day 11 filter average			**25.63**	**0.2**	**25.63**	**0.4**	**25.63**	**0.2**	**25.63**	**0.2**
12	24.1	270	25	4	24.8	3	24.9	3	24.90	3
		750	24.9	3	24.8	3	24.9	3	24.87	3
		1000	24.9	3	25	4	25	4	24.97	4
Day 12 filter average			**24.93**	**3**	**24.87**	**3**	**24.93**	**3**	**24.91**	**3**
13	24.1	270	25	4	24.9	3	25	4	24.97	4
		750	25	4	24.9	3	25	4	24.97	4
		1000	25	4	25.1	4	25	4	25.03	4
Day 13 filter average			**25.00**	**4**	**24.97**	**4**	**25.00**	**4**	**24.99**	**4**
14	24.5	270	25.4	4	25.5	4	25.6	4	25.50	4
		750	25.5	4	25.6	4	25.7	5	25.60	4
		1000	25.5	4	25.7	5	25.7	5	25.63	5
Day 14 filter average			**25.47**	**4**	**25.60**	**4**	**25.67**	**5**	**25.58**	**4**
15	24.7	270	25.3	2	25.5	3	25.5	3	25.43	3
		750	25.6	4	25.6	4	25.7	4	25.63	4
		1000	25.7	4	25.8	4	25.7	4	25.73	4
Day 15 filter average			**25.53**	**3**	**25.63**	**4**	**25.63**	**4**	**25.60**	**4**
16	25	270	26.1	4	26	4	26	4	26.03	4
		750	26.1	4	26	4	26.1	4	26.07	4
		1000	26.1	4	26.1	4	26.1	4	26.10	4
Day 16 filter average			**26.10**	**4**	**26.03**	**4**	**26.07**	**4**	**26.07**	**4**
17	24.7	270	25.4	3	25.4	3	25.3	2	25.37	3
		750	25.5	3	25.4	3	25.4	3	25.43	3
		1000	25.4	3	25.5	3	25.5	3	25.47	3
Day 17 filter average			**25.43**	**3**	**25.43**	**3**	**25.40**	**3**	**25.42**	**3**
18	22.9	270	23.6	3	23.6	3	23.9	4	23.70	3.5
		750	23.6	3	23.7	3	23.9	4	23.73	3.6
		1000	23.5	3	23.7	3	24	5	23.73	3.6
Day 18 filter average			**23.57**	**2.9**	**23.67**	**3.3**	**23.93**	**4.5**	**23.72**	**3.6**
19	23	270	24	4	24	4	24.1	5	24.03	4
		750	24.1	5	24	4	24.1	5	24.07	5
		1000	24.1	5	24.1	5	24.2	5	24.13	5
Day 19 filter average			**24.07**	**5**	**24.03**	**4**	**24.13**	**5**	**24.08**	**5**
20	23.3	270	23.7	2	23.6	1	23.5	1	23.60	1
		750	23.6	1	23.6	1	23.4	0.4	23.53	1
		1000	23.6	1	23.5	1	23.5	1	23.53	1
Day 20 filter average			**23.63**	**1**	**23.57**	**1**	**23.47**	**1**	**23.56**	**1**
Total Average	**24.85**	270	**25.47**	**3**	**25.41**	**2**	**25.48**	**3**	**25.45**	**2**
		750	**25.49**	**3**	**25.50**	**3**	**25.55**	**3**	**25.51**	**3**
		1000	**25.50**	**3**	**25.59**	**3**	**25.54**	**3**	**25.54**	**3**
			25.49	**3**	**25.50**	**3**	**25.52**	**3**	**25.50**	**3**

Appendix H. Dissolved Oxygen (DO) concentration at varied filter depths

The tables below represent the daily DO variation with depth in the filter with and without a Carbon source during the filter operation.

H.1. DO concentration at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table H.26 Daily DO concentration with depth in the filter with a Carbon source.

Filter with a carbon source										
Sampling interval (Day)	**Initial DO concentration (mg/L)**	**Filter column depths (mm)**	**Column 1 DO concentration with depth (mg/L)**	**Column 1 change in DO concentration (%)**	**Column 2 DO concentration with depth (mg/L)**	**Column 2 change in DO concentration (%)**	**Column 3 DO concentration with depth (mg/L)**	**Column 3 change in DO concentration (%)**	**Average DO concentration with depth**	**Avarage change in DO (%)**
1	4.31	270	2.86	34	2.91	32	3.02	30	2.93	32
		750	3.25	25	3.44	20	3.43	20	3.37	22
		1000	5.3	23	3.79	12	4.21	2	4.43	12
Day 1 filter average			**3.80**	**27**	**3.38**	**22**	**3.55**	**18**	**3.58**	**22**
2	6.08	270	2.2	64	1.88	69	1.79	71	1.96	68
		750	2.47	59	2.61	57	2.04	66	2.37	61
		1000	3.76	38	3.44	43	2.97	51	3.39	44
Day 2 filter average			**2.81**	**54**	**2.64**	**57**	**2.27**	**63**	**2.57**	**58**
3	6.39	270	2.07	68	2.22	65	1.56	76	1.95	69
		750	1.98	69	1.99	69	2.11	67	2.03	68
		1000	4.4	31	2.22	65	2.06	68	2.89	55
Day 3 filter average			**2.82**	**56**	**2.14**	**66**	**1.91**	**70**	**2.29**	**64**
4	6.88	270	1.99	71	2.03	70	1.82	74	1.95	72
		750	2.1	69	2.8	59	2.43	65	2.44	64
		1000	3.91	43	3.57	48	3.6	48	3.69	46
Day 4 filter average			**2.67**	**61**	**2.80**	**59**	**2.62**	**62**	**2.69**	**61**
5	6.09	270	3.65	40	3.09	49	3.02	50	3.25	47
		750	3.72	39	3.59	41	2.89	53	3.40	44
		1000	3.53	42	2.69	56	4.12	32	3.45	43
Day 5 filter average			**3.63**	**40**	**3.12**	**49**	**3.34**	**45**	**3.37**	**45**
6	5.98	270	2.73	54	2.49	58	3.61	40	2.94	51
		750	2.5	58	2.98	50	3.4	43	2.96	51
		1000	3.21	46	3.31	45	3.95	34	3.49	42
Day 6 filter average			**2.81**	**53**	**2.93**	**51**	**3.65**	**39**	**3.13**	**48**
7	4.22	270	4.26	1	2.24	47	2.06	51	2.85	33
		750	3.1	27	2.3	45	2.26	46	2.55	39
		1000	5.57	32	2.24	47	1.85	56	3.22	45
Day 7 filter average			**4.31**	**20**	**2.26**	**46**	**2.06**	**51**	**2.88**	**39**
8	6.12	270	2.97	51	3.32	46	2.19	64	2.83	54
		750	3.77	38	4.1	33	3.23	47	3.70	40
		1000	3.9	36	4.67	24	4.14	32	4.24	31
Day 8 filter average			**3.55**	**42**	**4.03**	**34**	**3.19**	**48**	**3.59**	**41**
9	4.93	270	3.82	23	3.1	37	3.94	20	3.62	27
		750	3.55	28	4.36	12	3.98	19	3.96	20
		1000	3.9	21	3.83	22	4.18	15	3.97	19
Day 9 filter average			**3.76**	**24**	**3.76**	**24**	**4.03**	**18**	**3.85**	**22**
10	5.5	270	2.89	47	2.48	55	3.1	44	2.82	49
		750	3.12	43	2.9	47	2.2	60	2.74	50
		1000	3.7	33	3.55	35	3.9	29	3.72	32
Day 10 filter average			**3.24**	**41**	**2.98**	**46**	**3.07**	**44**	**3.09**	**44**
11	4.88	270	3.9	20	3.4	30	4.06	17	3.79	22
		750	3.64	25	3.06	37	3.26	33	3.32	32
		1000	2.26	54	2.67	45	2.42	50	2.45	50
Day 11 filter average			**3.27**	**33**	**3.04**	**38**	**3.25**	**33**	**3.19**	**35**
12	6.13	270	2.87	53	3.5	43	2.3	62	2.89	53
		750	3.2	48	4.22	31	3.63	41	3.68	40
		1000	3.77	38	4.89	20	4.92	20	4.53	26
Day 12 filter average			**3.28**	**46**	**4.20**	**31**	**3.62**	**41**	**3.70**	**40**
13	7.15	270	4.5	37	4.1	43	4.3	40	4.30	40
		750	4.49	37	4.4	38	4.61	36	4.50	37
		1000	3.6	50	4	44	4.46	38	4.02	44
Day 13 filter average			**4.20**	**41**	**4.17**	**42**	**4.46**	**38**	**4.27**	**40**
14	6.86	270	3.78	45	2.44	64	3.55	48	3.26	53
		750	3.22	53	3.52	49	4.38	36	3.71	46
		1000	4.87	29	4.63	33	4.9	29	4.80	30
Day 14 filter average			**3.96**	**42**	**3.53**	**49**	**4.28**	**38**	**3.92**	**43**
15	7.06	270	4.61	35	3.82	46	4.23	40	4.22	40
		750	3.94	44	4.36	38	4.34	39	4.21	40
		1000	4.04	43	4.08	42	4.43	37	4.18	41
Day 15 filter average			**4.20**	**41**	**4.09**	**42**	**4.33**	**39**	**4.21**	**40**
16	5.92	270	3.83	35	2.88	51	3.58	40	3.43	42
		750	2.97	50	3.19	46	4.6	22	3.59	39
		1000	4.77	19	5.5	7	5.71	4	5.33	10
Day 16 a filter verage			**3.86**	**35**	**3.86**	**35**	**4.63**	**22**	**4.11**	**30**
17	6.25	270	4.41	29	3.62	42	4.14	34	4.06	35
		750	4.19	33	4.14	34	4.42	29	4.25	32
		1000	3.62	42	3.88	38	4.47	28	3.99	36
Day 17 filter average			**4.07**	**35**	**3.88**	**38**	**4.34**	**31**	**4.10**	**34**
18	7.33	270	3.48	53	2.97	59	3.26	56	3.24	56
		750	3.18	57	3.66	50	2.77	62	3.20	56
		1000	4.38	40	4.8	35	4.14	44	4.44	39
Day 18 filter average			**3.68**	**50**	**3.81**	**48**	**3.39**	**54**	**3.63**	**51**
19	7.04	270	4	43	3.91	44	4.25	40	4.05	42
		750	3.92	44	4.66	34	4.08	42	4.22	40
		1000	3.87	45	3.66	48	5.05	28	4.19	40
Day 19 filter average			**3.93**	**44**	**4.08**	**42**	**4.46**	**37**	**4.16**	**41**
20	6.84	270	3.22	53	2.79	59	3.17	54	3.06	55.3
		750	3.5	49	3.31	52	4.04	41	3.62	47
		1000	4.82	30	5.24	23	5.88	14	5.31	22
Day 20 filter average			**3.85**	**44**	**3.78**	**45**	**4.36**	**36**	**4.00**	**42**
Total Average	**6.10**	270	**3.40**	**43**	**2.96**	**51**	**3.15**	**47**	**3.17**	**47**
		750	**3.29**	**45**	**3.48**	**42**	**3.41**	**43**	**3.39**	**43**
		1000	**4.06**	**37**	**3.83**	**37**	**4.07**	**33**	**3.99**	**35**
			3.58	**41**	**3.42**	**43**	**3.54**	**41**	**3.52**	**42**

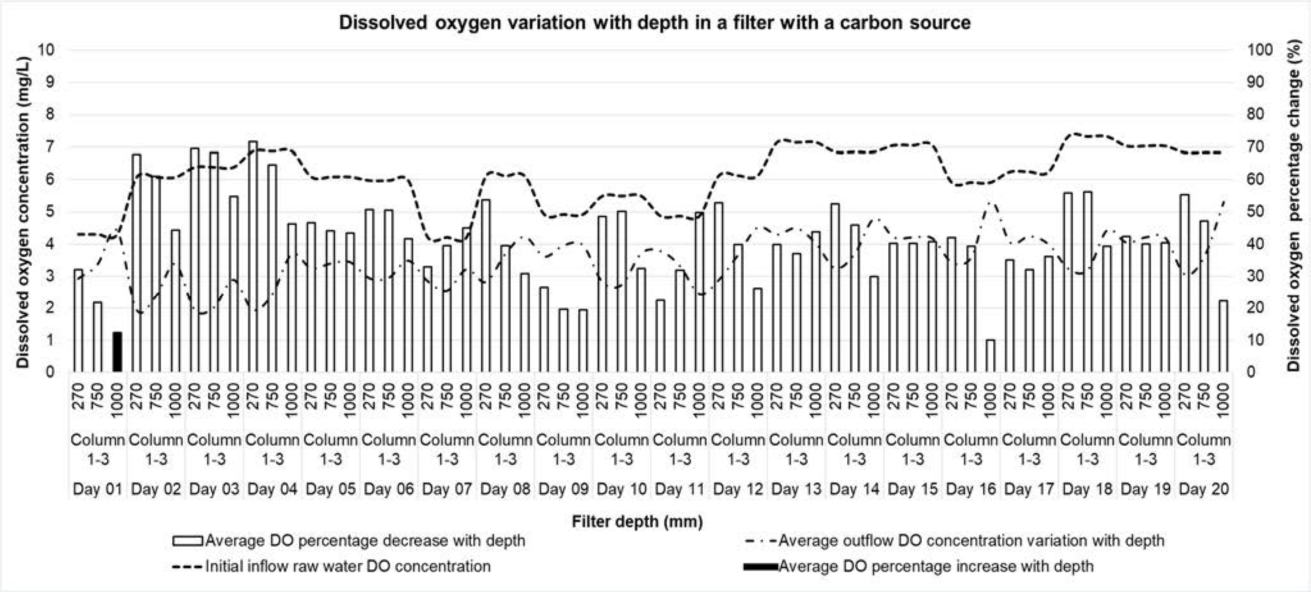


Figure H.27 Overall average dissolved Oxygen variation in a filter with an external source of Carbon at C/N ratio of 1.05.

Table H.28 Daily DO concentration with depth in the filter without a Carbon source.

Filter without a carbon source										
Sampling interval (Day)	**Initial DO concentration (mg/L)**	**Filter column depths (mm)**	**Column 1 DO concentration with depth (mg/L)**	**Column 1 change in DO concentration (%)**	**Column 2 DO concentration with depth (mg/L)**	**Column 2 change in DO concentration (%)**	**Column 3 DO concentration with depth (mg/L)**	**Column 3 change in DO concentration (%)**	**Average DO concentration with depth**	**Avarage change in DO (%)**
1	4.31	270	5.8	35	5.24	22	5.17	20	5.40	25
		750	5.45	26	5.43	26	4.75	10	5.21	21
		1000	6.14	42	5.93	38	6.29	46	6.12	42
Day 1 filter average			**5.80**	**34**	**5.53**	**28**	**5.40**	**25**	**5.58**	**29**
2	6.08	270	5.3	13	4.92	19	5.15	15	5.12	16
		750	4.87	20	5.22	14	4.4	28	4.83	21
		1000	5.69	6	5.8	5	5.53	9	5.67	7
Day 2 filter average			**5.29**	**13**	**5.31**	**13**	**5.03**	**17**	**5.21**	**14**
3	6.39	270	5.29	17	5.98	6	5.45	15	5.57	13
		750	5.55	13	6.16	4	5.7	11	5.80	9
		1000	5.92	7	5.59	13	6.1	5	5.87	8
Day 3 filter average			**5.59**	**13**	**5.91**	**8**	**5.75**	**10**	**5.75**	**10**
4	6.88	270	4.2	39	3.96	42	2.95	57	3.70	46
		750	5.04	27	4.4	36	4.92	28	4.79	30
		1000	6.11	11	5.83	15	5.5	20	5.81	16
Day 4 filter average			**5.12**	**26**	**4.73**	**31**	**4.46**	**35**	**4.77**	**31**
5	6.09	270	4.28	30	5.62	8	5.53	9	5.14	16
		750	4.96	19	5.98	2	4.81	21	5.25	14
		1000	5.86	4	5.16	15	5.82	4	5.61	8
Day 5 filter average			**5.03**	**17**	**5.59**	**8**	**5.39**	**12**	**5.34**	**12**
6	5.98	270	5.73	4	5.4	10	4.29	28	5.14	14
		750	5.39	10	3.98	33	3.84	36	4.40	26
		1000	6.01	1	5.7	5	5.01	16	5.57	7
Day 6 filter average			**5.71**	**5**	**5.03**	**16**	**4.38**	**27**	**5.04**	**16**
7	4.22	270	5.27	25	4.62	9	4.49	6	4.79	14
		750	5.4	28	5.02	19	4.48	6	4.97	18
		1000	5.57	32	4.91	16	5.24	24	5.24	24
Day 7 filter average			**5.41**	**28**	**4.85**	**15**	**4.74**	**12**	**5.00**	**18**
8	6.12	270	4.98	19	3.98	35	4.1	33	4.35	29
		750	5.02	18	5.4	12	5.28	14	5.23	14
		1000	5.88	4	5.78	6	5.79	5	5.82	5
Day 8 filter average			**5.29**	**14**	**5.05**	**17**	**5.06**	**17**	**5.13**	**16**
9	4.93	270	5.81	18	5.28	7	5.19	5	5.43	10
		750	5.68	15	5.56	13	5.03	2	5.42	10
		1000	5.43	10	5.25	6	6.24	27	5.64	14
Day 9 filter average			**5.64**	**14**	**5.36**	**9**	**5.49**	**11**	**5.50**	**11**
10	5.5	270	4.91	11	4.7	15	4.5	18	4.70	14
		750	4.3	22	5.04	8	3.9	29	4.41	20
		1000	5.3	4	5.39	2	5.74	4	5.48	3
Day 10 filter average			**4.84**	**12**	**5.04**	**8**	**4.71**	**17**	**4.86**	**13**
11	4.88	270	5.1	5	5.39	10	5.43	11	5.31	9
		750	5.68	16	5.8	19	5.23	7	5.57	14
		1000	5.57	14	5.77	18	6.11	25	5.82	19
Day 11 filter average			**5.45**	**12**	**5.65**	**16**	**5.59**	**15**	**5.56**	**14**
12	6.13	270	5.8	5	4.02	34	4.21	31	4.68	24
		750	4.43	28	3.98	35	4.1	33	4.17	32
		1000	6.09	1	5.91	4	5.77	6	5.92	3
Day 12 filter average			**5.44**	**11**	**4.64**	**24**	**4.69**	**23**	**4.92**	**20**
13	7.15	270	5.64	21	6.4	10	5.56	22	5.87	18
		750	5.8	19	6.28	12	5.24	27	5.77	19
		1000	6.46	10	5.81	19	6.05	15	6.11	15
Day 13 filter average			**5.97**	**17**	**6.16**	**14**	**5.62**	**21**	**5.92**	**17**
14	6.86	270	5.54	19	3.99	42	4.2	39	4.58	33
		750	4.48	35	4.82	30	3.65	47	4.32	37
		1000	6.6	4	5.9	14	5.67	17	6.06	12
Day 14 filter average			**5.54**	**19**	**4.90**	**29**	**4.51**	**34**	**4.98**	**27**
15	7.06	270	6.55	7	5.17	27	5.9	16	5.87	17
		750	6.44	9	5.76	18	5.51	22	5.90	16
		1000	7.15	1	6.2	12	6.55	7	6.63	7
Day 15 filter average			**6.71**	**6**	**5.71**	**19**	**5.99**	**15**	**6.14**	**13**
16	5.92	270	4.1	31	5.3	10	4.9	17	4.77	19
		750	4.79	19	4.28	28	5.94	0	5.00	15
		1000	5.82	2	6.1	3	6.08	3	6.00	2.5
Day 16 a filter verage			**4.90**	**17**	**5.23**	**14**	**5.64**	**7**	**5.26**	**12**
17	6.25	270	6.58	5	6.36	2	5.19	17	6.04	8
		750	6.63	6	6.02	4	5.02	20	5.89	10
		1000	6.8	9	5.9	6	6.1	2	6.27	6
Day 17 filter average			**6.67**	**7**	**6.09**	**4**	**5.44**	**13**	**6.07**	**8**
18	7.33	270	4.98	32	4.37	40	5.6	24	4.98	32
		750	5.04	31	4.1	44	6.11	17	5.08	31
		1000	5.79	21	6.7	9	6.55	11	6.35	13
Day 18 filter average			**5.27**	**28**	**5.06**	**31**	**6.09**	**17**	**5.47**	**25**
19	7.04	270	5.92	16	6.33	10	5.75	18	6.00	15
		750	6.83	3	6.47	8	5.82	17	6.37	9
		1000	6.83	3	6.45	8	6.55	7	6.61	6
Day 19 filter average			**6.53**	**7**	**6.42**	**9**	**6.04**	**14**	**6.33**	**10**
20	6.84	270	5.44	20	4.98	27	3.74	45	4.72	31.0
		750	5.8	15	5.39	21	5.04	26	5.41	21
		1000	6.13	10	5.97	13	5.77	16	5.96	13
Day 20 filter average			**5.79**	**15**	**5.45**	**20**	**4.85**	**29**	**5.36**	**22**
Total Average	**6.10**	270	**5.36**	**19**	**5.10**	**19**	**4.87**	**22**	**5.11**	**20**
		750	**5.38**	**19**	**5.25**	**19**	**4.94**	**20**	**5.19**	**19**
		1000	**6.06**	**10**	**5.80**	**11**	**5.92**	**14**	**5.93**	**12**
			5.60	**16**	**5.39**	**17**	**5.24**	**19**	**5.41**	**17**

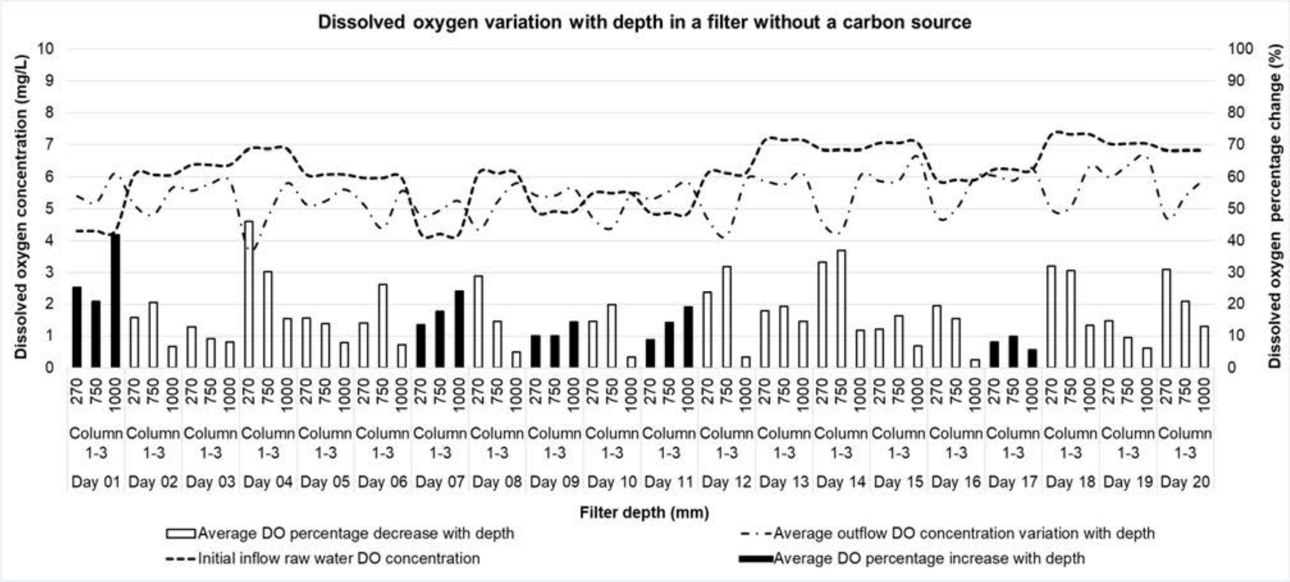


Figure H.29 Overall average dissolved Oxygen variation in a filter without an external source of Carbon at C/N ratio of 1.05.

H.2. DO concentration at C/N ratio of 1.08 and nitrate concentration of 25 mg/L-

Table H.30 Daily DO concentration with depth in the filter with a Carbon source.

Filter with a carbon source										
Sampling interval (Days)	**Initial DO concentration (mg/L)**	**Filter column depths (mm)**	**Column 1 DO concentration with depth (mg/L)**	**Column 1 change in DO concentration (%)**	**Column 2 DO concentration with depth (mg/L)**	**Column 2 change in DO concentration (%)**	**Column 3 DO concentration with depth (mg/L)**	**Column 3 change in DO concentration (%)**	**Average DO concentration with depth**	**Avarage change in DO (%)**
1	0.18	270	0.18	0	0.18	0	0.18	0	0.18	0
		750	0.18	0	0.18	0	0.18	0	0.18	0
		1000	0.18	0	0.18	0	0.18	0	0.18	0
Day 1 filter average			**0.18**	**0**	**0.18**	**0**	**0.18**	**0**	**0.18**	**0**
2	0.16	270	0.16	0	0.16	0	0.16	0	0.16	0
		750	0.16	0	0.16	0	0.16	0	0.16	0
		1000	0.16	0	0.16	0	0.16	0	0.16	0
Day 2 filter average			**0.16**	**0**	**0.16**	**0**	**0.16**	**0**	**0.16**	**0**
3	0.18	270	0.18	0	0.18	0	0.18	0	0.18	0
		750	0.18	0	0.18	0	0.18	0	0.18	0
		1000	0.18	0	0.18	0	0.18	0	0.18	0
Day 3 filter average			**0.18**	**0**	**0.18**	**0**	**0.18**	**0**	**0.18**	**0**
4	9.75	270	1.67	83	1.53	84	1.61	83	1.60	84
		750	1.62	83	1.64	83	1.97	80	1.74	82
		1000	3.56	63	1.57	84	2.21	77	2.45	75
Day 4 filter average			**2.28**	**77**	**1.58**	**84**	**1.93**	**80**	**1.93**	**80**
5	8.02	270	2.06	74	2.33	71	5.21	35	3.20	60
		750	1.46	82	3.09	61	2.61	67	2.39	70
		1000	2.87	64	2.29	71	1.6	80	2.25	72
Day 5 filter average			**2.13**	**73**	**2.57**	**68**	**3.14**	**61**	**2.61**	**67**
6	8.83	270	1.32	85	1.32	85	1.83	79	1.49	83
		750	1.46	83	1.47	83	1.33	85	1.42	84
		1000	1.38	84	1.41	84	1.24	86	1.34	85
Day 6 filter average			**1.39**	**84**	**1.40**	**84**	**1.47**	**83**	**1.42**	**84**
7	8.96	270	1.52	83	1.37	85	1.76	80	1.55	83
		750	2.09	77	1.53	83	1.49	83	1.70	81
		1000	2.03	77	1.46	84	1.79	80	1.76	80
Day 7 filter average			**1.88**	**79**	**1.45**	**84**	**1.68**	**81**	**1.67**	**81**
8	5.9	270	1.23	79	1.02	83	1.54	74	1.26	79
		750	1.39	76	1.1	81	1.4	76	1.30	78
		1000	1.15	81	1.78	70	2.33	61	1.75	70
Day 8 filter average			**1.26**	**79**	**1.30**	**78**	**1.76**	**70**	**1.44**	**76**
9	9.84	270	1.83	81	1.84	81	1.87	81	1.85	81
		750	1.58	84	1.91	81	1.9	81	1.80	82
		1000	1.43	85	1.48	85	1.66	83	1.52	85
Day 9 filter average			**1.61**	**84**	**1.74**	**82**	**1.81**	**82**	**1.72**	**82**
10	5.58	270	1.3	77	1.64	71	1.86	67	1.60	71
		750	2.01	64	4.13	26	1.28	77	2.47	56
		1000	2	64	1.27	77	2.37	58	1.88	66
Day 10 filter average			**1.77**	**68**	**2.35**	**58**	**1.84**	**67**	**1.98**	**64**
11	2.74	270	2.17	21	2.05	25	2.03	26	2.08	24
		750	2.62	4	2.52	8	1.96	28	2.37	14
		1000	2.29	16	1.85	32	2.34	15	2.16	21
Day 11 filter average			**2.36**	**14**	**2.14**	**22**	**2.11**	**23**	**2.20**	**20**
12	7.53	270	3.55	53	3.49	54	3.29	56	3.44	54
		750	3.35	56	3.1	59	3.36	55	3.27	57
		1000	4.38	42	4.21	44	3.88	48	4.16	45
Day 12 filter average			**3.76**	**50**	**3.60**	**52**	**3.51**	**53**	**3.62**	**52**
13	8.3	270	3.2	61	3.15	62	3.37	59	3.24	61
		750	2.97	64	2.54	69	3.37	59	2.96	64
		1000	3.68	56	3.44	59	3.56	57	3.56	57
Day 13 filter average			**3.28**	**60**	**3.04**	**63**	**3.43**	**59**	**3.25**	**61**
14	6.7	270	1.78	73	2.01	70	1.81	73	1.87	72
		750	2.81	58	1.96	71	1.87	72	2.21	67
		1000	2.67	60	2.54	62	2.56	62	2.59	61
Day 14 filter average			**2.42**	**64**	**2.17**	**68**	**2.08**	**69**	**2.22**	**67**
15	6	270	2.71	55	2.04	66	1.98	67	2.24	63
		750	2.12	65	2.17	64	2.5	58	2.26	62
		1000	2.58	57	1.86	69	2.01	67	2.15	64
Day 15 filter average			**2.47**	**59**	**2.02**	**66**	**2.16**	**64**	**2.22**	**63**
16	6.88	270	1.81	74	1.51	78	2.02	71	1.78	74
		750	2.1	69	2.14	69	1.34	81	1.86	73
		1000	1.87	73	1.39	80	2.35	66	1.87	73
Day 16 a filter verage			**1.93**	**72**	**1.68**	**76**	**1.90**	**72**	**1.84**	**73**
17	5.81	270	3.06	47	3.37	42	3.59	38	3.34	43
		750	2.96	49	3.09	47	3.31	43	3.12	46
		1000	2.99	49	3.65	37	3.85	34	3.50	40
Day 17 filter average			**3.00**	**48**	**3.37**	**42**	**3.58**	**38**	**3.32**	**43**
18	6.67	270	2.86	57	2.24	66	2.61	61	2.57	61
		750	3.1	54	2.44	63	2	70	2.51	62
		1000	1.73	74	1.77	73	2.69	60	2.06	69
Day 18 filter average			**2.56**	**62**	**2.15**	**68**	**2.43**	**64**	**2.38**	**64**
19	5.69	270	2.11	63	3.9	31	2.34	59	2.78	51
		750	1.97	65	3.22	43	2.41	58	2.53	55
		1000	2.04	64	2.98	48	3.3	42	2.77	51
Day 19 filter average			**2.04**	**64**	**3.37**	**41**	**2.68**	**53**	**2.70**	**53**
20	5.14	270	2.4	53	2.47	52	2.78	46	2.55	50.4
		750	2.28	56	2.47	52	2.51	51	2.42	53
		1000	3.13	39	3.27	36	2.82	45	3.07	40
Day 20 filter average			**2.60**	**49**	**2.74**	**47**	**2.70**	**47**	**2.68**	**48**
Total Average	**5.94**	270	**1.86**	**56**	**1.89**	**55**	**2.10**	**53**	**1.95**	**55**
		750	**1.92**	**54**	**2.05**	**52**	**1.86**	**56**	**1.94**	**54**
		1000	**2.12**	**52**	**1.94**	**55**	**2.15**	**51**	**2.07**	**53**
			1.96	**54**	**1.96**	**54**	**2.04**	**53**	**1.99**	**54**

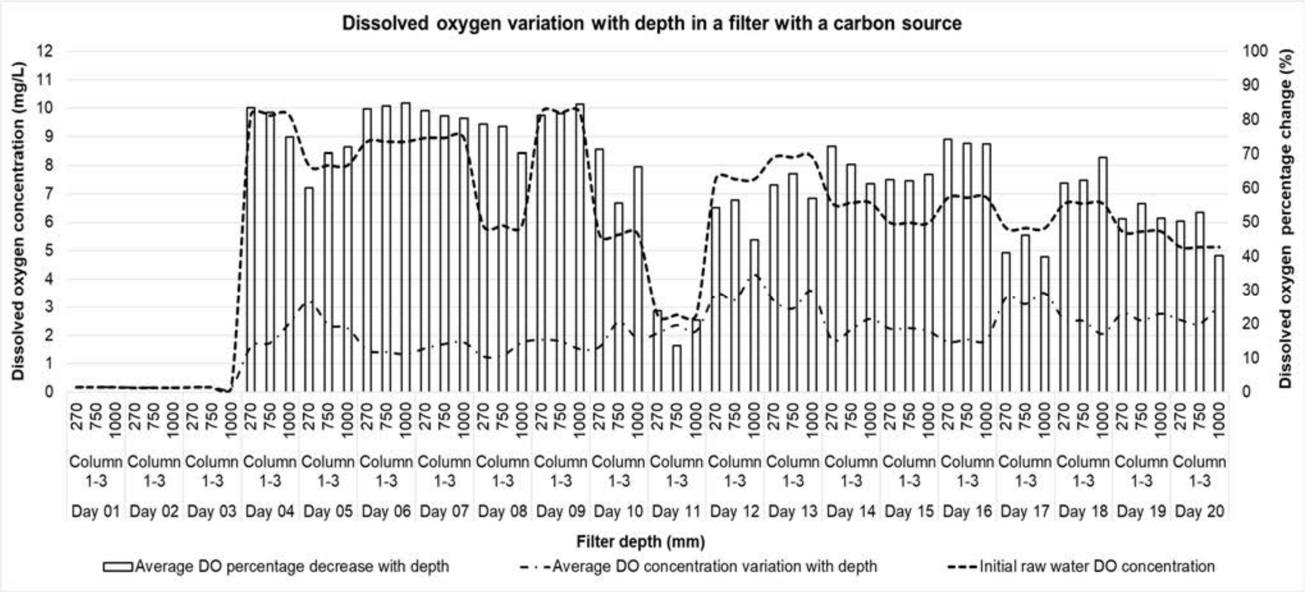


Figure H.31 Overall average dissolved Oxygen variation in a filter with an external Carbon source at C/N ratio of 1.08.

Table H.32 Daily DO concentration with depth in the filter with a Carbon source.

Filter without a carbon source										
Sampling interval (Days)	**Initial DO concentration (mg/L)**	**Filter column depths (mm)**	**Column 1 DO concentration with depth (mg/L)**	**Column 1 change in DO concentration (%)**	**Column 2 DO concentration with depth (mg/L)**	**Column 2 change in DO concentration (%)**	**Column 3 DO concentration with depth (mg/L)**	**Column 3 change in DO concentration (%)**	**Average DO concentration with depth**	**Avarage change in DO (%)**
1	0.18	270	0.18	0	0.18	0	0.18	0	0.18	0
		750	0.18	0	0.18	0	0.18	0	0.18	0
		1000	0.18	0	0.18	0	0.18	0	0.18	0
Day 1 filter average			**0.18**	**0**	**0.18**	**0**	**0.18**	**0**	**0.18**	**0**
2	0.16	270	0.16	0	0.16	0	0.16	0	0.16	0
		750	0.16	0	0.16	0	0.16	0	0.16	0
		1000	0.16	0	0.16	0	0.16	0	0.16	0
Day 2 filter average			**0.16**	**0**	**0.16**	**0**	**0.16**	**0**	**0.16**	**0**
3	0.18	270	0.18	0	0.18	0	0.18	0	0.18	0
		750	0.18	0	0.18	0	0.18	0	0.18	0
		1000	0.18	0	0.18	0	0.18	0	0.18	0
Day 3 filter average			**0.18**	**0**	**0.18**	**0**	**0.18**	**0**	**0.18**	**0**
4	9.75	270	6.65	32	7.43	24	6.85	30	6.98	28
		750	7.75	21	7.71	21	7.2	26	7.55	23
		1000	7.85	19	7.62	22	7.53	23	7.67	21
Day 4 filter average			**7.42**	**24**	**7.59**	**22**	**7.19**	**26**	**7.40**	**24**
5	8.02	270	7.65	5	6.43	20	6.85	15	6.98	13
		750	7.75	3	7.71	4	7.2	10	7.55	6
		1000	7.85	2	7.62	5	7.53	6	7.67	4
Day 5 filter average			**7.75**	**3**	**7.25**	**10**	**7.19**	**10**	**7.40**	**8**
6	8.83	270	5.5	38	4.73	46	4.16	53	4.80	46
		750	5.56	37	5.04	43	6.46	27	5.69	36
		1000	4.87	45	5.14	42	5.74	35	5.25	41
Day 6 filter average			**5.31**	**40**	**4.97**	**44**	**5.45**	**38**	**5.24**	**41**
7	8.96	270	7.31	18	7.24	19	7.88	12	7.48	17
		750	7.5	16	8	11	7.24	19	7.58	15
		1000	8.03	10	7.49	16	7.43	17	7.65	15
Day 7 filter average			**7.61**	**15**	**7.58**	**15**	**7.52**	**16**	**7.57**	**16**
8	5.9	270	5.88	0.3	5.15	13	4.42	25	5.15	13
		750	5.76	2	5.15	13	3.38	43	4.76	19
		1000	5.57	6	5.37	9	5.58	5	5.51	7
Day 8 filter average			**5.74**	**3**	**5.22**	**11**	**4.46**	**24**	**5.14**	**13**
9	9.84	270	7.89	20	6.4	35	4.99	49	6.43	35
		750	7.21	27	6.56	33	5.05	49	6.27	36
		1000	6.62	33	5.68	42	5.85	41	6.05	39
Day 9 filter average			**7.24**	**26**	**6.21**	**37**	**5.30**	**46**	**6.25**	**36**
10	5.58	270	3.7	34	3.17	43	2.43	56	3.10	44
		750	3.39	39	3.34	40	2.97	47	3.23	42
		1000	2.82	49	2.78	50	4.55	18	3.38	39
Day 10 filter average			**3.30**	**41**	**3.10**	**45**	**3.32**	**41**	**3.24**	**42**
11	2.74	270	4.71	72	4.26	55	2.57	6	3.85	45
		750	3.51	28	3.16	15	3	9	3.22	18
		1000	2.75	0.4	3.19	16	4.72	72	3.55	30
Day 11 filter average			**3.66**	**33**	**3.54**	**29**	**3.43**	**29**	**3.54**	**31**
12	7.53	270	6.05	20	5.5	27	4.88	35	5.48	27
		750	5.82	23	5.39	28	4.83	36	5.35	29
		1000	5.64	25	4.97	34	4.65	38	5.09	32
Day 12 filter average			**5.84**	**22**	**5.29**	**30**	**4.79**	**36**	**5.30**	**30**
13	8.3	270	6.6	20	5.85	30	5.74	31	6.06	27
		750	6.57	21	6.07	27	6.09	27	6.24	25
		1000	6.82	18	6.09	27	7.55	9	6.82	18
Day 13 filter average			**6.66**	**20**	**6.00**	**28**	**6.46**	**22**	**6.38**	**23**
14	6.7	270	5.72	15	5.47	18	4.82	28	5.34	20
		750	5.06	24	4.36	35	4.5	33	4.64	31
		1000	5.99	11	5.8	13	5.62	16	5.80	13
Day 14 filter average			**5.59**	**17**	**5.21**	**22**	**4.98**	**26**	**5.26**	**21**
15	6	270	5.72	5	5.73	4	5.2	13	5.55	8
		750	6.2	3	5.26	12	5.48	9	5.65	8
		1000	6.35	6	6.37	6	6.48	8	6.40	7
Day 15 filter average			**6.09**	**5**	**5.79**	**8**	**5.72**	**10**	**5.87**	**7**
16	6.88	270	5.99	13	5.83	15	5.61	18	5.81	16
		750	6.23	9	5.67	18	4.74	31	5.55	19
		1000	6.3	8	5.89	14	5.73	17	5.97	13
Day 16 a filter verage			**6.17**	**10**	**5.80**	**16**	**5.36**	**22**	**5.78**	**16**
17	5.81	270	6.09	5	5.65	3	5.58	4	5.77	4
		750	6.07	4	5.76	1	5.47	6	5.77	4
		1000	5.54	5	5.71	2	6.12	5	5.79	4
Day 17 filter average			**5.90**	**5**	**5.71**	**2**	**5.72**	**5**	**5.78**	**4**
18	6.67	270	5.34	20	5.31	20	5.07	24	5.24	21
		750	5.94	11	4.81	28	4.72	29	5.16	23
		1000	6.14	8	5.4	19	5.34	20	5.63	16
Day 18 filter average			**5.81**	**13**	**5.17**	**22**	**5.04**	**24**	**5.34**	**20**
19	5.69	270	5.9	4	5.6	2	5.2	9	5.57	5
		750	6.02	6	5.59	2	5.07	11	5.56	6
		1000	6.31	11	5.87	3	5.74	1	5.97	5
Day 19 filter average			**6.08**	**7**	**5.69**	**2**	**5.34**	**7**	**5.70**	**5**
20	5.14	270	5.92	15	5.99	17	6.03	17	5.98	16
		750	6.26	22	6.44	25	5.49	7	6.06	18
		1000	6.45	25	6.08	18	6.49	26	6.34	23
Day 20 filter average			**6.21**	**21**	**6.17**	**20**	**6.00**	**17**	**6.13**	**19**
Total Average	**5.94**	270	**5.16**	**17**	**4.81**	**20**	**4.44**	**21**	**4.80**	**19**
		750	**5.16**	**15**	**4.83**	**18**	**4.47**	**21**	**4.82**	**18**
		1000	**5.12**	**14**	**4.88**	**17**	**5.16**	**18**	**5.05**	**16**
			5.14	**15**	**4.84**	**18**	**4.69**	**20**	**4.89**	**18**

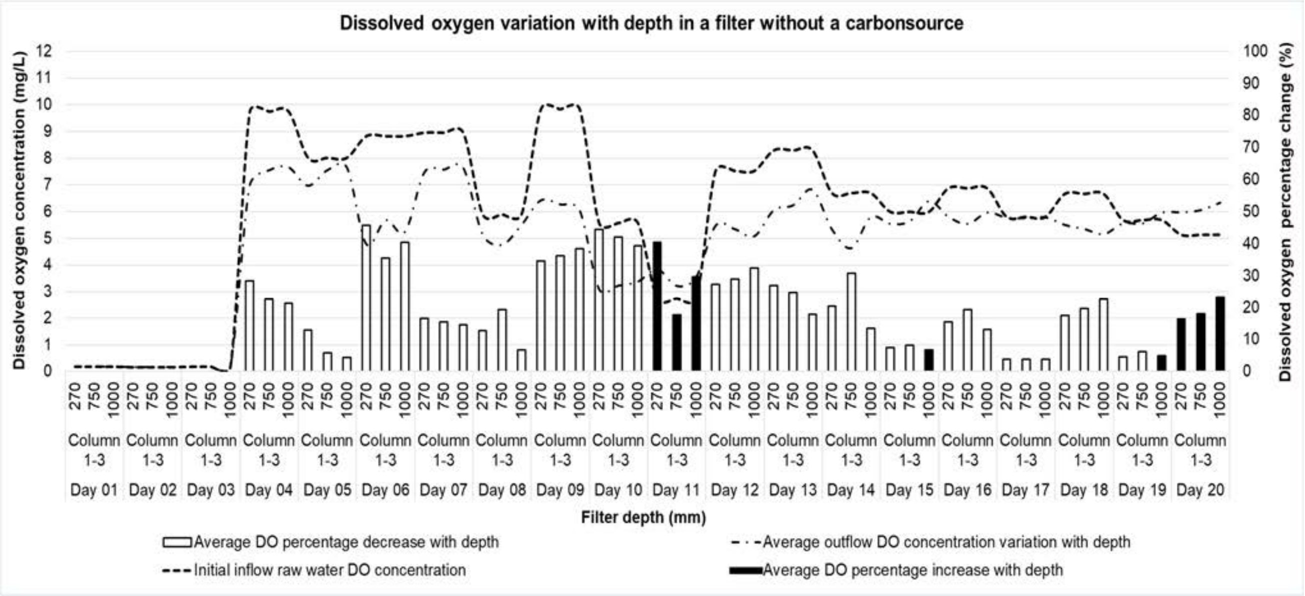


Figure H.33 Overall average dissolved Oxygen variation in a filter without an external source of Carbon at C/N ratio of 1.08.

H.3. DO concentration at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table H.34 Daily DO concentration with depth in the filter with a Carbon source

Filter with a carbon source										
Sampling interval (Day)	**Initial DO concentration (mg/L)**	**Filter column depths (mm)**	**Column 1 DO concentration with depth (mg/L)**	**Column 1 change in DO concentration (%)**	**Column 2 DO concentration with depth (mg/L)**	**Column 2 change in DO concentration (%)**	**Column 3 DO concentration with depth (mg/L)**	**Column 3 change in DO concentration (%)**	**Average DO concentration with depth**	**Avarage change in DO (%)**
1	8.3	270	3.99	52	2.58	69	2.88	65	3.15	62
		750	2.41	71	3.99	52	3.04	63	3.15	62
		1000	4.94	40	3	64	3.56	57	3.83	54
Day 1 filter average			**3.78**	**54**	**3.19**	**62**	**3.16**	**62**	**3.38**	**59**
2	6.21	270	1.77	71	2.08	67	2.25	64	2.03	67
		750	1.41	77	2.42	61	2.47	60	2.10	66
		1000	2.21	64	3.11	50	2.2	65	2.51	60
Day 2 filter average			**1.80**	**71**	**2.54**	**59**	**2.31**	**63**	**2.21**	**64**
3	8.45	270	2.02	76	2.95	65	2.46	71	2.48	71
		750	2.8	67	3.89	54	3.08	64	3.26	61
		1000	2.31	73	2.79	67	3.44	59	2.85	66
Day 3 filter average			**2.38**	**72**	**3.21**	**62**	**2.99**	**65**	**2.86**	**66**
4	7.26	270	2.63	64	2.65	63	2.88	60	2.72	63
		750	3.83	47	2.75	62	2.72	63	3.10	57
		1000	2.36	67	3.22	56	3.11	57	2.90	60
Day 4 filter average			**2.94**	**60**	**2.87**	**60**	**2.90**	**60**	**2.91**	**60**
5	8.65	270	2.21	74	2.45	72	2.52	71	2.39	72
		750	2.62	70	3.59	58	2.27	74	2.83	67
		1000	1.97	77	4.27	51	2.79	68	3.01	65
Day 5 filter average			**2.27**	**74**	**3.44**	**60**	**2.53**	**71**	**2.74**	**68**
6	6.74	270	2.04	70	2.92	57	3.31	51	2.76	59
		750	3.52	48	4.27	37	3.54	47	3.78	44
		1000	2.52	63	2.83	58	3.34	50	2.90	57
Day 6 filter average			**2.69**	**60**	**3.34**	**50**	**3.40**	**50**	**3.14**	**53**
7	6.16	270	2.99	51	3.68	40	2.91	53	3.19	48
		750	3.9	37	3.33	46	3.4	45	3.54	42
		1000	3.29	47	3.02	51	4.34	30	3.55	42
Day 7 filter average			**3.39**	**45**	**3.34**	**46**	**3.55**	**42**	**3.43**	**44**
8	6.02	270	3.76	38	2.59	57	3.11	48	3.15	48
		750	3.49	42	2.58	57	2.28	62	2.78	54
		1000	4.16	31	2.65	56	3.29	45	3.37	44
Day 8 filter average			**3.80**	**37**	**2.61**	**57**	**2.89**	**52**	**3.10**	**48**
9	5.61	270	1.41	75	1.96	65	1.48	74	1.62	71
		750	2.86	49	2.74	51	2.9	48	2.83	49
		1000	2.02	64	3.26	42	3.03	46	2.77	51
Day 9 filter average			**2.10**	**63**	**2.65**	**53**	**2.47**	**56**	**2.41**	**57**
10	6.2	270	3.4	45	2.38	62	3.09	50	2.96	52
		750	2.98	52	2.51	60	2.6	58	2.70	57
		1000	3.72	40	3.45	44	3.19	49	3.45	44
Day 10 filter average			**3.37**	**46**	**2.78**	**55**	**2.96**	**52**	**3.04**	**51**
11	6.46	270	1.82	72	2.09	68	2.15	67	2.02	69
		750	2.04	68	2.21	66	2.32	64	2.19	66
		1000	2.46	62	3.21	50	2.43	62	2.70	58
Day 11 filter average			**2.11**	**67**	**2.50**	**61**	**2.30**	**64**	**2.30**	**64**
12	6.97	270	1.43	79	2.42	65	2.66	62	2.17	69
		750	3.19	54	3.31	53	3.23	54	3.24	53
		1000	3.34	52	3.67	47	3.2	54	3.40	51
Day 12 filter average			**2.65**	**62**	**3.13**	**55**	**3.03**	**57**	**2.94**	**58**
13	5.63	270	1.97	65	2.73	52	2.07	63	2.26	60
		750	2.49	56	2.71	52	3.14	44	2.78	51
		1000	3.13	44	3.04	46	3.37	40	3.18	44
Day 13 filter average			**2.53**	**55**	**2.83**	**50**	**2.86**	**49**	**2.74**	**51**
14	4.82	270	2.97	38	2.58	46	2.65	45	2.73	43
		750	4.05	16	2.61	46	2.24	54	2.97	38
		1000	4.29	11	3.33	31	2.86	41	3.49	28
Day 14 filter average			**3.77**	**22**	**2.84**	**41**	**2.58**	**46**	**3.06**	**36**
15	6.35	270	2.91	54	2.52	60	2.28	64	2.57	60
		750	3.71	42	2.92	54	3.65	43	3.43	46
		1000	4.09	36	3.2	50	3.17	50	3.49	45
Day 15 filter average			**3.57**	**44**	**2.88**	**55**	**3.03**	**52**	**3.16**	**50**
16	5.83	270	3.09	47	3.82	34	2.5	57	3.14	46
		750	3.88	33	2.03	65	2.61	55	2.84	51
		1000	4.33	26	2.2	62	3.41	42	3.31	43
Day 16 a filter verage			**3.77**	**35**	**2.68**	**54**	**2.84**	**51**	**3.10**	**47**
17	6.1	270	3.99	35	3.18	48	3.48	43	3.55	42
		750	3.38	45	2.53	59	3.26	47	3.06	50
		1000	3.18	48	4.39	28	4.31	29	3.96	35
Day 17 filter average			**3.52**	**42**	**3.37**	**45**	**3.68**	**40**	**3.52**	**42**
18	4.38	270	2.92	33	2.69	39	2.26	48	2.62	40
		750	3.11	29	2.72	38	1.91	56	2.58	41
		1000	4.2	4	3.77	14	3.15	28	3.71	15
Day 18 filter average			**3.41**	**22**	**3.06**	**30**	**2.44**	**44**	**2.97**	**32**
19	5.67	270	3.77	34	3.31	42	3.86	32	3.65	36
		750	3.87	32	3.79	33	3.84	32	3.83	32
		1000	4.3	24	4.25	25	4.51	20	4.35	23
Day 19 filter average			**3.98**	**30**	**3.78**	**33**	**4.07**	**28**	**3.94**	**30**
20	4.81	270	3.32	31	3.4	29	3.4	29	3.37	30
		750	2.94	39	2.91	40	3.54	26	3.13	35
		1000	3.68	23	3.75	22	3.86	20	3.76	22
Day 20 filter average			**3.31**	**31**	**3.35**	**30**	**3.60**	**25**	**3.42**	**29**
Total Average	**6.33**	270	**2.72**	**55**	**2.75**	**55**	**2.71**	**56**	**2.73**	**55**
		750	**3.12**	**49**	**2.99**	**52**	**2.90**	**53**	**3.01**	**51**
		1000	**3.33**	**45**	**3.32**	**46**	**3.33**	**46**	**3.32**	**45**
			3.06	**50**	**3.02**	**51**	**2.98**	**51**	**3.02**	**51**

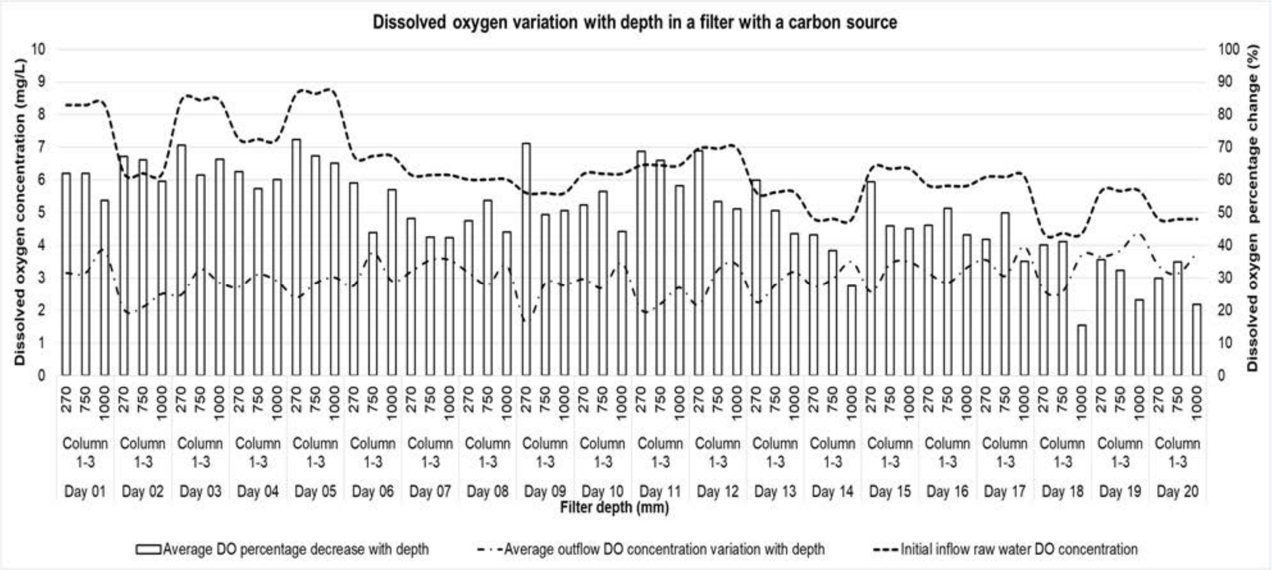


Figure H.35 Overall average dissolved Oxygen variation in a filter with a source of Carbon at C/N ratio of 1.1.

Table H.36 Daily DO concentration with depth in the filter without a Carbon source.

Filter without a carbon source										
Sampling interval (Day)	**Initial DO concentration (mg/L)**	**Filter column depths (mm)**	**Column 1 DO concentration with depth (mg/L)**	**Column 1 change in DO concentration (%)**	**Column 2 DO concentration with depth (mg/L)**	**Column 2 change in DO concentration (%)**	**Column 3 DO concentration with depth (mg/L)**	**Column 3 change in DO concentration (%)**	**Average DO concentration with depth**	**Avarage change in DO (%)**
1	8.3	270	6.48	22	5.96	28	5.35	36	5.93	29
		750	7.77	6	5.61	32	5.45	34	6.28	24
		1000	6.19	25	5.77	30	6.03	27	6.00	28
Day 1 filter average			**6.81**	**18**	**5.78**	**30**	**5.61**	**32**	**6.07**	**27**
2	6.21	270	6.4	3	5.08	18	4.63	25	5.37	16
		750	5.75	7	5.24	16	4.74	24	5.24	16
		1000	7.2	16	5.21	16	5.56	10	5.99	14
Day 2 filter average			**6.45**	**9**	**5.18**	**17**	**4.98**	**20**	**5.53**	**15**
3	8.45	270	6.3	25	6.27	26	5.33	37	5.97	29
		750	6.42	24	5.88	30	5.56	34	5.95	30
		1000	6.06	28	5.56	34	5.75	32	5.79	31
Day 3 filter average			**6.26**	**26**	**5.90**	**30**	**5.55**	**34**	**5.90**	**30**
4	7.26	270	5.72	21	5.4	26	5.01	31	5.38	26
		750	6.11	16	5.49	24	5.2	28	5.60	23
		1000	5.55	24	4.89	33	5.76	21	5.40	26
Day 4 filter average			**5.79**	**20**	**5.26**	**28**	**5.32**	**27**	**5.46**	**25**
5	8.65	270	6.7	23	5.91	32	5.45	37	6.02	30
		750	6.5	25	5.9	32	5.71	34	6.04	30
		1000	7.22	17	5.94	31	6.39	26	6.52	25
Day 5 filter average			**6.81**	**21**	**5.92**	**32**	**5.85**	**32**	**6.19**	**28**
6	6.74	270	5.9	12	5.02	26	5.04	25	5.32	21
		750	5.26	22	4.76	29	4.26	37	4.76	29
		1000	6.05	10	5.59	17	6.24	7	5.96	12
Day 6 filter average			**5.74**	**15**	**5.12**	**24**	**5.18**	**23**	**5.35**	**21**
7	6.16	270	5.24	15	4.89	21	4.72	23	4.95	20
		750	5.72	7	5.01	19	4.73	23	5.15	16
		1000	5.48	11	4.67	24	5.69	8	5.28	14
Day 7 filter average			**5.48**	**11**	**4.86**	**21**	**5.05**	**18**	**5.13**	**17**
8	6.02	270	5.96	1	5.43	10	4.83	20	5.41	10
		750	5.79	4	5.36	11	4.93	18	5.36	11
		1000	5.4	10	5.18	14	6.02	0	5.53	8
Day 8 filter average			**5.72**	**5**	**5.32**	**12**	**5.26**	**13**	**5.43**	**10**
9	5.61	270	5.42	3	4.96	12	4.16	26	4.85	14
		750	4.99	11	4.61	18	3.8	32	4.47	20
		1000	4.4	22	5.49	2	5.24	7	5.04	10
Day 9 filter average			**4.94**	**12**	**5.02**	**11**	**4.40**	**22**	**4.79**	**15**
10	6.2	270	5.89	5	5.13	17	4.23	32	5.08	18
		750	5.59	10	4.66	25	4.33	30	4.86	22
		1000	5.7	8	5.28	15	5.1	18	5.36	14
Day 10 filter average			**5.73**	**8**	**5.02**	**19**	**4.55**	**27**	**5.10**	**18**
11	6.46	270	5.2	20	4.98	23	5.01	22	5.06	22
		750	5.45	16	4.4	32	4.1	37	4.65	28
		1000	6.01	7	5.88	9	5.9	9	5.93	8
Day 11 filter average			**5.55**	**14**	**5.09**	**21**	**5.00**	**23**	**5.21**	**19**
12	6.97	270	6.03	13	5.48	21	4.76	32	5.42	22
		750	6.86	2	5.71	18	5.46	22	6.01	14
		1000	6.65	5	5.71	18	6.15	12	6.17	11
Day 12 filter average			**6.51**	**7**	**5.63**	**19**	**5.46**	**22**	**5.87**	**16**
13	5.63	270	5.53	2	5.58	1	5.01	11	5.37	5
		750	5.41	4	5.39	4	4.48	20	5.09	10
		1000	5.29	6	5.16	8	5.45	3	5.30	6
Day 13 filter average			**5.41**	**4**	**5.38**	**4**	**4.98**	**12**	**5.26**	**7**
14	4.82	270	5.83	21	6.93	44	6.15	28	6.30	31
		750	5.85	21	5.88	22	5.17	7	5.63	17
		1000	6.33	31	5.33	11	6.67	38	6.11	27
Day 14 filter average			**6.00**	**25**	**6.05**	**25**	**6.00**	**24**	**6.02**	**25**
15	6.35	270	6.61	4	5.93	7	5.59	12	6.04	8
		750	6.74	6	6.04	5	5.38	15	6.05	9
		1000	6.35	0	5.82	8	6.93	9	6.37	6
Day 15 filter average			**6.57**	**3**	**5.93**	**7**	**5.97**	**12**	**6.15**	**7**
16	5.83	270	6.74	16	5.75	1	5.37	8	5.95	8
		750	7.91	36	6.1	5	5.45	7	6.49	16
		1000	6.56	13	6.29	8	6.52	12	6.46	11
Day 16 a filter verage			**7.07**	**21**	**6.05**	**5**	**5.78**	**9**	**6.30**	**12**
17	6.1	270	6.17	1	5.49	10	5.34	12	5.67	8
		750	6.08	0.3	5.76	6	6.83	12	6.22	6
		1000	5.81	5	5.95	2	6.02	1	5.93	3
Day 17 filter average			**6.02**	**2**	**5.73**	**6**	**6.06**	**9**	**5.94**	**6**
18	4.38	270	6.23	42	5.65	29	4.99	14	5.62	28
		750	5.58	27	5.48	25	5.75	31	5.60	28
		1000	5.43	24	4.93	13	6.45	47	5.60	28
Day 18 filter average			**5.75**	**31**	**5.35**	**22**	**5.73**	**31**	**5.61**	**28**
19	5.67	270	6.29	11	5.67	0	5.52	3	5.83	5
		750	6.04	7	5.67	0	5.17	9	5.63	5
		1000	5.59	1	5.53	2	6.04	7	5.72	3
Day 19 filter average			**5.97**	**6**	**5.62**	**1**	**5.58**	**6**	**5.72**	**4**
20	4.81	270	6.28	31	5.26	9	5.08	6	5.54	15.2
		750	6	25	5.59	16	5.08	6	5.56	16
		1000	5.29	10	5.18	8	6.12	27	5.53	15
Day 20 filter average			**5.86**	**22**	**5.34**	**11**	**5.43**	**13**	**5.54**	**15**
Total Average	**6.33**	270	**6.05**	**15**	**5.54**	**18**	**5.08**	**22**	**5.55**	**18**
		750	**6.09**	**14**	**5.43**	**18**	**5.08**	**23**	**5.53**	**18**
		1000	**5.93**	**14**	**5.47**	**15**	**6.00**	**16**	**5.80**	**15**
			6.02	**14**	**5.48**	**17**	**5.39**	**20**	**5.63**	**17**

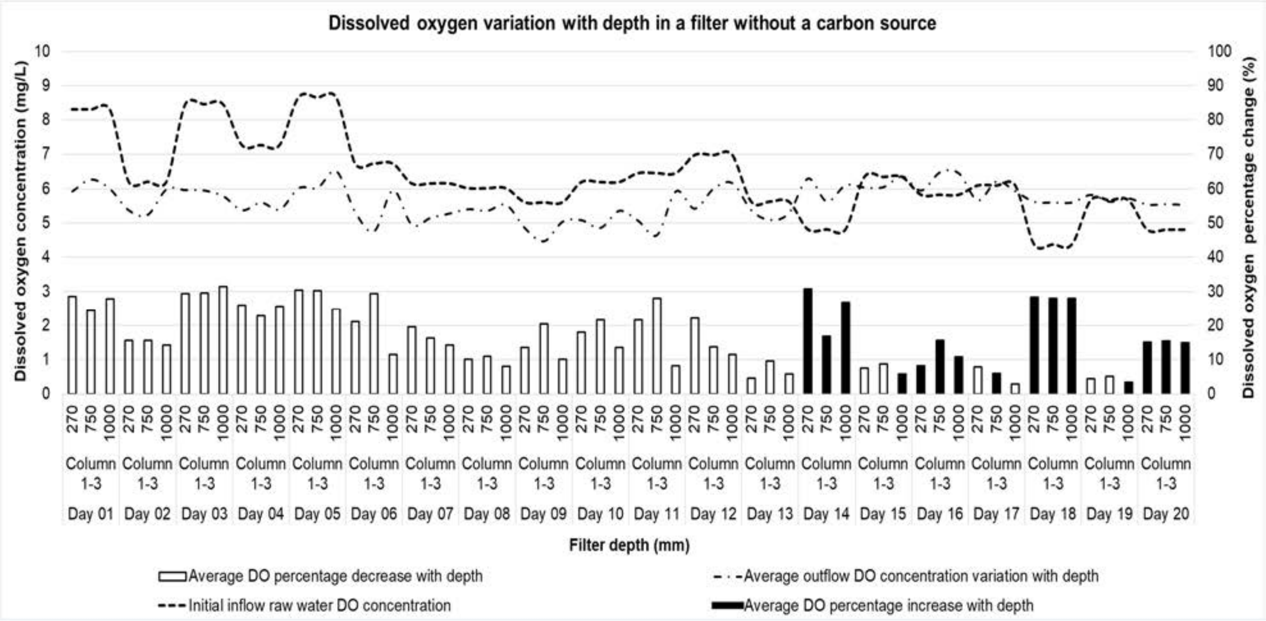


Figure H.37 Overall average dissolved Oxygen variation in a filter without a source of Carbon at C/N ratio of 1.1.

Appendix I. Carbon Oxygen demand (COD) in the filtrate

The tables below represent the COD variation in the filter with a Carbon source during the filter run and before the start of the filter run.

I.1. Chemical Oxygen demand at C/N ratio of 1.05 and nitrate concentration of 15 mg/L-N

Table I.38 Daily COD variations in the filter with a Carbon source.

Sampling Time interval (Day)	Raw water COD concentration (mg/L-O2)	Spiked raw water COD concentration (mg/L-O2)	Spiked filtrate COD concentration during filter run (mg/L-O2)	Filtrate COD removal efficiency during filter run %	Spiked filtrate COD concentration before filter run (mg/L-O2)	Filtrate COD removal efficiency before filter run %
1	110.00	380.00	68.00	84	25.00	93
2	102.00	418.00	118.00	65	36.00	91
3	95.00	340.00	85.00	79	58.00	83
4	112.00	405.00	110.00	69	35.00	91
5	98.00	360.00	78.00	80	52.00	86
6	85.00	385.00	92.00	77	32.00	92
7	108.00	392.00	88.00	70	48.00	88
8	75.00	295.00	75.00	77	37.00	87
9	92.00	325.00	86.00	76	33.00	90
10	68.00	355.00	103.00	63	46.00	87
11	45.00	280.00	110.00	65	55.00	80
12	78.00	310.00	90.00	75	62.00	80
13	58.00	365.00	82.00	72	43.00	88
14	80.00	290.00	55.00	87	36.00	88
15	96.00	415.00	107.00	65	30.00	93
16	110.00	308.00	78.00	81	58.00	81
17	90.00	403.00	102.00	66	32.00	92
18	62.00	298.00	58.00	84	43.00	86
19	84.00	370.00	72.00	81	28.00	92
20	98.00	386.00	52.00	87	37.00	90
Total average	**87.30**	**354.00**	**85.45**	**75**	**41.30**	**88**

I.2. Chemical Oxygen demand at C/N ratio of 1.08 and nitrate concentration of 25 mg/L-N

Table I.39 Daily COD variations in the filter with a Carbon source.

Sampling Time interval (Day)	Raw water COD concentration (mg/L-O2)	Spiked raw water COD concentration (mg/L-O2)	Spiked filtrate COD concentration during filter running (mg/L-O2)	Filtrate COD removal efficiency during filter running %	Spiked filtrate COD concentration before filter running (mg/L-O2)	Filtrate COD removal efficiency before filter running %
1	128.00	1258.00	760.00	31	760.00	40
2	120.00	1100.00	870.00	19	645.00	41
3	138.00	1074.00	770.00	31	721.00	33
4	111.70	1123.00	580.00	53	535.00	52
5	118.00	1228.00	610.00	47	502.00	59
6	110.80	1152.00	680.00	31	588.00	49
7	112.50	979.00	598.00	43	597.00	39
8	109.80	1056.00	522.00	47	517.00	51
9	106.00	989.00	557.00	50	538.00	46
10	113.06	1117.00	780.00	25	498.00	55
11	110.72	1037.00	688.00	31	677.00	35
12	111.70	996.00	621.00	43	620.00	38
13	113.46	1084.00	705.00	40	582.00	46
14	205.40	1178.00	722.00	28	644.00	45
15	262.30	998.00	641.00	50	568.00	43
16	111.60	1282.00	538.00	46	509.00	60
17	143.70	1005.00	518.00	51	495.00	51
18	232.00	1048.00	575.00	56	452.00	57
19	208.60	1310.00	497.00	61	436.00	67
20	288.00	1271.00	408.00	68	341.00	73
Total average	**147.77**	**1114.25**	**632.00**	**43**	**561.25**	**49**

I.3. Chemical Oxygen demand at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table I.40 Daily COD variations in the filter with a Carbon source.

Sampling Time interval (Day)	Raw water COD concentration (mg/L-O2)	Spiked raw water COD concentration (mg/L-O2)	Spiked filtrate COD concentration during filter run (mg/L-O2)	Filtrate COD removal efficiency during filter run %	Spiked filtrate COD concentration before filter run (mg/L-O2)	Filtrate COD removal efficiency before filter run %
1	864.00	1106.00	801.00	41	762.00	31
2	785.00	1350.00	832.00	23	743.00	45
3	912.00	1084.00	788.00	34	684.00	37
4	822.00	1196.00	693.00	44	571.00	52
5	738.00	1245.00	745.00	35	535.00	57
6	698.00	1155.00	648.00	43	627.00	46
7	903.00	1128.00	689.00	37	626.00	45
8	685.00	1100.00	583.00	45	517.00	53
9	775.00	1058.00	548.00	53	498.00	53
10	848.00	1175.00	675.00	41	475.00	60
11	786.00	1140.00	570.00	53	512.00	55
12	720.00	1215.00	625.00	46	488.00	60
13	825.00	1150.00	590.00	51	510.00	56
14	937.00	1207.00	582.00	46	526.00	56
15	755.00	1085.00	550.00	53	458.00	58
16	728.00	1180.00	470.00	55	438.00	63
17	800.00	1050.00	390.00	65	355.00	66
18	750.00	1100.00	520.00	50	455.00	59
19	685.00	1030.00	538.00	50	438.00	57
20	715.00	1085.00	522.00	52	442.00	59
Total average	**786.55**	**1141.95**	**617.95**	**46**	**533.00**	**53**

Appendix J. Total suspended solids (TSS) in the raw water and filtrate

The tables below represent the TSS concentration and removal efficiency in the filter with and without a Carbon source during the filter run.

J.1. TSS at C/N ratio of 1.05 and nitrate concentration of 15 mg/L-N

Table J.41. Total suspended solids concentration and removal efficiency in the filter with and without a Carbon source.

Sampling interval (Days)	Filter column position in series	Filter column depths (mm)	Initial TSS in raw water (mg/L)	Final TSS in the filtrate using a filter with a carbon source (mg/L)	TSS removal efficiency using a filter with a carbon source (mg/L)	Final TSS in the filtrate using a filter without a carbon source (mg/L)	TSS removal efficiency using a filter without a carbon source (mg/L)
Day 01	Column 3	1000	28.70	4.98	83	3.13	89
Day 02	Column 3	1000	34.20	4.34	87	3.50	90
Day 03	Column 3	1000	22.70	3.45	85	2.89	87
Day 04	Column 3	1000	19.64	2.92	85	1.88	90
Day 05	Column 3	1000	18.96	3.07	84	2.32	88
Day 06	Column 3	1000	27.40	3.30	88	2.69	90
Day 07	Column 3	1000	35.40	4.80	86	3.22	91
Day 08	Column 3	1000	30.30	3.72	88	3.08	90
Day 09	Column 3	1000	27.30	3.44	87	2.80	90
Day 10	Column 3	1000	25.30	3.21	87	2.30	91
Day 11	Column 3	1000	22.70	3.07	86	2.13	91
Day 12	Column 3	1000	19.40	2.44	87	1.87	90
Day 13	Column 3	1000	35.80	4.12	88	2.97	92
Day 14	Column 3	1000	29.30	3.80	87	2.32	92
Day 15	Column 3	1000	38.20	4.55	88	3.10	92
Day 16	Column 3	1000	33.10	3.20	90	2.83	91
Day 17	Column 3	1000	20.70	3.13	85	2.20	89
Day 18	Column 3	1000	23.40	3.48	85	2.77	88
Day 19	Column 3	1000	17.90	2.96	83	1.66	91
Day 20	Column 3	1000	28.60	3.31	88	2.53	91
Average			**26.95**	**3.56**	**87**	**2.61**	**90**

J.2. TSS at C/N ratio of 1.08 and nitrate concentration of 25 mg/L-N

Table J.42 . Total suspended solids concentration and removal efficiency in the filter with and without a Carbon source.

Sampling interval (Days)	Filter column position in series	Filter column depths (mm)	Initial TSS in raw water (mg/L)	TSS in the filtrate using a filter with a carbon source (mg/L)	TSS removal efficiency using a filter with a carbon source (mg/L)	TSS in the filtrate using a filter without a carbon source (mg/L)	TSS removal efficiency using a filter without a carbon source (mg/L)
Day 01	Column 3	1000	12.00	8.00	33	4.00	67
Day 02	Column 3	1000	75.80	16.00	79	9.00	88
Day 03	Column 3	1000	118.00	28.00	76	8.50	93
Day 04	Column 3	1000	88.00	20.00	77	12.00	86
Day 05	Column 3	1000	28.00	7.00	75	5.00	82
Day 06	Column 3	1000	20.00	12.00	40	9.00	55
Day 07	Column 3	1000	8.00	4.00	50	1.60	80
Day 08	Column 3	1000	24.00	13.00	46	7.00	71
Day 09	Column 3	1000	18.00	10.00	44	4.00	78
Day 10	Column 3	1000	32.00	11.40	64	6.80	79
Day 11	Column 3	1000	38.00	8.79	77	5.27	86
Day 12	Column 3	1000	22.00	6.14	72	3.89	82
Day 13	Column 3	1000	18.70	4.97	73	3.07	84
Day 14	Column 3	1000	23.80	5.06	79	4.68	80
Day 15	Column 3	1000	35.70	6.03	83	4.92	86
Day 16	Column 3	1000	28.70	4.30	85	3.62	87
Day 17	Column 3	1000	18.90	3.07	84	2.38	87
Day 18	Column 3	1000	25.00	3.60	86	2.88	88
Day 19	Column 3	1000	17.82	3.12	82	2.28	87
Day 20	Column 3	1000	22.40	3.30	85	2.54	89
Average			**33.74**	**8.89**	**70**	**5.12**	**82**

J.3. TSS at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table J.43 Total suspended solids concentration and removal efficiency in the filter with and without a Carbon source.

Sampling interval (Days)	**Filter column position in series**	**Filter column depths (mm)**	**Initial TSS in raw water (mg/L)**	**Final TSS in the filtrate using a filter with a carbon source (mg/L)**	**TSS removal efficiency using a filter with a carbon source (mg/L)**	**Final TSS in the filtrate using a filter without a carbon source (mg/L)**	**TSS removal efficiency using a filter without a carbon source (mg/L)**
Day 01	Column 3	1000	22.80	6.30	72	5.64	75
Day 02	Column 3	1000	17.84	4.20	76	3.07	83
Day 03	Column 3	1000	21.80	5.07	77	4.30	80
Day 04	Column 3	1000	18.40	4.56	75	3.90	79
Day 05	Column 3	1000	25.40	4.97	80	3.42	87
Day 06	Column 3	1000	22.80	4.05	82	3.87	83
Day 07	Column 3	1000	17.80	3.82	79	2.96	83
Day 08	Column 3	1000	21.31	5.18	76	4.22	80
Day 09	Column 3	1000	14.97	3.38	77	2.84	81
Day 10	Column 3	1000	18.90	4.40	77	3.74	80
Day 11	Column 3	1000	20.83	3.97	81	2.88	86
Day 12	Column 3	1000	22.67	4.06	82	3.74	84
Day 13	Column 3	1000	17.87	3.31	81	2.46	86
Day 14	Column 3	1000	28.70	5.82	80	3.77	87
Day 15	Column 3	1000	21.96	4.62	79	3.24	85
Day 16	Column 3	1000	26.80	6.09	77	4.73	82
Day 17	Column 3	1000	33.60	6.77	80	3.84	89
Day 18	Column 3	1000	28.60	4.40	85	3.17	89
Day 19	Column 3	1000	32.80	4.98	85	3.74	89
Day 20	Column 3	1000	21.80	3.02	86	2.53	88
Average			**22.88**	**4.65**	**79**	**3.60**	**84**

Appendix K. Turbidity removal efficiency in the filter

The tables and figures below represent the daily turbidity removal with depth in the filter with and without a Carbon source during the filter operation.

K.1. Turbidity at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table K.44 Daily turbidity concentration and removal efficiency with depth in the filter with a Carbon source

Filter with a carbon source											
Sampling interval (Day)	**Spiked Raw water turbidity (NTU)**	**Unspiked Raw water turbidity (NTU)**	**Filter column depths (mm)**	**Column 1 turbidity concentration at depth (NTU)**	**Column 1 change in turbidity concentration (%)**	**Column 2 turbidity concentration at depth (NTU)**	**Column 2 change in turbidity concentration (%)**	**Column 3 turbidity concentration at depth (NTU)**	**Column 3 change in turbidity concentration (%)**	**Filter average turbidity concentration at depth (NTU)**	**Filter turbidity removal efficiency (%)**
1	225	3.43	270	90.9	60	48.6	78	44	80	61.17	73
			750	42.4	81	42.1	81	53.6	76	46.03	80
			1000	49.3	78	61.8	73	68.3	70	59.80	73
Day 1 filter average				**60.87**	**73**	**50.83**	**77**	**55.30**	**75**	**55.67**	**75**
2	298	5.1	270	169	43	103	65	61.2	79	111.07	63
			750	122	59	58.3	80	44.3	85	74.87	75
			1000	87.4	71	52.6	82	39.8	87	59.93	80
Day 2 filter average				**126.13**	**58**	**71.30**	**76**	**48.43**	**84**	**81.96**	**72**
3	304	1.76	270	192	37	47.7	84	17.05	94	85.58	72
			750	63.1	79	39.9	87	44.4	85	49.13	84
			1000	56.1	82	54.7	82	62.9	79	57.90	81
Day 3 filter average				**103.73**	**66**	**47.43**	**84**	**41.45**	**86**	**64.21**	**79**
4	310	4.42	270	118	62	74.6	76	38.4	88	77.00	75
			750	82.2	73	55.3	82	25.6	92	54.37	82
			1000	66.1	79	52.7	83	32.7	89	50.50	84
Day 4 filter average				**88.77**	**71**	**60.87**	**80**	**32.23**	**90**	**60.62**	**80**
5	335	1.83	270	106	68	34.9	90	20.3	94	53.73	84
			750	51.3	85	41.2	88	31.5	91	41.33	88
			1000	49.1	85	33.1	90	43.3	87	41.83	88
Day 5 filter average				**68.80**	**79**	**36.40**	**89**	**31.70**	**91**	**45.63**	**86**
6	345	2.98	270	118	66	67.4	80	42.4	88	75.93	78
			750	88.7	74	56.2	84	38.3	89	61.07	82
			1000	53.5	84	53.6	84	40.2	88	49.10	86
Day 6 filter average				**86.73**	**75**	**59.07**	**83**	**40.30**	**88**	**62.03**	**82**
7	362	3.82	270	164	55	49.7	86	50.7	86	88.13	76
			750	62	83	56.2	84	54.9	85	57.70	84
			1000	53.2	85	61	83	62.4	83	58.87	84
Day 7 filter average				**93.07**	**74**	**55.63**	**85**	**56.00**	**85**	**68.23**	**81**
8	377	4.81	270	189	50	112	70	61.9	84	120.97	68
			750	121	68	78.6	79	53.2	86	84.27	78
			1000	92	76	72.2	81	55.1	85	73.10	81
Day 8 filter average				**134.00**	**64**	**87.60**	**77**	**56.73**	**85**	**92.78**	**75**
9	382	2.9	270	82.6	78	28.2	93	5.65	99	38.82	90
			750	58.8	85	44.3	88	30.9	92	44.67	88
			1000	44.4	88	46	88	53	86	47.80	87
Day 9 filter average				**61.93**	**84**	**39.50**	**90**	**29.85**	**92**	**43.76**	**89**
10	388	1.92	270	192	51	88.9	77	52.2	87	111.03	71
			750	121	69	73.2	81	42.2	89	78.80	80
			1000	110	72	57.2	85	35.1	91	67.43	83
Day 10 filter average				**141.00**	**64**	**73.10**	**81**	**43.17**	**89**	**85.76**	**78**
11	398	1.59	270	118	70	15.49	96	9.51	98	47.67	88
			750	69.7	82	43.6	89	37.4	91	50.23	87
			1000	55.5	86	43.8	89	55.7	86	51.67	87
Day 11 filter average				**81.07**	**80**	**34.30**	**91**	**34.20**	**91**	**49.86**	**87**
12	403	5.32	270	176	56	89.7	78	63.3	84	109.67	73
			750	132	67	55.9	86	34.2	92	74.03	82
			1000	108	73	72.4	82	38.1	91	72.83	82
Day 12 filter average				**138.67**	**66**	**72.67**	**82**	**45.20**	**89**	**85.51**	**79**
13	405	3.94	270	230	43	54.8	86	30.2	93	105.00	74
			750	96.6	76	62.6	85	44.5	89	67.90	83
			1000	96.5	76	80.9	80	68	83	81.80	80
Day 13 filter average				**141.03**	**65**	**66.10**	**84**	**47.57**	**88**	**84.90**	**79**
14	419	4.4	270	144	66	72.2	83	42.4	90	86.20	79
			750	103	75	54	87	33.8	92	63.60	85
			1000	89.5	79	61.3	85	22.6	95	57.80	86
Day 14 filter average				**112.17**	**73**	**62.50**	**85**	**32.93**	**92**	**69.20**	**83**
15	411	2.4	270	289	30	88.4	78	47.9	88	141.77	66
			750	140	66	94.7	77	65.7	84	100.13	76
			1000	132	68	103	75	86.7	79	107.23	74
Day 15 filter average				**187.00**	**55**	**95.37**	**77**	**66.77**	**84**	**116.38**	**72**
16	426	6.7	270	189	56	77.2	82	42.4	90	102.87	76
			750	133	69	58	86	39.5	91	76.83	82
			1000	110	74	61.4	86	29.3	93	66.90	84
Day 16 filter average				**144.00**	**66**	**65.53**	**85**	**37.07**	**91**	**82.20**	**81**
17	427	4.06	270	218	49	65.6	85	36.7	91	106.77	75
			750	122	71	82.1	81	57.9	86	87.33	80
			1000	131	69	97.8	77	77.9	82	102.23	76
Day 17 filter average				**157.00**	**63**	**81.83**	**81**	**57.50**	**87**	**98.78**	**77**
18	431	5.79	270	191	56	98.3	77	39.3	91	109.53	75
			750	155	64	69.9	84	42.3	90	89.07	79
			1000	123	71	51.3	88	33.8	92	69.37	84
Day 18 filter average				**156.33**	**64**	**73.17**	**83**	**38.47**	**91**	**89.32**	**79**
19	434	3.11	270	172	60	90.2	79	58.5	87	106.90	75
			750	128	71	73.7	83	53.3	88	85.00	80
			1000	83.4	81	73.6	83	88.8	80	81.93	81
Day 19 filter average				**127.80**	**71**	**79.17**	**82**	**66.87**	**85**	**91.28**	**79**
20	462	5.66	270	113	76	62	87	50.3	89	75.10	84
			750	105	77	55.9	88	24.2	95	61.70	87
			1000	73.4	84	43.7	91	21.4	95	46.17	90
Day 20 filter average				**97.13**	**79**	**53.87**	**88**	**31.97**	**93**	**60.99**	**87**
Total Average	**377.10**	**3.80**	270	**163.08**	**57**	**68.44**	**82**	**40.72**	**89**	**90.75**	**76**
			750	**99.84**	**74**	**59.79**	**84**	**42.59**	**88**	**67.40**	**82**
			1000	**83.17**	**78**	**61.71**	**83**	**50.76**	**86**	**65.21**	**82**
				115.36	**69**	**63.31**	**83**	**44.69**	**88**	**74.45**	**80**

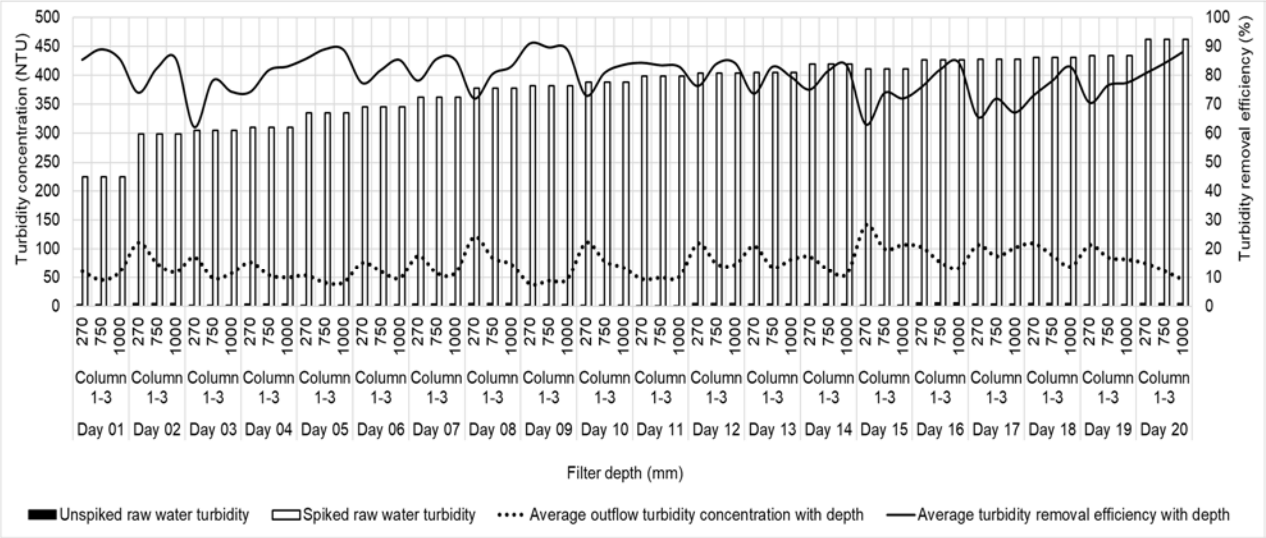


Figure K.45 Overall average turbidity removal in a filter with a source of Carbon at C/N ratio of 1.05 and inflow nitrate concentration of 15mg/L-N.

Table K.46 Daily turbidity concentration and removal efficiency with depth in the filter without a Carbon source

Filter without a carbon source											
Sampling interval (Day)	**Spiked Raw water turbidity (NTU)**	**Unspiked Raw water turbidity (NTU)**	**Filter column depths (mm)**	**Column 1 turbidity concentration at depth (NTU)**	**Column 1 change in turbidity concentration (%)**	**Column 2 turbidity concentration at depth (NTU)**	**Column 2 change in turbidity concentration (%)**	**Column 3 turbidity concentration at depth (NTU)**	**Column 3 change in turbidity concentration (%)**	**Filter average turbidity concentration at depth (NTU)**	**Filter turbidity removal efficiency (%)**
1	225	3.43	270	43.9	80	25.3	89	16.03	93	28.41	87
			750	27	88	21.8	90	15.88	93	21.56	90
			1000	28.1	88	21	91	14.39	94	21.16	91
Day 1 filter average				**33.00**	**85**	**22.70**	**90**	**15.43**	**93**	**23.71**	**89**
2	298	5.1	270	113	62	29.5	90	15.4	95	52.63	82
			750	48.2	84	22.1	93	12.88	96	27.73	91
			1000	33.4	89	19.93	93	10.9	96	21.41	93
Day 2 filter average				**64.87**	**78**	**23.84**	**92**	**13.06**	**96**	**33.92**	**89**
3	304	1.76	270	42.8	86	10.6	97	14.46	95	22.62	93
			750	17.67	94	7.76	97	10.14	97	11.86	96
			1000	43	86	10.09	97	6.2	98	19.76	93
Day 3 filter average				**34.49**	**89**	**9.48**	**97**	**10.27**	**97**	**18.08**	**94**
4	310	4.42	270	62.7	80	21.2	93	10.3	97	31.40	90
			750	41.4	87	15.6	95	9.2	97	22.07	93
			1000	52.6	83	12.9	96	7.8	97	24.43	92
Day 4 filter average				**52.23**	**83**	**16.57**	**95**	**9.10**	**97**	**25.97**	**92**
5	335	1.83	270	41.7	88	7.18	98	7.72	98	18.87	94
			750	11.07	97	4.49	99	7.66	98	7.74	98
			1000	28.1	92	6.22	98	7.79	98	14.04	96
Day 5 filter average				**26.96**	**92**	**5.96**	**98**	**7.72**	**98**	**13.55**	**96**
6	345	2.98	270	77.4	78	59.5	83	19.1	94	52.00	85
			750	68.3	80	31.2	91	13.5	96	37.67	89
			1000	43.4	87	23.4	93	11.3	97	26.03	92
Day 6 filter average				**63.03**	**82**	**38.03**	**89**	**14.63**	**96**	**38.57**	**89**
7	362	3.82	270	28.7	92	24.1	93	7.44	98	20.08	94
			750	38.8	89	2.88	99	4.47	99	15.38	96
			1000	7.74	98	3.07	99	3.41	99	4.74	99
Day 7 filter average				**25.08**	**93**	**10.02**	**97**	**5.11**	**99**	**13.40**	**96**
8	377	4.81	270	113	70	62.5	83	32.4	91	69.30	82
			750	88.6	76	51.9	86	27.6	93	56.03	85
			1000	73.2	81	44.8	88	19.7	95	45.90	88
Day 8 filter average				**91.60**	**76**	**53.07**	**86**	**26.57**	**93**	**57.08**	**85**
9	382	2.9	270	34.4	91	4.99	99	4.64	99	14.68	96
			750	11.52	97	3.84	99	7.1	98	7.49	98
			1000	152	60	10.93	97	9.51	98	57.48	85
Day 9 filter average				**65.97**	**83**	**6.59**	**98**	**7.08**	**98**	**26.55**	**93**
10	388	1.92	270	105	73	62.2	84	34.4	91	67.20	83
			750	92.1	76	52.8	86	26.2	93	57.03	85
			1000	78.8	80	43.7	89	17.6	95	46.70	88
Day 10 filter average				**91.97**	**76**	**52.90**	**86**	**26.07**	**93**	**56.98**	**85**
11	398	1.59	270	263	34	29.3	93	12.63	97	101.64	74
			750	50.7	87	15.15	96	10.92	97	25.59	94
			1000	66.7	83	14.91	96	8.65	98	30.09	92
Day 11 filter average				**126.80**	**68**	**19.79**	**95**	**10.73**	**97**	**52.44**	**87**
12	403	5.32	270	112	72	58.3	86	38.7	90	69.67	83
			750	97.4	76	49.9	88	22.3	94	56.53	86
			1000	74.2	82	52.3	87	17.4	96	47.97	88
Day 12 filter average				**94.53**	**77**	**53.50**	**87**	**26.13**	**94**	**58.06**	**86**
13	405	3.94	270	103	75	62.4	85	23	94	62.80	84
			750	57.6	86	51.1	87	19.18	95	42.63	89
			1000	74.4	82	24.4	94	14.12	97	37.64	91
Day 13 filter average				**78.33**	**81**	**45.97**	**89**	**18.77**	**95**	**47.69**	**88**
14	419	4.4	270	85.2	80	42.4	90	16.3	96	47.97	89
			750	66.2	84	31.2	93	11.3	97	36.23	91
			1000	58	86	22	95	8.9	98	29.63	93
Day 14 filter average				**69.80**	**83**	**31.87**	**92**	**12.17**	**97**	**37.94**	**91**
15	411	2.4	270	136	67	60.3	85	41.3	90	79.20	81
			750	69.7	83	44	89	38.4	91	50.70	88
			1000	80.6	80	50.8	88	28.2	93	53.20	87
Day 15 filter average				**95.43**	**77**	**51.70**	**87**	**35.97**	**91**	**61.03**	**85**
16	426	6.7	270	113	73	59.2	86	24.8	94	65.67	85
			750	89.4	79	41.1	90	17.3	96	49.27	88
			1000	67.3	84	39.3	91	12.8	97	39.80	91
Day 16 filter average				**89.90**	**79**	**46.53**	**89**	**18.30**	**96**	**51.58**	**88**
17	427	4.06	270	112	74	58.6	86	35.1	92	68.57	84
			750	79.9	81	43.2	90	32.6	92	51.90	88
			1000	83	81	43.3	90	18.8	96	48.37	89
Day 17 filter average				**91.63**	**79**	**48.37**	**89**	**28.83**	**93**	**56.28**	**87**
18	431	5.79	270	126	71	56.3	87	24.7	94	69.00	84
			750	114	74	44.1	90	18.7	96	58.93	86
			1000	84.2	80	32.1	93	12.3	97	42.87	90
Day 18 filter average				**108.07**	**75**	**44.17**	**90**	**18.57**	**96**	**56.93**	**87**
19	434	3.11	270	59.3	86	35.4	92	22.4	95	39.03	91
			750	42.4	90	27	94	19.64	95	29.68	93
			1000	40.8	91	24.9	94	16.78	96	27.49	94
Day 19 filter average				**47.50**	**89**	**29.10**	**93**	**19.61**	**95**	**32.07**	**93**
20	462	5.66	270	85.6	81	38.2	92	13.2	97	45.67	90
			750	68.4	85	23.6	95	11.5	98	34.50	93
			1000	52	89	17.3	96	8.33	98	25.88	94
Day 20 filter average				**68.67**	**85**	**26.37**	**94**	**11.01**	**98**	**35.35**	**92**
Total Average	**377.10**	**3.80**	270	**92.89**	**76**	**40.37**	**89**	**20.70**	**95**	**51.32**	**87**
			750	**59.02**	**85**	**29.24**	**92**	**16.82**	**96**	**35.03**	**91**
			1000	**61.08**	**84**	**25.87**	**93**	**12.74**	**97**	**33.23**	**91**
				70.99	**81**	**31.83**	**92**	**16.76**	**96**	**39.86**	**90**

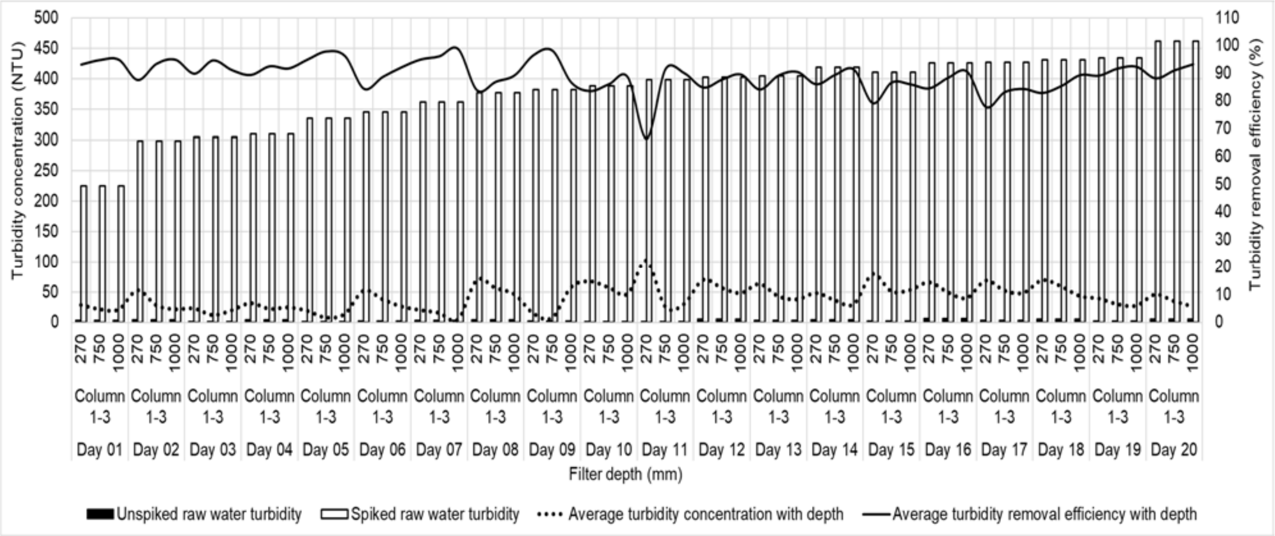


Figure K.47 Overall average turbidity removal in a filter without a source of Carbon at inflow nitrate concentration of 15mg/L-N.

K.2. Turbidity at C/N ratio of 1.08 and nitrate concentration of 25 mg/L-N

Table K.48 Daily turbidity concentration and removal efficiency with depth in the filter without a Carbon source

Filter with a carbon source											
Sampling interval (Day)	**Spiked Raw water turbidity (NTU)**	**Unspiked Raw water turbidity (NTU)**	**Filter column depths (mm)**	**Column 1 turbidity concentration with depth (NTU)**	**Column 1 change in turbidity concentration (%)**	**Column 2 turbidity concentration with depth (NTU)**	**Column 2 change in turbidity concentration (%)**	**Column 3 turbidity concentration with depth (NTU)**	**Column 3 change in turbidity concentration (%)**	**Filter average turbidity concentration at depth (NTU)**	**Filter turbidity removal efficiency (%)**
1	105.7	24.1	270	23.7	78	17.27	84	10.21	90	17.06	84
			750	19.72	81	15.37	85	9.98	91	15.02	86
			1000	18.11	83	11.9	89	9.67	91	13.23	87
Day 1 filter average				**20.51**	**81**	**14.85**	**86**	**9.95**	**91**	**15.10**	**86**
2	125.6	16.16		44.6	64	21.7	83	9.02	93	25.11	80
				38.3	70	13.52	89	8.19	93	20.00	84
				24.5	80	13.67	89	7.78	94	15.32	88
Day 2 filter average				**35.80**	**71**	**16.30**	**87**	**8.33**	**93**	**20.14**	**84**
3	143	19.7	270	33.1	77	22.3	84	21.4	85	25.60	82
			750	20.6	86	20.7	86	19.93	86	20.41	86
			1000	36.6	74	27.9	80	32.6	77	32.37	77
Day 3 filter average				**30.10**	**79**	**23.63**	**83**	**24.64**	**83**	**26.13**	**82**
4	156	5.84	270	73.1	53	18.97	88	16.4	89	36.16	77
			750	17.14	89	14.04	91	14.34	91	15.17	90
			1000	19.09	88	13.59	91	10.58	93	14.42	91
Day 4 filter average				**36.44**	**77**	**15.53**	**90**	**13.77**	**91**	**21.92**	**86**
5	164	4.96	270	93	43	96.8	41	89.8	45	93.20	43
			750	70.2	57	96.4	41	84.2	49	83.60	49
			1000	94.4	42	92.6	44	77.9	53	88.30	46
Day 5 filter average				**85.87**	**48**	**95.27**	**42**	**83.97**	**49**	**88.37**	**46**
6	174	5.86	270	130	25	56.3	68	55.5	68	80.60	54
			750	82.3	53	59.8	66	33.5	81	58.53	66
			1000	36.3	79	60.4	65	42.8	75	46.50	73
Day 6 filter average				**82.87**	**52**	**58.83**	**66**	**43.93**	**75**	**61.88**	**64**
7	200	2.6	270	162	19	59.8	70	69.3	65	97.03	51
			750	143	29	55.8	72	92.5	54	97.10	51
			1000	55.1	72	69.3	65	66.6	67	63.67	68
Day 7 filter average				**120.03**	**40**	**61.63**	**69**	**76.13**	**62**	**85.93**	**57**
8	269	6.56	270	120	55	38.3	86	50.3	81	69.53	74
			750	108	60	47.2	82	73.4	73	76.20	72
			1000	44.2	84	66.2	75	61	77	57.13	79
Day 8 filter average				**90.73**	**66**	**50.57**	**81**	**61.57**	**77**	**67.62**	**75**
9	301	7.39	270	121	60	28.1	91	20.7	93	56.60	81
			750	40.7	86	37.5	88	39.4	87	39.20	87
			1000	35.3	88	54.7	82	54.6	82	48.20	84
Day 9 filter average				**65.67**	**78**	**40.10**	**87**	**38.23**	**87**	**48.00**	**84**
10	305	12.68	270	76.4	75	39.9	87	32.2	89	49.50	84
			750	71.2	77	38.7	87	47.9	84	52.60	83
			1000	57.2	81	45.3	85	20.9	93	41.13	87
Day 10 filter average				**68.27**	**78**	**41.30**	**86**	**33.67**	**89**	**47.74**	**84**
11	318	23.5	270	204	36	49.3	84	40	87	97.77	69
			750	111	65	38.5	88	40.9	87	63.47	80
			1000	66.6	79	57.2	82	42.8	87	55.53	83
Day 11 filter average				**127.20**	**60**	**48.33**	**85**	**41.23**	**87**	**72.26**	**77**
12	330	19.87	270	152	54	54.6	83	59.7	82	88.77	73
			750	72.8	78	64.5	80	64.4	80	67.23	80
			1000	50.6	85	79.3	76	36.8	89	55.57	83
Day 12 filter average				**91.80**	**72**	**66.13**	**80**	**53.63**	**84**	**70.52**	**79**
13	344	1.84	270	67.9	80	35.2	90	41.3	88	48.13	86
			750	72.9	79	28.3	92	47.9	86	49.70	86
			1000	28.2	92	56.2	84	24.7	93	36.37	89
Day 13 filter average				**56.33**	**84**	**39.90**	**88**	**37.97**	**89**	**44.73**	**87**
14	348	44.8	270	111	68	66.9	81	16.94	95	64.95	81
			750	63.2	82	49.3	86	32.6	91	48.37	86
			1000	93.7	73	44.7	87	47.3	86	61.90	82
Day 14 filter average				**89.30**	**74**	**53.63**	**85**	**32.28**	**91**	**58.40**	**83**
15	350	9.1	270	185	47	37.2	89	16.48	95	79.56	77
			750	67.4	81	43.4	88	32.4	91	47.73	86
			1000	56.9	84	39	89	49.7	86	48.53	86
Day 15 filter average				**103.10**	**71**	**39.87**	**89**	**32.86**	**91**	**58.61**	**83**
16	387	3.34	270	209	46	70.8	82	55.5	86	111.77	71
			750	72.3	81	65.2	83	53.1	86	63.53	84
			1000	105	73	60.1	84	64.7	83	76.60	80
Day 16 filter average				**128.77**	**67**	**65.37**	**83**	**57.77**	**85**	**83.97**	**78**
17	407	1.18	270	181	56	53.7	87	24.4	94	86.37	79
			750	94.7	77	43.5	89	48.5	88	62.23	85
			1000	91	78	54	87	71.1	83	72.03	82
Day 17 filter average				**122.23**	**70**	**50.40**	**88**	**48.00**	**88**	**73.54**	**82**
18	416	0.62	270	120	71	30.5	93	12.11	97	54.20	87
			750	26.3	94	35	92	33.3	92	31.53	92
			1000	59.8	86	40.1	90	49.7	88	49.87	88
Day 18 filter average				**68.70**	**83**	**35.20**	**92**	**31.70**	**92**	**45.20**	**89**
19	438	2.87	270	178	59	36.2	92	21.3	95	78.50	82
			750	35.8	92	32.7	93	18.9	96	29.13	93
			1000	49.1	89	39.2	91	33	92	40.43	91
Day 19 filter average				**87.63**	**80**	**36.03**	**92**	**24.40**	**94**	**49.36**	**89**
20	446	1.93	270	187	58	41	91	15.56	97	81.19	82
			750	77.3	83	36.4	92	28.5	94	47.40	89
			1000	68.9	85	38.9	91	47	89	51.60	88
Day 20 filter average				**111.07**	**75**	**38.77**	**91**	**30.35**	**93**	**60.06**	**87**
Total Average	**286.37**	**10.75**	270	**123.59**	**56**	**43.74**	**83**	**33.91**	**86**	**67.08**	**75**
			750	**65.24**	**75**	**41.79**	**83**	**41.19**	**84**	**49.41**	**81**
			1000	**54.53**	**80**	**48.21**	**81**	**42.56**	**84**	**48.43**	**82**
				81.12	**70**	**44.58**	**82**	**39.22**	**85**	**54.97**	**79**

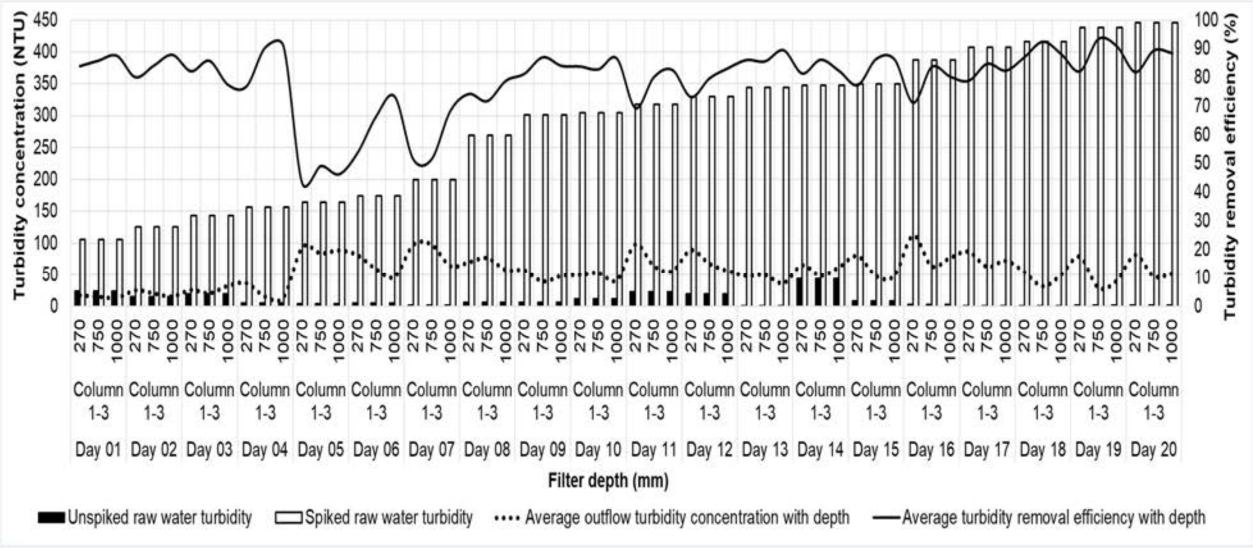


Figure K.49 Overall average turbidity removal in a filter with a source of Carbon at C/N ratio of 1.08 and inflow nitrate concentration of 25mg/L-N.

Table K.50 Daily turbidity concentration and removal efficiency with depth in the filter without a Carbon source.

Filter without a carbon source											
Sampling interval (Day)	**Spiked Raw water turbidity (NTU)**	**Unspiked Raw water turbidity (NTU)**	**Filter column depths (mm)**	**Column 1 turbidity concentration with depth (NTU)**	**Column 1 change in turbidity concentration (%)**	**Column 2 turbidity concentration with depth (NTU)**	**Column 2 change in turbidity concentration (%)**	**Column 3 turbidity concentration with depth (NTU)**	**Column 3 change in turbidity concentration (%)**	**Filter average turbidity concentration at depth (NTU)**	**Filter turbidity removal efficiency (%)**
1	105.7	24.1	270	18.58	82	11.86	89	8.05	92	12.83	88
			750	13	88	10.54	90	5.65	95	9.73	91
			1000	12.2	88	7.71	93	3.33	97	7.75	93
Day 1 filter average				**14.59**	**86**	**10.04**	**91**	**5.68**	**95**	**10.10**	**90**
2	125.6	16.16	270	18.36	85	16.82	87	29.3	77	21.49	83
			750	15.91	87	15	88	11.8	91	14.24	89
			1000	49.1	61	13.98	89	12.07	90	25.05	80
Day 2 filter average				**27.79**	**78**	**15.27**	**88**	**17.72**	**86**	**20.26**	**84**
3	143	19.7	270	15.08	89	9.72	93	9.99	93	11.60	92
			750	11.24	92	6.78	95	11.01	92	9.68	93
			1000	16.08	89	9.36	93	7.83	95	11.09	92
Day 3 filter average				**14.13**	**90**	**8.62**	**94**	**9.61**	**93**	**10.79**	**92**
4	156	5.84	270	49.3	68	39.6	75	44.9	71	44.60	71
			750	38	76	30.6	80	39.6	75	36.07	77
			1000	35.4	77	32.3	79	42.9	73	36.87	76
Day 4 filter average				**40.90**	**74**	**34.17**	**78**	**42.47**	**73**	**39.18**	**75**
5	164	4.96	270	71.4	56	23.4	86	19.5	88	38.10	77
			750	43	74	27.4	83	17.85	89	29.42	82
			1000	50.8	69	27.5	83	4.71	97	27.67	83
Day 5 filter average				**55.07**	**66**	**26.10**	**84**	**14.02**	**91**	**31.73**	**81**
6	174	5.86	270	36.1	79	20.9	88	13.55	92	23.52	86
			750	23.6	86	14.32	92	11.26	94	16.39	91
			1000	22.9	87	16.68	90	13.35	92	17.64	90
Day 6 filter average				**27.53**	**84**	**17.30**	**90**	**12.72**	**93**	**19.18**	**89**
7	200	2.6	270	24.3	88	21.9	89	19.15	90	21.78	89
			750	23.5	88	17.72	91	12.71	94	17.98	91
			1000	42.2	79	20.8	90	4.93	98	22.64	89
Day 7 filter average				**30.00**	**85**	**20.14**	**90**	**12.26**	**94**	**20.80**	**90**
8	269	6.56	270	33.7	87	13.9	95	10.63	96	19.41	93
			750	23.5	91	13.03	95	9.19	97	15.24	94
			1000	24.5	91	12.11	95	2.9	99	13.17	95
Day 8 filter average				**27.23**	**90**	**13.01**	**95**	**7.57**	**97**	**15.94**	**94**
9	301	7.39	270	34.6	89	17.18	94	10.04	97	20.61	93
			750	27.4	91	15.35	95	13.11	96	18.62	94
			1000	41.6	86	13.93	95	2.83	99	19.45	94
Day 9 filter average				**34.53**	**89**	**15.49**	**95**	**8.66**	**97**	**19.56**	**94**
10	305	12.68	270	46.5	85	26	91	16.97	94	29.82	90
			750	38.8	87	21.6	93	25.8	92	28.73	91
			1000	38.9	87	20.9	93	6.06	98	21.95	93
Day 10 filter average				**41.40**	**86**	**22.83**	**93**	**16.28**	**95**	**26.84**	**91**
11	318	23.5	270	52	84	29.1	91	17.89	94	33.00	90
			750	45.2	86	26.4	92	18.32	94	29.97	91
			1000	36.7	88	24.3	92	17.55	94	26.18	92
Day 11 filter average				**44.63**	**86**	**26.60**	**92**	**17.92**	**94**	**29.72**	**91**
12	330	19.87	270	51.1	85	23	93	11.33	97	28.48	91
			750	84.1	75	18.69	94	11.97	96	38.25	88
			1000	32	90	21.3	94	9.42	97	20.91	94
Day 12 filter average				**55.73**	**83**	**21.00**	**94**	**10.91**	**97**	**29.21**	**91**
13	344	1.84	270	65.1	81	30.1	91	14.7	96	36.63	89
			750	67.1	80	20.4	94	14.19	96	33.90	90
			1000	33.4	90	25.3	93	13.58	96	24.09	93
Day 13 filter average				**55.20**	**84**	**25.27**	**93**	**14.16**	**96**	**31.54**	**91**
14	348	44.8	270	98.5	72	25.7	93	20	94	48.07	86
			750	58.3	83	22.4	94	12.96	96	31.22	91
			1000	34.1	90	23.6	93	11.15	97	22.95	93
Day 14 filter average				**63.63**	82	**23.90**	**93**	**14.70**	**96**	**34.08**	**90**
15	350	9.1	270	53.6	85	32.8	91	22.9	93	36.43	90
			750	47.9	86	23.4	93	20.4	94	30.57	91
			1000	38.4	89	28.3	92	17	95	27.90	92
Day 15 filter average				**46.63**	**87**	**28.17**	**92**	**20.10**	**94**	**31.63**	**91**
16	387	3.34	270	71.4	82	31.3	92	19.57	95	40.76	89
			750	57.2	85	26.8	93	9.65	98	31.22	92
			1000	51.6	87	13.83	96	9.07	98	24.83	94
Day 16 filter average				**60.07**	**84**	**23.98**	**94**	**12.76**	**97**	**32.27**	**92**
17	407	1.18	270	84.7	79	39.9	90	20.2	95	48.27	88
			750	65.4	84	25.3	94	18.86	95	36.52	91
			1000	49.1	88	22.6	94	17.9	96	29.87	93
Day 17 filter average				**66.40**	**84**	**29.27**	**93**	**18.99**	**95**	**38.22**	**91**
18	416	0.62	270	74.5	82	30	93	19.5	95	41.33	90
			750	47.9	88	27.4	93	21.2	95	32.17	92
			1000	40.4	90	29.1	93	8.78	98	26.09	94
Day 18 filter average				**54.27**	**87**	**28.83**	**93**	**16.49**	**96**	**33.20**	**92**
19	438	2.87	270	104	76	31.3	93	15.8	96	50.37	89
			750	52	88	25	94	12.9	97	29.97	93
			1000	44.8	90	22.4	95	10.4	98	25.87	94
Day 19 filter average				**66.93**	**85**	**26.23**	**94**	**13.03**	**97**	**35.40**	**92**
20	446	1.93	270	49.8	89	34.6	92	21.4	95	35.27	92
			750	35.3	92	23.8	95	17.31	96	25.47	94
			1000	32	93	25.8	94	20.2	95	26.00	94
Day 20 filter average				**39.03**	**91**	**28.07**	**94**	**19.64**	**96**	**28.91**	**94**
Total Average	**286.37**	**10.75**	270	**52.63**	**81**	**25.45**	**90**	**18.27**	**92**	**32.12**	**88**
			750	**40.92**	**85**	**20.60**	**92**	**15.79**	**94**	**25.77**	**90**
			1000	**36.31**	**86**	**20.59**	**92**	**11.80**	**95**	**22.90**	**91**
				43.29	**84**	**22.21**	**91**	**15.28**	**94**	**26.93**	**90**

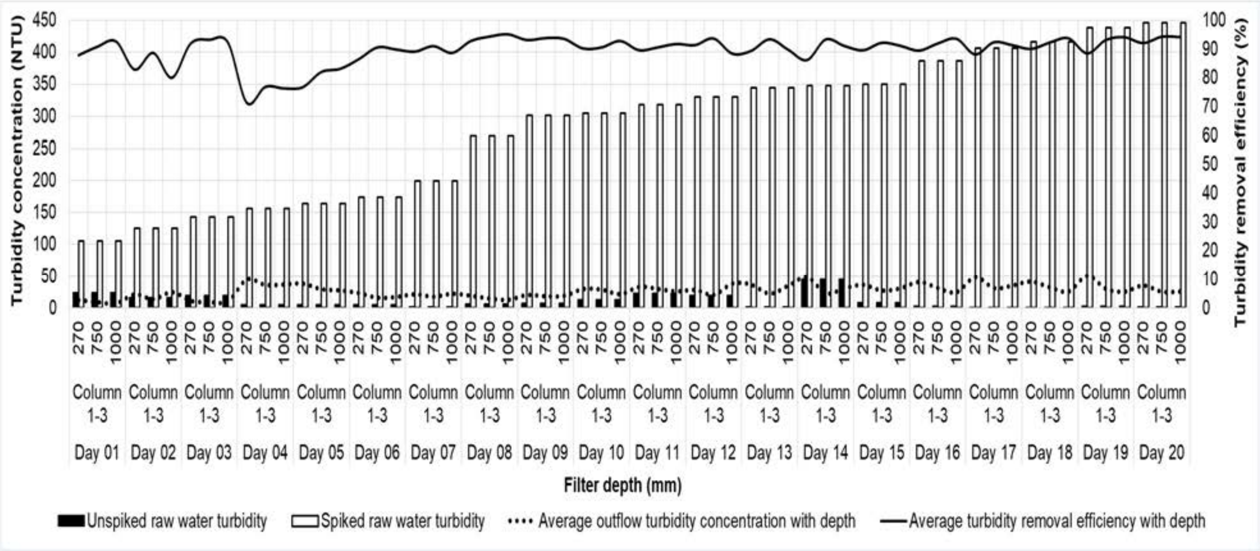


Figure K.51 Overall average turbidity removal in a filter without a source of Carbon at inflow nitrate concentration of 25mg/L-N.

K.3. Turbidity at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table K.52 Daily turbidity concentration and removal efficiency with depth in the filter without a Carbon source.

Filter with a carbon source											
Sampling interval (Day)	Spiked Raw water turbidity (NTU)	Unspiked Raw water turbidity (NTU)	Filter column depths (mm)	Column 1 turbidity concentration at depth (NTU)	Column 1 change in turbidity concentration (%)	Column 2 turbidity concentration at depth (NTU)	Column 2 change in turbidity concentration (%)	Column 3 turbidity concentration at depth (NTU)	Column 3 change in turbidity concentration (%)	Filter average turbidity concentration at depth (NTU)	Filter turbidity removal efficiency (%)
1	296	4.64	270	78.2	74	30.2	90	34.6	88	47.67	84
			750	26.5	91	25.9	91	40	86	30.80	90
			1000	32.8	89	51	83	32.6	89	38.80	87
Day 1 filter average				**45.83**	**85**	**35.70**	**88**	**35.73**	**88**	**39.09**	**87**
2	303	1.39	270	75.4	75	43.6	86	27.9	91	48.97	84
			750	50.9	83	34	89	28.9	90	37.93	87
			1000	32.6	89	37.5	88	21.5	93	30.53	90
Day 2 filter average				**52.97**	**83**	**38.37**	**87**	**26.10**	**91**	**39.14**	**87**
3	318	2.28	270	60	81	24.7	92	28.3	91	37.67	88
			750	25.9	92	18.3	94	19.8	94	21.33	93
			1000	31.1	90	19.35	94	17.53	94	22.66	93
Day 3 filter average				**39.00**	**88**	**20.78**	**93**	**21.88**	**93**	**27.22**	**91**
4	336	0.57	270	55.5	83	43.8	87	39.8	88	46.37	86
			750	42.6	87	24.7	93	28.8	91	32.03	90
			1000	50.8	85	41.7	88	27.4	92	39.97	88
Day 4 filter average				**49.63**	**85**	**36.73**	**89**	**32.00**	**90**	**39.46**	**88**
5	354	2.89	270	79.2	78	76.2	78	73.8	79	76.40	78
			750	63.5	82	65.9	81	54.8	85	61.40	83
			1000	71	80	71.1	80	45.9	87	62.67	82
Day 5 filter average				**71.23**	**80**	**71.07**	**80**	**58.17**	**84**	**66.82**	**81**
6	356	2.28	270	213	40	66.3	81	47.3	87	108.87	69
			750	75.5	79	49	86	40.6	89	55.03	85
			1000	69.7	80	53.4	85	35.9	90	53.00	85
Day 6 filter average				**119.40**	**66**	**56.23**	**84**	**41.27**	**88**	**72.30**	**80**
7	384	1.4	270	166	57	83.7	78	27.2	93	92.30	76
			750	48.8	87	32.6	92	47.8	88	43.07	89
			1000	57.7	85	38.8	90	27.4	93	41.30	89
Day 7 filter average				**90.83**	**76**	**51.70**	**87**	**34.13**	**91**	**58.89**	**85**
8	404	3.42	270	130	68	69.1	83	46.8	88	81.97	80
			750	71.9	82	67	83	56.6	86	65.17	84
			1000	72.7	82	70.7	83	69.1	83	70.83	82
Day 8 filter average				**91.53**	**77**	**68.93**	**83**	**57.50**	**86**	**72.66**	**82**
9	434	0.75	270	169	61	194	55	82.5	81	148.50	66
			750	119	73	99.3	77	66.8	85	95.03	78
			1000	75.1	83	55.3	87	71.5	84	67.30	84
Day 9 filter average				**121.03**	**72**	**116.20**	**73**	**73.60**	**83**	**103.61**	**76**
10	476	1.78	270	239	50	71.3	85	37.2	92	115.83	76
			750	66	86	44	91	34.6	93	48.20	90
			1000	59.8	87	41.3	91	29.2	94	43.43	91
Day 10 filter average				**121.60**	**74**	**52.20**	**89**	**33.67**	**93**	**69.16**	**85**
11	519	1.78	270	224	57	57.9	89	48.3	91	110.07	79
			750	88.5	83	54.8	89	37.1	93	60.13	88
			1000	70.1	86	60.06	88	35.7	93	55.29	89
Day 11 filter average				**127.53**	**75**	**57.59**	**89**	**40.37**	**92**	**75.16**	**86**
12	544	1.96	270	204	63	61.1	89	45.4	92	103.50	81
			750	65.8	88	59.7	89	48.7	91	58.07	89
			1000	84	85	56.2	90	43.7	92	61.30	89
Day 12 filter average				**117.93**	**78**	**59.00**	**89**	**45.93**	**92**	**74.29**	**86**
13	550	1.33	270	202	63	82.2	85	57.8	89	114.00	79
			750	74.3	86	86.6	84	57.3	90	72.73	87
			1000	79.6	86	63.4	88	60.6	89	67.87	88
Day 13 filter average				**118.63**	**78**	**77.40**	**86**	**58.57**	**89**	**84.87**	**85**
14	582	3.09	270	152	74	80.3	86	45.1	92	92.47	84
			750	48.1	92	68.1	88	52.5	91	56.23	90
			1000	67.7	88	72.1	88	56.3	90	65.37	89
Day 14 filter average				**89.27**	**85**	**73.50**	**87**	**51.30**	**91**	**71.36**	**88**
15	632	1	270	156	75	72.2	89	31.8	95	86.67	86
			750	48	92	55.6	91	54.5	91	52.70	92
			1000	64.6	90	65.6	90	69.8	89	66.67	89
Day 15 filter average				**89.53**	**86**	**64.47**	**90**	**52.03**	**92**	**68.68**	**89**
16	645	1.27	270	187	71	73.6	89	21.7	97	94.10	85
			750	49	92	31.9	95	46.5	93	42.47	93
			1000	59.2	91	46.4	93	64.1	90	56.57	91
Day 16 filter average				**98.40**	**85**	**50.63**	**92**	**44.10**	**93**	**64.38**	**90**
17	694	1.96	270	175	75	85.4	88	26.4	96	95.60	86
			750	43.2	94	32.6	95	40.8	94	38.87	94
			1000	65.2	91	49	93	67.3	90	60.50	91
Day 17 filter average				**94.47**	**86**	**55.67**	**92**	**44.83**	**94**	**64.99**	**91**
18	698	1.78	270	172	75	64.5	91	172.5	75	136.33	80
			750	92.9	87	62.5	91	27.8	96	61.07	91
			1000	60.4	91	58.2	92	38.5	94	52.37	92
Day 18 filter average				**108.43**	**84**	**61.73**	**91**	**79.60**	**89**	**83.26**	**88**
19	713	1.86	270	163	77	28.6	96	18.31	97	69.97	90
			750	77.2	89	20.3	97	16.04	98	37.85	95
			1000	54.3	92	18.43	97	18.75	97	30.49	96
Day 19 filter average				**98.17**	**86**	**22.44**	**97**	**17.70**	**98**	**46.10**	**94**
20	877	1.45	270	206	77	98.3	89	35.9	96	113.40	87
			750	141.4	84	64.6	93	70.5	92	92.17	89
			1000	113	87	68.7	92	91.1	90	90.93	90
Day 20 filter average				**153.47**	**83**	**77.20**	**91**	**65.83**	**92**	**98.83**	**89**
Total Average	**505.75**	**1.94**	270	**155.32**	**69**	**70.35**	**85**	**47.43**	**90**	**91.03**	**81**
			750	**65.95**	**86**	**49.87**	**90**	**43.52**	**91**	**53.11**	**89**
			1000	**63.57**	**87**	**51.91**	**89**	**46.19**	**91**	**53.89**	**89**
				94.95	**81**	**57.38**	**88**	**45.72**	**90**	**66.01**	**86**

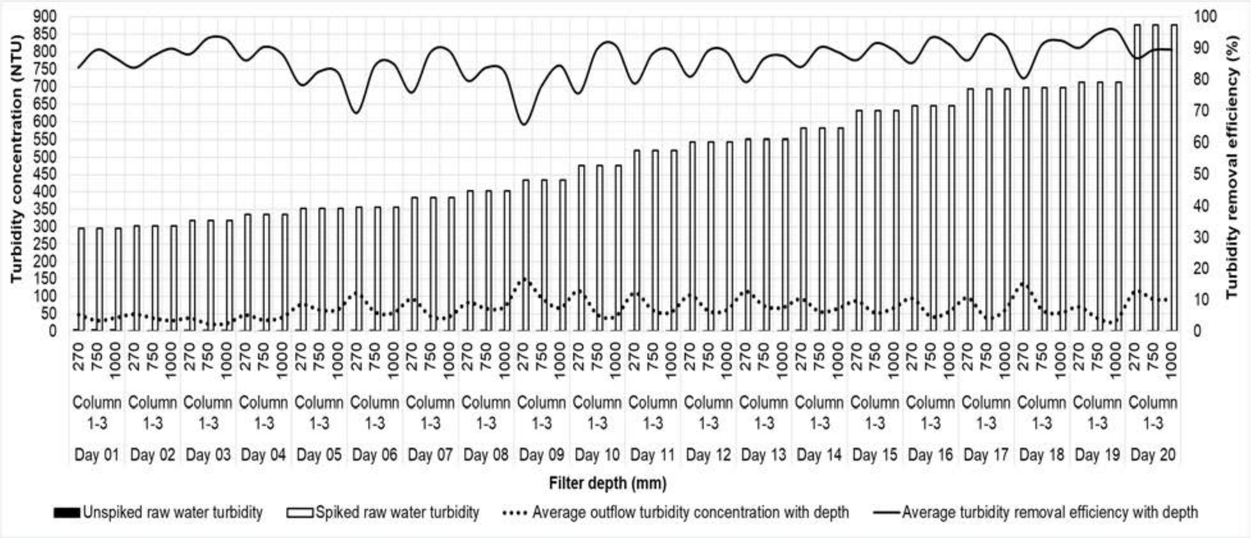


Figure K.53 Overall average turbidity removal in a filter with a source of Carbon at C/N ratio of 1.1 and inflow nitrate concentration of 50 mg/L-N.

Table K.54 Daily turbidity concentration and removal efficiency with depth in the filter without a Carbon source

Filter without a carbon source											
Sampling interval (Day)	**Spiked Raw water turbidity (NTU)**	**Unspiked Raw water turbidity (NTU)**	**Filter column depths (mm)**	**Column 1 turbidity concentration at depth (NTU)**	**Column 1 change in turbidity concentration (%)**	**Column 2 turbidity concentration at depth (NTU)**	**Column 2 change in turbidity concentration (%)**	**Column 3 turbidity concentration at depth (NTU)**	**Column 3 change in turbidity concentration (%)**	**Filter average turbidity concentration at depth (NTU)**	**Filter turbidity removal efficiency (%)**
1	296	4.64	270	48	84	31.6	89	11.03	96	30.21	90
			750	46.2	84	18.7	94	14.73	95	26.54	91
			1000	38.3	87	15.51	95	10.17	97	21.33	93
Day 1 filter average				**44.17**	**85**	**21.94**	**93**	**11.98**	**96**	**26.03**	**91**
2	303	1.39	270	80.6	73	35.8	88	19.89	93	45.43	85
			750	27.9	91	22.9	92	17.76	94	22.85	92
			1000	81.2	73	18.75	94	10.19	97	36.71	88
Day 2 filter average				**63.23**	**79**	**25.82**	**91**	**15.95**	**95**	**35.00**	**88**
3	318	2.28	270	144	55	31.8	90	18.82	94	64.87	80
			750	41.8	87	31	90	26.9	92	33.23	90
			1000	80.8	75	29.4	91	19.53	94	43.24	86
Day 3 filter average				**88.87**	**72**	**30.73**	**90**	**21.75**	**93**	**47.12**	**85**
4	336	0.57	270	90.4	73	43	87	28.2	92	53.87	84
			750	57.8	83	40.7	88	28.1	92	42.20	87
			1000	64.5	81	31	91	25.3	92	40.27	88
Day 4 filter average				**70.90**	**79**	**38.23**	**89**	**27.20**	**92**	**45.44**	**86**
5	354	2.89	270	127	64	51.5	85	29	92	69.17	80
			750	67.4	81	41.6	88	28.5	92	45.83	87
			1000	85.7	76	41.2	88	27.2	92	51.37	85
Day 5 filter average				**93.37**	**74**	**44.77**	**87**	**28.23**	**92**	**55.46**	**84**
6	356	2.28	270	131	63	71	80	38	89	80.00	78
			750	99.9	72	49.9	86	41.3	88	63.70	82
			1000	103	71	43.1	88	33	91	59.70	83
Day 6 filter average				**111.30**	**69**	**54.67**	**85**	**37.43**	**89**	**67.80**	**81**
7	384	1.4	270	96	75	48.8	87	25.9	93	56.90	85
			750	66.2	83	34.4	91	19.73	95	40.11	90
			1000	114	70	37.9	90	18.46	95	56.79	85
Day 7 filter average				**92.07**	**76**	**40.37**	**89**	**21.36**	**94**	**51.27**	**87**
8	404	3.42	270	114	72	68.9	83	37.5	91	73.47	82
			750	70.6	83	50.4	88	34.4	91	51.80	87
			1000	72.4	82	53.7	87	34.5	91	53.53	87
Day 8 filter average				**85.67**	**79**	**57.67**	**86**	**35.47**	**91**	**59.60**	**85**
9	434	0.75	270	154	65	187	57	29.6	93	123.53	72
			750	116	73	23.1	95	20.4	95	53.17	88
			1000	68.9	84	20.8	95	13.62	97	34.44	92
Day 9 filter average				**112.97**	**74**	**76.97**	**82**	**21.21**	**95**	**70.38**	**84**
10	476	1.78	270	108	77	54.3	89	29.3	94	63.87	87
			750	88.3	81	42.6	91	18.49	96	49.80	90
			1000	97	80	38.7	92	16.27	97	50.66	89
Day 10 filter average				**97.77**	**79**	**45.20**	**91**	**21.35**	**96**	**54.77**	**88**
11	519	1.78	270	192	63	52.3	90	31.1	94	91.80	82
			750	84.9	84	48.4	91	22.4	96	51.90	90
			1000	88	83	39.6	92	18.3	96	48.63	91
Day 11 filter average				**121.63**	**77**	**46.77**	**91**	**23.93**	**95**	**64.11**	**88**
12	544	1.96	270	278	49	80.9	85	30.9	94	129.93	76
			750	72.4	87	42.8	92	30.8	94	48.67	91
			1000	140	74	45.2	92	25.7	95	70.30	87
Day 12 filter average				**163.47**	**70**	**56.30**	**90**	**29.13**	**95**	**82.97**	**85**
13	550	1.33	270	139	75	65.8	88	37.2	93	80.67	85
			750	84.3	85	45.1	92	34.1	94	54.50	90
			1000	73	87	56.1	90	31.5	94	53.53	90
Day 13 filter average				**98.77**	**82**	**55.67**	**90**	**34.27**	**94**	**62.90**	**89**
14	582	3.09	270	73.9	87	37.4	94	22.9	96	44.73	92
			750	63.4	89	27.3	95	20.7	96	37.13	94
			1000	98	83	29.8	95	19	97	48.93	92
Day 14 filter average				**78.43**	**87**	**31.50**	**95**	**20.87**	**96**	**43.60**	**93**
15	632	1	270	112	82	31.6	95	22.9	96	55.50	91
			750	51.4	92	24.8	96	19.97	97	32.06	95
			1000	60.9	90	27.2	96	14.53	98	34.21	95
Day 15 filter average				**74.77**	**88**	**27.87**	**96**	**19.13**	**97**	**40.59**	**94**
16	645	1.27	270	108	83	45.9	93	28.1	96	60.67	91
			750	55.5	91	27.7	96	24.1	96	35.77	94
			1000	82.6	87	32.4	95	18.1	97	44.37	93
Day 16 filter average				**82.03**	**87**	**35.33**	**95**	**23.43**	**96**	**46.93**	**93**
17	694	1.96	270	161.9	77	37	95	22.5	97	73.80	89
			750	48.3	93	27.2	96	19.53	97	31.68	95
			1000	80.1	88	29.5	96	22.1	97	43.90	94
Day 17 filter average				**96.77**	**86**	**31.23**	**95**	**21.38**	**97**	**49.79**	**93**
18	698	1.78	270	181	74	28.3	96	20.6	97	76.63	89
			750	80	89	29.9	96	16	98	41.97	94
			1000	179	74	38.1	95	14.64	98	77.25	89
Day 18 filter average				**146.67**	**79**	**32.10**	**95**	**17.08**	**98**	**65.28**	**91**
19	713	1.86	270	146.2	79	30.1	96	17.17	98	64.49	91
			750	59.4	92	22.9	97	13.53	98	31.94	96
			1000	30	96	18.61	97	14.17	98	20.93	97
Day 19 filter average				**78.53**	**89**	**23.87**	**97**	**14.96**	**98**	**39.12**	**95**
20	877	1.45	270	168	81	110	87	20.9	98	99.63	89
			750	115	87	22.4	97	15.13	98	50.84	94
			1000	124	86	20.3	98	13.99	98	52.76	94
Day 20 filter average				**135.67**	**85**	**50.90**	**94**	**16.67**	**98**	**67.75**	**92**
Total Average	**505.75**	**1.94**	270	**132.65**	**73**	**57.15**	**88**	**26.08**	**94**	**71.96**	**85**
			750	**69.84**	**85**	**33.69**	**93**	**23.33**	**95**	**42.28**	**91**
			1000	**88.07**	**81**	**33.34**	**93**	**20.01**	**96**	**47.14**	**90**
				96.85	**80**	**41.39**	**91**	**23.14**	**95**	**53.80**	**89**

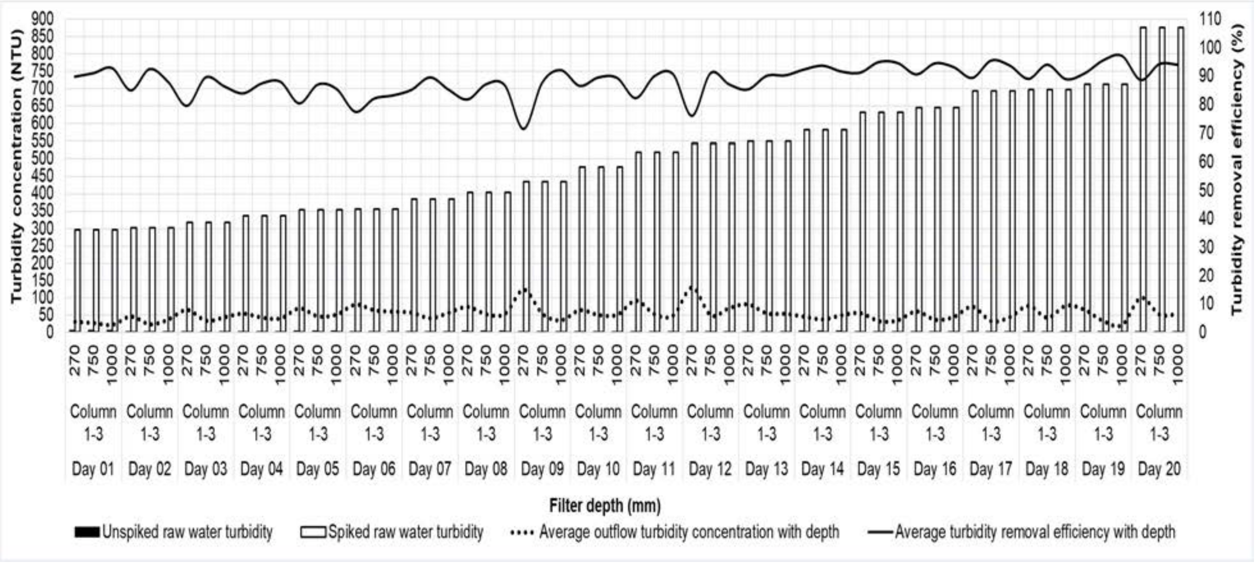


Figure K.55 Overall average turbidity removal in a filter without a source of Carbon at inflow nitrate concentration of 50 mg/L-N.

Appendix L. Nitrite concentration at varied filter depth

The tables and figures below represent detailed daily nitrite concentration and removal efficiency with depth in the filter with and without a Carbon source during the filter operation.

L.1. Nitrite at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table L.56 Daily nitrite concentration and removal efficiency with depth in the filter with a Carbon source.

Filter with a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrite concentration (mg/L-N)**	**Spiked raw water nitrite concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 nitrite concentration at depth (mg/L-N)**	**Column 1 removal efficiency (%)**	**Column 2 nitrite concentration at depth (mg/L-N)**	**Column 2 removal efficiency (%)**	**Column 3 nitrite concentration at depth (mg/L-N)**	**Column 3 removal efficiency (%)**	**Filter average nitrite concentration at depth (mg/L-N)**	**Filter avarage removal efficiency (%)**
1	0.04	0.56	270	0.06	89	0.02	96	0.03	95	0.04	93
			750	0.04	93	0.02	96	0.02	96	0.03	95
			1000	0.02	96	0.01	98	0.05	91	0.03	95
Day 1 filter average				**0.04**	**93**	**0.02**	**97**	**0.03**	**94**	**0.03**	**95**
2	0.03	0.45	270	0.05	89	0.03	93	0.02	96	0.03	93
			750	0.05	89	0.02	96	0.01	98	0.03	94
			1000	0.03	93	0.02	96	0.02	96	0.02	95
Day 2 filter average				**0.04**	**90**	**0.02**	**95**	**0.02**	**96**	**0.03**	**94**
3	0.08	0.58	270	0	100	0.01	98	0	100	0.00	99
			750	0	100	0	100	0	100	0.00	100
			1000	0	100	0.01	98	0	100	0.00	99
Day 3 filter average				**0.00**	**100**	**0.01**	**99**	**0.00**	**100**	**0.00**	**100**
4	0.09	0.47	270	0.01	98	0	100	0	100	0.00	99
			750	0.01	98	0.01	98	0.01	98	0.01	98
			1000	0.01	98	0	100	0.01	98	0.01	99
Day 4 filter average				**0.01**	**98**	**0.00**	**99**	**0.01**	**99**	**0.01**	**99**
5	0.08	0.64	270	0	100	0	100	0.01	98	0.00	99
			750	0	100	0.01	98	0.01	98	0.01	99
			1000	0.01	98	0.01	98	0.02	97	0.01	98
Day 5 filter average				**0.00**	**99**	**0.01**	**99**	**0.01**	**98**	**0.01**	**99**
6	0.05	0.71	270	0.01	99	0.01	99	0.01	99	0.01	99
			750	0	100	0.01	99	0.01	99	0.01	99
			1000	0	100	0	100	0.01	99	0.00	100
Day 6 filter average				**0.00**	**100**	**0.01**	**99**	**0.01**	**99**	**0.01**	**99**
7	0.07	0.69	270	0.03	96	0.03	96	0.01	99	0.02	97
			750	0.03	96	0	100	0	100	0.01	99
			1000	0.04	94	0.02	97	0	100	0.02	97
Day 7 filter average				**0.03**	**95**	**0.02**	**98**	**0.00**	**100**	**0.02**	**97**
8	0.09	0.76	270	0.02	97	0.02	97	0.03	96	0.02	97
			750	0.01	99	0.02	97	0.01	99	0.01	98
			1000	0	100	0.01	99	0.02	97	0.01	99
Day 8 filter average				**0.01**	**99**	**0.02**	**98**	**0.02**	**97**	**0.02**	**98**
9	0.11	0.85	270	0.01	99	0	100	0	100	0.00	100
			750	0.01	99	0.01	99	0	100	0.01	99
			1000	0	100	0.02	98	0	100	0.01	99
Day 9 filter average				**0.01**	**99**	**0.01**	**99**	**0.00**	**100**	**0.01**	**99**
10	0.06	0.66	270	0.03	95	0.02	97	0.03	95	0.03	96
			750	0.02	97	0.01	98	0.02	97	0.02	97
			1000	0.03	95	0.01	98	0	100	0.01	98
Day 10 filter average				**0.03**	**96**	**0.01**	**98**	**0.02**	**97**	**0.02**	**97**
11	0.15	0.51	270	0.02	96	0	100	0	100	0.01	99
			750	0.01	98	0	100	0.01	98	0.01	99
			1000	0.02	96	0	100	0	100	0.01	99
Day 11 filter average				**0.02**	**97**	**0.00**	**100**	**0.00**	**99**	**0.01**	**99**
12	0.1	0.69	270	0.02	97	0.01	99	0	100	0.01	99
			750	0.02	97	0.02	97	0.01	99	0.02	98
			1000	0.03	96	0.01	99	0.03	96	0.02	97
Day 12 filter average				**0.02**	**97**	**0.01**	**98**	**0.01**	**98**	**0.02**	**98**
13	0.09	0.7	270	0.01	99	0.01	99	0	100	0.01	99
			750	0	100	0.01	99	0.01	99	0.01	99
			1000	0.01	99	0	100	0.01	99	0.01	99
Day 13 filter average				**0.01**	**99**	**0.01**	**99**	**0.01**	**99**	**0.01**	**99**
14	0.07	0.64	270	0.02	97	0.01	98	0.03	95	0.02	97
			750	0.02	97	0.01	98	0.02	97	0.02	97
			1000	0.01	98	0.01	98	0.03	95	0.02	97
Day 14 filter average				**0.02**	**97**	**0.01**	**98**	**0.03**	**96**	**0.02**	**97**
15	0.13	0.66	270	0.01	98	0	100	0.01	98	0.01	99
			750	0.01	98	0	100	0.01	98	0.01	99
			1000	0	100	0.01	98	0.01	98	0.01	99
Day 15 filter average				**0.01**	**99**	**0.00**	**99**	**0.01**	**98**	**0.01**	**99**
16	0.06	0.57	270	0.03	95	0.01	98	0.01	98	0.02	97
			750	0.02	96	0.03	95	0.01	98	0.02	96
			1000	0.01	98	0.02	96	0.03	95	0.02	96
Day 16 filter average				**0.02**	**96**	**0.02**	**96**	**0.02**	**97**	**0.02**	**97**
17	0.09	0.6	270	0.01	98	0	100	0.02	97	0.01	98
			750	0.03	95	0	100	0.01	98	0.01	98
			1000	0.01	98	0	100	0.01	98	0.01	99
Day 17 filter average				**0.02**	**97**	**0.00**	**100**	**0.01**	**98**	**0.01**	**98**
18	0.17	0.75	270	0.04	95	0.01	99	0.03	96	0.03	96
			750	0.03	96	0.02	97	0.01	99	0.02	97
			1000	0.05	93	0.02	97	0.02	97	0.03	96
Day 18 filter average				**0.04**	**95**	**0.02**	**98**	**0.02**	**97**	**0.03**	**97**
19	0.08	0.77	270	0.01	99	0	100	0.01	99	0.01	96
			750	0	100	0	100	0.03	96	0.01	97
			1000	0.01	99	0.01	99	0.03	96	0.02	96
Day 19 filter average				**0.01**	**99**	**0.00**	**100**	**0.02**	**97**	**0.01**	**99**
20	0.12	0.61	270	0.02	97	0.03	95	0.01	98	0.02	97
			750	0.03	95	0.03	95	0.01	98	0.02	96
			1000	0.02	97	0.01	98	0.02	97	0.02	97
Day 20 filter average				**0.02**	**96**	**0.02**	**96**	**0.01**	**98**	**0.02**	**97**
Total Average	**0.09**	**0.64**	270	**0.02**	**97**	**0.01**	**98**	**0.01**	**98**	**0.01**	**97**
			750	**0.02**	**97**	**0.01**	**98**	**0.01**	**98**	**0.01**	**98**
			1000	**0.02**	**97**	**0.01**	**98**	**0.02**	**97**	**0.01**	**98**
				0.02	**97**	**0.01**	**98**	**0.01**	**98**	**0.01**	**98**

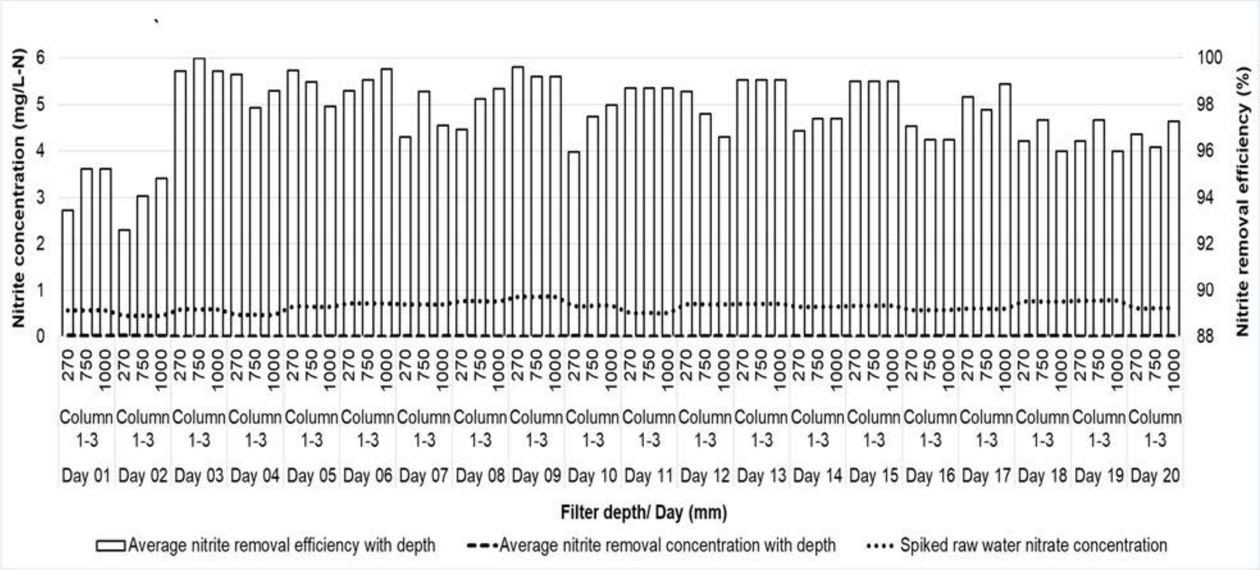


Figure L.57 Overall average nitrite removal in a filter with a source of Carbon at C/N ratio of 1.05.

Table L.58 Daily nitrite concentration and removal efficiency with depth in the filter without a carbon source.

Filter without a carbon source											
Sampling interval (Day)	Unspiked raw water nitrite concentration (mg/L-N)	Spiked raw water nitrite concentration (mg/L-N)	Filter column depths (mm)	Column 1 nitrite concentration at depth (mg/L-N)	Column 1 removal efficiency (%)	Column 2 nitrite concentration at depth (mg/L-N)	Column 2 removal efficiency (%)	Column 3 nitrite concentration at depth (mg/L-N)	Column 3 removal efficiency (%)	Filter average nitrite concentrationat depth (mg/L-N)	Filter avarage removal efficiency (%)
1	0.04	0.56	270	0.16	71	0.08	86	0.13	77	0.12	78
			750	0.15	73	0.14	75	0.17	70	0.15	73
			1000	0.16	71	0.16	71	0.15	73	0.16	72
Day 1 filter average				**0.16**	**72**	**0.13**	**77**	**0.15**	**73**	**0.14**	**74**
2	0.03	0.45	270	0.12	73	0.09	80	0.11	76	0.11	76
			750	0.17	62	0.13	71	0.12	73	0.14	69
			1000	0.12	73	0.15	67	0.14	69	0.14	70
Day 2 filter average				**0.14**	**70**	**0.12**	**73**	**0.12**	**73**	**0.13**	**72**
3	0.08	0.58	270	0.01	98	0.01	98	0.02	97	0.01	98
			750	0.01	98	0.01	98	0.02	97	0.01	98
			1000	0.02	97	0.01	98	0.02	97	0.02	97
Day 3 filter average				**0.01**	**98**	**0.01**	**98**	**0.02**	**97**	**0.01**	**98**
4	0.09	0.47	270	0.03	94	0.02	96	0.03	94	0.03	94
			750	0.06	87	0.03	94	0.02	96	0.04	92
			1000	0.03	94	0.02	96	0.02	96	0.02	95
Day 4 filter average				**0.04**	**91**	**0.02**	**95**	**0.02**	**95**	**0.03**	**94**
5	0.08	0.64	270	0.01	98	0.02	97	0.01	98	0.01	98
			750	0.01	98	0.03	95	0	100	0.01	98
			1000	0	100	0.02	97	0.01	98	0.01	98
Day 5 filter average				**0.01**	**99**	**0.02**	**96**	**0.01**	**99**	**0.01**	**98**
6	0.05	0.71	270	0.03	96	0.04	94	0.03	96	0.03	95
			750	0.02	97	0.02	97	0.02	97	0.02	97
			1000	0.03	96	0.02	97	0.03	96	0.03	96
Day 6 filter average				**0.03**	**96**	**0.03**	**96**	**0.03**	**96**	**0.03**	**96**
7	0.07	0.69	270	0.09	87	0.05	93	0.01	99	0.05	93
			750	0.05	93	0.03	96	0.04	94	0.04	94
			1000	0.04	94	0.02	97	0.01	99	0.02	97
Day 7 filter average				**0.06**	**91**	**0.03**	**95**	**0.02**	**97**	**0.04**	**95**
8	0.09	0.76	270	0.1	87	0.07	91	0.04	95	0.07	91
			750	0.08	89	0.03	96	0.05	93	0.05	93
			1000	0.06	92	0.03	96	0.05	93	0.05	94
Day 8 filter average				**0.08**	**89**	**0.04**	**94**	**0.05**	**94**	**0.06**	**93**
9	0.11	0.85	270	0.03	96	0.05	94	0.01	99	0.03	96
			750	0.01	99	0.01	99	0.01	99	0.01	99
			1000	0.03	96	0.01	99	0	100	0.01	98
Day 9 filter average				**0.02**	**97**	**0.02**	**97**	**0.01**	**99**	**0.02**	**98**
10	0.06	0.66	270	0.07	89	0.05	92	0.03	95	0.05	92
			750	0.06	91	0.02	97	0.02	97	0.03	95
			1000	0.03	95	0.02	97	0.06	91	0.04	94
Day 10 filter average				**0.05**	**92**	**0.03**	**95**	**0.04**	**94**	**0.04**	**94**
11	0.15	0.51	270	0	100	0	100	0.02	96	0.01	99
			750	0.03	94	0.03	94	0.02	96	0.03	95
			1000	0.04	92	0.04	92	0.03	94	0.04	93
Day 11 filter average				**0.02**	**95**	**0.02**	**95**	**0.02**	**95**	**0.02**	**95**
12	0.1	0.69	270	0.07	90	0.04	94	0.03	96	0.05	93
			750	0.09	87	0.06	91	0.03	96	0.06	91
			1000	0.06	91	0.05	93	0.02	97	0.04	94
Day 12 filter average				**0.07**	**89**	**0.05**	**93**	**0.03**	**96**	**0.05**	**93**
13	0.09	0.7	270	0.04	94	0.04	94	0.02	97	0.03	95
			750	0.03	96	0.02	97	0.03	96	0.03	96
			1000	0.03	96	0.03	96	0.04	94	0.03	95
Day 13 filter average				**0.03**	**95**	**0.03**	**96**	**0.03**	**96**	**0.03**	**96**
14	0.07	0.64	270	0.05	92	0.03	95	0.02	97	0.03	95
			750	0.07	89	0.05	92	0.06	91	0.06	91
			1000	0.04	94	0.02	97	0.03	95	0.03	95
Day 14 filter average				**0.05**	**92**	**0.03**	**95**	**0.04**	**94**	**0.04**	**94**
15	0.13	0.66	270	0.05	92	0.03	95	0.02	97	0.03	95
			750	0.04	94	0.03	95	0.02	97	0.03	95
			1000	0.05	92	0.02	97	0.02	97	0.03	95
Day 15 filter average				**0.05**	**93**	**0.03**	**96**	**0.02**	**97**	**0.03**	**95**
16	0.06	0.57	270	0.06	89	0.07	88	0.04	93	0.06	90
			750	0.05	91	0.06	89	0.05	91	0.05	91
			1000	0.09	84	0.05	91	0.06	89	0.07	88
Day 16 filter average				**0.07**	**88**	**0.06**	**89**	**0.05**	**91**	**0.06**	**90**
17	0.09	0.6	270	0.04	93	0.02	97	0.02	97	0.03	96
			750	0.05	92	0.02	97	0.03	95	0.03	94
			1000	0.03	95	0.03	95	0.02	97	0.03	96
Day 17 filter average				**0.04**	**93**	**0.02**	**96**	**0.02**	**96**	**0.03**	**95**
18	0.17	0.75	270	0.09	88	0.06	92	0.03	96	0.06	92
			750	0.06	92	0.06	92	0.03	96	0.05	93
			1000	0.11	85	0.04	95	0.02	97	0.06	92
Day 18 filter average				**0.09**	**88**	**0.05**	**93**	**0.03**	**96**	**0.06**	**93**
19	0.08	0.77	270	0.05	94	0.05	94	0.03	96	0.04	94
			750	0.05	94	0.04	95	0.02	97	0.04	95
			1000	0.03	96	0.03	96	0.02	97	0.03	97
Day 19 filter average				**0.04**	**94**	**0.04**	**95**	**0.02**	**97**	**0.04**	**95**
20	0.12	0.61	270	0.1	84	0.03	95	0.05	92	0.06	90
			750	0.08	87	0.07	89	0.04	93	0.06	90
			1000	0.06	90	0.06	90	0.02	97	0.05	92
Day 20 filter average				**0.08**	**87**	**0.05**	**91**	**0.04**	**94**	**0.06**	**91**
Total Average	**0.09**	**0.64**	270	**0.06**	**90**	**0.04**	**93**	**0.04**	**94**	**0.05**	**93**
			750	**0.06**	**90**	**0.04**	**92**	**0.04**	**93**	**0.05**	**92**
			1000	**0.05**	**91**	**0.04**	**93**	**0.04**	**93**	**0.04**	**92**
				0.06	**91**	**0.04**	**93**	**0.04**	**94**	**0.05**	**92**

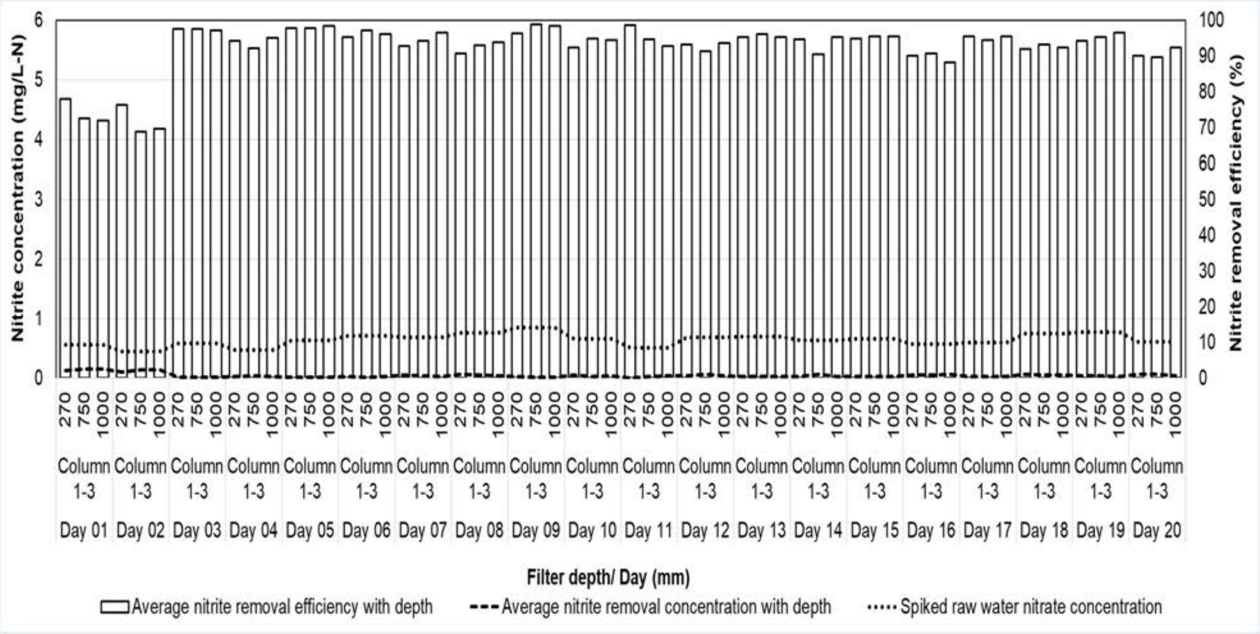


Figure L.59 Overall average nitrite removal in a filter without a source of carbon at inflow nitrate concentration of 15mg/L-N.

L.2. Nitrite at C/N ratio of 1.08 and nitrate concentration of 25mg/L-N

Table L.60 Daily nitrite concentration and removal efficiency with depth in the filter with a carbon source**.**

Filter with carbon source											
Sampling interval (Day)	**Unspiked raw water nitrite concentration (mg/L-N)**	**Spiked raw water nitrite concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 nitrite concentration with depth (mg/L-N)**	**Column 1 removal efficiency (%)**	**Column 2 nitrite concentration with depth (mg/L-N)**	**Column 2 removal efficiency (%)**	**Column 3 nitrite concentration with depth (mg/L-N)**	**Column 3 removal efficiency (%)**	**Filter average nitrite concentrationat depth (mg/L-N)**	**Filter avarage removal efficiency (%)**
1	0.08	2.49	270	2.34	6	2.06	17	2.02	19	2.14	14
			750	2.25	10	1.97	21	0.62	75	1.61	35
			1000	2.3	8	2.13	14	0.58	77	1.67	33
Day 1 filter average				**2.30**	**8**	**2.05**	**18**	**1.07**	**57**	**1.81**	**27**
2	0.19	2.39	270	2.06	14	2.09	13	0.98	59	1.71	28
			750	1.97	18	1.73	28	0.32	87	1.34	44
			1000	1.91	20	1.71	28	0.35	85	1.32	45
Day 2 filter average				**1.98**	**17**	**1.84**	**23**	**0.55**	**77**	**1.46**	**39**
3	0.23	2.61	270	1.18	55	1.36	48	1.79	31	1.44	45
			750	1.97	25	1.61	38	0.64	75	1.41	46
			1000	1.94	26	0.3	89	0.3	89	0.85	68
Day 3 filter average				**1.70**	**35**	**1.09**	**58**	**0.91**	**65**	**1.23**	**53**
4	0.25	2.56	270	0.73	71	1.64	36	0.76	70	1.04	59
			750	1.52	41	1.61	37	0.36	86	1.16	55
			1000	1.88	27	1.06	59	0.03	99	0.99	61
Day 4 filteraverage				**1.38**	**46**	**1.44**	**44**	**0.38**	**85**	**1.07**	**58**
5	0.21	2.54	270	0.91	64	0.78	69	0.88	65	0.86	66
			750	1.64	35	1.37	46	0.54	79	1.18	53
			1000	1.79	30	1.1	57	0.31	88	1.07	58
Day 5 filter average				**1.45**	**43**	**1.08**	**57**	**0.58**	**77**	**1.04**	**59**
6	0.24	2.45	270	1.21	51	0.36	85	0.15	94	0.57	77
			750	0.98	60	0.33	87	0.29	88	0.53	78
			1000	0.42	83	0.36	85	0.32	87	0.37	85
Day 6 filter average				**0.87**	**64**	**0.35**	**86**	**0.25**	**90**	**0.49**	**80**
7	0.18	2.5	270	0.26	90	0.08	97	0.02	99	0.12	95
			750	0.18	93	0.02	99	0.02	99	0.07	97
			1000	0.14	94	0.02	99	0.03	99	0.06	97
Day 7 filter average				**0.19**	**92**	**0.04**	**98**	**0.02**	**99**	**0.09**	**97**
8	0.03	2.45	270	0.12	95	0	100	0	100	0.04	98
			750	0.15	94	0	100	0.03	99	0.06	98
			1000	0.09	96	0.03	99	0.06	98	0.06	98
Day 8 filter average				**0.12**	**95**	**0.01**	**100**	**0.03**	**99**	**0.05**	**98**
9	0.31	2.52	270	0.67	73	0.1	96	0.08	97	0.28	89
			750	0.43	83	0	100	0.09	96	0.17	93
			1000	0.12	95	0.09	96	0.09	96	0.10	96
Day 9 filter average				**0.41**	**84**	**0.06**	**97**	**0.09**	**97**	**0.19**	**93**
10	0	2.48	270	0.15	94	0.24	90	0.02	99	0.14	94
			750	0.47	81	0.19	92	0.02	99	0.23	91
			1000	0.38	85	0.03	99	0.02	99	0.14	94
Day 10 filter average				**0.33**	**87**	**0.15**	**94**	**0.02**	**99**	**0.17**	**93**
11	0.02	2.45	270	0.17	93	0.24	90	0.05	98	0.15	94
			750	0.22	91	0.19	92	0.04	98	0.15	94
			1000	0.27	89	0.07	97	0.01	100	0.12	95
Day 11 filter average				**0.22**	**91**	**0.17**	**93**	**0.03**	**99**	**0.14**	**94**
12	0.01	2.51	270	0.82	67	0.34	86	0.01	100	0.39	84
			750	0.83	67	0.31	88	0.01	100	0.38	85
			1000	0.79	69	0.03	99	0	100	0.27	89
Day 12 filter average				**0.81**	**68**	**0.23**	**91**	**0.01**	**100**	**0.35**	**86**
13	0.14	2.45	270	0.48	80	0.56	77	0.45	82	0.50	80
			750	0.58	76	0.52	79	0.36	85	0.49	80
			1000	0.67	73	0.39	84	0.1	96	0.39	84
Day 13 filter average				**0.58**	**76**	**0.49**	**80**	**0.30**	**88**	**0.46**	**81**
14	0.04	2.56	270	0.05	98	0.02	99	0.01	100	0.03	99
			750	0.04	98	0	100	0.01	100	0.02	99
			1000	0.05	98	0.02	99	0.02	99	0.03	99
Day 14 filter average				**0.05**	**98**	**0.01**	**99**	**0.01**	**99**	**0.02**	**99**
15	0.06	2.45	270	0.02	99	0.02	99	0.01	100	0.02	99
			750	0.03	99	0.02	99	0	100	0.02	99
			1000	0.04	98	0.03	99	0	100	0.02	99
Day 15 filter average				**0.03**	**99**	**0.02**	**99**	**0.00**	**100**	**0.02**	**99**
16	0.05	2.62	270	0.15	94	0.01	100	0.06	98	0.07	97
			750	0.23	91	0.01	100	0.05	98	0.10	96
			1000	0.01	100	0	100	0	100	0.00	100
Day 16 filter average				**0.13**	**95**	**0.01**	**100**	**0.04**	**99**	**0.06**	**98**
17	0.07	2.55	270	0.05	98	0.02	99	0.01	100	0.03	99
			750	0.04	98	0	100	0.02	99	0.02	99
			1000	0.06	98	0.03	99	0.03	99	0.04	98
Day 17 filter average				**0.05**	**98**	**0.02**	**99**	**0.02**	**99**	**0.03**	**99**
18	0.01	2.42	270	0.15	94	0.01	100	0.06	98	0.07	97
			750	0.14	94	0.01	100	0.05	98	0.07	97
			1000	0.12	95	0.02	99	0	100	0.05	98
Day 18 filter average				**0.14**	**94**	**0.01**	**99**	**0.04**	**98**	**0.06**	**97**
19	0.03	2.68	270	0.12	96	0.03	99	0.05	98	0.07	98
			750	0.17	94	0.02	99	0	100	0.06	98
			1000	0.05	98	0.01	100	0.01	100	0.02	99
Day 19 filter average				**0.11**	**96**	**0.02**	**99**	**0.02**	**99**	**0.05**	**98**
20	0.12	2.47	270	0.07	97	0.02	99	0.01	100	0.03	99
			750	0.08	97	0	100	0	100	0.03	99
			1000	0.09	96	0	100	0.02	99	0.04	99
Day 20 filter average				**0.08**	**97**	**0.01**	**100**	**0.01**	**100**	**0.03**	**99**
Total Average	**0.11**	**2.51**	270	**0.59**	**76**	**0.50**	**80**	**0.37**	**85**	**0.49**	**81**
			750	**0.70**	**72**	**0.50**	**80**	**0.17**	**93**	**0.46**	**82**
			1000	**0.66**	**74**	**0.37**	**85**	**0.11**	**95**	**0.38**	**85**
				0.65	**74**	**0.46**	**82**	**0.22**	**91**	**0.44**	**82**

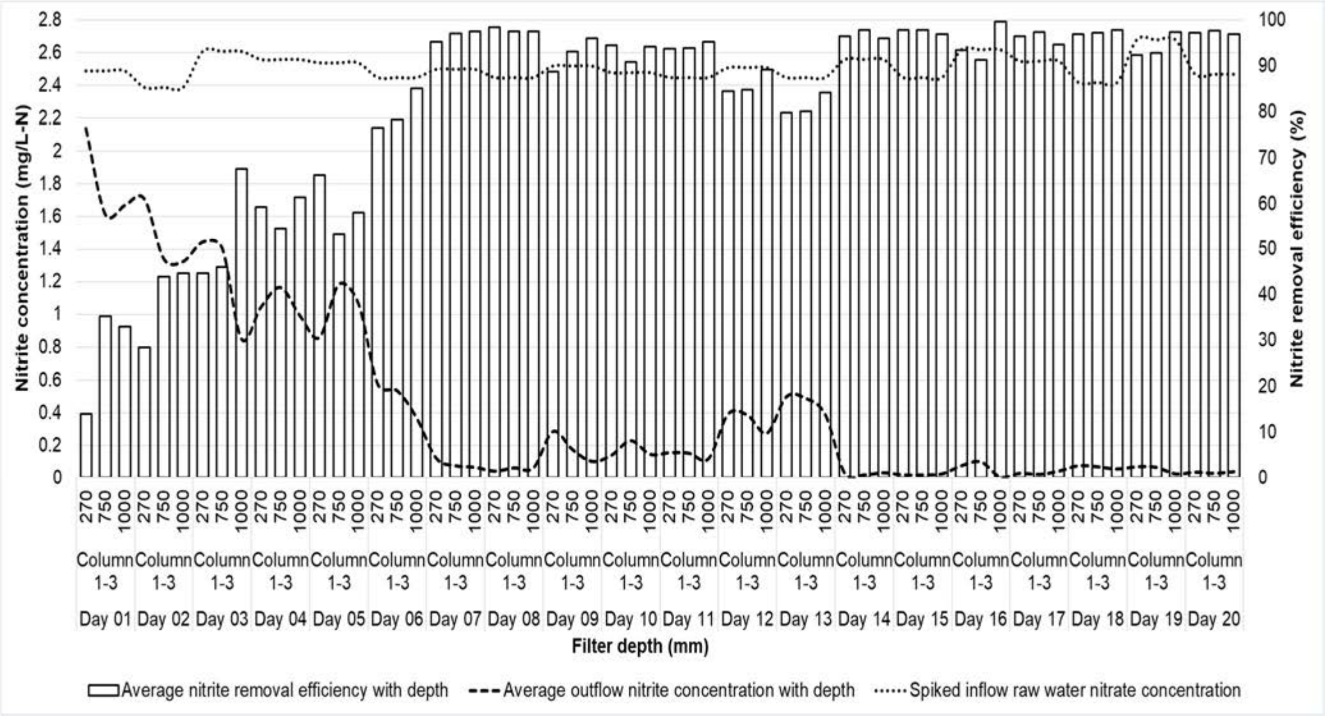


Figure L.61 Overall average nitrite removal in a filter with a source of carbon at C/N ratio of 1.08.

Table L.62 Daily nitrite concentration and removal efficiency with depth in the filter without a carbon source.

Filter without carbon source											
Sampling interval (Day)	**Unspiked raw water nitrite concentration (mg/L-N)**	**Spiked raw water nitrite concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 nitrite concentration with depth (mg/L-N)**	**Column 1 removal efficiency (%)**	**Column 2 nitrite concentration with depth (mg/L-N)**	**Column 2 removal efficiency (%)**	**Column 3 nitrite concentration with depth (mg/L-N)**	**Column 3 removal efficiency (%)**	**Filter average nitrite concentrationat depth (mg/L-N)**	**Filter avarage removal efficiency (%)**
1	0.08	2.49	270	2.18	12	2.17	13	2	20	2.12	15
			750	2.07	17	2.13	14	1.82	27	2.01	19
			1000	2.22	11	2.09	16	0.65	74	1.65	34
Day 1 filter average				**2.16**	**13**	**2.13**	**14**	**1.49**	**40**	**1.93**	**23**
2	0.19	2.39	270	2.18	9	1.98	17	1.93	19	2.03	15
			750	2.1	12	1.81	24	1.73	28	1.88	21
			1000	2.05	14	2.09	13	0.42	82	1.52	36
Day 2 filter average				**2.11**	**12**	**1.96**	**18**	**1.36**	**43**	**1.81**	**24**
3	0.23	2.61	270	2.36	10	2.03	22	1.83	30	2.07	21
			750	2.08	20	2.19	16	1.81	31	2.03	22
			1000	2.03	22	1.93	26	0.36	86	1.44	45
Day 3 filter average				**2.16**	**17**	**2.05**	**21**	**1.33**	**49**	**1.85**	**29**
4	0.25	2.56	270	1.12	56	2	22	1.67	35	1.60	38
			750	2.39	7	1.91	25	1.52	41	1.94	24
			1000	2.39	7	2	22	1.73	32	2.04	20
Day 4 filteraverage				**1.97**	**23**	**1.97**	**23**	**1.64**	**36**	**1.86**	**27**
5	0.21	2.54	270	1.29	49	1.24	51	1.69	33	1.41	45
			750	2.12	17	1.88	26	1.57	38	1.86	27
			1000	2.16	15	1.77	30	1.43	44	1.79	30
Day 5 filter average				**1.86**	**27**	**1.63**	**36**	**1.56**	**38**	**1.68**	**34**
6	0.24	2.45	270	1.15	53	1.18	52	1.12	54	1.15	53
			750	1.15	53	1.21	51	1.12	54	1.16	53
			1000	1.15	53	1.15	53	0.09	96	0.80	67
Day 6 filter average				**1.15**	**53**	**1.18**	**52**	**0.78**	**68**	**1.04**	**58**
7	0.18	2.5	270	1.11	56	0.85	66	0.64	74	0.87	65
			750	1.11	56	0.98	61	0.72	71	0.94	63
			1000	1.11	56	0.79	68	0.81	68	0.90	64
Day 7 filter average				**1.11**	**56**	**0.87**	**65**	**0.72**	**71**	**0.90**	**64**
8	0.03	2.45	270	0.62	75	0.55	78	0.43	82	0.53	78
			750	0.58	76	0.48	80	0.35	86	0.47	81
			1000	0.52	79	0.54	78	0.3	88	0.45	81
Day 8 filter average				**0.57**	**77**	**0.52**	**79**	**0.36**	**85**	**0.49**	**80**
9	0.31	2.52	270	0.27	89	0.22	91	0.18	93	0.22	91
			750	0.32	87	0.25	90	0.15	94	0.24	90
			1000	0.25	90	0.23	91	0.13	95	0.20	92
Day 9 filter average				**0.28**	**89**	**0.23**	**91**	**0.15**	**94**	**0.22**	**91**
10	0	2.48	270	0.11	96	0.07	97	0.09	96	0.09	96
			750	0.09	96	0.05	98	0.08	97	0.07	97
			1000	0.1	96	0.04	98	0.1	96	0.08	97
Day 10 filter average				**0.10**	**96**	**0.05**	**98**	**0.09**	**96**	**0.08**	**97**
11	0.02	2.45	270	0.02	99	0.03	99	0.05	98	0.03	99
			750	0.03	99	0.04	98	0.09	96	0.05	98
			1000	0.04	98	0.05	98	0.1	96	0.06	97
Day 11 filter average				**0.03**	**99**	**0.04**	**98**	**0.08**	**97**	**0.05**	**98**
12	0.01	2.51	270	0.07	97	0.09	96	0.07	97	0.08	97
			750	0.06	98	0.17	93	0.08	97	0.10	96
			1000	0.05	98	0.09	96	0.09	96	0.08	97
Day 12 filter average				**0.06**	**98**	**0.12**	**95**	**0.08**	**97**	**0.09**	**97**
13	0.14	2.45	270	0.13	95	0.15	94	0.15	94	0.14	94
			750	0.13	95	0.14	94	0.14	94	0.14	94
			1000	0.12	95	0.14	94	0.13	95	0.13	95
Day 13 filter average				**0.13**	**95**	**0.14**	**94**	**0.14**	**94**	**0.14**	**94**
14	0.04	2.56	270	0.05	98	0.09	96	0.14	95	0.09	96
			750	0.05	98	0.11	96	0.16	94	0.11	96
			1000	0.07	97	0.12	95	0.11	96	0.10	96
Day 14 filter average				**0.06**	**98**	**0.11**	**96**	**0.14**	**95**	**0.10**	**96**
15	0.06	2.45	270	0.04	98	0.03	99	0.4	84	0.16	94
			750	0.04	98	0.04	98	0.05	98	0.04	98
			1000	0.05	98	0.05	98	0.05	98	0.05	98
Day 15 filter average				**0.04**	**98**	**0.04**	**98**	**0.17**	**93**	**0.08**	**97**
16	0.05	2.62	270	0.04	98	0.03	99	0.05	98	0.04	98
			750	0.04	98	0.04	98	0.04	98	0.04	98
			1000	0.04	98	0.03	99	0.01	100	0.03	99
Day 16 filter average				**0.04**	**98**	**0.03**	**99**	**0.03**	**99**	**0.04**	**99**
17	0.07	2.55	270	0	100	0.02	99	0.02	99	0.01	99
			750	0.01	100	0.01	100	0.01	100	0.01	100
			1000	0.02	99	0.01	100	0.01	100	0.01	99
Day 17 filter average				**0.01**	**100**	**0.01**	**99**	**0.01**	**99**	**0.01**	**100**
18	0.01	2.42	270	0.04	98	0.02	99	0.05	98	0.04	98
			750	0.04	98	0.04	98	0.04	98	0.04	98
			1000	0.04	98	0.01	100	0.01	100	0.02	99
Day 18 filter average				**0.04**	**98**	**0.02**	**99**	**0.03**	**99**	**0.03**	**99**
19	0.03	2.68	270	0.06	98	0.05	98	0.04	99	0.05	98
			750	0.05	98	0.02	99	0.02	99	0.03	99
			1000	0.03	99	0.04	99	0.27	90	0.11	96
Day 19 filter average				**0.05**	**98**	**0.04**	**99**	**0.11**	**96**	**0.06**	**98**
20	0.12	2.47	270	0.04	98	0.03	99	0.02	99	0.03	99
			750	0.05	98	0.04	98	0.02	99	0.04	99
			1000	0.06	98	0.05	98	0.04	98	0.05	98
Day 20 filter average				**0.05**	**98**	**0.04**	**98**	**0.03**	**99**	**0.04**	**98**
Total Average	**0.11**	**2.51**	270	**0.64**	**74**	**0.64**	**74**	**0.63**	**75**	**0.64**	**75**
			750	**0.73**	**71**	**0.68**	**73**	**0.58**	**77**	**0.66**	**74**
			1000	**0.73**	**71**	**0.66**	**74**	**0.34**	**86**	**0.58**	**77**
				0.70	**72**	**0.66**	**74**	**0.52**	**79**	**0.62**	**75**

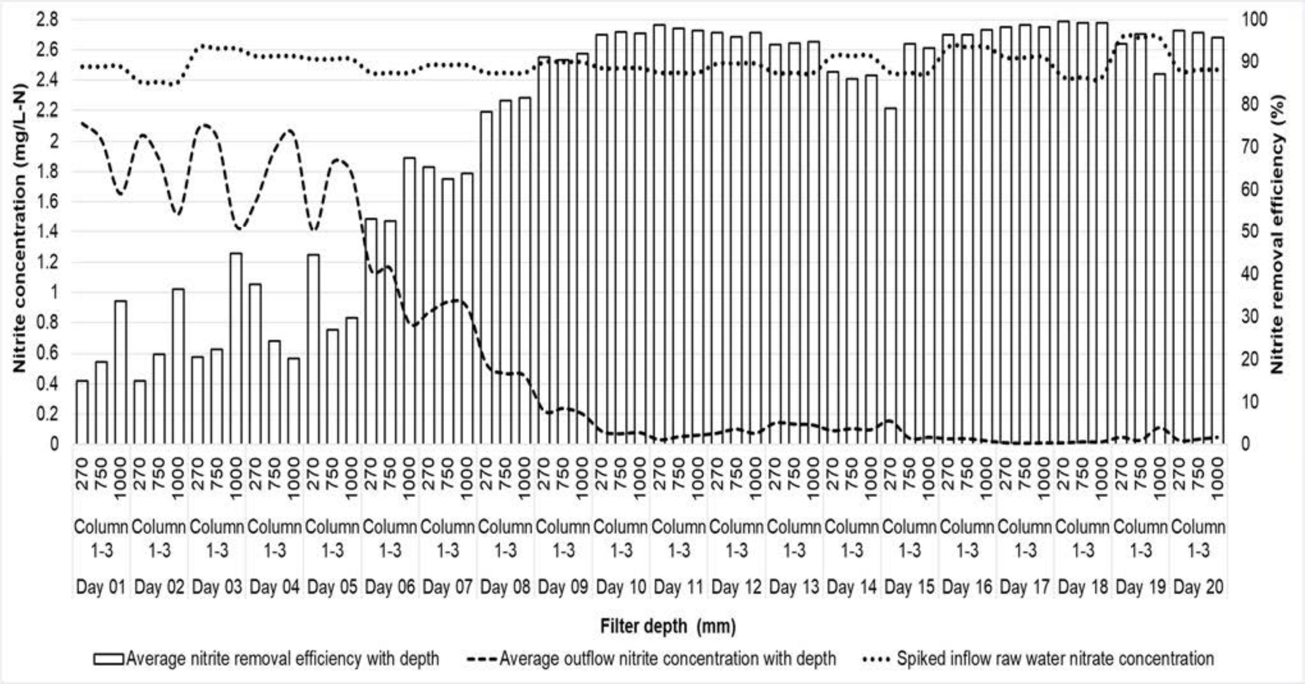


Figure L.63 Overall average nitrite removal in a filter without a source of carbon at inflow nitrate concentration of 25mg/L-N

L.3. Nitrite at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table L.64 Daily nitrite concentration and removal efficiency with depth in the filter with a carbon source.

Filter with a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrite concentration (mg/L-N)**	**Spiked raw water nitrite concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 nitrite concentration at depth (mg/L-N)**	**Column 1 removal efficiency (%)**	**Column 2 nitrite concentration at depth (mg/L-N)**	**Column 2 removal efficiency (%)**	**Column 3 nitrite concentration at depth (mg/L-N)**	**Column 3 removal efficiency (%)**	**Filter average nitrite concentrationat depth (mg/L-N)**	**Filter avarage removal efficiency (%)**
1	0.14	5.67	270	0.52	91	1.27	78	1.15	80	0.98	83
			750	0.85	85	1.48	74	1.09	81	1.14	80
			1000	0.91	84	1.52	73	1.24	78	1.22	78
Day 1 filter average				**0.76**	**87**	**1.42**	**75**	**1.16**	**80**	**1.11**	**80**
2	0.03	5.79	270	0.55	91	2.45	58	1.67	71	1.56	73
			750	0.95	84	2.42	58	2.45	58	1.94	66
			1000	1.69	71	2.52	56	2.3	60	2.17	63
Day 2 filter average				**1.06**	**82**	**2.46**	**57**	**2.14**	**63**	**1.89**	**67**
3	0.07	5.67	270	1.58	72	4.1	28	5	12	3.56	37
			750	2.36	58	5	12	4.82	15	4.06	28
			1000	3.03	47	3.85	32	2.69	53	3.19	44
Day 3 filter average				**2.32**	**59**	**4.32**	**24**	**4.17**	**26**	**3.60**	**36**
4	0.12	5.36	270	0.76	86	1.69	68	1.85	65	1.43	73
			750	1.15	79	3.18	41	2.39	55	2.24	58
			1000	1.76	67	3.33	38	2.64	51	2.58	52
Day 4 filter average				**1.22**	**77**	**2.73**	**49**	**2.29**	**57**	**2.08**	**61**
5	0.04	5.62	270	0.52	91	2.15	62	0.94	83	1.20	79
			750	1.45	74	2.06	63	1.18	79	1.56	72
			1000	1.82	68	2.03	64	1.42	75	1.76	69
Day 5 filter average				**1.26**	**78**	**2.08**	**63**	**1.18**	**79**	**1.51**	**73**
6	0.03	5.66	270	1.12	80	2.85	50	2.67	53	2.21	61
			750	1.45	74	3.21	43	2.09	63	2.25	60
			1000	3.18	44	3.42	40	1.67	70	2.76	51
Day 6 filter average				**1.92**	**66**	**3.16**	**44**	**2.14**	**62**	**2.41**	**57**
7	0.03	5.97	270	0.73	88	2.79	53	3.09	48	2.20	63
			750	1.36	77	1.51	75	3.94	34	2.27	62
			1000	1.97	67	3.5	41	4.09	31	3.19	47
Day 7 filter average				**1.35**	**77**	**2.60**	**56**	**3.71**	**38**	**2.55**	**57**
8	0.03	4.96	270	0.69	86	0.15	97	0.09	98	0.31	94
			750	0.59	88	0.09	98	0.15	97	0.28	94
			1000	0.55	89	0.03	99	0.24	95	0.27	94
Day 8 filter average				**0.61**	**88**	**0.09**	**98**	**0.16**	**97**	**0.29**	**94**
9	0.02	5.69	270	0.58	90	0.03	99	0.05	99	0.22	96
			750	0.29	95	0.03	99	0.04	99	0.12	98
			1000	0.09	98	0.02	100	0.01	100	0.04	99
Day 9 filter average				**0.32**	**94**	**0.03**	**100**	**0.03**	**99**	**0.13**	**98**
10	0.02	5.42	270	1.15	79	0.58	89	0.27	95	0.67	88
			750	0.89	84	0.56	90	0.23	96	0.56	90
			1000	0.67	88	0.45	92	0.06	99	0.39	93
Day 10 filter average				**0.90**	**83**	**0.53**	**90**	**0.19**	**97**	**0.54**	**90**
11	0.03	5.5	270	0.82	85	1.91	65	1.27	77	1.33	76
			750	1.38	75	2.07	62	1.13	79	1.53	72
			1000	1.76	68	1.42	74	0.98	82	1.39	75
Day 11 filter average				**1.32**	**76**	**1.80**	**67**	**1.13**	**80**	**1.42**	**74**
12	0.05	5.48	270	1.3	76	1.09	80	1.55	72	1.31	76
			750	1.52	72	1.24	77	0.5	91	1.09	80
			1000	1.98	64	1.88	66	0.3	95	1.39	75
Day 12 filter average				**1.60**	**71**	**1.40**	**74**	**0.78**	**86**	**1.26**	**77**
13	0.02	4.65	270	1.88	60	1.45	69	0.2	96	1.18	75
			750	1.27	73	1.79	62	0.09	98	1.05	77
			1000	1.55	67	1.27	73	0.14	97	0.99	79
Day 13 filter average				**1.57**	**66**	**1.50**	**68**	**0.14**	**97**	**1.07**	**77**
14	0.03	4.67	270	1.52	67	2.06	56	0.58	88	1.39	70
			750	0.91	81	1.64	65	0.28	94	0.94	80
			1000	2.58	45	0.97	79	0.21	96	1.25	73
Day 14 filter average				**1.67**	**64**	**1.56**	**67**	**0.36**	**92**	**1.19**	**74**
15	0.04	5.15	270	0.88	83	0.42	92	0.03	99	0.44	91
			750	0.55	89	0.01	100	0	100	0.19	96
			1000	0.67	87	0.13	97	0.03	99	0.28	95
Day 15 filter average				**0.70**	**86**	**0.19**	**96**	**0.02**	**100**	**0.30**	**94**
16	0.05	4.93	270	0.61	88	0.05	99	0.02	100	0.23	95
			750	0.48	90	0.02	100	0.01	100	0.17	97
			1000	0.38	92	0.03	99	0.04	99	0.15	97
Day 16 filter average				**0.49**	**90**	**0.03**	**99**	**0.02**	**100**	**0.18**	**96**
17	0.03	4.73	270	0.45	90	0.06	99	0.01	100	0.17	96
			750	0.36	92	0.01	100	0	100	0.12	97
			1000	0.32	93	0.02	100	0.02	100	0.12	97
Day 17 filter average				**0.38**	**92**	**0.03**	**99**	**0.01**	**100**	**0.14**	**97**
18	0.05	5.56	270	0.46	92	0.03	99	0.01	100	0.17	97
			750	0.49	91	0.02	100	0	100	0.17	97
			1000	0.53	90	0.02	100	0.02	100	0.19	97
Day 18 filter average				**0.49**	**91**	**0.02**	**100**	**0.01**	**100**	**0.18**	**97**
19	0.05	4.68	270	0.14	97	0.04	99	0.14	97	0.11	98
			750	0.03	99	0.03	99	0.16	97	0.07	98
			1000	0.08	98	0.06	99	0.18	96	0.11	98
Day 19 filter average				**0.08**	**98**	**0.04**	**99**	**0.16**	**97**	**0.10**	**98**
20	0.05	5.62	270	0.28	95	0.03	99	0.01	100	0.11	98
			750	0.33	94	0.01	100	0	100	0.11	98
			1000	0.27	95	0.02	100	0.03	99	0.11	98
Day 20 filter average				**0.29**	**95**	**0.02**	**100**	**0.01**	**100**	**0.11**	**98**
Total Average	**0.05**	**5.34**	270	**0.83**	**84**	**1.26**	**77**	**1.03**	**82**	**1.04**	**81**
			750	**0.93**	**83**	**1.32**	**76**	**1.03**	**82**	**1.09**	**80**
			1000	**1.29**	**76**	**1.32**	**76**	**0.92**	**84**	**1.18**	**79**
				1.02	**81**	**1.30**	**76**	**0.99**	**82**	**1.10**	**80**

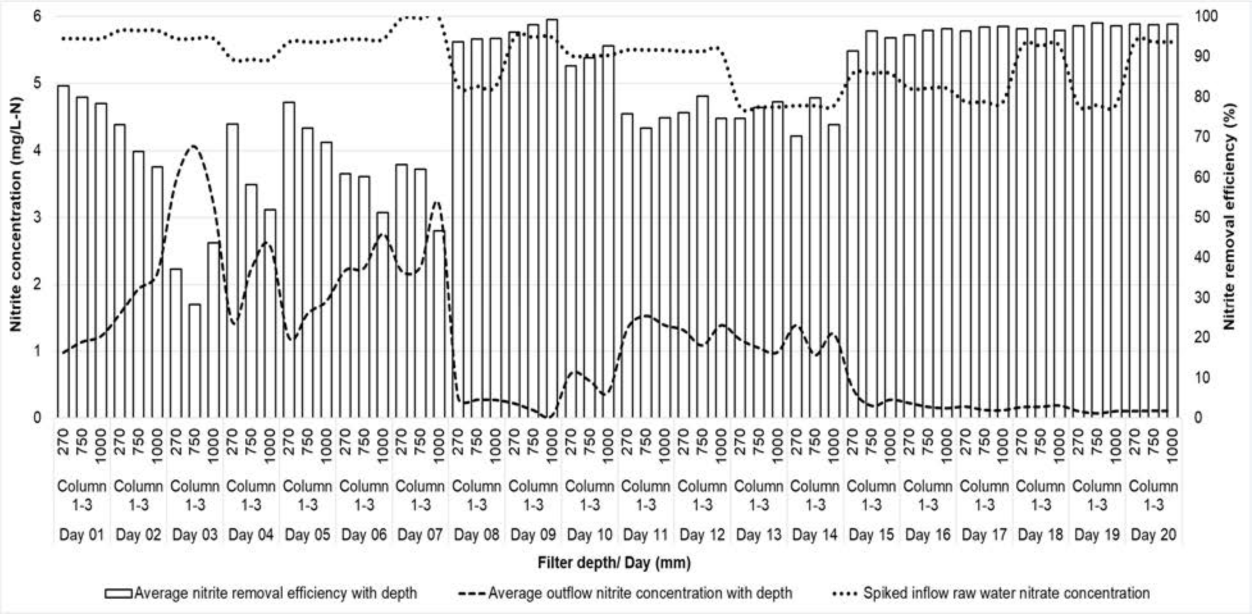


Figure L.65 Overall average nitrite removal in a filter with a source of carbon at C/N ratio of 1.1.

Table L.66 Daily nitrite concentration and removal efficiency with depth in the filter without a carbon source.

Filter without a carbon source											
Sampling interval (Day)	Unspiked raw water nitrite concentration (mg/L-N)	Spiked raw water nitrite concentration (mg/L-N)	Filter column depths (mm)	Column 1 nitrite concentration at depth (mg/L-N)	Column 1 removal efficiency (%)	Column 2 nitrite concentration at depth (mg/L-N)	Column 2 removal efficiency (%)	Column 3 nitrite concentration at depth (mg/L-N)	Column 3 removal efficiency (%)	Filter average nitrite concentrationat depth (mg/L-N)	Filter avarage removal efficiency (%)
1	0.14	5.67	270	0.13	98	0.15	97	0.15	97	0.14	97
			750	0.13	98	0.14	98	0.14	98	0.14	98
			1000	0.12	98	0.14	98	0.13	98	0.13	98
Day 1 filter average				**0.13**	**98**	**0.14**	**97**	**0.14**	**98**	**0.14**	**98**
2	0.03	5.79	270	0.69	88	0.67	88	1.45	75	0.94	84
			750	0.57	90	0.76	87	1.18	80	0.84	86
			1000	0.61	89	0.82	86	0.91	84	0.78	87
Day 2 filter average				**0.62**	**89**	**0.75**	**87**	**1.18**	**80**	**0.85**	**85**
3	0.07	5.67	270	0.89	84	1.06	81	1.12	80	1.02	82
			750	0.94	83	1.12	80	1.09	81	1.05	81
			1000	0.91	84	1.15	80	1.12	80	1.06	81
Day 3 filter average				**0.91**	**84**	**1.11**	**80**	**1.11**	**80**	**1.04**	**82**
4	0.12	5.36	270	0.06	99	0.16	97	0.07	99	0.10	98
			750	0.05	99	0.08	99	0.07	99	0.07	99
			1000	0.05	99	0.04	99	4	25	1.36	75
Day 4 filter average				**0.05**	**99**	**0.09**	**98**	**1.38**	**74**	**0.51**	**91**
5	0.04	5.62	270	0.12	98	0.05	99	0.16	97	0.11	98
			750	0.07	99	0.05	99	0.07	99	0.06	99
			1000	0.04	99	0.05	99	0.05	99	0.05	99
Day 5 filter average				**0.08**	**99**	**0.05**	**99**	**0.09**	**98**	**0.07**	**99**
6	0.03	5.66	270	0.05	99	0.05	99	0.07	99	0.06	99
			750	0.06	99	0.05	99	0.06	99	0.06	99
			1000	0.07	99	0.06	99	0.05	99	0.06	99
Day 6 filter average				**0.06**	**99**	**0.05**	**99**	**0.06**	**99**	**0.06**	**99**
7	0.03	5.97	270	0.02	100	0.02	100	0.19	97	0.08	99
			750	0.03	99	0.01	100	0.05	99	0.03	99
			1000	0.03	99	0.02	100	0.01	100	0.02	100
Day 7 filter average				**0.03**	**100**	**0.02**	**100**	**0.08**	**99**	**0.04**	**99**
8	0.03	4.96	270	0.03	99	0.02	100	0.14	97	0.06	99
			750	0.03	99	0.02	100	0.05	99	0.03	99
			1000	0.03	99	0.02	100	0.02	100	0.02	100
Day 8 filter average				**0.03**	**99**	**0.02**	**100**	**0.07**	**99**	**0.04**	**99**
9	0.02	5.69	270	0.03	99	0.03	99	0.16	97	0.07	99
			750	0.03	99	0.02	100	0.05	99	0.03	99
			1000	0.02	100	0.01	100	0.02	100	0.02	100
Day 9 filter average				**0.03**	**100**	**0.02**	**100**	**0.08**	**99**	**0.04**	**99**
10	0.02	5.42	270	0.03	99	0.27	95	0.6	89	0.30	94
			750	0.02	100	0.02	100	0.04	99	0.03	100
			1000	0.02	100	0.01	100	0.02	100	0.02	100
Day 10 filter average				**0.02**	**100**	**0.10**	**98**	**0.22**	**96**	**0.11**	**98**
11	0.03	5.5	270	0.19	97	0.06	99	0.07	99	0.11	98
			750	0.13	98	0.05	99	0.07	99	0.08	98
			1000	0.12	98	0.05	99	0.04	99	0.07	99
Day 11 filter average				**0.15**	**97**	**0.05**	**99**	**0.06**	**99**	**0.09**	**98**
12	0.05	5.48	270	0.02	100	0.04	99	0.19	97	0.08	98
			750	0.02	100	0.04	99	0.15	97	0.07	99
			1000	0.03	99	0.05	99	0.11	98	0.06	99
Day 12 filter average				**0.02**	**100**	**0.04**	**99**	**0.15**	**97**	**0.07**	**99**
13	0.02	4.65	270	0.12	97	0.04	99	0.05	99	0.07	98
			750	0.04	99	0.03	99	0.05	99	0.04	99
			1000	0.09	98	0.02	100	0.07	98	0.06	99
Day 13 filter average				**0.08**	**98**	**0.03**	**99**	**0.06**	**99**	**0.06**	**99**
14	0.03	4.67	270	0.09	98	0.03	99	0.06	99	0.06	99
			750	0.01	100	0.01	100	0.02	100	0.01	100
			1000	0.04	99	0.03	99	0.07	99	0.05	99
Day 14 filter average				**0.05**	**99**	**0.02**	**100**	**0.05**	**99**	**0.04**	**99**
15	0.04	5.15	270	0.08	98	0.13	97	0.12	98	0.11	98
			750	0.05	99	0.05	99	0.05	99	0.05	99
			1000	0.07	99	0.08	98	0.06	99	0.07	99
Day 15 filter average				**0.07**	**99**	**0.09**	**98**	**0.08**	**99**	**0.08**	**99**
16	0.05	4.93	270	0.05	99	0.06	99	0.05	99	0.05	99
			750	0.04	99	0.03	99	0.04	99	0.04	99
			1000	0.06	99	0.07	99	0.01	100	0.05	99
Day 16 filter average				**0.05**	**99**	**0.05**	**99**	**0.03**	**99**	**0.05**	**99**
17	0.03	4.73	270	0.01	100	0.03	99	0.04	99	0.03	99
			750	0.02	100	0	100	0.03	99	0.02	100
			1000	0.06	99	0.03	99	0.04	99	0.04	99
Day 17 filter average				**0.03**	**99**	**0.02**	**100**	**0.04**	**99**	**0.03**	**99**
18	0.05	5.56	270	0.13	98	0.16	97	0.21	96	0.17	97
			750	0.17	97	0.17	97	0.22	96	0.19	97
			1000	0.15	97	0.19	97	0.21	96	0.18	97
Day 18 filter average				**0.15**	**97**	**0.17**	**97**	**0.21**	**96**	**0.18**	**97**
19	0.05	4.68	270	0.09	98	0.07	99	0.08	98	0.08	98
			750	0.07	99	0.08	98	0.09	98	0.08	98
			1000	0.16	97	0.12	97	0.12	97	0.13	97
Day 19 filter average				**0.11**	**98**	**0.09**	**98**	**0.10**	**98**	**0.10**	**98**
20	0.05	5.62	270	0.04	99	0	100	0.03	99	0.02	100
			750	0.02	100	0.01	100	0.03	99	0.02	100
			1000	0.02	100	0.02	100	0.04	99	0.03	100
Day 20 filter average				**0.03**	**100**	**0.01**	**100**	**0.03**	**99**	**0.02**	**100**
Total Average	**0.05**	**5.34**	270	**0.14**	**97**	**0.16**	**97**	**0.25**	**95**	**0.18**	**97**
			750	**0.13**	**98**	**0.14**	**98**	**0.18**	**97**	**0.15**	**97**
			1000	**0.14**	**98**	**0.15**	**97**	**0.36**	**93**	**0.21**	**96**
				0.13	**98**	**0.15**	**97**	**0.26**	**95**	**0.18**	**97**

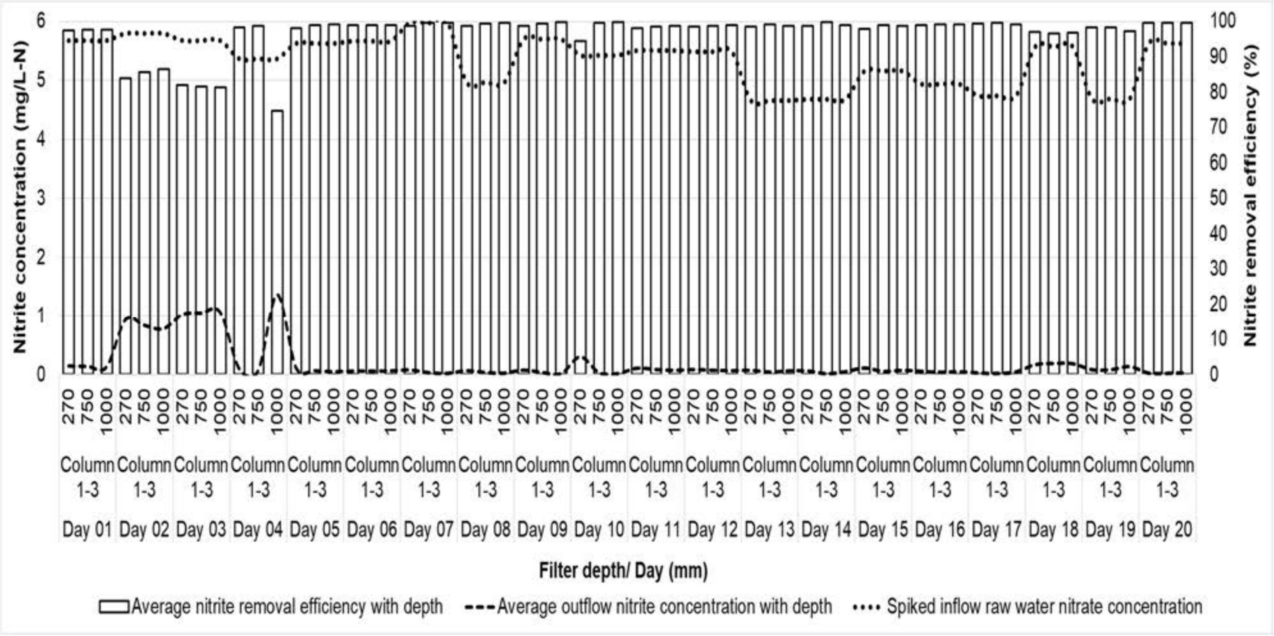


Figure L.67 Overall average nitrite removal in a filter without a source of carbon at inflow nitrate concentration of 50mg/L-N**.**

Appendix M. Nitrate concentration at varied filter depth

The tables below represent the daily nitrate concentration and removal efficiency with depth in the filter with and without a Carbon source during the filter operation.

M.1. Nitrate at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Table M.68 Daily nitrate concentration and removal efficiency with depth in the filter with a carbon source.

Filter with a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrate concentration (mg/L-N)**	**Spiked raw water nitrate concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 filtrate concentration (mg/L-N)**	**Column 1 Nitrate removal efficiency (%)**	**Column 2 filtrate concentration (mg/L-N)**	**Column 2 Nitrate removal efficiency (%)**	**Column 3 average concentration (mg/L-N)**	**Column 3 Nitrate removal efficiency (%)**	**Filter average concentration at depth (mg/L-N)**	**Filter avarage depth nitrate removal efficiency (%)**
1	12.27	15.16	270	2.86	81	3.39	78	2.23	85	2.83	81
			750	3.16	79	4.45	71	2.5	84	3.37	78
			1000	4.02	73	5.07	67	3.77	75	4.29	72
Day 1 filter average				**3.35**	**78**	**4.30**	**72**	**2.83**	**81**	**3.49**	**77**
2	10.23	15.07	270	2.7	82	3.14	79	2.32	85	2.72	82
			750	2.82	81	3.77	75	2.66	82	3.08	80
			1000	3.57	76	4.07	73	3.27	78	3.64	76
Day 2 filter average				**3.03**	**80**	**3.66**	**76**	**2.75**	**82**	**3.15**	**79**
3	8.86	15.12	270	3.41	77	2.82	81	2.64	83	2.96	80
			750	5	67	4.18	72	3.64	76	4.27	72
			1000	4	74	4.32	71	4.45	71	4.26	72
Day 3 filter average				**4.14**	**73**	**3.77**	**75**	**3.58**	**76**	**3.83**	**75**
4	9.55	15.06	270	2.32	85	1.41	91	2.27	85	2.00	87
			750	1.68	89	2.23	85	2.09	86	2.00	87
			1000	2.75	82	2.82	81	2.64	82	2.74	82
Day 4 filter average				**2.25**	**85**	**2.15**	**86**	**2.33**	**85**	**2.25**	**85**
5	12.73	15.24	270	1.86	88	2.14	86	1.64	89	1.88	88
			750	2.27	85	1.43	91	1.32	91	1.67	89
			1000	2.84	81	2.52	83	2.41	84	2.59	83
Day 5 filter average				**2.32**	**85**	**2.03**	**87**	**1.79**	**88**	**2.05**	**87**
6	10.91	15.08	270	2.48	84	3.14	79	2.09	86	2.57	83
			750	2.2	85	3.45	77	2.34	84	2.66	82
			1000	2.57	83	3.73	75	2.75	82	3.02	80
Day 6 filter average				**2.42**	**84**	**3.44**	**77**	**2.39**	**84**	**2.75**	**82**
7	11.36	15.04	270	4	73	3.05	80	3	80	3.35	78
			750	2.36	84	2.91	81	3.27	78	2.85	81
			1000	4.32	71	2.82	81	3.73	75	3.62	76
Day 7 filter average				**3.56**	**76**	**2.93**	**81**	**3.33**	**78**	**3.27**	**78**
8	8.64	15.28	270	3.59	77	3.91	74	4.41	71	3.97	74
			750	3.14	79	3.27	79	3.29	78	3.23	79
			1000	3.73	76	4.02	74	5.58	63	4.44	71
Day 8 filter average				**3.49**	**77**	**3.73**	**76**	**4.43**	**71**	**3.88**	**75**
9	9.55	15.16	270	2.64	83	2.36	84	2.82	81	2.61	83
			750	3.27	78	2.73	82	3	80	3.00	80
			1000	4	74	3.23	79	3.18	79	3.47	77
Day 9 filter average				**3.30**	**78**	**2.77**	**82**	**3.00**	**80**	**3.03**	**80**
10	8.41	15.18	270	1.34	91	1.09	93	0.89	94	1.11	93
			750	1.07	93	1.34	91	0.98	94	1.13	93
			1000	1.52	90	1.61	89	1.43	91	1.52	90
Day 10 filter average				**1.31**	**91**	**1.35**	**91**	**1.10**	**93**	**1.25**	**92**
11	8	15.01	270	0.23	98	0.09	99	0.14	99	0.15	99
			750	0.36	98	0.14	99	0.27	98	0.26	98
			1000	0.41	97	0.23	98	0.36	98	0.33	98
Day 11 filter average				**0.33**	**98**	**0.15**	**99**	**0.26**	**98**	**0.25**	**98**
12	13.27	15.17	270	0.43	97	0.38	97	0.2	99	0.34	98
			750	0.5	97	0.29	98	0.15	99	0.31	98
			1000	0.57	96	0.48	97	0.27	98	0.44	97
Day 12 filter average				**0.50**	**97**	**0.38**	**97**	**0.21**	**99**	**0.36**	**98**
13	14.5	15.03	270	0.5	97	0.14	99	0.68	95	0.44	97
			750	0.41	97	0.18	99	0.55	96	0.38	97
			1000	0.59	96	0.27	98	0.82	95	0.56	96
Day 13 filter average				**0.50**	**97**	**0.20**	**99**	**0.68**	**95**	**0.46**	**97**
14	9.02	15.14	270	0.7	95	0.41	97	0.36	98	0.49	97
			750	0.57	96	0.61	96	0.43	97	0.54	96
			1000	0.2	99	0.75	95	0.55	96	0.50	97
Day 14 filter average				**0.49**	97	**0.59**	**96**	**0.45**	**97**	**0.51**	**97**
15	13.18	15.23	270	0.18	99	0.45	97	0.5	97	0.38	98
			750	0.27	98	0.14	99	0.32	98	0.24	98
			1000	0.41	97	0.86	94	0.68	96	0.65	96
Day 15 filter average				**0.29**	**98**	**0.48**	**97**	**0.50**	**97**	**0.42**	**97**
16	9.32	15.03	270	1.5	90	0.7	95	1.09	93	1.10	93
			750	0.95	94	1.29	91	1.41	91	1.22	92
			1000	1.77	88	2.09	86	1.97	87	1.94	87
Day 16 filter average				**1.41**	**91**	**1.36**	**91**	**1.49**	**90**	**1.42**	**91**
17	11.36	15.11	270	0.23	98	0.91	94	0.55	96	0.56	96
			750	0.27	98	2	87	1.36	91	1.21	92
			1000	0.45	97	2.27	85	1.73	89	1.48	90
Day 17 filter average				**0.32**	**98**	**1.73**	**89**	**1.21**	**92**	**1.09**	**93**
18	8.18	15.16	270	1.57	90	1.29	91	1.34	91	1.40	91
			750	1.2	92	1.86	88	1.43	91	1.50	90
			1000	1.77	88	2.14	86	1.98	87	1.96	87
Day 18 filter average				**1.51**	**90**	**1.76**	**88**	**1.58**	**90**	**1.62**	**89**
19	9.55	15.25	270	0.09	99	1.27	92	1.36	91	0.91	94
			750	0.18	99	1.64	89	1.55	90	1.12	93
			1000	0.5	97	1.73	89	1.91	87	1.38	91
Day 19 filter average				**0.26**	**98**	**1.55**	**90**	**1.61**	**89**	**1.14**	**93**
20	11.59	15.02	270	0.25	98	0.4	97	0.5	97	0.38	97
			750	0.17	99	0.33	98	0.65	96	0.38	97
			1000	0.52	97	0.83	94	0.86	94	0.74	95
Day 20 filter average				**0.31**	**98**	**0.52**	**97**	**0.67**	**96**	**0.50**	**97**
Total Average	**10.52**	**15.13**	270	**1.64**	**89**	**1.62**	**89**	**1.55**	**90**	**1.61**	**89**
			750	**1.59**	**89**	**1.91**	**87**	**1.66**	**89**	**1.72**	**89**
			1000	**2.03**	**87**	**2.29**	**85**	**2.22**	**85**	**2.18**	**86**
				1.75	**88**	**1.94**	**87**	**1.81**	**88**	**1.84**	**88**

Table M.69 Daily nitrate concentration and removal efficiency with depth in the filter without a carbon source**.**

Filter without a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrate concentration (mg/L-N)**	**Spiked raw water nitrate concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 filtrate concentration (mg/L-N)**	**Column 1 Nitrate removal efficiency (%)**	**Column 2 filtrate concentration (mg/L-N)**	**Column 2 Nitrate removal efficiency (%)**	**Column 3 average concentration (mg/L-N)**	**Column 3 Nitrate removal efficiency (%)**	**Filter average concentration at depth (mg/L-N)**	**Filter avarage depth nitrate removal efficiency (%)**
1	12.27	15.16	270	7.34	52	6.93	54	6.68	56	6.98	54
			750	9.18	39	6.57	57	7.07	53	7.61	50
			1000	9.57	37	7.57	50	7.45	51	8.20	46
Day 1 filter average				**8.70**	**43**	**7.02**	**54**	**7.07**	**53**	**7.60**	**50**
2	10.23	15.07	270	7.09	53	6.68	56	5.98	60	6.58	56
			750	8.23	45	6.18	59	5.09	66	6.50	57
			1000	9.48	37	7.77	48	6.39	58	7.88	48
Day 2 filter average				**8.27**	**45**	**6.88**	**54**	**5.82**	**61**	**6.99**	**54**
3	8.86	15.12	270	5.77	62	6.36	58	6.82	55	6.32	58
			750	5.07	66	6.64	56	7.82	48	6.51	57
			1000	6.27	59	7.18	53	8.41	44	7.29	52
Day 3 filter average				**5.70**	**62**	**6.73**	**56**	**7.68**	**49**	**6.70**	**56**
4	9.55	15.06	270	3.79	75	4.09	73	6.68	56	4.85	68
			750	2.91	81	3.61	76	7.07	53	4.53	70
			1000	4.64	69	4.47	70	7.45	51	5.52	63
Day 4 filter average				**3.78**	**75**	**4.06**	**73**	**7.07**	**53**	**4.97**	**67**
5	12.73	15.24	270	5.55	64	5.07	67	7	54	5.87	61
			750	4.64	70	4.45	71	7.91	48	5.67	63
			1000	6.41	58	5.64	63	8.09	47	6.71	56
Day 5 filter average				**5.53**	**64**	**5.05**	**67**	**7.67**	**50**	**6.08**	**60**
6	10.91	15.08	270	6.91	54	5.75	62	6.02	60	6.23	59
			750	6.5	57	4.93	67	5.55	63	5.66	62
			1000	7.48	50	6.18	59	8.36	45	7.34	51
Day 6 filter average				**6.96**	**54**	**5.62**	**63**	**6.64**	**56**	**6.41**	**58**
7	11.36	15.04	270	5.39	64	4.52	70	4.16	72	4.69	69
			750	4.59	69	3.95	74	3.55	76	4.03	73
			1000	5.86	61	4.93	67	4.68	69	5.16	66
Day 7 filter average				**5.28**	**65**	**4.47**	**70**	**4.13**	**73**	**4.63**	**69**
8	8.64	15.28	270	5.89	61	5.05	67	4.43	71	5.12	66
			750	4.84	68	4.16	73	3.73	76	4.24	72
			1000	6.91	55	5.59	63	4.95	68	5.82	62
Day 8 filter average				**5.88**	**62**	**4.93**	**68**	**4.37**	**71**	**5.06**	**67**
9	9.55	15.16	270	6.8	55	3.27	78	4.45	71	4.84	68
			750	7.64	50	3.55	77	3.36	78	4.85	68
			1000	8.59	43	5	67	5.41	64	6.33	58
Day 9 filter average				**7.68**	**49**	**3.94**	**74**	**4.41**	**71**	**5.34**	**65**
10	8.41	15.18	270	7.77	49	6.55	57	7.5	51	7.27	52
			750	7.11	53	6.98	54	5.75	62	6.61	56
			1000	8.18	46	7.36	52	8.43	44	7.99	47
Day 10 filter average				**7.69**	**49**	**6.96**	**54**	**7.23**	**52**	**7.29**	**52**
11	8	15.01	270	5.75	62	4.41	71	4.05	73	4.74	68
			750	4.86	68	3.93	74	3.55	76	4.11	73
			1000	6.16	59	5.14	66	4.5	70	5.27	65
Day 11 filter average				**5.59**	**63**	**4.49**	**70**	**4.03**	**73**	**4.71**	**69**
12	13.27	15.17	270	2.64	83	6.73	56	5.55	63	6.36	67
			750	5.82	62	7.55	50	3.73	75	5.70	62
			1000	6.82	55	8.09	47	4.43	71	6.45	58
Day 12 filter average				**5.09**	**66**	**7.46**	**51**	**4.57**	**70**	**5.71**	**62**
13	14.5	15.03	270	5.55	63	3.64	76	4.59	69	4.59	69
			750	6	60	3.45	77	3.55	76	4.33	71
			1000	6.27	58	4.32	71	5.09	66	5.23	65
Day 13 filter average				**5.94**	**60**	**3.80**	**75**	**4.41**	**71**	**4.72**	**69**
14	9.02	15.14	270	3.39	78	5.09	66	6.02	60	4.83	68
			750	4.73	69	6.41	58	7.59	50	6.24	59
			1000	5.41	64	7.07	53	8.11	46	6.86	55
Day 14 filter average				**4.51**	70	**6.19**	**59**	**7.24**	**52**	**5.98**	**61**
15	13.18	15.23	270	4.14	73	3.73	76	4.02	74	3.96	74
			750	3.43	77	5.86	62	3.73	76	4.34	72
			1000	4.84	68	6.45	58	4.43	71	5.24	66
Day 15 filter average				**4.14**	**73**	**5.35**	**65**	**4.06**	**73**	**4.51**	**70**
16	9.32	15.03	270	3.2	79	2.23	85	1.86	88	2.43	84
			750	2.57	83	2.41	84	2.29	85	2.42	84
			1000	3.5	77	3	80	2.86	81	3.12	79
Day 16 filter average				**3.09**	**79**	**2.55**	**83**	**2.34**	**84**	**2.66**	**82**
17	11.36	15.11	270	2.93	81	3.32	78	2.34	85	2.86	81
			750	2.14	86	2.66	82	1.73	89	2.18	86
			1000	3.73	75	3.59	76	2.82	81	3.38	78
Day 17 filter average				**2.93**	**81**	**3.19**	**79**	**2.30**	**85**	**2.81**	**81**
18	8.18	15.16	270	2.88	81	1.98	87	2.16	86	2.34	85
			750	2.23	85	2.57	83	2.41	84	2.40	84
			1000	2.32	85	2.82	81	2.91	81	2.68	82
Day 18 filter average				**2.48**	**84**	**2.46**	**84**	**2.49**	**84**	**2.48**	**84**
19	9.55	15.25	270	0.82	95	1.09	93	1.45	90	1.12	93
			750	1	93	1.27	92	1.64	89	1.30	91
			1000	1.36	91	1.55	90	1.82	88	1.58	90
Day 19 filter average				**1.06**	**93**	**1.30**	**91**	**1.64**	**89**	**1.33**	**91**
20	11.59	15.02	270	1.66	89	1.08	93	1.15	92	1.30	91
			750	1.34	91	0.9	94	1.75	88	1.33	91
			1000	2.15	86	1.94	87	2.08	86	2.06	86
Day 20 filter average				**1.72**	**89**	**1.31**	**91**	**1.66**	**89**	**1.56**	**90**
Total Average	**10.52**	**15.13**	270	**4.76**	**69**	**4.38**	**71**	**4.65**	**69**	**4.67**	**70**
			750	**4.74**	**69**	**4.40**	**71**	**4.44**	**71**	**4.53**	**70**
			1000	**5.80**	**62**	**5.28**	**65**	**5.43**	**64**	**5.50**	**64**
				5.10	**66**	**4.69**	**69**	**4.84**	**68**	**4.88**	**68**

M.2. Nitrate at C/N ratio of 1.08 and nitrate concentration of 25 mg/L-N

Table M.70 Daily nitrate concentration and removal efficiency with depth in the filter with a carbon source.

Filter with a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrate concentration (mg/L-N)**	**Spiked raw water nitrate concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 filtrate concentration (mg/L-N)**	**Column 1 Nitrate removal efficiency (%)**	**Column 2 filtrate concentration (mg/L-N)**	**Column 2 Nitrate removal efficiency (%)**	**Column 3 filtrate concentration (mg/L-N)**	**Column 3 Nitrate removal efficiency (%)**	**Filter average concentration at depth (mg/L-N)**	**Filter avarage depth nitrate removal efficiency (%)**
1	15.9	25.59	270	5.93	77	7.95	69	11.8	54	8.56	67
			750	6.82	73	6.39	75	4.82	81	6.01	77
			1000	12.27	52	5.18	80	5.36	79	7.60	70
Day 1 filter average				**8.34**	**67**	**6.51**	**75**	**7.33**	**71**	**7.39**	**71**
2	6.09	25	270	8.45	66	10.91	56	10.91	56	10.09	60
			750	5.27	79	15.45	38	8.82	65	9.85	61
			1000	7.18	71	14.09	44	14.09	44	11.79	53
Day 2 filter average				**6.97**	**72**	**13.48**	**46**	**11.27**	**55**	**10.57**	**58**
3	8.73	25.68	270	8.27	68	11.8	54	11.8	54	10.62	59
			750	10	61	11.8	54	7.91	69	9.90	61
			1000	10	61	12.27	52	14.55	43	12.27	52
Day 3 filter average				**9.42**	**63**	**11.96**	**53**	**11.42**	**56**	**10.93**	**57**
4	8	26.07	270	10.45	60	15	42	18.18	30	14.54	44
			750	8.41	68	13.64	48	18.64	29	13.56	48
			1000	13.18	49	16.36	37	19.09	27	16.21	38
Day 4 filter average				**10.68**	**59**	**15.00**	**42**	**18.64**	**29**	**14.77**	**43**
5	15	25.64	270	11.81	54	9.18	64	15.45	40	12.15	53
			750	10.45	59	11.82	54	13.64	47	11.97	53
			1000	15.45	40	15.91	38	10.45	59	13.94	46
Day 5 filter average				**12.57**	**51**	**12.30**	**52**	**13.18**	**49**	**12.68**	**51**
6	9.55	25.32	270	10.91	57	14.55	43	12.5	51	12.65	50
			750	11.82	53	13.64	46	10.75	58	12.07	52
			1000	12.73	50	16.82	34	13.18	48	14.24	44
Day 6 filter average				**11.82**	**53**	**15.00**	**41**	**12.14**	**52**	**12.99**	**49**
7	14.55	25.19	270	12.7	50	17.27	31	15	40	14.99	40
			750	8.18	68	20.45	19	10.27	59	12.97	49
			1000	16.82	33	20.9	17	3.09	88	13.60	46
Day 7 filter average				**12.57**	**50**	**19.54**	**22**	**9.45**	**62**	**13.85**	**45**
8	17.27	25.29	270	11.82	53	13.18	48	9.09	64	11.36	55
			750	12.7	50	14.09	44	10.45	59	12.41	51
			1000	19.9	21	15.91	37	11.82	53	15.88	37
Day 8 filter average				**14.81**	**41**	**14.39**	**43**	**10.45**	**59**	**13.22**	**48**
9	17.73	25.19	270	10.45	59	10.91	57	9.02	64	10.13	60
			750	10	60	8.84	65	9.57	62	9.47	62
			1000	11.82	53	12.55	50	11.05	56	11.81	53
Day 9 filter average				**10.76**	**57**	**10.77**	**57**	**9.88**	**61**	**10.47**	**58**
10	15.91	25.39	270	6.5	74	6.95	73	7.36	71	6.94	73
			750	6.5	74	7.27	71	10.45	59	8.07	68
			1000	6.64	74	9.45	63	11.8	54	9.30	63
Day 10 filter average				**6.55**	**74**	**7.89**	**69**	**9.87**	**61**	**8.10**	**68**
11	17.73	25.19	270	4.64	82	5.91	77	8.18	68	6.24	75
			750	1.96	92	7.27	71	9.09	64	6.11	76
			1000	5.36	79	14.5	42	10	60	9.95	60
Day 11 filter average				**3.99**	**84**	**9.23**	**63**	**9.09**	**64**	**7.43**	**70**
12	5.73	25.33	270	5.27	79	6.91	73	5.14	80	5.77	77
			750	5.82	77	8.27	67	5.45	78	6.51	74
			1000	6.45	75	8.73	66	5.82	77	7.00	72
Day 12 filter average				**5.85**	**77**	**7.97**	**69**	**5.47**	**78**	**6.43**	**75**
13	7.55	25.25	270	3.45	86	4.5	82	4.27	83	4.07	84
			750	3.86	85	4.82	81	3.59	86	4.09	84
			1000	4.18	83	4.27	83	3	88	3.82	85
Day 13 filter average				**3.83**	**85**	**4.53**	**82**	**3.62**	**86**	**3.99**	**84**
14	11.36	25.18	270	2.89	89	2.55	90	3.98	84	3.14	88
			750	3.25	87	3.77	85	3.57	86	3.53	86
			1000	3.5	86	4.29	83	4.16	83	3.98	84
Day 14 filter average				**3.21**	**87**	**3.54**	**86**	**3.90**	**84**	**3.55**	**86**
15	15.9	25.24	270	1.82	93	2.05	92	3.55	86	2.47	90
			750	1.27	95	2.82	89	8.59	66	4.23	83
			1000	3.18	87	4.18	83	8.73	65	5.36	79
Day 15 filter average				**2.09**	**92**	**3.02**	**88**	**6.96**	**72**	**4.02**	**84**
16	9.45	25.31	270	2.52	90	1.77	93	1.86	93	2.05	92
			750	2.23	91	1.55	94	3.73	85	2.50	90
			1000	2.86	89	2.36	91	4.11	84	3.11	88
Day 16 filter average				**2.54**	**90**	**1.89**	**93**	**3.23**	**87**	**2.55**	**90**
17	10.45	25.2	270	1.91	92	1.14	95	3.45	86	2.17	91
			750	2.5	90	1.32	95	2.5	90	2.11	92
			1000	3.14	88	1.41	94	4.6	82	3.05	88
Day 17 filter average				**2.52**	**90**	**1.29**	**95**	**3.52**	**86**	**2.44**	**90**
18	20	25.18	270	2.23	91	1.09	96	3.27	87	2.20	91
			750	2.36	91	2.41	90	2.91	88	2.56	90
			1000	4.4	83	2.57	90	4.52	82	3.83	85
Day 18 filter average				**3.00**	**88**	**2.02**	**92**	**3.57**	**86**	**2.86**	**89**
19	16.36	25.03	270	2	92	1.36	95	2.49	90	1.95	92
			750	2.16	91	1.32	95	2.87	89	2.12	92
			1000	2.57	90	1.95	92	3.13	87	2.55	90
Day 19 filter average				**2.24**	**91**	**1.54**	**94**	**2.83**	**89**	**2.21**	**91**
20	9	25.23	270	1.96	92	2.22	91	2.57	90	2.25	91
			750	1.59	94	1.32	95	2.47	90	1.79	93
			1000	2.86	89	1.5	94	3.23	87	2.53	90
Day 20 filter average				**2.14**	**92**	**1.68**	**93**	**2.76**	**89**	**2.19**	**91**
Total Average	**12.61**	**25.33**	270	**6.30**	**75**	**7.36**	**71**	**7.99**	**69**	**7.22**	**72**
			750	**5.86**	**77**	**7.91**	**69**	**7.50**	**70**	**7.09**	**72**
			1000	**8.22**	**68**	**9.26**	**64**	**8.29**	**67**	**8.59**	**66**
				6.79	**73**	**8.18**	**68**	**7.93**	**69**	**7.63**	**70**

Table M.71 Daily nitrate concentration and removal efficiency with depth in the filter without a carbon source**.**

Filter without a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrate concentration (mg/L-N)**	**Spiked raw water nitrate concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 filtrate concentration (mg/L-N)**	**Column 1 Nitrate removal efficiency (%)**	**Column 2 filtrate concentration (mg/L-N)**	**Column 2 Nitrate removal efficiency (%)**	**Column 3 filtrate concentration (mg/L-N)**	**Column 3 Nitrate removal efficiency (%)**	**Filter average concentration at depth (mg/L-N)**	**Filter avarage depth nitrate removal efficiency (%)**
1	15.9	25.59	270	5.36	79	8.09	68	4.36	83	5.94	77
			750	4.69	82	6.91	73	3.18	88	4.93	81
			1000	5.86	77	4.18	84	5.09	80	5.04	80
Day 1 filter average				**5.30**	**79**	**6.39**	**75**	**4.21**	**84**	**5.30**	**79**
2	6.09	25	270	4.95	80	3.73	85	6.73	73	5.14	79
			750	11.81	53	3.45	86	7	72	7.42	70
			1000	4.18	83	8	68	6.73	73	6.30	75
Day 2 filter average				**6.98**	**72**	**5.06**	**80**	**6.82**	**73**	**6.29**	**75**
3	8.73	25.68	270	6.73	74	9.55	63	4.45	83	6.91	73
			750	10.45	59	4.45	83	8.09	68	7.66	70
			1000	11.36	56	3.64	86	8.73	66	7.91	69
Day 3 filter average				**9.51**	**63**	**5.88**	**77**	**7.09**	**72**	**7.49**	**71**
4	8	26.07	270	13.86	47	14.09	46	15.55	40	14.50	44
			750	19	27	13.79	47	15	42	15.93	39
			1000	19.09	27	13.64	48	15	42	15.91	39
Day 4 filter average				**17.32**	**34**	**13.84**	**47**	**15.18**	**42**	**15.45**	**41**
5	15	25.64	270	11.36	56	14.09	45	16.36	36	13.94	46
			750	13.64	47	12.73	50	16.82	34	14.40	44
			1000	16.82	34	17.05	34	18.64	27	17.50	32
Day 5 filter average				**13.94**	**46**	**14.62**	**43**	**17.27**	**33**	**15.28**	**40**
6	9.55	25.32	270	7.9	69	14.55	43	13.18	48	11.88	53
			750	8.05	68	18.64	26	18.64	26	15.11	40
			1000	8.18	68	13.64	46	12.73	50	11.52	55
Day 6 filter average				**8.04**	**68**	**15.61**	**38**	**14.85**	**41**	**12.83**	**49**
7	14.55	25.19	270	11.09	56	5.77	77	6.18	75	7.68	70
			750	7.45	70	5.82	77	6	76	6.42	75
			1000	12.27	51	6.36	75	7.27	71	8.63	66
Day 7 filter average				**10.27**	**59**	**5.98**	**76**	**6.48**	**74**	**7.58**	**70**
8	17.27	25.29	270	15.45	39	13.64	46	15.91	37	15.00	41
			750	16.36	35	15	41	13.18	48	14.85	41
			1000	18.18	28	10.91	57	12.27	51	13.79	45
Day 8 filter average				**16.66**	**34**	**13.18**	**48**	**13.79**	**45**	**14.54**	**42**
9	17.73	25.19	270	9.64	62	10.55	58	10.79	57	10.33	59
			750	7.68	70	8.7	65	9.55	62	8.64	66
			1000	10.95	57	11.98	52	13.32	47	12.08	52
Day 9 filter average				**9.42**	**63**	**10.41**	**59**	**11.22**	**55**	**10.35**	**59**
10	15.91	25.39	270	7.09	72	10	61	10	61	9.03	64
			750	9.09	64	10.45	59	12.73	50	10.76	58
			1000	10.45	59	12.73	50	15.45	39	12.88	49
Day 10 filter average				**8.88**	**65**	**11.06**	**56**	**12.73**	**50**	**10.89**	**57**
11	17.73	25.19	270	8.91	65	8.64	66	15.91	37	11.15	56
			750	7.82	69	10.45	59	17.27	31	11.85	53
			1000	7	72	15.45	39	19.09	24	13.85	45
Day 11 filter average				**7.91**	**69**	**11.51**	**54**	**17.42**	**31**	**12.28**	**51**
12	5.73	25.33	270	7.82	69	9.77	61	8.91	65	8.83	65
			750	8.86	65	7.73	69	7.86	69	8.15	68
			1000	11.36	55	8.27	67	7.36	71	9.00	64
Day 12 filter average				**9.35**	**63**	**8.59**	**66**	**8.04**	**68**	**8.66**	**66**
13	7.55	25.25	270	7.73	69	6.27	75	8.09	68	7.36	71
			750	9.32	63	7.09	72	9.55	62	8.65	66
			1000	9.82	61	10	60	11.36	55	10.39	59
Day 13 filter average				**8.96**	**65**	**7.79**	**69**	**9.67**	**62**	**8.80**	**65**
14	11.36	25.18	270	7.36	71	8.77	65	14.32	43	10.15	60
			750	8.91	65	12.73	49	13.64	46	11.76	53
			1000	8.5	66	14.55	42	14.55	42	12.53	50
Day 14 filter average				**8.26**	67	**12.02**	**52**	**14.17**	**44**	**11.48**	**54**
15	15.9	25.24	270	14.55	42	7.5	70	7.5	70	9.85	61
			750	15.91	37	5.55	78	8.73	65	10.06	60
			1000	15.45	39	7.86	69	7.73	69	10.35	59
Day 15 filter average				**15.30**	**39**	**6.97**	**72**	**7.99**	**68**	**10.09**	**60**
16	9.45	25.31	270	9.36	63	10	60	3.45	86	7.60	70
			750	10.9	57	8.18	68	5.36	79	8.15	68
			1000	11.8	53	10.45	59	6.55	74	9.60	62
Day 16 filter average				**10.69**	**58**	**9.54**	**62**	**5.12**	**80**	**8.45**	**67**
17	10.45	25.2	270	9.36	63	8.64	66	12.2	52	10.07	60
			750	10	60	9.55	62	15.91	37	11.82	53
			1000	10.45	59	9.09	64	14.09	44	11.21	56
Day 17 filter average				**9.94**	**61**	**9.09**	**64**	**14.07**	**44**	**11.03**	**56**
18	20	25.18	270	11.25	55	10.45	58	10.23	59	10.64	58
			750	11.88	53	7.5	70	13.18	48	10.85	57
			1000	13.18	48	9.32	63	15.23	40	12.58	50
Day 18 filter average				**12.10**	**52**	**9.09**	**64**	**12.88**	**49**	**11.36**	**55**
19	16.36	25.03	270	9.55	62	8.36	67	10.89	56	9.60	62
			750	8.68	65	7.34	71	12.5	50	9.51	62
			1000	10.91	56	10.09	60	13.16	47	11.39	55
Day 19 filter average				**9.71**	**61**	**8.60**	**66**	**12.18**	**51**	**10.16**	**59**
20	9	25.23	270	10.57	58	8.77	65	13.55	46	10.96	57
			750	9.61	62	7.09	72	10.11	60	8.94	65
			1000	12.5	50	11.7	54	12.93	49	12.38	51
Day 20 filter average				**10.89**	**57**	**9.19**	**64**	**12.20**	**52**	**10.76**	**57**
Total Average	**12.61**	**25.33**	270	**9.49**	**63**	**9.56**	**62**	**10.43**	**59**	**9.83**	**61**
			750	**10.51**	**59**	**9.16**	**64**	**11.22**	**56**	**10.29**	**59**
			1000	**11.42**	**55**	**10.45**	**59**	**11.86**	**53**	**11.24**	**56**
				10.47	**59**	**9.72**	**62**	**11.17**	**56**	**10.45**	**59**

M.3. Nitrate at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

Table M.72 Daily nitrate concentration and removal efficiency with depth in the filter with a carbon source.

Filter with a carbon source											
Sampling interval (Day)	**Unspiked raw water nitrate concentration (mg/L-N)**	**Spiked raw water nitrate concentration (mg/L-N)**	**Filter column depths (mm)**	**Column 1 filtrate concentration (mg/L-N)**	**Column 1 Nitrate removal efficiency (%)**	**Column 2 filtrate concentration (mg/L-N)**	**Column 2 Nitrate removal efficiency (%)**	**Column 3 average concentration (mg/L-N)**	**Column 3 Nitrate removal efficiency (%)**	**Filter average concentration at depth (mg/L-N)**	**Filter avarage depth nitrate removal efficiency (%)**
1	12.27	50.32	270	6.91	86	8.68	83	14.09	72	9.89	80
			750	7.18	86	4.82	90	14.32	72	8.77	83
			1000	7.45	85	8.82	82	14.55	71	10.27	80
Day 1 filter average				**7.18**	**86**	**7.44**	**85**	**14.32**	**72**	**9.65**	**81**
2	3.45	50.08	270	3.82	92	4.32	91	4.64	91	4.26	91
			750	4.05	92	4.45	91	5.86	88	4.79	90
			1000	4.18	92	5.45	89	6.09	88	5.24	90
Day 2 filter average				**4.02**	**92**	**4.74**	**91**	**5.53**	**89**	**4.76**	**90**
3	13.64	50.24	270	6.82	86	12.7	75	13.18	74	10.90	78
			750	8.41	83	12.7	75	13.64	73	11.58	77
			1000	10	80	12.27	76	16.36	67	12.88	74
Day 3 filter average				**8.41**	**83**	**12.56**	**75**	**14.39**	**71**	**11.79**	**77**
4	19.55	50.39	270	11.8	77	9.09	82	8.09	84	9.66	81
			750	10	80	9.45	81	9.45	81	9.63	81
			1000	8.64	83	8.91	82	10	80	9.18	82
Day 4 filter average				**10.15**	**80**	**9.15**	**82**	**9.18**	**82**	**9.49**	**81**
5	16.36	50.18	270	8	84	6.91	86	4.36	91	6.42	87
			750	8.32	83	6.55	87	5.55	89	6.81	86
			1000	8.82	82	5.91	88	6.36	87	7.03	86
Day 5 filter average				**8.38**	**83**	**6.46**	**87**	**5.42**	**89**	**6.75**	**87**
6	8.27	50.24	270	12.3	76	18.18	64	17.27	66	15.92	68
			750	15	70	18.64	63	17.73	65	17.12	66
			1000	19.09	62	13.5	73	16.36	67	16.32	68
Day 6 filter average				**15.46**	**69**	**16.77**	**67**	**17.12**	**66**	**16.45**	**67**
7	4.45	50.31	270	15	70	11.36	77	5.82	88	10.73	79
			750	14.09	72	10.45	79	7.05	86	10.53	79
			1000	12.27	76	8.27	84	8.36	83	9.63	81
Day 7 filter average				**13.79**	**73**	**10.03**	**80**	**7.08**	**86**	**10.30**	**80**
8	7	50.26	270	7.9	84	6.32	87	10.45	79	8.22	84
			750	9	82	6.45	87	8.86	82	8.10	84
			1000	9.55	81	7	86	5.09	90	7.21	86
Day 8 filter average				**8.82**	**82**	**6.59**	**87**	**8.13**	**84**	**7.85**	**84**
9	19.55	50.21	270	6	88	4.41	91	3.18	94	4.53	91
			750	5.66	89	4.84	90	3.59	93	4.70	91
			1000	7.2	86	5.36	89	4.23	92	5.60	89
Day 9 filter average				**6.29**	**87**	**4.87**	**90**	**3.67**	**93**	**4.94**	**90**
10	16.36	50.14	270	6.52	87	3.75	93	2.07	96	4.11	92
			750	4.84	90	2.72	95	2.73	95	3.43	93
			1000	4.32	91	2.14	96	3.29	93	3.25	94
Day 10 filter average				**5.23**	**90**	**2.87**	**94**	**2.70**	**95**	**3.60**	**93**
11	13.18	50.25	270	7.36	85	4.19	92	2.7	95	4.75	91
			750	6.61	87	3.63	93	3.27	93	4.50	91
			1000	4.7	91	2.6	95	3.91	92	3.74	93
Day 11 filter average				**6.22**	**88**	**3.47**	**93**	**3.29**	**93**	**4.33**	**91**
12	15.91	50.09	270	10.4	79	13.64	73	12.73	75	12.26	76
			750	16.36	67	16.82	66	11.82	76	15.00	70
			1000	19.09	62	15.91	68	12.27	76	15.76	69
Day 12 filter average				**15.28**	**69**	**15.46**	**69**	**12.27**	**75**	**14.34**	**71**
13	9.55	50.19	270	15.45	69	9.36	81	6	88	10.27	80
			750	19.55	61	10.45	79	5.73	89	11.91	76
			1000	14.55	71	12.27	76	6.55	87	11.12	78
Day 13 filter average				**16.52**	**67**	**10.69**	**79**	**6.09**	**88**	**11.10**	**78**
14	11.36	50.29	270	9.5	81	4.45	91	6.73	87	6.89	86
			750	4.64	91	4.73	91	11.36	77	6.91	86
			1000	6.95	86	3.73	93	8.73	83	6.47	87
Day 14 filter average				**7.03**	86	**4.30**	**91**	**8.94**	**82**	**6.76**	**87**
15	17.27	50.18	270	9.68	81	8.36	83	6	88	8.01	84
			750	8.23	84	7.36	85	5.36	89	6.98	86
			1000	10.91	78	9.14	82	10	80	10.02	80
Day 15 filter average				**9.61**	**81**	**8.29**	**83**	**7.12**	**86**	**8.34**	**83**
16	12.73	50.11	270	10	80	10.45	79	9.64	81	10.03	80
			750	9	82	9.41	81	11.52	77	9.98	80
			1000	12	76	13.34	73	12.57	75	12.64	75
Day 16 filter average				**10.33**	**79**	**11.07**	**78**	**11.24**	**78**	**10.88**	**78**
17	10.91	50.24	270	7.18	86	4.64	91	6.09	88	5.97	88
			750	6.45	87	3.45	93	5	90	4.97	90
			1000	7.91	84	5.82	88	6.82	86	6.85	86
Day 17 filter average				**7.18**	**86**	**4.64**	**91**	**5.97**	**88**	**5.93**	**88**
18	17.27	50.19	270	8.55	83	2.73	95	8.86	82	6.71	87
			750	9.64	81	2.55	95	10	80	7.40	85
			1000	9.95	80	3.09	94	9.14	82	7.39	85
Day 18 filter average				**9.38**	**81**	**2.79**	**94**	**9.33**	**81**	**7.17**	**86**
19	19.55	50.33	270	7.64	85	8.86	82	9	82	8.50	83
			750	9.14	82	9.09	82	9.09	82	9.11	82
			1000	9.77	81	9.91	80	10.45	79	10.04	80
Day 19 filter average				**8.85**	**82**	**9.29**	**82**	**9.51**	**81**	**9.22**	**82**
20	17.73	50.15	270	2.41	95	7.02	86	5.59	89	5.01	90
			750	2.73	95	5.84	88	5.75	89	4.77	90
			1000	4.75	91	7.68	85	7.41	85	6.61	87
Day 20 filter average				**3.30**	**93**	**6.85**	**86**	**6.25**	**88**	**5.46**	**89**
Total Average	**13.32**	**50.22**	270	**8.66**	**83**	**7.97**	**84**	**7.82**	**84**	**8.15**	**84**
			750	**8.95**	**82**	**7.72**	**85**	**8.38**	**83**	**8.35**	**83**
			1000	**9.61**	**81**	**8.06**	**84**	**8.93**	**82**	**8.86**	**82**
				9.07	**82**	**7.92**	**84**	**8.38**	**83**	**8.45**	**83**

Table M.73 Daily nitrate concentration and removal efficiency with depth in the filter without a carbon source.

Filter without a carbon source											
Sampling interval (Day)	Unspiked raw water nitrate concentration (mg/L-N)	Spiked raw water nitrate concentration (mg/L-N)	Filter column depths (mm)	Column 1 filtrate concentration (mg/L-N)	Column 1 Nitrate removal efficiency (%)	Column 2 filtrate concentration (mg/L-N)	Column 2 Nitrate removal efficiency (%)	Column 3 average concentration (mg/L-N)	Column 3 Nitrate removal efficiency (%)	Filter average concentration at depth (mg/L-N)	Filter avarage depth nitrate removal efficiency (%)
1	12.27	50.32	270	15	70	15.45	69	11.36	77	13.94	72
			750	14.55	71	16.36	67	10.45	79	13.79	73
			1000	14.09	72	18.18	64	9.64	81	13.97	72
Day 1 filter average				**14.55**	**71**	**16.66**	**67**	**10.48**	**79**	**13.90**	**72**
2	3.45	50.32	270	9.73	81	10.68	79	11.36	77	10.59	79
			750	10.45	79	11.36	77	13.64	73	11.82	77
			1000	11.36	77	11.82	77	15.45	69	12.88	74
Day 2 filter average				**10.51**	**79**	**11.29**	**78**	**13.48**	**73**	**11.76**	**77**
3	13.64	50.24	270	17.59	65	15.84	68	19.23	62	17.55	65
			750	18.64	63	18.23	64	17.11	66	17.99	64
			1000	20.2	60	20.79	59	21.75	57	20.91	58
Day 3 filter average				**18.81**	**63**	**18.29**	**64**	**19.36**	**61**	**18.82**	**63**
4	19.55	50.39	270	32.73	35	20	60	20	60	24.24	52
			750	28.18	44	20.91	59	20.91	59	23.33	54
			1000	23.64	53	21.82	57	22.73	55	22.73	55
Day 4 filter average				**28.18**	**44**	**20.91**	**59**	**21.21**	**58**	**23.44**	**53**
5	16.36	50.18	270	37.27	26	20	60	22.73	55	26.67	47
			750	27.27	46	18.91	62	23.64	53	23.27	54
			1000	22.73	55	19.45	61	22.73	55	21.64	57
Day 5 filter average				**29.09**	**42**	**19.45**	**61**	**23.03**	**54**	**23.86**	**52**
6	8.27	50.24	270	27.36	46	24.84	51	25.29	50	25.83	49
			750	30	40	20.91	58	27.2	46	26.04	48
			1000	34.41	32	26.23	48	28	44	29.55	41
Day 6 filter average				**30.59**	**39**	**23.99**	**52**	**26.83**	**47**	**27.14**	**46**
7	4.45	50.31	270	33.64	33	39.09	22	30	40	34.24	32
			750	29.09	42	38.18	24	20	60	29.09	42
			1000	27.27	46	25.45	49	16.36	67	23.03	54
Day 7 filter average				**30.00**	**40**	**34.24**	**32**	**22.12**	**56**	**28.79**	**43**
8	7	50.26	270	40.91	19	17.73	65	15.45	69	24.70	51
			750	27.7	45	16	68	18	64	20.57	59
			1000	38.18	24	16.73	67	18.36	63	24.42	51
Day 8 filter average				**35.60**	**29**	**16.82**	**67**	**17.27**	**66**	**23.23**	**54**
9	19.55	50.21	270	17.34	65	26.59	47	27.48	45	23.80	53
			750	19.52	61	27.79	45	28.77	43	25.36	49
			1000	20.16	60	29.18	42	30.09	40	26.48	47
Day 9 filter average				**19.01**	**62**	**27.85**	**45**	**28.78**	**43**	**25.21**	**50**
10	16.36	50.14	270	14.27	72	20.84	58	23.7	53	19.60	61
			750	12.75	75	25.45	49	22.36	55	20.19	60
			1000	17.23	66	27.66	44.8	25.9	48	23.60	53
Day 10 filter average				**14.75**	**71**	**24.65**	**51**	**23.99**	**52**	**21.13**	**58**
11	13.18	50.25	270	13.39	73	24.77	51	22.18	56	20.11	60
			750	14.23	72	26.14	48	20.05	60	20.14	60
			1000	19.66	61	29.09	42	23.18	54	23.98	52
Day 11 filter average				**15.76**	**69**	**26.67**	**47**	**21.80**	**57**	**21.41**	**57**
12	15.91	50.09	270	15.86	68	13.27	74	21.18	58	16.77	67
			750	18	64	15.09	70	13.64	73	15.58	69
			1000	17	66	16.45	67	20	60	17.82	64
Day 12 filter average				**16.95**	**66**	**14.94**	**70**	**18.27**	**64**	**16.72**	**67**
13	9.55	50.19	270	17.73	65	11.36	77	12.73	75	13.94	72
			750	13.18	74	9.32	81	20.45	59	14.32	71
			1000	14.55	71	9.91	80	17.27	66	13.91	72
Day 13 filter average				**15.15**	**70**	**10.20**	**80**	**16.82**	**66**	**14.06**	**72**
14	11.36	50.29	270	17.41	65	14.5	71	10	80	13.97	72
			750	12.18	76	20.45	59	17.27	66	16.63	67
			1000	14.64	71	12.45	75	13.86	72	13.65	73
Day 14 filter average				**14.74**	**71**	**15.80**	**69**	**13.71**	**73**	**14.75**	**71**
15	17.27	50.18	270	12.8	74	18	64	9.82	80	13.54	73
			750	12	76	10.55	79	8.18	84	10.24	80
			1000	13.18	74	14.7	71	10.18	80	12.69	75
Day 15 filter average				**12.66**	**75**	**14.42**	**71**	**9.39**	**81**	**12.16**	**76**
16	12.73	50.11	270	15.2	70	15.5	69	14.73	71	15.14	70
			750	13	74	19.16	62	17.61	65	16.59	67
			1000	16.57	67	23.64	53	22.3	55	20.84	58
Day 16 filter average				**14.92**	**70**	**19.43**	**61**	**18.21**	**64**	**17.52**	**65**
17	10.91	50.24	270	26.73	47	11.45	77	10.55	79	16.24	68
			750	23.64	53	8.91	82	8	84	13.52	73
			1000	27.91	44	15.55	69	11.09	78	18.18	64
Day 17 filter average				**26.09**	**48**	**11.97**	**76**	**9.88**	**80**	**15.98**	**68**
18	17.27	50.19	270	16.6	67	15	70	15.64	69	15.75	69
			750	20	60	17.45	65	16.91	66	18.12	64
			1000	22.64	55	18.27	64	18.73	63	19.88	60
Day 18 filter average				**19.75**	**61**	**16.91**	**66**	**17.09**	**66**	**17.92**	**64**
19	19.55	50.33	270	25.91	49	11.36	77	10.91	78	16.06	68
			750	23.82	53	11.09	78	10.73	79	15.21	70
			1000	28.18	44	12.73	75	12.8	75	17.90	64
Day 19 filter average				**25.97**	**48**	**11.73**	**77**	**11.48**	**77**	**16.39**	**67**
20	17.73	50.15	270	11	78	7.45	85	10.91	78	9.79	80
			750	12.2	76	10	80	13.18	74	11.79	76
			1000	12.7	75	10.45	79	12.55	75	11.90	76
Day 20 filter average				**11.97**	**76**	**9.30**	**81**	**12.21**	**76**	**11.16**	**78**
Total Average	**13.32**	**50.23**	270	**20.92**	**58**	**17.69**	**65**	**17.26**	**66**	**18.62**	**63**
			750	**19.02**	**62**	**18.11**	**64**	**17.41**	**65**	**18.18**	**64**
			1000	**20.82**	**59**	**19.03**	**62**	**18.65**	**63**	**19.50**	**61**
				20.25	**60**	**18.28**	**64**	**17.77**	**65**	**18.77**	**63**

Appendix N. Results validation

The tables below represent results validation in the filter with and without a carbon source during the filter run. The parameters validated included pH, turbidity, dissolved oxygen, temperature, COD, and nitrate.

N.1. Result validation at C/N ratio of 1.05 and nitrate concentration of 15mg/L-N

Tables N.1 to N.5 represent results validation in both the filter with and without a carbon source when the C/N ratio was 1.05.

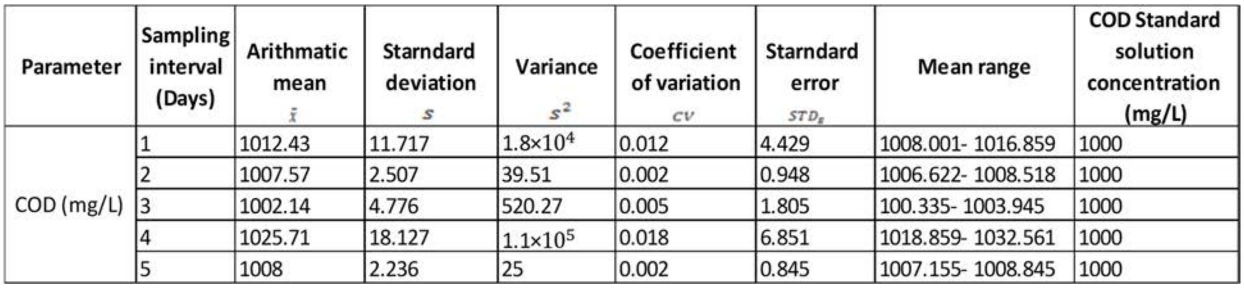
Table N.74 Results validation for nitrite concentration in the filter with and without a carbon source using C/N ratio of 1.05.

Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	Nitrite standard solution concentration (mg/L-N)
Nitrite (mg/L-N)	1	0.52	0.005	1.0×10^{-9}	0.01	0.002	0.518- 0.522	0.5
	2	0.51	0.016	6.6×10^{-8}	0.032	0.006	0.494-0.516	0.5
	3	0.52	0.005	1.9×10^{-9}	0.01	0.002	0.518- 0.522	0.5
	4	0.49	0.013	9.9×10^{-8}	0.036	0.007	0.483 - 0.497	0.5
	5	0.5	0.012	1.8×10^{-8}	0.023	0.004	0.496- 0.504	0.5
	6	0.51	0.009	6.6×10^{-9}	0.018	0.003	0.507- 0.513	0.5
	7	0.5	0.014	4.0×10^{-8}	0.028	0.005	0.495- 0.505	0.5
	8	0.51	0.007	2.3×10^{-9}	0.014	0.003	0.507- 0.513	0.5
	9	0.52	0.005	1.0×10^{-9}	0.01	0.002	0.518- 0.522	0.5
	10	0.53	0.011	1.7×10^{-8}	0.021	0.004	0.526- 0.534	0.5
	11	0.54	0.01	9.1×10^{-9}	0.018	0.004	0.536- 0.544	0.5
	12	0.55	0.013	2.6×10^{-8}	0.024	0.005	0.545- 0.555	0.5
	13	0.54	0.014	3.8×10^{-8}	0.026	0.005	0.535-0.545	0.5
	14	0.52	0.008	3.3×10^{-9}	0.014	0.003	0.517- 0.523	0.5
	15	0.56	0.008	3.3×10^{-9}	0.013	0.003	0.557- 0.563	0.5
	16	0.56	0.016	6.6×10^{-8}	0.028	0.006	0.554- 0.566	0.5
	17	0.5	0.008	3.8×10^{-9}	0.016	0.003	0.497-0.503	0.5
	18	0.53	0.005	1.0×10^{-9}	0.01	0.002	0.528- 0.532	0.5
	19	0.53	0.013	2.5×10^{-8}	0.024	0.005	0.525- 0.535	0.5
	20	0.5	0.011	1.3×10^{-8}	0.021	0.004	0.496-0.504	0.5

Table N.75 Results validation for pH in the filter with and without a carbon source using C/N ratio of 1.05.

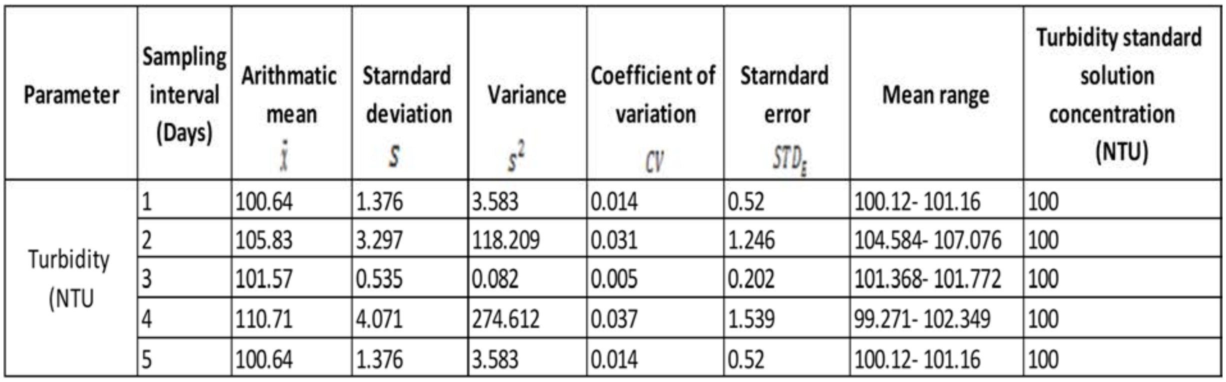
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	pH Standard solution
pH	1	7.14	0.029	6.9×10^{-7}	0.004	0.011	7.129- 7.151	7
	2	7.26	0.039	2.2×10^{-6}	0.005	0.015	7.245- 7.275	7
	3	7.39	0.085	5.3×10^{-5}	0.012	0.032	7.358-7.422	7
	4	6.97	0.08	4.0×10^{-5}	0.011	0.03	6.940- 7.00	7
	5	7	0.152	5.3×10^{-4}	0.022	0.057	6.943- 7.057	7

Table N.76 Results validation for COD concentration in the filter with and without a carbon source using C/N ratio of 1.05



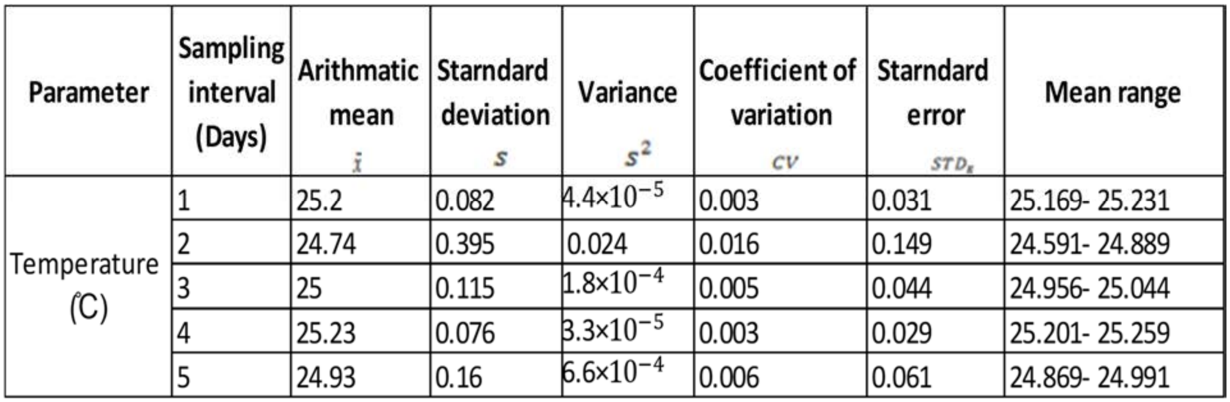
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	COD Standard solution concentration (mg/L)
COD (mg/L)	1	1012.43	11.717	1.8×10^{4}	0.012	4.429	1008.001- 1016.859	1000
	2	1007.57	2.507	39.51	0.002	0.948	1006.622- 1008.518	1000
	3	1002.14	4.776	520.27	0.005	1.805	100.335- 1003.945	1000
	4	1025.71	18.127	1.1×10^{5}	0.018	6.851	1018.859- 1032.561	1000
	5	1008	2.236	25	0.002	0.845	1007.155- 1008.845	1000

Table N.77 Results validation for turbidity concentration in the filter with and without a carbon source using C/N ratio of 1.05



Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation S	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	Turbidity standard solution concentration (NTU)
Turbidity (NTU	1	100.64	1.376	3.583	0.014	0.52	100.12- 101.16	100
	2	105.83	3.297	118.209	0.031	1.246	104.584- 107.076	100
	3	101.57	0.535	0.082	0.005	0.202	101.368- 101.772	100
	4	110.71	4.071	274.612	0.037	1.539	99.271- 102.349	100
	5	100.64	1.376	3.583	0.014	0.52	100.12- 101.16	100

Table N.78 Results validation for temperature in the filter with and without a carbon source using C/N ratio of 1.05

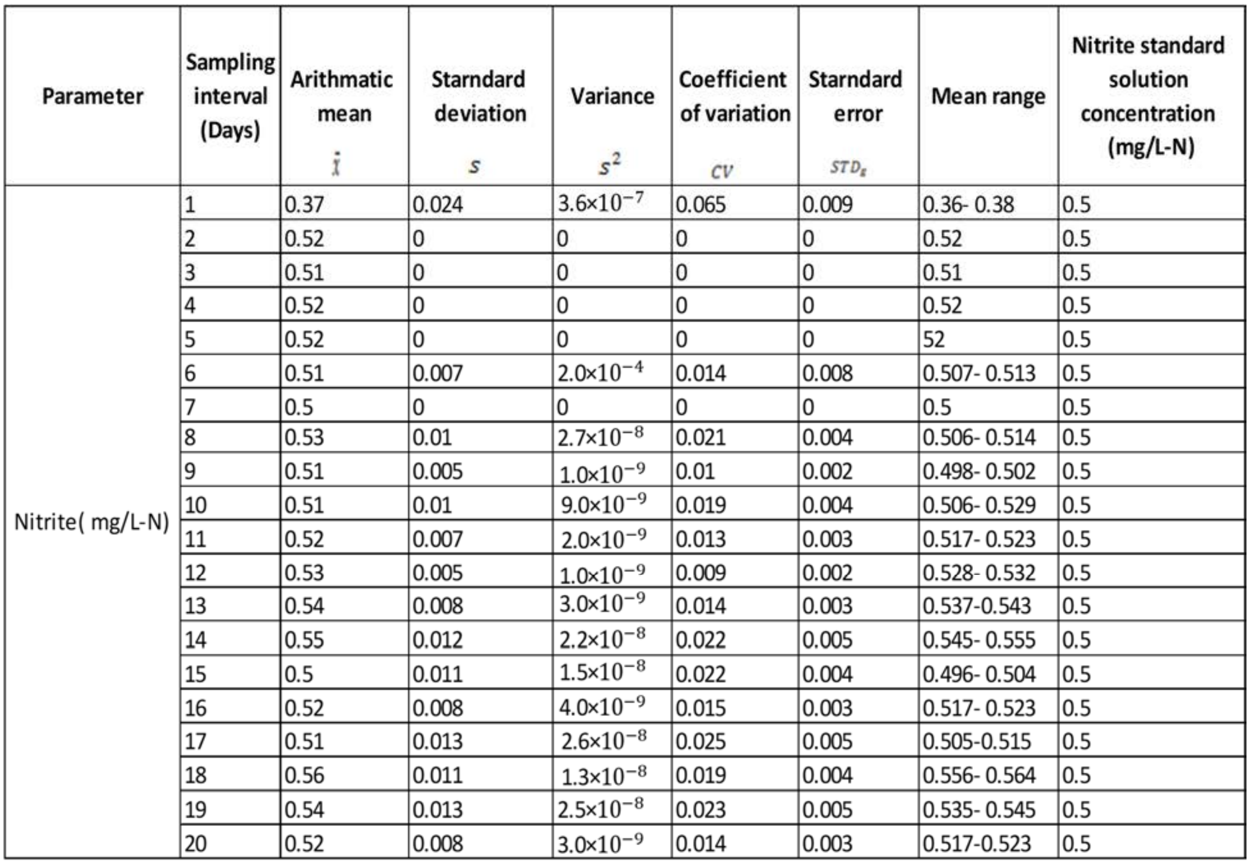


Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range
Temperature (°C)	1	25.2	0.082	4.4×10^{-5}	0.003	0.031	25.169- 25.231
	2	24.74	0.395	0.024	0.016	0.149	24.591- 24.889
	3	25	0.115	1.8×10^{-4}	0.005	0.044	24.956- 25.044
	4	25.23	0.076	3.3×10^{-5}	0.003	0.029	25.201- 25.259
	5	24.93	0.16	6.6×10^{-4}	0.006	0.061	24.869- 24.991

N.2. Result validation at C/N ratio of 1.08 and nitrate concentration of 25mg/L-N

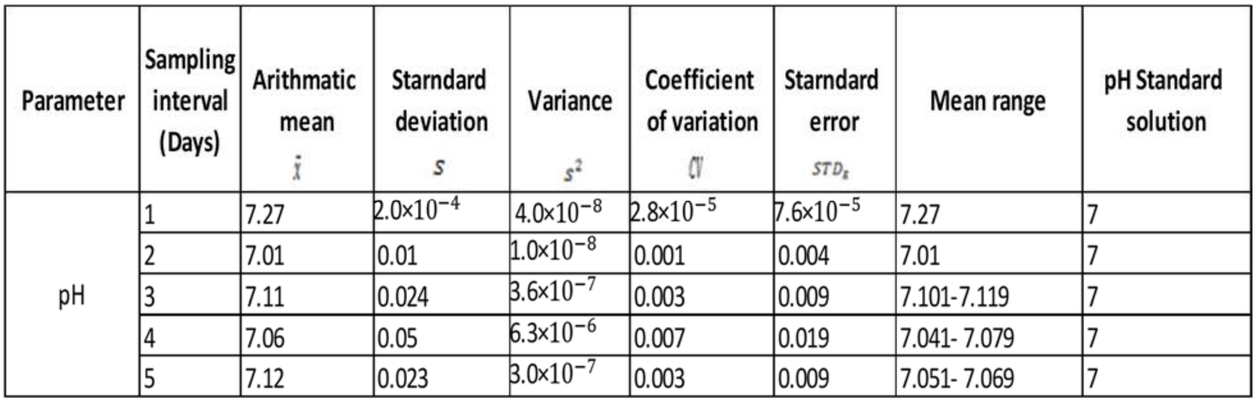
Tables N.6 to N.10 represent results validation in both the filter with and without a carbon source when the C/N ratio was 1.08.

Table N.79 Results validation for nitrite concentration in the filter with and without a carbon source using C/N ratio of 1.08.



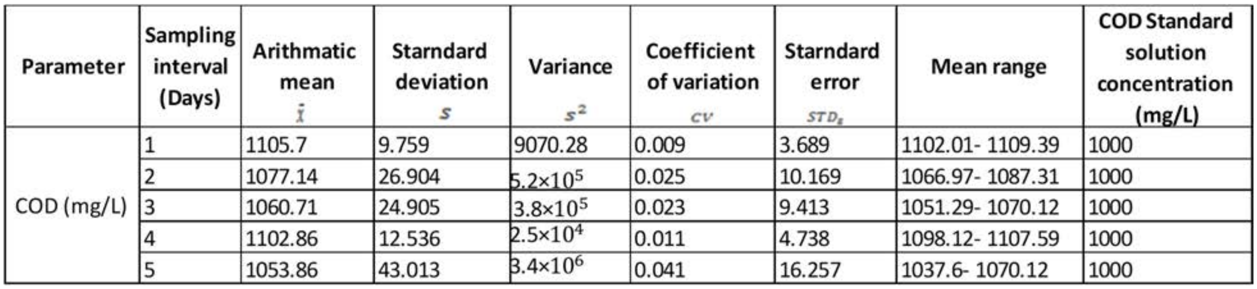
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error STD_E	Mean range	Nitrite standard solution concentration (mg/L-N)
Nitrite(mg/L-N)	1	0.37	0.024	3.6×10^{-7}	0.065	0.009	0.36- 0.38	0.5
	2	0.52	0	0	0	0	0.52	0.5
	3	0.51	0	0	0	0	0.51	0.5
	4	0.52	0	0	0	0	0.52	0.5
	5	0.52	0	0	0	0	52	0.5
	6	0.51	0.007	2.0×10^{-4}	0.014	0.008	0.507- 0.513	0.5
	7	0.5	0	0	0	0	0.5	0.5
	8	0.53	0.01	2.7×10^{-8}	0.021	0.004	0.506- 0.514	0.5
	9	0.51	0.005	1.0×10^{-9}	0.01	0.002	0.498- 0.502	0.5
	10	0.51	0.01	9.0×10^{-9}	0.019	0.004	0.506- 0.529	0.5
	11	0.52	0.007	2.0×10^{-9}	0.013	0.003	0.517- 0.523	0.5
	12	0.53	0.005	1.0×10^{-9}	0.009	0.002	0.528- 0.532	0.5
	13	0.54	0.008	3.0×10^{-9}	0.014	0.003	0.537-0.543	0.5
	14	0.55	0.012	2.2×10^{-8}	0.022	0.005	0.545- 0.555	0.5
	15	0.5	0.011	1.5×10^{-8}	0.022	0.004	0.496- 0.504	0.5
	16	0.52	0.008	4.0×10^{-9}	0.015	0.003	0.517- 0.523	0.5
	17	0.51	0.013	2.6×10^{-8}	0.025	0.005	0.505-0.515	0.5
	18	0.56	0.011	1.3×10^{-8}	0.019	0.004	0.556- 0.564	0.5
	19	0.54	0.013	2.5×10^{-8}	0.023	0.005	0.535- 0.545	0.5
	20	0.52	0.008	3.0×10^{-9}	0.014	0.003	0.517-0.523	0.5

Table N.80 Results validation for pH in the filter with and without a carbon source using C/N ratio of 1.08.



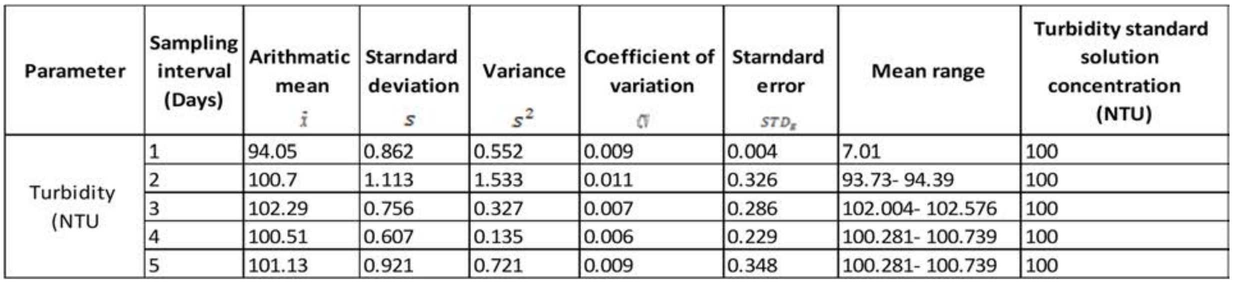
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error STD_E	Mean range	pH Standard solution
pH	1	7.27	2.0×10^{-4}	4.0×10^{-8}	2.8×10^{-5}	7.6×10^{-5}	7.27	7
	2	7.01	0.01	1.0×10^{-8}	0.001	0.004	7.01	7
	3	7.11	0.024	3.6×10^{-7}	0.003	0.009	7.101-7.119	7
	4	7.06	0.05	6.3×10^{-6}	0.007	0.019	7.041- 7.079	7
	5	7.12	0.023	3.0×10^{-7}	0.003	0.009	7.051- 7.069	7

Table N.81 Results validation for COD concentration in the filter with and without a carbon source using C/N ratio of 1.08.



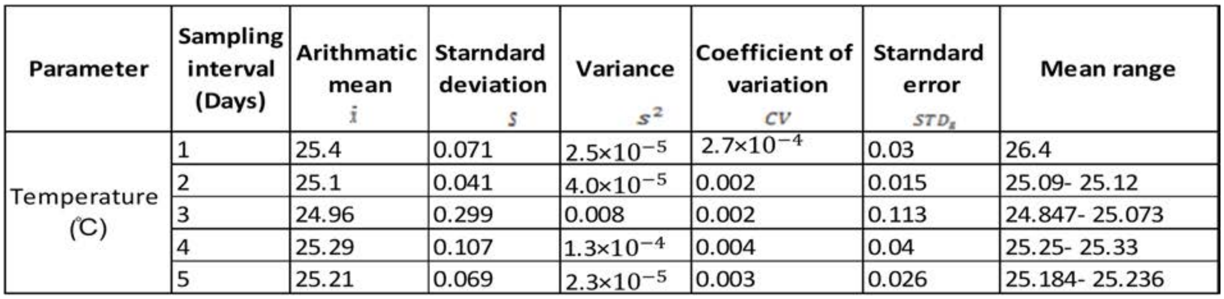
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	COD Standard solution concentration (mg/L)
COD (mg/L)	1	1105.7	9.759	9070.28	0.009	3.689	1102.01- 1109.39	1000
	2	1077.14	26.904	5.2×10^5	0.025	10.169	1066.97- 1087.31	1000
	3	1060.71	24.905	3.8×10^5	0.023	9.413	1051.29- 1070.12	1000
	4	1102.86	12.536	2.5×10^4	0.011	4.738	1098.12- 1107.59	1000
	5	1053.86	43.013	3.4×10^6	0.041	16.257	1037.6- 1070.12	1000

Table N.82 Results validation for turbidity concentration in the filter with and without a carbon source using C/N ratio of 1.08.



Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	Turbidity standard solution concentration (NTU)
Turbidity (NTU	1	94.05	0.862	0.552	0.009	0.004	7.01	100
	2	100.7	1.113	1.533	0.011	0.326	93.73- 94.39	100
	3	102.29	0.756	0.327	0.007	0.286	102.004- 102.576	100
	4	100.51	0.607	0.135	0.006	0.229	100.281- 100.739	100
	5	101.13	0.921	0.721	0.009	0.348	100.281- 100.739	100

Table N.83 Results validation for temperature in the filter with and without a carbon source using C/N ratio of 1.08.

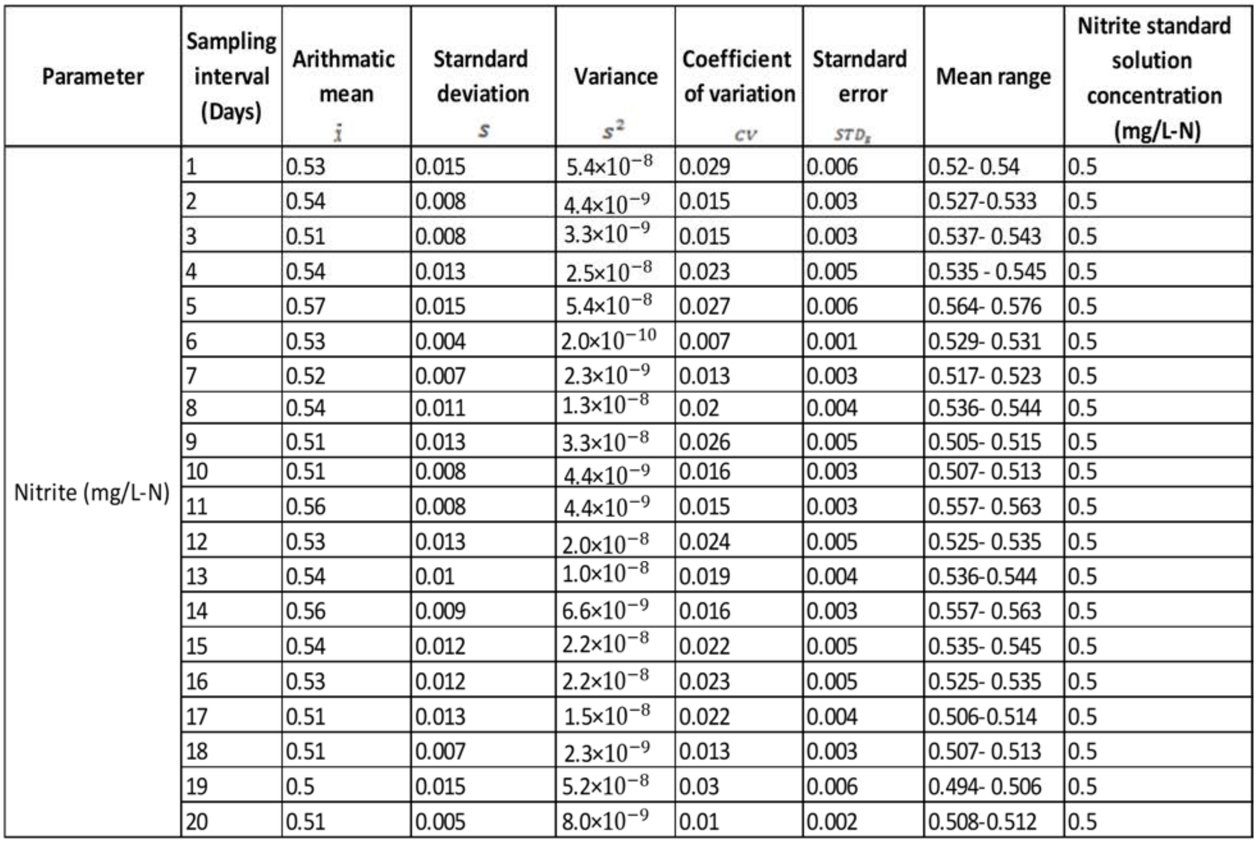


Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range
Temperature (℃)	1	25.4	0.071	2.5×10^{-5}	2.7×10^{-4}	0.03	26.4
	2	25.1	0.041	4.0×10^{-5}	0.002	0.015	25.09- 25.12
	3	24.96	0.299	0.008	0.002	0.113	24.847- 25.073
	4	25.29	0.107	1.3×10^{-4}	0.004	0.04	25.25- 25.33
	5	25.21	0.069	2.3×10^{-5}	0.003	0.026	25.184- 25.236

N.3. Result validation at C/N ratio of 1.1 and nitrate concentration of 50 mg/L-N

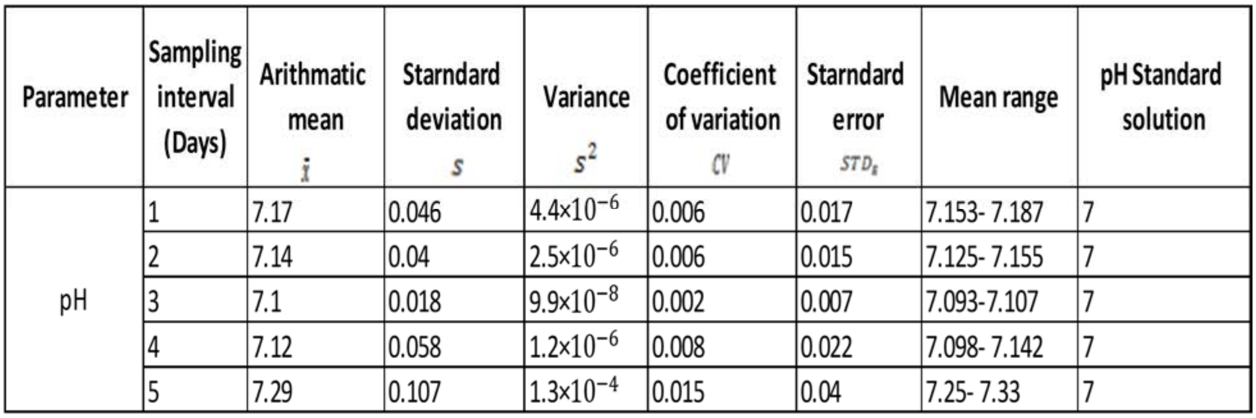
Tables N.11 to N.15 represent results validation in both the filter with and without a carbon source when the C/N ratio was 1.1.

Table N.84 Results validation for nitrite concentration in the filter with and without a carbon source using C/N ratio of 1.1.



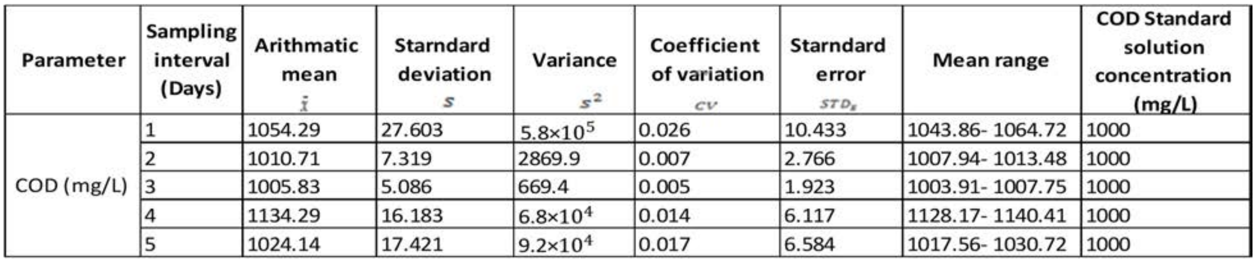
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	Nitrite standard solution concentration (mg/L-N)
Nitrite (mg/L-N)	1	0.53	0.015	5.4×10^{-8}	0.029	0.006	0.52- 0.54	0.5
	2	0.54	0.008	4.4×10^{-9}	0.015	0.003	0.527-0.533	0.5
	3	0.51	0.008	3.3×10^{-9}	0.015	0.003	0.537- 0.543	0.5
	4	0.54	0.013	2.5×10^{-8}	0.023	0.005	0.535 - 0.545	0.5
	5	0.57	0.015	5.4×10^{-8}	0.027	0.006	0.564- 0.576	0.5
	6	0.53	0.004	2.0×10^{-10}	0.007	0.001	0.529- 0.531	0.5
	7	0.52	0.007	2.3×10^{-9}	0.013	0.003	0.517- 0.523	0.5
	8	0.54	0.011	1.3×10^{-8}	0.02	0.004	0.536- 0.544	0.5
	9	0.51	0.013	3.3×10^{-8}	0.026	0.005	0.505- 0.515	0.5
	10	0.51	0.008	4.4×10^{-9}	0.016	0.003	0.507- 0.513	0.5
	11	0.56	0.008	4.4×10^{-9}	0.015	0.003	0.557- 0.563	0.5
	12	0.53	0.013	2.0×10^{-8}	0.024	0.005	0.525- 0.535	0.5
	13	0.54	0.01	1.0×10^{-8}	0.019	0.004	0.536-0.544	0.5
	14	0.56	0.009	6.6×10^{-9}	0.016	0.003	0.557- 0.563	0.5
	15	0.54	0.012	2.2×10^{-8}	0.022	0.005	0.535- 0.545	0.5
	16	0.53	0.012	2.2×10^{-8}	0.023	0.005	0.525- 0.535	0.5
	17	0.51	0.013	1.5×10^{-8}	0.022	0.004	0.506-0.514	0.5
	18	0.51	0.007	2.3×10^{-9}	0.013	0.003	0.507- 0.513	0.5
	19	0.5	0.015	5.2×10^{-8}	0.03	0.006	0.494- 0.506	0.5
	20	0.51	0.005	8.0×10^{-9}	0.01	0.002	0.508-0.512	0.5

Table N.8586 Results validation for pH in the filter with and without a carbon source using C/N ratio of 1.1.



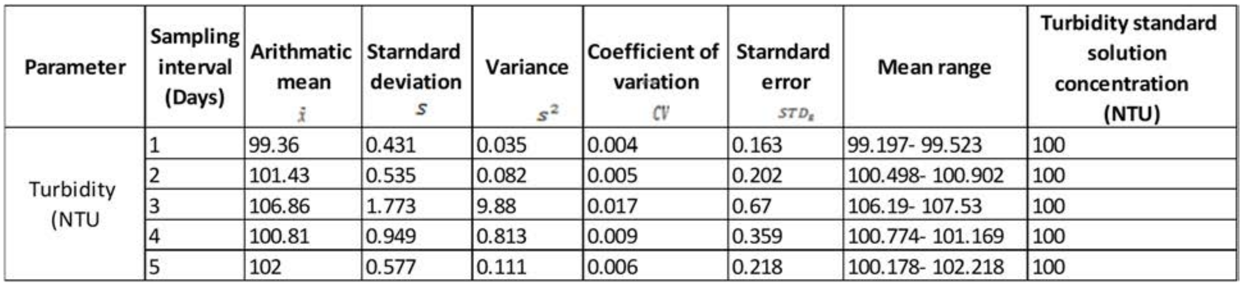
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error $STD_{\bar{x}}$	Mean range	pH Standard solution
pH	1	7.17	0.046	4.4×10^{-6}	0.006	0.017	7.153- 7.187	7
	2	7.14	0.04	2.5×10^{-6}	0.006	0.015	7.125- 7.155	7
	3	7.1	0.018	9.9×10^{-8}	0.002	0.007	7.093-7.107	7
	4	7.12	0.058	1.2×10^{-6}	0.008	0.022	7.098- 7.142	7
	5	7.29	0.107	1.3×10^{-4}	0.015	0.04	7.25- 7.33	7

Table N.8788 Results validation for COD concentration in the filter with and without a carbon source using C/N ratio of 1.1.



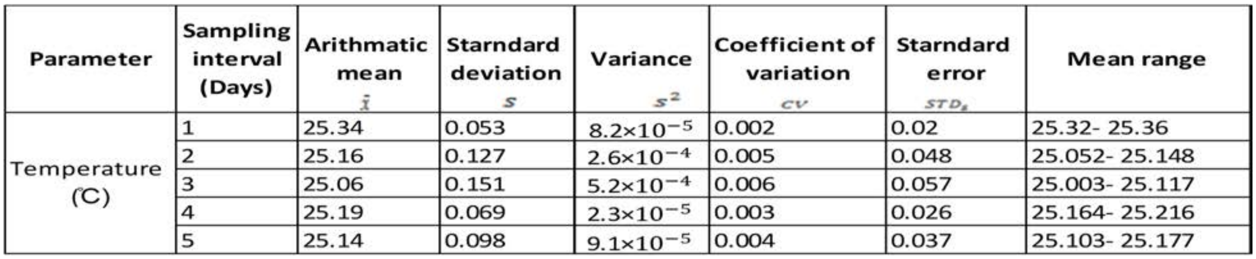
Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation cv	Starndard error STD_x	Mean range	COD Standard solution concentration (mg/L)
COD (mg/L)	1	1054.29	27.603	5.8×10^5	0.026	10.433	1043.86- 1064.72	1000
	2	1010.71	7.319	2869.9	0.007	2.766	1007.94- 1013.48	1000
	3	1005.83	5.086	669.4	0.005	1.923	1003.91- 1007.75	1000
	4	1134.29	16.183	6.8×10^4	0.014	6.117	1128.17- 1140.41	1000
	5	1024.14	17.421	9.2×10^4	0.017	6.584	1017.56- 1030.72	1000

Table N.8990 Results validation for turbidity concentration in the filter with and without a carbon source using C/N ratio of 1.1**.**



Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation CV	Starndard error STD_x	Mean range	Turbidity standard solution concentration (NTU)
Turbidity (NTU	1	99.36	0.431	0.035	0.004	0.163	99.197- 99.523	100
	2	101.43	0.535	0.082	0.005	0.202	100.498- 100.902	100
	3	106.86	1.773	9.88	0.017	0.67	106.19- 107.53	100
	4	100.81	0.949	0.813	0.009	0.359	100.774- 101.169	100
	5	102	0.577	0.111	0.006	0.218	100.178- 102.218	100

Table N.9192 Results validation for temperature in the filter with and without a carbon source using C/N ratio of 1.1.

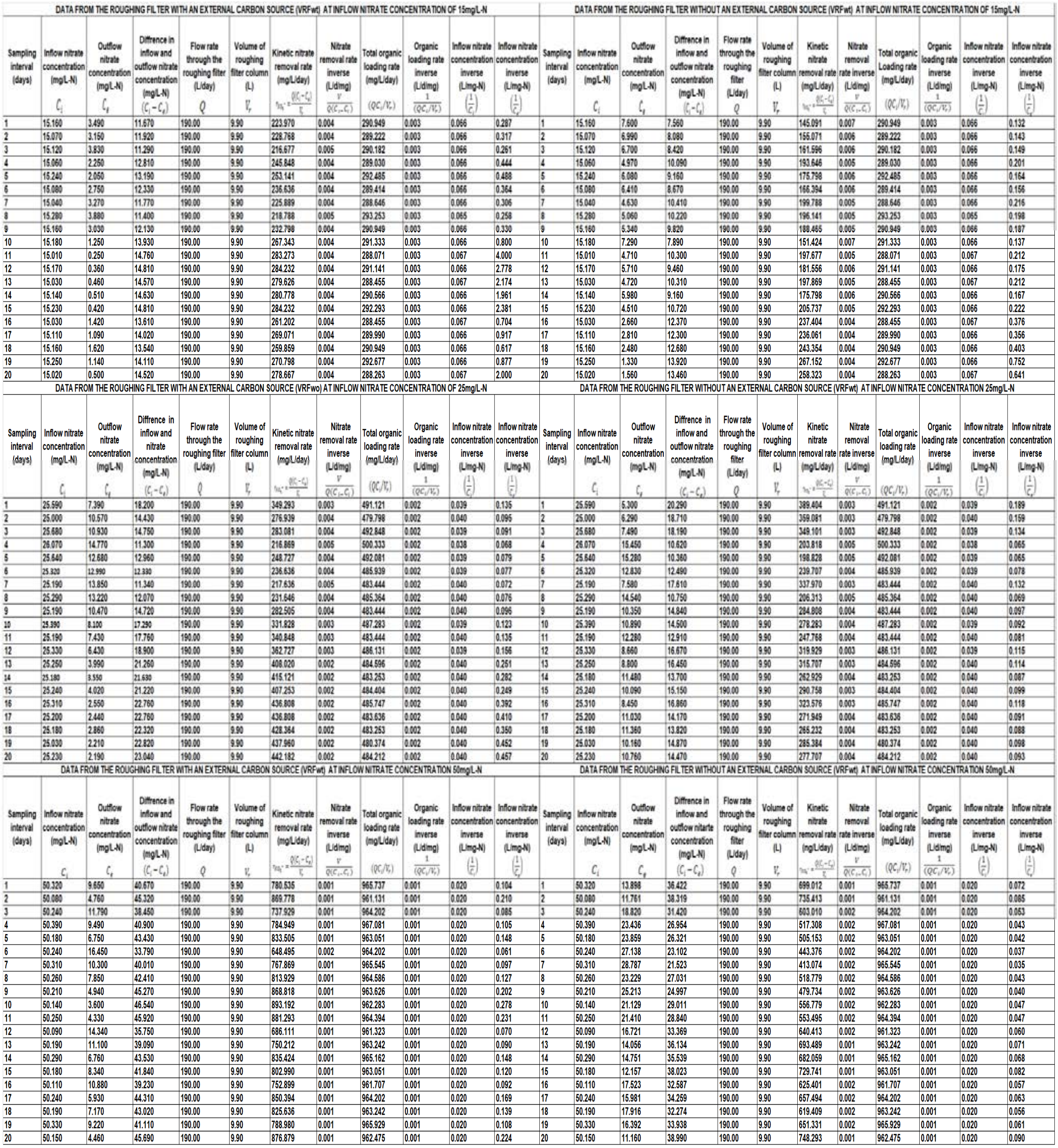


Parameter	Sampling interval (Days)	Arithmatic mean $\bar{x}$	Starndard deviation s	Variance s^2	Coefficient of variation cv	Starndard error STD_x	Mean range
Temperature (℃)	1	25.34	0.053	8.2×10^{-5}	0.002	0.02	25.32- 25.36
	2	25.16	0.127	2.6×10^{-4}	0.005	0.048	25.052- 25.148
	3	25.06	0.151	5.2×10^{-4}	0.006	0.057	25.003- 25.117
	4	25.19	0.069	2.3×10^{-5}	0.003	0.026	25.164- 25.216
	5	25.14	0.098	9.1×10^{-5}	0.004	0.037	25.103- 25.177

Appendix O. Predictive nitrate removal reaction rate analysis data

The table below represents detailed analysis and laboratory results data for the predictive nitrate removal rate model development from the filter with and without a carbon source.

Table O.93 Laboratory results data for the predictive nitrate removal rate model development



DATA FROM THE ROUGHING FILTER WITH AN EXTERNAL CARBON SOURCE (VRFwt) AT INFLOW NITRATE CONCENTRATION OF 15mg/L-N

Sampling interval (days)	Inflow nitrate concentration (mg/L-N) C_i	Outflow nitrate concentration (mg/L-N) C_e	Diffrence in inflow and outflow nitrate concentration (mg/L-N) $(C_i - C_e)$	Flow rate through the roughing filter (L/day) Q	Volume of roughing filter column (L) V_r	Kinetic nitrate removal rate (mg/L/day) $r_{NO_3^-} = \frac{Q(C_i - C_e)}{V_r}$	Nitrate removal rate inverse (L/d/mg) $\frac{V}{Q(C_i - C_e)}$	Total organic loading rate (mg/L/day) (QC_i/V_r)	Organic loading rate inverse (L/d/mg) $\frac{1}{(QC_i/V_r)}$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_i}\right)$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_e}\right)$
1	15.160	3.490	11.670	190.00	9.90	223.970	0.004	290.949	0.003	0.066	0.287
2	15.070	3.160	11.920	190.00	9.90	228.768	0.004	289.222	0.003	0.066	0.317
3	15.120	3.830	11.290	190.00	9.90	216.677	0.005	290.182	0.003	0.066	0.261
4	15.060	2.250	12.810	190.00	9.90	245.848	0.004	289.030	0.003	0.066	0.444
5	15.240	2.050	13.190	190.00	9.90	253.141	0.004	292.485	0.003	0.066	0.488
6	15.080	2.750	12.330	190.00	9.90	236.636	0.004	289.414	0.003	0.066	0.364
7	15.040	3.270	11.770	190.00	9.90	225.889	0.004	288.646	0.003	0.066	0.306
8	15.280	3.880	11.400	190.00	9.90	218.788	0.005	293.253	0.003	0.065	0.258
9	15.160	3.030	12.130	190.00	9.90	232.798	0.004	290.949	0.003	0.066	0.330
10	15.180	1.250	13.930	190.00	9.90	267.343	0.004	291.333	0.003	0.066	0.800
11	15.010	0.250	14.760	190.00	9.90	283.273	0.004	288.071	0.003	0.067	4.000
12	15.170	0.360	14.810	190.00	9.90	284.232	0.004	291.141	0.003	0.066	2.778
13	15.030	0.460	14.570	190.00	9.90	279.626	0.004	288.455	0.003	0.067	2.174
14	15.140	0.510	14.630	190.00	9.90	280.778	0.004	290.566	0.003	0.066	1.961
15	15.230	0.420	14.810	190.00	9.90	284.232	0.004	292.293	0.003	0.066	2.381
16	15.030	1.420	13.610	190.00	9.90	261.202	0.004	288.455	0.003	0.067	0.704
17	15.110	1.090	14.020	190.00	9.90	269.071	0.004	289.990	0.003	0.066	0.917
18	15.160	1.620	13.540	190.00	9.90	259.859	0.004	290.949	0.003	0.066	0.617
19	15.250	1.140	14.110	190.00	9.90	270.798	0.004	292.677	0.003	0.066	0.877
20	15.020	0.500	14.520	190.00	9.90	278.667	0.004	288.263	0.003	0.067	2.000

DATA FROM THE ROUGHING FILTER WITHOUT AN EXTERNAL CARBON SOURCE (VRFwt) AT INFLOW NITRATE CONCENTRATION OF 15mg/L-N

Sampling interval (days)	Inflow nitrate concentration (mg/L-N) C_i	Outflow nitrate concentration (mg/L-N) C_e	Diffrence in inflow and outflow nitrate concentration (mg/L-N) $(C_i - C_e)$	Flow rate through the roughing filter (L/day) Q	Volume of roughing filter column (L) V_r	Kinetic nitrate removal rate (mg/L/day) $r_{NO_3^-} = \frac{Q(C_i - C_e)}{V_r}$	Nitrate removal rate inverse (L/d/mg) $\frac{V}{Q(C_i - C_e)}$	Total organic Loading rate (mg/L/day) (QC_i/V_r)	Organic loading rate inverse (L/d/mg) $\frac{1}{(QC_i/V_r)}$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_i}\right)$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_e}\right)$
1	15.160	7.600	7.560	190.00	9.90	145.091	0.007	290.949	0.003	0.066	0.132
2	15.070	6.990	8.080	190.00	9.90	155.071	0.006	289.222	0.003	0.066	0.143
3	15.120	6.700	8.420	190.00	9.90	161.596	0.006	290.182	0.003	0.066	0.149
4	15.060	4.970	10.090	190.00	9.90	193.646	0.005	289.030	0.003	0.066	0.201
5	15.240	6.080	9.160	190.00	9.90	175.798	0.006	292.485	0.003	0.066	0.164
6	15.080	6.410	8.670	190.00	9.90	166.394	0.006	289.414	0.003	0.066	0.156
7	15.040	4.630	10.410	190.00	9.90	199.788	0.005	288.646	0.003	0.066	0.216
8	15.280	5.060	10.220	190.00	9.90	196.141	0.005	293.253	0.003	0.065	0.198
9	15.160	5.340	9.820	190.00	9.90	188.465	0.005	290.949	0.003	0.066	0.187
10	15.180	7.290	7.890	190.00	9.90	151.424	0.007	291.333	0.003	0.066	0.137
11	15.010	4.710	10.300	190.00	9.90	197.677	0.005	288.071	0.003	0.067	0.212
12	15.170	5.710	9.460	190.00	9.90	181.556	0.006	291.141	0.003	0.066	0.175
13	15.030	4.720	10.310	190.00	9.90	197.869	0.005	288.455	0.003	0.067	0.212
14	15.140	5.980	9.160	190.00	9.90	175.798	0.006	290.566	0.003	0.066	0.167
15	15.230	4.510	10.720	190.00	9.90	205.737	0.005	292.293	0.003	0.066	0.222
16	15.030	2.660	12.370	190.00	9.90	237.404	0.004	288.455	0.003	0.067	0.376
17	15.110	2.810	12.300	190.00	9.90	236.061	0.004	289.990	0.003	0.066	0.356
18	15.160	2.480	12.680	190.00	9.90	243.354	0.004	290.949	0.003	0.066	0.403
19	15.250	1.330	13.920	190.00	9.90	267.152	0.004	292.677	0.003	0.066	0.752
20	15.020	1.560	13.460	190.00	9.90	258.323	0.004	288.263	0.003	0.067	0.641

DATA FROM THE ROUGHING FILTER WITH AN EXTERNAL CARBON SOURCE (VRFwo) AT INFLOW NITRATE CONCENTRATION OF 25mg/L-N

Sampling interval (days)	Inflow nitrate concentration (mg/L-N) C_i	Outflow nitrate concentration (mg/L-N) C_e	Diffrence in inflow and nitrate concentration (mg/L-N) $(C_i - C_e)$	Flow rate through the roughing filter (L/day) Q	Volume of roughing filter column (L) V_r	Kinetic nitrate removal rate (mg/L/day) $r_{NO_3^-} = \frac{Q(C_i - C_e)}{V_r}$	Nitrate removal rate inverse (L/d/mg) $\frac{V}{Q(C_i - C_e)}$	Total organic loading rate (mg/L/day) (QC_i/V_r)	Organic loading rate inverse (L/d/mg) $\frac{1}{(QC_i/V_r)}$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_i}\right)$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_e}\right)$
1	25.590	7.390	18.200	190.00	9.90	349.293	0.003	491.121	0.002	0.039	0.135
2	25.000	10.570	14.430	190.00	9.90	276.939	0.004	479.798	0.002	0.040	0.095
3	25.680	10.930	14.750	190.00	9.90	283.081	0.004	492.848	0.002	0.039	0.091
4	26.070	14.770	11.300	190.00	9.90	216.869	0.005	500.333	0.002	0.038	0.068
5	25.640	12.680	12.960	190.00	9.90	248.727	0.004	492.081	0.002	0.039	0.079
6	25.320	12.990	12.330	190.00	9.90	236.636	0.004	485.939	0.002	0.039	0.077
7	25.190	13.850	11.340	190.00	9.90	217.636	0.005	483.444	0.002	0.040	0.072
8	25.290	13.220	12.070	190.00	9.90	231.646	0.004	485.364	0.002	0.040	0.076
9	25.190	10.470	14.720	190.00	9.90	282.505	0.004	483.444	0.002	0.040	0.096
10	25.390	8.100	17.290	190.00	9.90	331.828	0.003	487.283	0.002	0.039	0.123
11	25.190	7.430	17.760	190.00	9.90	340.848	0.003	483.444	0.002	0.040	0.135
12	25.330	6.430	18.900	190.00	9.90	362.727	0.003	486.131	0.002	0.039	0.156
13	25.250	3.990	21.260	190.00	9.90	408.020	0.002	484.596	0.002	0.040	0.251
14	25.180	3.550	21.630	190.00	9.90	415.121	0.002	483.253	0.002	0.040	0.282
15	25.240	4.020	21.220	190.00	9.90	407.253	0.002	484.404	0.002	0.040	0.249
16	25.310	2.550	22.760	190.00	9.90	436.808	0.002	485.747	0.002	0.040	0.392
17	25.200	2.440	22.760	190.00	9.90	436.808	0.002	483.636	0.002	0.040	0.410
18	25.180	2.860	22.320	190.00	9.90	428.364	0.002	483.253	0.002	0.040	0.350
19	25.030	2.210	22.820	190.00	9.90	437.960	0.002	480.374	0.002	0.040	0.452
20	25.230	2.190	23.040	190.00	9.90	442.182	0.002	484.212	0.002	0.040	0.457

DATA FROM THE ROUGHING FILTER WITHOUT AN EXTERNAL CARBON SOURCE (VRFwt) AT INFLOW NITRATE CONCENTRATION 25mg/L-N

Sampling interval (days)	Inflow nitrate concentration (mg/L-N) C_i	Outflow nitrate concentration (mg/L-N) C_e	Diffrence in inflow and outflow nitrate concentration (mg/L-N) $(C_i - C_e)$	Flow rate through the roughing filter (L/day) Q	Volume of roughing filter column (L) V_r	Kinetic nitrate removal rate (mg/L/day) $r_{NO_3^-} = \frac{Q(C_i - C_e)}{V_r}$	Nitrate removal rate inverse (L/d/mg) $\frac{V}{Q(C_i - C_e)}$	Total organic loading rate (mg/L/day) (QC_i/V_r)	Organic loading rate inverse (L/d/mg) $\frac{1}{(QC_i/V_r)}$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_i}\right)$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_e}\right)$
1	25.590	5.300	20.290	190.00	9.90	389.404	0.003	491.121	0.002	0.039	0.189
2	25.000	6.290	18.710	190.00	9.90	359.081	0.003	479.798	0.002	0.040	0.159
3	25.680	7.490	18.190	190.00	9.90	349.101	0.003	492.848	0.002	0.039	0.134
4	26.070	15.450	10.620	190.00	9.90	203.818	0.005	500.333	0.002	0.038	0.065
5	25.640	15.280	10.360	190.00	9.90	198.828	0.005	492.081	0.002	0.039	0.065
6	25.320	12.830	12.490	190.00	9.90	239.707	0.004	485.939	0.002	0.039	0.078
7	25.190	7.580	17.610	190.00	9.90	337.970	0.003	483.444	0.002	0.040	0.132
8	25.290	14.540	10.750	190.00	9.90	206.313	0.005	485.364	0.002	0.040	0.069
9	25.190	10.350	14.840	190.00	9.90	284.808	0.004	483.444	0.002	0.040	0.097
10	25.390	10.890	14.500	190.00	9.90	278.283	0.004	487.283	0.002	0.039	0.092
11	25.190	12.280	12.910	190.00	9.90	247.768	0.004	483.444	0.002	0.040	0.081
12	25.330	8.660	16.670	190.00	9.90	319.929	0.003	486.131	0.002	0.039	0.115
13	25.250	8.800	16.450	190.00	9.90	315.707	0.003	484.596	0.002	0.040	0.114
14	25.180	11.480	13.700	190.00	9.90	262.929	0.004	483.253	0.002	0.040	0.087
15	25.240	10.090	15.150	190.00	9.90	290.758	0.003	484.404	0.002	0.040	0.099
16	25.310	8.450	16.860	190.00	9.90	323.576	0.003	485.747	0.002	0.040	0.118
17	25.200	11.030	14.170	190.00	9.90	271.949	0.004	483.636	0.002	0.040	0.091
18	25.180	11.360	13.820	190.00	9.90	265.232	0.004	483.253	0.002	0.040	0.088
19	25.030	10.160	14.870	190.00	9.90	285.384	0.004	480.374	0.002	0.040	0.098
20	25.230	10.760	14.470	190.00	9.90	277.707	0.004	484.212	0.002	0.040	0.093

DATA FROM THE ROUGHING FILTER WITH AN EXTERNAL CARBON SOURCE (VRFwt) AT INFLOW NITRATE CONCENTRATION 50mg/L-N

Sampling interval (days)	Inflow nitrate concentration (mg/L-N) C_i	Outflow nitrate concentration (mg/L-N) C_e	Diffrence in inflow and outflow nitrate concentration (mg/L-N) $(C_i - C_e)$	Flow rate through the roughing filter (L/day) Q	Volume of roughing filter column (L) V_r	Kinetic nitrate removal rate (mg/L/day) $r_{NO_3^-} = \frac{Q(C_i - C_e)}{V_r}$	Nitrate removal rate inverse (L/d/mg) $\frac{V}{Q(C_i - C_e)}$	Total organic loading rate (mg/L/day) (QC_i/V_r)	Organic loading rate inverse (L/d/mg) $\frac{1}{(QC_i/V_r)}$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_i}\right)$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_e}\right)$
1	50.320	9.650	40.670	190.00	9.90	780.535	0.001	965.737	0.001	0.020	0.104
2	50.080	4.760	45.320	190.00	9.90	869.778	0.001	961.131	0.001	0.020	0.210
3	50.240	11.790	38.450	190.00	9.90	737.929	0.001	964.202	0.001	0.020	0.085
4	50.390	9.490	40.900	190.00	9.90	784.949	0.001	967.081	0.001	0.020	0.105
5	50.180	6.750	43.430	190.00	9.90	833.505	0.001	963.051	0.001	0.020	0.148
6	50.240	16.450	33.790	190.00	9.90	648.495	0.002	964.202	0.001	0.020	0.061
7	50.310	10.300	40.010	190.00	9.90	767.869	0.001	965.545	0.001	0.020	0.097
8	50.260	7.850	42.410	190.00	9.90	813.929	0.001	964.586	0.001	0.020	0.127
9	50.210	4.940	45.270	190.00	9.90	868.818	0.001	963.626	0.001	0.020	0.202
10	50.140	3.600	46.540	190.00	9.90	893.192	0.001	962.283	0.001	0.020	0.278
11	50.250	4.330	45.920	190.00	9.90	881.293	0.001	964.394	0.001	0.020	0.231
12	50.090	14.340	35.750	190.00	9.90	686.111	0.001	961.323	0.001	0.020	0.070
13	50.190	11.100	39.090	190.00	9.90	750.212	0.001	963.242	0.001	0.020	0.090
14	50.290	6.760	43.530	190.00	9.90	835.424	0.001	965.162	0.001	0.020	0.148
15	50.180	8.340	41.840	190.00	9.90	802.990	0.001	963.051	0.001	0.020	0.120
16	50.110	10.880	39.230	190.00	9.90	752.899	0.001	961.707	0.001	0.020	0.092
17	50.240	5.930	44.310	190.00	9.90	850.394	0.001	964.202	0.001	0.020	0.169
18	50.190	7.170	43.020	190.00	9.90	825.636	0.001	963.242	0.001	0.020	0.139
19	50.330	9.220	41.110	190.00	9.90	788.980	0.001	965.929	0.001	0.020	0.108
20	50.150	4.460	45.690	190.00	9.90	876.879	0.001	962.475	0.001	0.020	0.224

DATA FROM THE ROUGHING FILTER WITHOUT AN EXTERNAL CARBON SOURCE (VRFwt) AT INFLOW NITRATE CONCENTRATION 50mg/L-N

Sampling interval (days)	Inflow nitrate concentration (mg/L-N) C_i	Outflow nitrate concentration (mg/L-N) C_e	Diffrence in inflow and outflow nitarte concentration (mg/L-N) $(C_i - C_e)$	Flow rate through the roughing filter (L/day) Q	Volume of roughing filter column (L) V_r	Kinetic nitrate removal rate (ng/L/day) $r_{NO_3^-} = \frac{Q(C_i - C_e)}{V_r}$	Nitrate removal rate inverse (L/d/mg) $\frac{V}{Q(C_i - C_e)}$	Total organic loading rate (mg/L/day) (QC_i/V_r)	Organic loading rate inverse (L/d/mg) $\frac{1}{(QC_i/V_r)}$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_i}\right)$	Inflow nitrate concentration inverse (L/mg-N) $\left(\frac{1}{C_e}\right)$
1	50.320	13.898	36.422	190.00	9.90	699.012	0.001	965.737	0.001	0.020	0.072
2	50.080	11.761	38.319	190.00	9.90	735.413	0.001	961.131	0.001	0.020	0.085
3	50.240	18.820	31.420	190.00	9.90	603.010	0.002	964.202	0.001	0.020	0.053
4	50.390	23.436	26.954	190.00	9.90	517.308	0.002	967.081	0.001	0.020	0.043
5	50.180	23.859	26.321	190.00	9.90	505.153	0.002	963.051	0.001	0.020	0.042
6	50.240	27.138	23.102	190.00	9.90	443.376	0.002	964.202	0.001	0.020	0.037
7	50.310	28.787	21.523	190.00	9.90	413.074	0.002	965.545	0.001	0.020	0.035
8	50.260	23.229	27.031	190.00	9.90	518.779	0.002	964.586	0.001	0.020	0.043
9	50.210	25.213	24.997	190.00	9.90	479.734	0.002	963.626	0.001	0.020	0.040
10	50.140	21.129	29.011	190.00	9.90	556.779	0.002	962.283	0.001	0.020	0.047
11	50.250	21.410	28.840	190.00	9.90	553.495	0.002	964.394	0.001	0.020	0.047
12	50.090	16.721	33.369	190.00	9.90	640.413	0.002	961.323	0.001	0.020	0.060
13	50.190	14.056	36.134	190.00	9.90	693.489	0.001	963.242	0.001	0.020	0.071
14	50.290	14.751	35.539	190.00	9.90	682.059	0.001	965.162	0.001	0.020	0.068
15	50.180	12.157	38.023	190.00	9.90	729.741	0.001	963.051	0.001	0.020	0.082
16	50.110	17.523	32.587	190.00	9.90	625.401	0.002	961.707	0.001	0.020	0.057
17	50.240	15.981	34.259	190.00	9.90	657.494	0.002	964.202	0.001	0.020	0.063
18	50.190	17.916	32.274	190.00	9.90	619.409	0.002	963.242	0.001	0.020	0.056
19	50.330	16.392	33.938	190.00	9.90	651.331	0.002	965.929	0.001	0.020	0.061
20	50.150	11.160	38.990	190.00	9.90	748.293	0.001	962.475	0.001	0.020	0.090