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Simulation of constructed wetland treatment in wastewater polishing using PREWet model

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ABSTRACT

To minimize the negative impact of wastewater when disposed into water bodies, proper treatment before its disposal is vital. Different wastewater treatment scenarios can be tested using predictive and analytical models. A screening-level, analytical model known as the PREWet model was calibrated and validated. The model assumes steady-state conditions and one-dimensional longitudinally varying concentration. The model was calibrated on a pilot-scale wetland and used to predict treatment through a constructed wetland. Performance of the calibrated model was statistically evaluated for its predictive ability by simulating the wastewater treatment through a constructed wetland. Different constituents were modelled which include: total phosphorous (TP), total coliform (TC), biochemical oxygen demand (BOD) and total suspended solids (TSS). The model coefficients were estimated using field and laboratory studies. Sensitivity analysis indicated that detention time of wastewater in constructed wetland was the most sensitive parameter in the PREWet model. Coefficient of determination and Nash–Sutcliffe coefficient were used to compare the observed and simulated results. The Nash–Sutcliffe coefficient of model efficiency for TP, TC, BOD and TSS was 0.97, 0.96, 0.97 and 0.77, respectively. The PREWet model was found to be an effective tool in simulating wastewater treatment through constructed wetlands.

Keywords: Calibration; Coefficient of determination; Constructed wetlands; PREWet model; Sensitivity analysis; Simulation; Subsurface flow and tertiary treatment

1. Introduction

Proper treatment of wastewater before its disposal is vital if its negative impacts on people, animals and aquatic life were to be minimized. Untreated or partially treated wastewater discharge pollutes the receiving water bodies, thus diminishing the aesthetic quality of surface water sources [1]. To address the issues of wastewater treatment, a holistic management approach which includes all stakeholders concerned should be used [2]. Different wastewater treatment scenarios can be tested by use of predictive models that are already in existence. For instance, an integrated water quality management is possible when the impact of wastewater discharged to the aquatic water ecosystem is predicted quantitatively by means of integrated wastewater models [3]. The prediction of wastewater treatment using analytical models gives a picture of what will be expected before the actual implementation of the wastewater treatment plant. In most developing countries,

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waste stabilization ponds are used in wastewater treatment. However, according to US EPA [4], stabilization ponds are less effective in the reduction of nutrients in wastewater. With increased human population and as a result increased wastewater generation, the ponds tend to be overloaded. This leads to partially treated wastewater being disposed off into the environment or receiving water bodies. In order to polish the wastewater treatment, a number of tertiary treatments can be carried out. These may include the use of constructed wetlands and sand filters.

The constructed wetlands have shown promising performance in reducing the nutrients from wastewater in many countries especially when used at secondary- or tertiary-treatment levels. However, the viability of this option has not been well tested in most of the developing countries. In most developing countries, constructed wetlands have not been adopted thus limited data is available to aid in modelling of their performance. Extensive data is required to construct a detailed predictive model that can adequately describe the pollutant removal processes in a wetland [5]. In most developing countries, minimal data are available and it is also costly to collect such extensive data. As a result, an option of using minimal data input and sizing the constructed wetland to protect the environment was selected in this study. In order to test the viability of wastewater treatment using constructed wetlands, a screening-level, analytical model known as the PREWet model was used. The model was preferred because of its robustness and its minimal input data requirements in modelling of the wastewater treatment using constructed wetlands.

Given the basic characteristics about the wetland, pollutant removal efficiency (RE) can be computed using the PREWet model [6]. The constituents that can be modelled include: total phosphorus (TP), total coliforrn (TC), biochemical oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), and contaminants such as organic chemicals and trace metals. The RE depends on the wetland's detention time and the removal rate, K (day^{-1}), for the constituent. The removal rates depend on a number of processes, such as microbial metabolism, adsorption, volatilization, denitrification, settling and ambient temperature conditions. The model focuses on the dominant long-term removal mechanisms, making use of literature values of mathematical formulations for those mechanisms when possible [7].

The main objective of the study was to use a simple, user friendly, long-term simulation model that can be used with minimal wetland data available. This involved: (i) sensitivity analysis and Calibration of PREWet model, (ii) simulating the treatment of the constructed wetland using the PREWet model and (iii) predicting TP, TC, BOD and TSS retention in the wetland system. The information obtained was to aid watershed managers in decision-making for constructing wetlands that can be used in polishing of effluent from waste stabilization ponds in the tropics. This paper, therefore presents results from the study where a pilot constructed wetland was used to polish the effluent from the waste stabilization ponds. The results from the pilot constructed wetland were used in calibration and validation of the PREWet model.

2. Materials and methods

The study was conducted at the Municipal Council of Nakuru (MCN) and Egerton University Njoro Campus in Kenya; where the focus was on the Kaloleni and Egerton University waste stabilization ponds. Egerton University is located at 35°55′46.8″ East, 0° 22′19.48″ South, at an average elevation of 2,265 m while the MCN is located at 36°05′32″ East, 0°19′41.08″ South and at an average elevation of 1,755 m. A pilot-scale subsurface flow constructed wetland was run to polish the effluent from Egerton and Kaloleni wastewater stabilization ponds and the results obtained were used in the calibration and validation of the PREWet model. Half of the dataset was used in calibration of the model and the other half was used in validation of the model.

2.1. Pilot subsurface flow constructed wetland

Vertical flow constructed wetlands which are vegetated systems in which the flow of water is from top to bottom through the substrate and the effluent is collected at the bottom was adopted for this study. Subsurface vertical flow constructed wetlands are extremely effective in removing suspended solids, BOD_5 and for nitrification of ammonia [8]. They have been put into use because of their ability to provide high-level secondary and tertiary wastewater treatment at a fraction of land use. In this study, the pilot wetland run had a surface area of 1 m^2, hydraulic depth of 0.6 m and was operated at a hydraulic loading rate ranging between 1.4 and 17.4 cm/day. To design the wetland, the Hydraulic Loading Rate (HLR) was calculated using equation below;

$$\mathrm{HLR} = \frac{100Q}{A_s} \tag{1}$$

the water balance to a wetland was calculated using equation [9];

$$\frac{dv}{dt} = Q_i - Q_e + P - ET \quad (2)$$

where Q_i = influent wastewater flow (volume/time)
Q_e = effluent wastewater flow (volume/time)
P = precipitation (volume/time)
ET = evapotranspiration (volume/time)
v = volume (m^3)
t = time (days)
also the depth of water within the system was calculated;

$$y = Q\frac{(\ln C_i - \ln C_e)}{A_s K_T n} \quad (3)$$

where C_e = effluent pollutant concentration, mg/l
C_i = influent pollutant concentration, mg/l
Q = average flow rate
t = hydraulic residence time, days
y = depth of water in wetland
A_s = surface area of the wetland
n = porosity
K_T = temperature dependent first-order reaction rate

The temperature correction factor for BOD was calculated using the equation below;

$$K_T = K_{20}(\theta)^{T_W - 20} \quad (4)$$

where K_T = temperature—dependent first order reaction rate constant
K_{20} for SSF is first-order reaction rate constant at 20°C, K_{20} = 1.06 [9]
T_W = temperature of water
The constructed wetland was run at a hydraulic retention time of 0.5–6 days. The substrate used consisted of sand as the top layer, expanded clay as the main layer and gravel as the drainage layer. Vetiver grass was the wetland plant used. The pilot wetland was run for a period of 8 months. Samples were collected weekly and analysed for TP, TC, BOD and TSS. The influent average concentration and standard deviation of the parameters was 6 ± 2 mg/l, 3000 ± 250 MPN/100 ml, 241 ± 64 mg/l and 96 ± 5 mg/l, respectively. The average effluent concentration and standard deviation from the pilot constructed wetland was 0.95 ± 0.13 mg/l, 106 ± 40 MPN/100 ml, 10 ± 3 mg/l and 9 ± 3 mg/l, respectively. The pilot constructed wetland had average RE for TP, TC, BOD and TSS of 84, 96, 96 and 91%, respectively.

2.2. The PREWet model inputs and output

Inputs to the model were system properties (which included length, width, hydraulic depth, surface area and volume), hydraulic retention time, and velocity of flow and temperature of the surrounding area. The constituents modelled were also input which included; TP, TC, BOD and TSS (Table 1). The inflow characteristics of these constituents were entered. The output of the PREWet model included; removal rate per day, removal efficiencies and the out flow concentration of the constituents modelled [10].

The PREWet model was calibrated, validated, tested for sensitivity and used to predict the performance of the system. The model was calibrated to reduce its performance uncertainty. In the calibration process, the model coefficients values which included temperature correction and removal rates were adjusted in order to match closely with the measured values. Half of the data-set collected from the system was used in calibrating the model and the remaining half of the data-set was used in validating the model. Model validation is the process of demonstrating a given site-specific model is capable of giving sufficiently accurate simulations [10].

2.3. Sensitivity analysis

The PREWet 2.4 model was subjected to sensitivity analysis in order to identify its critical parameters. The model was tested with several runs for different wetland design parameters. These parameters included wetland dimensions (i.e. area, volume, depth, width and length). Each parameter was studied by changing its corresponding value while holding the other parameters constant. The discharge and retention time that corresponded with the estimated parameters were calculated. To study the effects of changing modeling parameters, that is retention time and discharge, the removal rate constants were fixed. Initially, one of the wetland dimension parameter was changed keeping retention time to 2 days as had earlier been calculated. This necessitated changing the wetland capacity and discharge, Q. In addition, the designed discharge (Q) value was maintained and by changing one wetland dimension, different values of retention time were applied.

2.4. Model simulation

The PREWet model was used in simulation of pollutant treatment through the constructed wetland. The removal rate coefficients that were obtained during calibration of the model were used during the simulations. The simulation was run using the plug flow and fully mixed options. Values of the collected and simulated data for each constituent (TSS, TP, BOD and TC) were used to draw a scatter plot. To validate

Table 1
PREWet model input parameters

Parameter	Units	Default values
Detention time	Days	
Temperature	°C	20°C
Constituents modelled	TSS (mg/l), BOD (mg/l), TP (mg/l), Total Coliforms (mpn/100 ml), TN (mg/l) contaminants (organic chemicals and trace metals)	BOD decay factor = 0.8 Chosen value = 0.68 Temperature correction factor = 1.013 and 1.03
Hydraulic depth	m	Chosen value 0.6 m
Volume	M^3	Chosen value 0.6 m^3
Area	M^2	Chosen value 1 m^2
Influent concentrations	Modelled parameters	
Length	m	Chosen 1 m
Width	m	

the model, simulated data from PREWet model was compared with observed data from the pilot wetland run. Correlation analysis of the simulated and observed data was undertaken using the statistical package SPSS 17.0.

The Nash–Sutcliffe method was also used as an additional way to quantify the relationship between simulated and observed results. The results were compared using the coefficient of model efficiency by [11].

$$COE = 1 - \left[\frac{\sum_i^n (q_w - q_s)^2}{\sum_i^n (q_w - q_m)^2} \right] \quad (5)$$

where COE = the coefficient of model efficiency,
q_w = measured parameter from the wetland
q_s = simulated value
q_m = mean of measured parameter
n = number of measurements taken

2.5. Prediction using PREWet model

The data from the analyses of physico-chemical, nutrients and microbial contamination from the effluent of MCN (Kaloleni) waste stabilization ponds was used in the PREWet model, which had been calibrated from data collected from pilot wetland set up in Egerton University. The data were used as the influent characteristics of the constituents modelled, while removal rates and decay factors were maintained constant in the calibrated model. This was undertaken for all the retention times operated during the study maintaining their RE. As a result, the concentration for the effluent from the constructed wetland was given as the model output. Prediction was run using the plug flow and fully mixed option.

3. Results and discussion

3.1. Model calibration

The PREWet model was applied on two assumptions, plug flow and the mixed flow conditions. The temperature correction factor for BOD and coliform in the plug flow condition was found to be 1.013 and 1.03, respectively. The model's default values for the temperature correction factor in the two options are 1.07 and 1.047 for coliform and BOD, respectively. The fully mixed option correction factor was significantly lower than the default values compared to the plug flow condition. Correction factors in plug flow condition were noted to have a difference of 0.034 and 0.04 for BOD and coliform, respectively. The change of temperature correction factor was not high since the temperature range within the place of application was around 22°C.

The change in temperature correction factors could be as a result of climate difference since PREWet model was developed in temperate regions while this application is in tropics. Also, the model had been developed for surface flow constructed wetland and its application is on subsurface flow constructed wetland.

PREWet model was developed with a view that vegetation has no net effect on uptake of nutrients. This is because the wetland vegetation is considered to take up nutrients, die off and release the nutrients back [12]. In this application, vegetation could have had an effect in reduction of nutrients since vetiver grass is hardy and was harvested as animal feed thus release back of the nutrients was not experienced. Due to the effect of vegetation, the TP volumetric and areal decay factor decreased.

3.2. Sensitivity analysis

Sensitivity analysis is the process of determining how a change in model input affects the model output parameters. The process helps in identifying the key parameters and parameter precision required for calibration [13]. Changing detention time and fixing wetland dimensions, the temperature correction factor and decay/degradation coefficients had an influence on the pollutant removal. As hydraulic detention time varied from 1 to 6 days, the RE and the outflow concentration of the constituent variables was changing. The removal rates were found to follow the trends of their respective measured and calculated values as detention time changed. A similar observation was made by Chavan and Dennet [12] in their study on wetland simulation for nitrogen, phosphorous and sediment retention in constructed wetlands.

With increasing hydraulic detention time, the pollutants treatment improved significantly. Similar findings were reported by Zidan et al. [14]. Detention time could be increased by changing the wetland volume and applying the same flow rate or by decreasing wetland discharge. The PREWet model was also found to be sensitive to the depth of water within the wetland system. When the model was operated in fully mixed option, increase in water depth reduced the RE of TSS and TP while decrease in water depth increased RE of TSS and TP (Table 2). According to Zidan et al. [12], the removal rate per day for TSS is calculated using the settling velocity and the water depth and as a result the change of water depth would affect the RE of TSS. Phosphorous removal is interrelated with TSS removal from the assumption that all the suspended sediment particles provide surface area for phosphorous attachment [15].

This variation could be as a result of reduced contact with the substrate media used in the wetland. The TC and BOD outflow concentrations were not affected by change indepth of water in the wetland. When the water depth within the wetland was changed under the plug flow condition, the model results showed that this had an effect on treatment performance on the TSS while the other modelled constituents were not affected (Table 3). When the hydraulic depth of the wetland was changed under plug flow condition the HRT also varied. Increase in hydraulic depth led to an increase in HRT while decrease in hydraulic depth resulted to a decrease in HRT. This was as a result of reduced amount/volume of water within the wetland system and since the flow rate was maintained constant the water took less HRT and vice versa. The TSS removal was affected by the change of water depth because more volume of water was to be filtered by the substrate.

When the detention time of the wetland was maintained constant and the volume of the wetland changed, the RE and outflow concentration were not affected. It was also noted that changing the width of the wetland and maintaining hydraulic detention time had no effect on out flow concentration of the constituents modelled.

3.3. Model simulation

The coefficients of correlation for the observed and simulated parameters from the model were determined. The parameters included TP, TC, BOD and TSS with coefficient of correlation of 0.985, 0.981, 0.983 and 0.901, respectively. A scatter plot diagram developed for TP and TSS constituent together with the line of best fit drawn and coefficient of determination (r^2) are given in Figs. 1 and 2.

The r^2 values for the TP, TC, BOD and TSS were 0.97, 0.96, 0.97 and 0.81, respectively.

The calculated Nash–Sutcliffe efficiency coefficient, which is a quantitative statistic measure for TP, TC, BOD and TSS were 0.97, 0.96, 0.97 and 0.77, respectively. According to Tuncsiper et al. [16], Nash–Sutcliffe efficiency greater than 0.5 indicates that the model performance is satisfactory. In all the constituents modelled in this study, the Nash–Sutcliffe efficiency was found to be greater than 0.5 with the least efficiency being 0.77. In this study, simulated and observed parameters of all the modelled constituents had a strong agreement and indicated that the model can be satisfactorily used. Both, coefficient of correlation and Nash–Sutcliffe coefficient indicated that TSS had the lowest agreement between the observed and simulated values. This could have been due to the assumption which was adopted from Refs. [17] and [18] where re-suspension of sediment was considered negligible compared to the burial rate and that the net-settling velocity for TSS was approximately equal to settling velocity of the particle.

3.4. Model prediction

The calibrated PREWet model was used to predict wastewater treatment from Municipal Council of Nakuru (Kaloleni), since the same boundary conditions of climate, influent wastewater characteristics and

Table 2
Effects of changing water depth on PREWet model performance (fully mixed option)

Depth (m)	TSS (mg/l)	TP (mg/l)	TC(MPN/100 ml)	BOD (mg/l)
Actual values (depth = 0.56)	8	0.50	38	7
0.40	6	0.37	38	7
0.46	7	0.42	38	7
0.50	8	0.45	38	7
0.60	9	0.53	38	7
0.66	10	0.58	38	7
0.76	11	0.65	38	7

Table 3
Effects of changing water depth on PREWet model treatment (plug flow condition)

Depth	TSS (mg/l)	TP (mg/l)	TC	BOD (mg/l)	HRT (days)
Actual values (depth = 0.56)	8	0.50	38	7	3.48
0.46	5	0.50	38	7	2.32
0.50	7	0.50	38	7	2.79
0.60	10	0.50	38	7	3.64
0.66	12	0.50	38	7	3.94

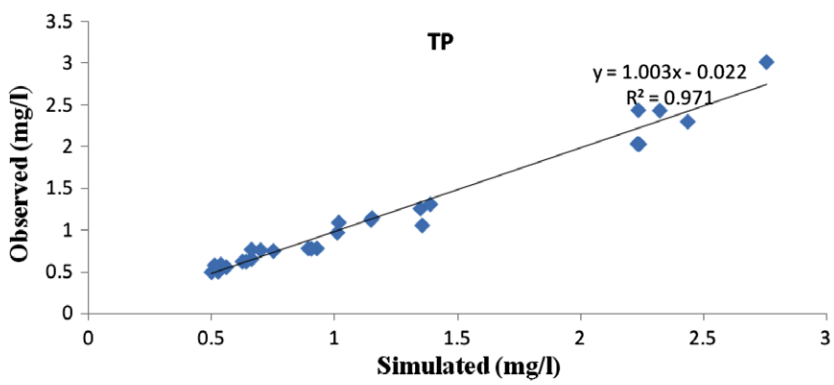

Fig. 1. The r^2 of observed and the simulated concentrations of TP.

vegetation existed. Wastewater data collected from the Municipal Council of Nakuru (Kaloleni) waste stabilization ponds had mean concentration for TP, TC, BOD and TSS of 5.19 mg/l, 1,350 Mpn/100 ml, 143 mg/l, and 21 mg/l, respectively. The TP, TC, BOD and TSS parameters did not meet the National Environment Management Authority (NEMA) discharge standards of 1 mg/l, 200–400 Mpn/100 ml, 30 mg/l and 15 mg/l, respectively. Tables 4 and 5 give the concentration of various variables from Kaloleni wastewater as predicted by the PREWet model at different detention times. The plug flow condition and fully mixed option predicted the treatment of the wastewater uniformly in all the detention times applied.

The PREWet model had an under estimation of TSS at all hydraulic detention time operated but all the other modelled constituents were predicted uniformly. The TSS under estimation could have been due to the reason discussed above on the assumption made that the settling velocity of the TSS being equal with the settling velocity of the particles.

It was noted that for the effluent from MCN (Kaloleni), waste stabilization pond requires a detention time of 2 days in a constructed wetland in order to

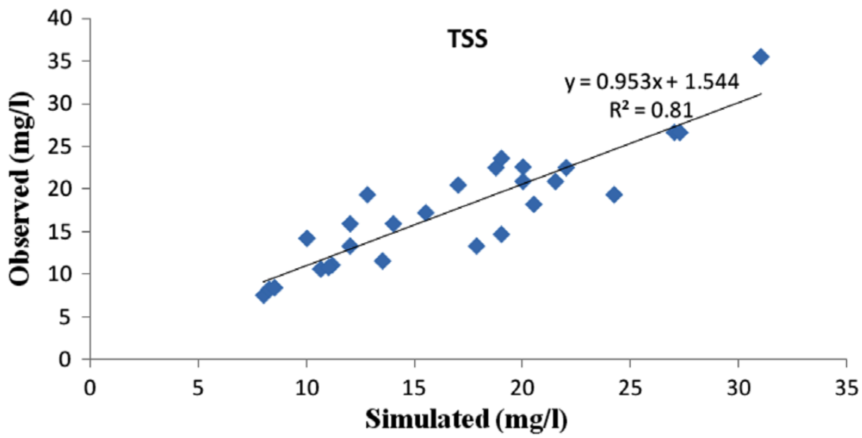

Fig. 2. The r^2 of observed and the simulated concentrations of TSS.

Table 4
Model prediction on Nakuru data using plug flow condition

HRT (days)	TSS (mg/l)	TP (mg/l)	BOD (mg/l)	Coliform (MPN/100 ml)
0.5	11	3.20	36	211
1	6	1.46	9	183
2	4	0.91	7	95
3	4	0.73	7	93
6	3	0.66	7	41

Table 5
Model prediction on Nakuru data using fully mixed condition

HRT (days)	TSS (mg/l)	TP (mg/l)	BOD (mg/l)	Coliform (MPN/100 ml)
0.5	11	3.20	36	210
1	6	1.52	9	183
2	4	0.91	7	95
3	4	0.73	7	93
6	2	0.66	5	42

meet the discharge, standards set by NEMA for all the constituents modelled.

4. Conclusion

Although, the variation of the depth of water in the wetland had an effect on the performance of the PREWet model in varying levels of concentration of TSS and TP, the main governing parameter in PREWet model application was found to be the hydraulic retention time. The physical dimensions (length, width or height) were found to have minimal effects on performance of the model. The study found out that the results simulated using the PREWet model and those observed or measured matched closely. The coefficient of determination for the simulated and observed values for the modelled constituents ranged between 0.81 and 0.97. In addition, the coefficient of correlation of the modelled constituents between the observed and simulated was between 0.901 and 0.985. Using the statistical Nash–Sutcliffe method, the observed and the simulated coefficient of model efficiency ranged between 0.77 and 0.97. Therefore, it was found that PREWet model can be used effectively in simulation of constructed wetland treatment in polishing of the effluent from waste stabilization ponds. From this study, it was concluded that the PREWet model can be useful in the planning of wastewater treatment when the data for influent characteristics and the volume of wastewater to be polished are available. The model can be useful in designing and sizing of constructed wetland for tertiary treatment of wastewater.

Abbreviations

BOD	—	biological oxygen demand
MCN	—	Municipal Council of Nakuru
PREWet	—	pollutant removal estimates for wetlands
TC	—	total coliform
TP	—	total phosphorous
TSS	—	total suspended solid

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