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Mathematical Modelling of a Composite Granular Filter of Effluent at Shirere Wastewater Treatment Plant in Kakamega County, Kenya

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Abstract

Insufficient technology for municipal wastewater treatment compromises the quality of effluent discharged into water bodies, elevating the risk of waterborne diseases (e.g., cholera, dysentery, typhoid). Previous research has associated the absence of clean water and sanitation with health issues such as skin problems, eye infections, and diarrhea among community members. Furthermore, studies indicate the proliferation of algae in the Shirere wastewater oxidation ponds, suggesting the presence of toxic cyanobacteria. Therefore, this study aimed to develop a mathematical model representing five critical parameters: COD, BOD, TSS, Phosphates, and Nitrates. Effluent from Shirere WWTP were collected for microbial quality analysis at MMUST and KACUWASCO laboratories. Data analysis involved, regression and correlation, and integration of wastewater mass balance equation using R-Programming and Fourth Order Runga Kutta (RK) method. The research employed purposeful sampling strategy, with a sample size of 8 of wastewater. The study followed an experimental design. Specifically, for the first season of March – May 2021 at 200mm filtration depth were carried out at effluent flow rate of $0.0032m^3/s$ and volume, $0.234 m^3$. the model arrived at was $C = C_{in}(1 - e^{-t(Q/V)})$. The model results showed minimal variation from the measured values.

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The first season measured COD as 0.236kg/m³ and model gave 0.2174kg/m³. The model can be used in prediction of parameter concentrations at any given time. The findings of this research will inform wastewater management policies and contribute to the development of sustainable wastewater treatment technologies.

Keywords: wastewater treatment; modelling; mass balance; composite granular filter; filter depth, Hydraulic retention time.

1. Introduction

The importance of water quality cannot be overstated in relation to social and economic development, environmental sustainability, and human health. Nevertheless, with the ongoing expansion of the global population, the accessibility of sufficient and uncontaminated water resources for the entire population is progressively diminishing. The implementation of efficient wastewater treatment methods has the capacity to safeguard our ecosystems, while concurrently offering significant resources, such as fertilizers, [1,2,3]. Presently, a staggering 1.8 billion individuals across the globe are subjected to the use of water that is tainted, so placing them at risk of contracting waterborne illnesses, including but not limited to cholera, dysentery, typhoid, and polio, [4]. Numerous urban areas exhibit deficiencies in the necessary infrastructure and resources essential for the effective and sustainable management of wastewater, [5].

The phenomenon of water contamination experienced a significant deterioration in multiple watersheds located in Africa, Asia, and South America over the 1990s, as revealed by author, [6]. According to [7], it is anticipated that nations with low- and middle-income, notably in Africa, will see the most significant rises in pollution exposure as a result of their dense population. The issue of cyanobacterial contamination, which is associated with the production of toxins that pose a threat to the health of both humans and animals, is a matter of significant importance. The potential of zinc peroxide in the removal of red dye for water purification in many sectors has been explained by author, [8]. Nevertheless, this approach exhibits several constraints, such as its dependence on a predetermined temperature and UV radiation, alongside the requirement for intricate experimental configurations.

According to [9], the existing methods of water and wastewater treatment in numerous African nations are insufficient. The primary methods utilized for wastewater treatment encompass onsite treatment, offsite treatment, conventional treatment, and stabilization ponds. Persistent challenges, such as inadequate infrastructure and inadequate operation maintenance, continue to hinder optimal performance. In the city of Addis Ababa, located in Ethiopia, the Kaliti treatment facility is seen to cater to a far less population than originally anticipated, primarily as a result of restricted sewer collection capabilities. The breakdown of pump stations in Kisumu, Kenya has led to the discharge of sewage into Lake Victoria.

Recent research has conducted evaluations on the quality of water in many geographical areas. In the study of [10], conducted an investigation of the river Molo watershed in Kenya. Their findings revealed that the pH, temperature, fluorides, and sodium levels in the river exceeded the allowed limits set by the World Health Organization (WHO). The author [11], conducted an assessment of the potability of groundwater in Langata Sub County, Nairobi-Kenya, employing a Water Quality Index. The findings of their investigation exhibited encouraging implications for the effective management of groundwater resources. Inadequate water quality can give rise to a variety of health problems, encompassing a broad spectrum of water-related disorders.

Moreover, the proliferation of cyanobacteria in aquatic environments presents a potential hazard to both human populations and wildlife. This issue is notably widespread in densely populated urban regions characterized by inadequate waste management procedures. Numerous metropolitan regions in Kenya encounter challenges pertaining to the management of wastewater and solid waste, resulting in the contamination of water resources such as the Athi River, [12]. The provision of water in Kakamega Town and its surrounding areas is predominantly dependent on the River Isiukhu and the Tindinyo gravity water system. Nevertheless, the existing water output is insufficient to meet the prevailing demand, hence necessitating the exploration of alternate sources such as shallow wells and rainfall collection. The field of solid waste management encounters various obstacles, including the prevalent practice of indiscriminate dumping and the resulting contamination of aquatic bodies.

The absence of adequate sanitary infrastructure in Kakamega poses a significant health hazard to its inhabitants, as it increases their vulnerability to various diseases including as amoebic infections, bilharzia, typhoid fever, malaria, dysentery, and cholera, [13]. The Kenya Water and Sanitation Civil Societies Network (KEWSNET) conducted investigations and found that defective wastewater treatment plants are a notable source of pollution in major towns, such as Kakamega, [14]. The primary objective of this study is to investigate the problem of wastewater quality at the Shirere Wastewater Treatment Plant. The proposed approach involves the incorporation of a granular composite filter at the exit of maturation pond, with the intention of improving the quality of effluent discharged into the river Isiukhu. In the foreseeable future prediction of effluents discharged from the effluent filter is to be found by the mathematical model. Several mathematical models were applied for the prediction including mass balance model. Considerable attention has been devoted to investigating the phenomenon of flooding in bigger rivers.

In summary, this research study examines the urgent concerns surrounding water quality, wastewater treatment, and public health in Kakamega Town and other urban settings. The primary objective is to develop mathematical model for prediction of several water parameters after installation of the filter. Efforts have been made to improve the quality of wastewater discharged into water bodies. Examples include a study by, [15] in which a vertical orientation of effluent flowing in the reactors from top to bottom. [16], in a vertical composite filter was using biochar and sand as filter media, flow of effluent was from top to bottom with high hydraulic transient which was a disadvantage. According to [17], revealed that, another vertical column filters composed of sand and pumice was used for removal of phosphates from top to bottom. However, none of these have been applied to improve wastewater discharged into River Isiukhu from Shirere Wastewater Treatment Plant.

This study adopted a horizontal -flow based reactor filled with composite filter at exit maturation pond in Shirere Wastewater Treatment Plant. The filter materials consisted of granular sand and pumice stone at depths of 200mm, 400mm and 600mm. The effluent entered in a lateral manner by gravity through perforations in the front screen. It was controlled by the principle of differentials in hydraulic heads of effluents before and after filtration. It is believed waste materials get adsorbed onto the composite materials as it passes through the filter.

2. Materials and Methods

2.1. Study Area

The study was conducted at Shirere wastewater treatment plant consisting of a Composite Filter, S1 sampling site and S2 sampling site. The catchment area for Shirere WWTP, Shikoye stream and river Isiukhu is defined by longitude 34°44'36.40"E, 34°45'8.65" E and latitude 0°16'4.61" N, 0°15'11.01" N. The location of the treatment plant is longitude 34°44'55.85'E, 34°44'53.93E and latitudes 0°15'58.76" N, 0°15'55.79" N. The wastewater from the plant is discharged into River Isiukhu via Shikoye stream. Figure 1 below gives the locations of the sampled points.



Figure 1: Schematic Diagram of Shirere Wastewater Treatment Plant

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2.2. Study Population

This study used points S1 and S2 for analysis.

2.3. Research design

This study employed experimental research design. The scientific analysis involved sample collection, preparation and laboratory analysis to determine among others concentration of COD, BOD, phosphates, total suspended solids (TSS) and nitrates while purposeful sampling technique was applied for data collection.

Table 1: Research design for the study

Specific objectives	Approach	Measurable	Research Design	Results	
		Indicator			
To develop a mathematical	Measure COD,	COD, BOD,	Correlation and	Tables and	
model for wastewater	BOD Nitrate,	Nitrates and	experimental	Graphical	
treatment plant for managing	Phosphates and	Phosphates.	designs.	representation	
the quality of the Isiukhu River	TSS.				

2.4 Sampling Strategy

Secondary data on effluent discharged and levels of contaminants in drinking water were obtained from Water Services Regulatory Board (WASREB). The sampling strategy for the scientific phase is shown in Table 2.

Table 2: Sampling strategies for the Scientific Phase

Study unit	Sampling methods	Sample size	
Wastewater	purposeful	8, 4 from each point of	2
		sampling sites	

2.5 Data Collection

The triplicates collected at sites S1-S2 were included for control sample conditions using labelled 500 millilitres sampling bottles and kept in ice boxes. In summary, samples were collected at the outlet of the maturation pond before filtration (S1). The above was repeated with experimental sample conditions collected after the introduction of sand-pumice composite filter within the exit chamber that created a three section of S1, reactor and S2. New Samples were therefore collected in S1, and S2. All samples were taken to MMUST laboratory for further analysis. This was done during the dry season, wet season and short rain season.

2.5.1 Particle size determination

Several particle sizes were obtained after passing ground pumice stones through various sieves. Particle size preparation was undertaken by mechanical sieving which is more efficient, [18]. In the British standard, sieving test procedure, a Bs 410 standard sieves are used. The sieve numbers are from 4 to 270 and corresponding sieves sizes ranges from 0.053 mm to 4.75mm, [19]. In this study the available sizes at MMUST Civil engineering laboratories had sieves sizes 0.6mm, 0.9mm, 1.18, 2.75mm and 3.25mm.

2.5.1.1 Optimal particle size determination

To obtain optimal particles sizes for filter material laboratory experiments involving determination of maximum wavelength (Lambda mark), and development of standard calibration curve were carried out. The optimum absorption wavelength Lambda mark for phosphate ions was determined in the range between 500nm to 950nm, [20]. A stock solution of 0.01mole of potassium dihydrogen phosphate was prepared by dissolving 1.36g of the salt into 500millilitres of distilled water and whose absorbance was measured in UV-vis spectrophotometer by varying the wavelength from 500nm to 950nm. Three trials of absorbance were carried for every wavelength in the range given and mean absorbance recorded. Using recorded results, the parameters of Gaussian function, $A = A_{max} \exp[\frac{\lambda - m}{s}]^2$ were determined by non-linear curve fitting in MATLAB and their optimal values were found as follows: $A_{max} = 0.65$, m = 752.02nm, and s = 146.24nm.



Figure 2: Plot of wavelength versus absorbance for the determination of optimum wavelength

From this graph, at maximum absorbance, using differential calculus, the lambda mark was found to be m = 752.02nm. Author, [20] conducted research using the same ratios and materials and revealed found lambda mark as 713nm and [21], at $\lambda = 715 nm$ which compares well with our results.

2.5.1.2 Standard Calibration curve

Obtained Lambda wavelength ($\lambda = 752$) was fixed on UV-VIS spectrophotometer for measurements of

absorbance of stock solution having concentrations of 5ppM, 10ppM, 15ppM, 20ppM, 25ppM, and 30ppM and recorded. Plotting stock concentrations against absorbance yielded standard calibration curve as shown in Figure 3.



Figure 3: Calibration curve showing a plot of concentration in ppm against absorbance of 0.01M potassium dihydrogen phosphate in distilled water

Absorbance was examined before and after filtering the stock solution through three cylinders with composite materials, each with a 50% mixture of 1.18 mm pumice and 1.18 mm sand, 1.18 mm sand and 0.9 mm pumice, and 1.18 mm sand and 0.6 mm pumice filtering material. The ideal composite filter was chosen using absorbance variation. The combination of 50% sand (1.18 mm) and 50% pumice (0.6 mm) at 0.248 absorbance variance was determined to have the best absorbance variance.

2.6 Adsorption time

Figure 4 shows the variation in phosphorous absorbance against incubation time in batch experimental conditions. In this case, waste water collected from Site S1, was used in batch experiment at MMUST chemistry laboratories.



Figure 4: Plot of time versus absorbance variance (%)

The phosphate removal efficiencies were 53%, 58%, 66%, 72%, 74% and 77% for contact time of a half an hour, 1, 2, 4, 8, 16, 32 and 64 hours respectively. The rate of phosphates removed under these conditions increased sharply up to 8 hours and gradually reached equilibrium after 16 hours reaction time. Thus, the equilibrium 77% adsorption of phosphates by the composite filter reached was attained after 16 hours beyond which minimum was observed. Inset is an adsorption model for the same composite filter developed for the same experimental conditions. This still showed 77% asymptotically success for phosphate removal.

The obtained results showed that the adsorption forces followed a decaying experimental equation of $y = 75.53 \exp(0.0003745x) - 29.45\exp(-0.53322x)$ a correlation coefficient of 0.994. This 16 hour was used by the researcher as minimal time after installation of composite filter reactor and material to the samples from S1 – S2.

2.7 Reactor design, and Material Installation

The main element of this study setting is the wastewater filtering apparatus. It is necessary for carrying out filtration studies and is specially made to fit the maturation pond's exit S1, [22]. According to Figure 5a, it was made to match the maturation pond's S1 exit. It measured 1170 mm in length, 1000 mm in breadth, and 600 mm in height to be fabricated of stainless steel.



Figure 5a: Design of Reactor/wastewater filtration instrument

Fabricated water-tight reactor with filter was installed into maturation pond outlet to fit its length and depth. This created sample collection zones along the width labeled S1 and S2 as previously described. Wastewaters were allowed to pass through it for 24 hours and samples were collected for analysis at points S1-S2. This was carried out to each at every 200mm, 400mm and 600mm depth of the composite filter into the maturation pond as shown in figure 5b below.





2.8. Water Quality Sampling

Fabricated water-tight reactor was installed into maturation pond outlet to fit its length and depth. This created sample collection zones along the width labeled S1 and S2 as previously described. Composite materials were

filled into it at heights of 200 mm, 400 mm and 600 mm. Wastewaters were allowed to pass through it overnight for 24 hours and samples collected for analysis at points S1 and S2. This was carried out to each at every 200mm, 400mm and 600mm depth of the composite filter at the maturation pond exit. Triplicate samples were collected during the seasons of March to May, June to August and September to November 2021.

The samples were collected in labelled 500 milliliters bottles sterilized by HNO₂ acid and stored under controlled container conditions before being transported to the laboratories. Three bottles per site were collected to enable sufficient analysis in the MMUST chemical laboratories, [23]. At the MMUST chemistry laboratory the field samples were filtered through 0.4- μ m pore membrane filters and kept at 4^oC until analysis. An aliquot of 50 milliliters of these used were digested with 20 milliliters of HCl acid at 80^oC until the solution became transparent, [24]. All samples were analyzed to determine biological oxygen demand (BOD), chemical oxygen demand (COD), nitrates (*NO*₃), phosphate (*P*₃*O*), and total suspended solids (TSS).

2.9. Mass Balance Model

2.9.1 Model Assumptions

The mass-balance analysis is the most basic method for determining the changes that occur when a reaction occurs in a container (reactor) or in a defined area of a body of liquid, [25]. Figure 6 depicts the mass balance for a single reactor in this research.



Figure 6: The system representation of WWTP using a composite filter

The system is displayed in Figure 6 where Q_{in} and Q_{out} are the volumetric flow rate into and out of the reactor. c_{in} = concentration of effluent into the reactor, and c = concentration of effluent out of the reactor. To apply a mass-balance analysis to the liquid contents of the reactor shown in Figure 6 above, the following assumptions were made:

i). the volumetric flow rate of effluent out of the reactor is equal to the volumetric flow rate of effluent into the reactor, $Q_{in} = Q_{out} = Q$,

- ii). the liquid within the reactor is not subject to evaporation (isothermal conditions), and
- iii). No reactions in the process of filtration.

2.9.2 Model Description

For the stated assumptions, the materials mass balance can be formulated as follows:

$$\frac{dC}{dt} = \frac{Q}{V}(C_{in} - C) \tag{1}$$

If only the steady-state effluent concentration is sought, Eq. (4) can be simplified by noting that the rate accumulation is zero under steady-state conditions (dc/dt=0), [26]. From Eq. (1), steady state is given as;

$$C = C_{in} \tag{2}$$

Eq. (1) is a first order ordinary differential equation with variables separable which can be easily integrated as follows. Integrating between the limits of 0 and C and 0 and t, and solving yields:

$$C=C_{in}(1-e^{-tt}0) \tag{3}$$

where $t_0 = Q/V$ is ponding time. In this study, the parameters C_{in} and C were replaced with BOD_{in} , COD_{in} , NO_{3in} , PO_{3in} , TSS_{in} and BOD, COD, NO_3 , PO_3 , and TSS respectively. MATLAB R2021a was used to plot the concentration curve for each water quality parameter.

2.10 Limitation of the Study

This study experienced inadequate sealing of the effluent on the sides of the reactor in the outlet manhole of maturation pond. This means that, the effluent was not fully filtered through the reactor. The limitation was addressed by incorporating more silica material on its external sides to reduce leakage.

3. Results and discussions

This section shows the results of the study and their discussion. It also includes establishment of a mathematical mass balance model of the filter performance and seasonal variability of pollutant removal from effluents.

3.1. Mathematical Mass Balance Model

To establish the mass balance model, data analysis was done by use of descriptive statistics of the parameters, standard deviations, means, frequencies, after which inferences were drawn from the analyses

The mass balance model was given as:

$$\frac{dBOD}{dt} = \frac{Q}{V} (BOD_{in} - BOD)$$

$$\frac{dCOD}{dt} = \frac{Q}{V} (COD_{in} - COD)$$

$$\frac{dPO_3}{dt} = \frac{Q}{V} (PO_{3in} - PO_3)$$

$$\frac{dNO_3}{dt} = \frac{Q}{V} (NO_{3in} - NO_3)$$

$$\frac{dTSS}{dt} = \frac{Q}{V} (TSS_{in} - TSS)$$
(4)

These equations were integrated using the fourth-order Runga Kutta (RK) method. The initial values of $C_{in}(BOD_{in}, COD_{in}, TSS_{in}, PO_{3in}, NO_{3in})$, C (BOD, COD, TSS, PO₃, NO₃), and t(time) for the method are given in Tables. The analytical solution for the same system of equations is given by Eq. 5 as shown below.

$$C = C_{in}(1 - e^{-t(Q/V)})$$

Which translates to specific model shown below;

$$BOD = BOD_{in}(1 - e^{-(Q/V)t})$$

$$COD = COD_{in}(1 - e^{-(Q/V)t})$$

$$PO_{3} = PO_{3in}(1 - e^{-(Q/V)t})$$

$$TSS = TSS_{in}(1 - e^{-(Q/V)t})$$

$$NO_{3} = NO_{3in}(1 - e^{-(Q/V)t})$$
(5)

The parameter Q (flow rate) was determined using Arcostic Doppler Velocimeter (ADV), while volume, V, was obtained by multiplying the depth of the filter and the reactor area. Using the values obtained by RK, non-linear least square method was applied to estimate the parameters of the above system of equations.

The mass balance equations for each season, flow rate, and depth were integrated via the use of the fourth-order Runga Kutta (RK) method for systems of equations given by Eq. (5). The results and discussions are given in the subsections 3.1 - 3.9.

3.1. 1 March – May 2021 at 200mm filter depth

March – May 2021 at 200mm filtration depth were carried out at effluent flow rate of $0.0032m^3/s$ and volume, $0.234 m^3$. Tables 3 provided C_{in} and C as starting values for numerical integration of Eq. (4)

Table 3: Concentrations of *BOD*, *COD*, *TSS*, *PO*₃ and *NO*₃ filtration for March – May season at 200mm and $0.0032m^3/s$

Filtration	Concentration (Kg/m^3)	<i>PO</i> ₃	NO ₃	COD	BOD	TSS
Before	C _{in}	0.0241	0.0199	0.3002	0.2813	0.3252
After	С	0.0220	0.0161	0.1909	0.2726	0.2913

The results of the integrations are shown in Figure 7. The corresponding equations of the graphs of Figure 7 are given by table 3



Figure 7: Concentrations of *BOD*, *COD*, *TSS*, NO_3 and PO_3 versus time with filter at depth of 200mm, $0.234m^3$ of volume, and input discharge of $0.0032m^3 / s$ for March-May season

Season	Depth	Parameters	Cin	$Q(m^3/s)$	$V(m^3)$	V/Q=	Q/V(t ₀)	Concentratio
	(mm)		Kg/m^3			(Detention		n (C) at to
			C			t/s)		
								(Kg/m^3)
March-	200	COD	0.3002	0.0032	0.234	73	0.0137	0.1891
may		BOD	0.2813	0.0032	0.234	73	0.0137	0.1772
		TSS	0.3252	0.0032	0.234	73	0.0137	0.2049
		NO ₃	0.0199	0.0032	0.234	73	0.0137	0.0125
		PO ₃	0.0241	0.0032	0.234	73	0.0137	0.0152

Table 4: Result Summary, season 1, at 200mm

From eq. 5, the concentration of each of the parameters increased until it reached steady-state. The steady-states of the graphs of Figure 7 given by Eqs. 5 was obtained by differentiating these equations, equating to zero, and the resulting concentrations was determined as shown in table 4. From the table, the model was predicting well the COD concentration at S2 sampling point which had very minimal variance. Measured COD was 0.1909 Kg/m^3 and the model predicted COD was 0.1891 Kg/m^3 . The Measured Phosphates was, 0.0220 kg/m³ while the model predicted phosphates was 0.0152 kg/m³ this indicates a minimal variance of 0.0078 kg/m³ implying that the model is accurate.

3.1.2March – May 2021 at 400mm filtration depth

March – May 2021 400mm filtration depth were determined at effluent flow rate of 0.0036 m^3/s and 0.468 m^3 of volume. The concentrations, C_{in} before and C after for BOD, COD, TSS, NO_3 and PO_3 represented in Table 5.

Table 5: Concentrations of BOD, COD, TSS, PO₃ and NO₃ filtration for Season March – May at 400mm depth

Filtration	Concentration (Kg/m^3)	PO ₃	NO ₃	COD	BOD	TSS
Before	C _{in}	0.0291	0.3278	0.3559	0.3002	0.3654
After	С	0.0255	0.0272	0.2311	0.2827	0.3305

These provided the initial values for the Runga Kutta (RK) method. The integration of the system of Eq. (4) using fourth-order Runga Kutta (RK) method for systems of equations gave the graphs shown Figure 8.



Figure 8: Concentrations of BOD_5 , COD, TSS, NO_3 and PO_3 versus time with filter at depth of 400mm, 0.468m³ of volume, and input discharge of 0.0036m³ / s for March-May season

Table 6: Result Summary for s	season 1, at 400mm
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Season	Depth (mm)	Parameters	$C_{in} (Kg/m^3)$	Q=(<i>m</i> ³ / <i>s</i>	V(<i>m</i> ³)	V/Q= (Detention time, sec)	Q/V(t ₀)	Concentrat ion (C) at t ₀ (<i>Kg/m</i> ³)
March-	400	COD	0.3559	0.0036	0.468	130	0.00769	0.2242
may		BOD	0.3002	0.0036	0.468	130	0.00769	0.1891
		TSS	0.3654	0.0036	0.468	130	0.00769	0.2302
		NO ₃	0.3278	0.0036	0.468	130	0.00769	0.2065
		PO ₃	0.0291	0.0036	0.468	130	0.00769	0.0183

From Eqs. 5, the concentration of each of BOD, COD, TSS, NO_3 and PO_3 increased until it reached steady-state. For steady-state, concentrations was as follows: $BOD = 0.300Kg/m^3$, $COD = 0.3559Kg/m^3$, $TSS = 0.3654Kg/m^3$, $PO_3 = 0.029Kg/m^3$, $NO_3 = 0.0328Kg/m^3$ and detention time, V/Q = 130 seconds. From table 6 the model was predicting well the COD concentration at S2 which had very minimal variance. Measured COD was $0.2311 Kg/m^3$ and the model COD was $0.2242 Kg/m^3$. In addition, the

measured PO³ was 0.0255 kg/m³, and the model predicted PO³ 0.0183 kg/m³. This also displays a minimum variance of 0.0072 kg/m³, which implies that the model is accurate in predicting the parameters, [27].

3.1.3 March - May 2021 at 600 mm filter depth

March – May 2021 at 600mm filter depth corresponded to $0.702m^3$ of the filter and effluent flow rate of $0.0045m^3/s$. The values of the concentration of BOD, COD, TSS, PO₃ and NO₃ before, C_{in} and after, C are given Table 7.

Table 7: Concentrations of BOD, COD, TSS, PO_3 and NO_3 filtration for March – May season at600mm

Filtration	Concentration (Kg/m^3)	<i>PO</i> ₃	NO ₃	COD	BOD	TSS
Before	C _{in}	0.0278	0.0319	0.2967	0.3220	0.3416
After	С	0.0221	26.783	0.1694	0.2853	0.3010

The C_{in} , C, and t = 0 were the starting initial values of the system of differential equations given by Eq. (4). The integration of the system of Eq. (4) using fourth-order Runga Kutta (RK) method for systems of equations and the results are depicted in Figure 9.



Figure 9: Concentrations of BOD_5 , COD, TSS, NO_3 and PO_3 versus time with filter at depth of 600mm, $0.702m^3$ of volume, and input discharge of $0.0045m^3 / s$ for March-May season

Table 8: Result Summary, season 1, at 600mm

Season	Depth (mm)	Parameter s	$C_{in}(Kg/m^3)$	Q=(<i>m</i> ³ / <i>s</i>	V(<i>m</i> ³)	V/Q=(De tention time, sec)	Q/V(t ₀)	Concentr ation (C) at t ₀
								(Kg/ m ³)
March-	600	COD	0.2967	0.0045	0.7020	156	0.0064	0.1869
may		BOD	0.3220	0.0045	0.7020	156	0.0064	0.2029
		TSS	0.3416	0.0045	0.7020	156	0.0064	0.2152
		NO ₃	0.0319	0.0045	0.7020	156	0.0064	0.0201
		PO ₃	0.0278	0.0045	0.7020	156	0.0064	0.0175

From Eqs. 5, the concentration of each of the BOD, COD, TSS, PO₃ and NO₃ increased until it reached maximum. For steady-state, concentrations was as follows: $BOD = 0.3220Kg/m^3$, $COD = 0.2967Kg/m^3$, $TSS = 0.3416Kg/m^3$, $PO_3 = 0.0280Kg/m^3$, $NO_3 = 0.0319Kg/m^3$ and detention time, V/Q = 156 seconds. The model in table 8 was predicting accurately the COD concentration at S2 which had very minimal variance. Measured COD was 0.1694 Kg/m^3 and the model COD was 0.1869 Kg/m^3 . The measured PO³ was 0.0221 kg/m³ while the model predicted 0.0175 kg/m³, which has a negligible variance.

The for three different depths, 200mm, 400mm, 600mm corresponding to volume: $0.468m^3$, $0.234m^3$, $0.702m^3$, gave the following detention times; 73.1 seconds, 130 seconds and 156 seconds. This is an indication that the detention time increases with the volume of the filter.

3.1.4 June – August at 200mm filter depth

June – August season effluent flow rate of $0.0039 m^3/s$ and volume, $0.234 m^3$. The concentrations of concentrations of C_{in} and C for BOD, COD, TSS, NO_3 and PO_3 before, and after are represented in Table 9.

Table 9: Concentrations of BOD, COD, TSS, NO_3 and PO_3 for March – May season at 200mm

Filtration	Concentration (Kg/m^3)	PO ₃	NO ₃	COD	BOD	TSS	
Before	C _{in}	0.0221	0.0179	0.2702	0.2813	0.3002	
After	С	0.0200	0.0141	0.1609	0.2526	0.2613	

The values in the Table 10 were used as the starting initial values of RK method for Eq. (4). Integration of the system of differential equation, Eq. (4) yielded



Figure 10: Concentrations of BOD_5 , COD, TSS, NO_3 and PO_3 versus time with filter at depth of 200mm, $0.234m^3$ of volume, and input discharge of $0.0039m^3 / s$ for June-August season

Table 10: Result Summary	, season 2, at	200mm
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Season	Depth (mm)	Parameter s	$\mathrm{C}_{\mathrm{in}}(Kg/m^3)$	$Q = (m^3/s)$	V (<i>m</i> ³)	V/Q=(De tention	Q/V(t ₀)	Concentr ation (C)
						t/s)		at to (<i>Kg/</i> <i>m</i> ³)
June-	200	COD	0.2702	0.0039	0.234	60	0.0167	0.1702
August		BOD	0.2813	0.0039	0.234	60	0.0167	0.1772
		TSS	0.3002	0.0039	0.234	60	0.0167	0.1891
		NO_3	0.0179	0.0039	0.234	60	0.0167	0.0113
		PO ₃	0.0221	0.0039	0.234	60	0.0167	0.0139

From Eqs. 5, the concentration of each of the variables (*BOD*, *COD*, *TSS*, *PO*₃, *NO*₃) increased until it reached maximum. Differentiating these equations and equating zero, the resulting concentrations were $BOD = 0.2813Kg/m^3$, $COD = 0.2702Kg/m^3$, $TSS = 0.3002Kg/m^3$, $PO_3 = 0.0221Kg/m^3$, $NO_3 = 0.0179Kg/m^3$

 m^3 and detention time, V/Q = 60 seconds. The model prediction in table 10 was accurately performing for the COD concentration at S2 which had very minimal variance. Measured COD was 0.1609 Kg/m^3 and the model COD was 0.1702 Kg/m^3 . Additionally, the measured PO3 was 0.0020 kg/m³, while the prediction of the model was 0.0139 kg/m³.

3.1.5 June – August at 400mm filter depth

The experiment was carried out at effluent flow rate of $0.0042m^3/s$ and $0.468m^3$.

Table 11: Concentration values before and after filtration for June – August season at 400mm and $0.0042m^3/s$

Filtration	Concentration	<i>PO</i> ₃	NO ₃	COD	BOD	TSS
	(Kg/m^3)					
Before	C _{in}	0.0212	0.0228	0.3209	0.2702	0.3254
After	С	0.0204	0.0173	0.2111	0.2427	0.3155

Table 11 provided the initial concentration values for system of differential equations. The integration of the system of Eq. (4) using fourth-order Runga Kutta (RK) method for systems of equations and the results are as follows.



Figure 11: Concentrations of *BOD*, *COD*, *TSS*, *NO*₃, and *PO*₃ versus time with filter at depth of 400 mm, 0.468 m^3 of volume, and input discharge of 0.0042 m^3/s for June-August season

Table 12: Result Summary, season 2, at 400mm

Season	Depth	Parameters	$C_{in} (Kg/m^3)$	$Q=(m^3/s)$	$V(m^3)$	V/Q=	$Q/V(t_0)$	Concent
	(mm)					(Detenti		ration
						on time,		(C) at
						sec)		t ₀ (Kg/
								$m^3)$
June-	400	COD	0.3209	0.0042	0.468	111	0.0090	0.2021
August		BOD	0.2702	0.0042	0.468	111	0.0090	0.1702
		TSS	0.3254	0.0042	0.468	111	0.0090	0.2050
		NO ₃	0.0218	0.0042	0.468	111	0.0090	0.0137
		PO ₃	0.0212	0.0042	0.468	111	0.0090	0.0134

From Eqs. 5, the concentration of each of the variables (*BOD*, *COD*, *TSS*, *PO*₃, *NO*₃) increased until it reached maximum. Differentiating these equations and equating zero, the resulting concentrations were $BOD = 0.2702Kg/m^3$, $COD = 0.321Kg/m^3$, $TSS = 0.3254Kg/m^3$, $PO_3 = 0.0212Kg/m^3$, $NO_3 = 0.02178Kg/m^3$ and detention time, V/Q = 111 seconds. The model in table 12 was predicting accurately the COD concentration at S2 which had very minimal variance. Measured COD was $0.2111 Kg/m^3$ and the model COD was $0.2021 Kg/m^3$. Also, the measured PO3, was 0.0204 and the predicted model was 0.0134 kg/m^3 , which is a minimal variance.

3.1.6 June – August season at the filter depth of 600mm

June – August filtration experiments were determined using effluent flow rate of $0.0045 m^3/s$, and volume $0.702m^3$

Table 13: Concentrations of BOD, COD, TSS, NO_3 and PO_3 before and after filtration for June –

August season at 600mm and 0.0045m ³	Ι	S
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Filtration	Concentration	<i>PO</i> ₃	NO ₃	COD	BOD	TSS
	(Kg/m^3)					
Before	C _{in}	0.0256	0.0318	0.2567	0.3313	0.3812
After	С	0.0221	0.0228	0.1619	0.2856	0.3413

Table 13 provided the initial parameter values and the state constants for following system of differential equations. The integration of the system of Eq. (4) results to the following

Eqs. 4.2 and their plots are given in Figure 12.



Figure 12: Concentrations of BOD_5 , COD, TSS, NO_3 and PO_3 versus time with filter at depth of 600mm, $0.702m^3$ of volume, and input discharge of $0.0045m^3 / s$ for June -August season

Season	Depth (mm)	Parameters	Cin	Q =(<i>m</i> ³ / <i>s</i>	V (<i>m</i> ³)	V/Q=(Detentio n time, sec)	Q/V(t ₀)	Concentration on (C) at to
								(Kg/m^3)
June-	600	COD	0.2567	0.0045	0.702	156	0.0064	0.1617
August		BOD	0.3313	0.0045	0.702	156	0.0064	0.2087
		TSS	0.3812	0.0045	0.702	156	0.0064	0.2402
		NO ₃	0.0318	0.0045	0.702	156	0.0064	0.0200
		PO ₃	0.0256	0.0045	0.702	156	0.0064	0.0161

From Eqs. 5, the concentration of each of the variables (*BOD*, *COD*, *TSS*, *PO*₃, *NO*₃) increased until it reached maximum. Differentiating these equations and equating zero, the resulting concentrations were $BOD = 0.3313Kg/m^3$, $COD = 0.2567Kg/m^3$, $TSS = 0.3812Kg/m^3$, $PO_3 = 0.0256Kg/m^3$, $NO_3 = 0.0318Kg/m^3$ and detention time, V/Q = 156 seconds. The model in table 14 was predicting accurately the COD concentration at S2 which had very minimal variance. Measured COD was 0.1619 Kg / m³ and the model COD was 0.1617 Kg / m³. The measured PO₃ was 0.021 kg/m³, while the prediction from the model was, 0.0161 kg/m³ showing a small variance.

Therefore, for June – August season, the three different depths, 200mm, 400mm, 600mm corresponding to volume: $0.468m^3$, $0.234m^3$, $0.702m^3$, gave the following detention times; 60 seconds, 111 seconds and

156 seconds. This is an indication that the detention time increases with the increase in volume of the filter.

3.1.7 September – November season at the filter depth of 200mm

The experiment was performed at effluent flow rate, $0.0039m^3/s$ and $0.234m^3$ of volume of the filter.

Table 15: Concentrations of *BOD*, *COD*, *TSS*, *NO*₃ and *PO*₃ before and after filtration for September – November season at 200mm and $0.0039m^3/s$

Filtration	Concentration (Kg/m^3)	<i>PO</i> ₃	NO ₃	COD	BOD	TSS
Before	C _{in}	0.0313	0.0251	0.3450	0.3071	0.3356
After	С	0.0290	0.0221	0.2360	0.2973	0.2984



Figure 14: Concentrations of BOD, COD, TSS, NO_3 and PO_3 versus time with filter at depth of 200mm, $0.234m^3$ of volume, and input discharge of $0.0039m^3 / s$ for June-August season

Table 16: Result Summary, season 3, at 200mm

Season	Depth (mm)	Parameters	$C_{in} (Kg/m^3)$	Q=(<i>m</i> ³ / <i>s</i>	V(<i>m</i> ³)	V/Q=(Detention time sec)	Q/V(t ₀)	Concentrat ion (C) at $t_0(Kg/m^3)$
Sept-Nov	200	COD	0.3450	0.0039	0.234	60	0.0167	0.2174
		BOD	0.3071	0.0039	0.234	60	0.0167	0.1935
		TSS	0.3356	0.0039	0.234	60	0.0167	0.2114
		NO ₃	0.0251	0.0039	0.234	60	0.0167	0.0158
		PO ₃	0.0313	0.0039	0.234	60	0.0167	0.0197

From Eqs. 5, the concentration of each of the variables (*BOD*, *COD*, *TSS*, *PO*₃, *NO*₃) increased until it reached maximum. Differentiating these equations and equating zero, the resulting concentrations were $BOD = 0.307Kg/m^3$, $COD = 0.345Kg/m^3$, $TSS = 0.3356Kg/m^3$, $PO_3 = 0.0313Kg/m^3$, $NO_3 = 0.0251Kg/m^3$ and detention time, V/Q = 60 seconds. The model in table 16 was predicting accurately the COD concentration at S2 which had very minimal variance. Measured COD was $0.2360 Kg/m^3$ and the model COD was $0.2174 Kg/m^3$. The prediction from the model showed PO3 of 0.0197 kg/m^3 , while the measured PO3 was 0.0290 kg/m^3

3.1.8 September – November season at the filter depth of 400mm

September – November season at the filter depth of 400mm corresponded to $0.468m^3$ of volume and effluent flow rate of $0.0042m^3/s$.

Table 17: Concentrations of BOD, COD, TSS, NO_3 and PO_3 before and after filtration for

September – November season at 400mm and $0.0036m^3/s$

Filtration Concentration		PO ₃	NO ₃	COD	BOD	TSS
	(Kg/m^3)					
Before	C _{in}	0.0367	0.0461	0.2650	0.3010	0.3803
After	С	0.0325	0.0385	0.1458	0.2902	0.3302

Table 17 provided the initial parameter values and the state constants for following system of differential equations. The integration of the system of Eq. (4) using fourth-order Runga Kutta (RK) method for systems of equations and the results are as follows.



Figure 14: Concentrations of BOD_5 , COD, TSS, NO_3 and PO_3 versus time with filter at depth of 400mm, $0.468m^3$ of volume, and input discharge of $0.0036m^3/s$ for March-May season

where Eqs. 5 are the equations for graphs shown in Figure 14.

Table 18: Result Summary, season 3, at	: 400mm
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Season	Depth (mm)	Parameter s	Cin (<i>Kg/m</i> ³)	Q=(<i>m</i> ³ / <i>s</i>	V(<i>m</i> ³)	V/Q=(De tention time, sec)	Q/V(t ₀)	Concent ration (C) at to (Kg/ m ³)
Sept- Nov	400	COD	0.2650	0.0036	0.468	130	0.0077	0.1670
		BOD	0.3010	0.0036	0.468	130	0.0077	0.1896
		TSS	0.3803	0.0036	0.468	130	0.0077	0.2396
		NO ₃	0.0461	0.0036	0.468	130	0.0077	0.0290
		PO ₃	0.0367	0.0036	0.468	130	0.0077	0.0231

From Eqs. 5, the concentration of each of the parameters increased until it reached maximum. Differentiating these equations and equating zero, the resulting concentrations were $BOD = 0.300Kg/m^3$, $COD = 0.3559Kg/m^3$, $TSS = 0.3654Kg/m^3$, $PO_3 = 0.029$, $NO_3 = 0.0328Kg/m^3$ and detention time, V/Q = 130 seconds. The model in table 18 was predicting accurately the COD concentration at S2 which had very minimal variance. Measured COD was $0.1458 Kg/m^3$ and the model COD was $0.1670 Kg/m^3$. The measured TSS was 0.3302 kg/m^3 and the prediction from the model was 0.2396 kg/m^3 which is equally a minimal variance. Just as it was revealed by a similar study, [27], this implies that the model can perfectly be

used for prediction of COD, BOD, TSS, as well as other related parameters.

3.1.9 September – November 600mm filter depth

September - November 600mm filter depth, corresponded filter volume of $0.702m^3$ and effluent flow rate of $0.0045m^3/s$. Table 19 represents the concentration values of variables, C_{in} and C.

Table 19: Concentrations of BOD, COD, TSS, NO_3 and PO_3 before and after filtration forSeptember – November season at 600mm

Filtration	Concentration	PO_3	NO ₃	COD	COD BOD	
	(Kg/m^3)					
Before	C _{in}	0.0222	0.0278	0.2834	0.3172	0.3692
After	С	0.0183	0.0214	0.1820	0.2676	0.3286

Table 19 provided the initial concentration values for the system of differential equations, Eq. (4). The integration of the system of Eq. (4) resulted to Eqs. 5 and their plots are given in Figure 15.



Figure 15 : Concentrations of BOD_5 , COD, TSS, NO_3 and PO_3 versus time with filter at depth of 600mm, $0.702m^3$ of volume, and input discharge of $0.0045m^3 / s$ for September - November season

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Table 20: Result Summary, season 3, at 600mm

Season	Depth (mm)	Parameter s	$C_{in} (Kg/m^3)$	Q=(<i>m</i> ³ / <i>s</i>	V(<i>m</i> ³)	V/Q=(De tention time, sec)	$Q/V(t_0)$	Concentration (C) at to
								(Kg/ m ³)
Sept-Nov	600	COD	0.2834	0.0045	0.702	156	0.0064	0.1785
		BOD	0.3172	0.0045	0.702	156	0.0064	0.1998
		TSS	0.3692	0.0045	0.702	156	0.0064	0.2326
		NO ₃	0.0278	0.0045	0.702	156	0.0064	0.0175
		PO ₃	0.0222	0.0045	0.702	156	0.0064	0.0140

From Eqs. 5, the concentration of each of the variables increased until it reached maximum. Differentiating these equations and equating zero, the resulting concentrations were $BOD = 0.317Kg/m^3$, $COD = 0.283Kg/m^3$, $TSS = 0.369Kg/m^3$, $PO_3 = 0.022Kg/m^3$, $NO_3 = 0.0328Kg/m^3$ and detention time, V/Q = 156 seconds. The model in table 20 was predicting accurately the COD concentration at S2 which had very minimal variance. Measured COD was $0.1820 Kg/m^3$ and the model COD was $0.1785 Kg/m^3$. While the measured PO³ was 0.0183 kg/m^3 and the model predicted PO³ of 0.0140 kg/m^3 which implies that the model is more accurate since the variance is minimal.

Also noted, for the September – November season, the three different depths, 200mm, 400mm, 600mm corresponding to volume: $0.468m^3$, $0.234m^3$, $0.702m^3$, gave the following detention times; 60 seconds, 130 seconds and 156 seconds. This is an indication that the detention time increases with the volume of the filter.

4. Conclusion

This study therefore concludes that, the model developed provides valuable information regarding performance of the composite filter and natural wetland downstream on wastewater treatment. Mass balance model can be used for a concentration prediction at any given time. This eventually reduces time and cost of other measurements.

Recommendation of the Study

The mathematical model for composite granular filter for managing the quality of effluent is recommended for prediction of any of the parameters by substituting the values for time. This will enable the design engineers to design the system that can still maintain the desired output but vary volumes and flow rates of the reactors

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