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Performance evaluation and numerical simulation of vertical subsurface flow constructed wetlands in wastewater treatment

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ABSTRACT

Constructed wetlands are extensively employed to treat wastewater in many countries and are an eco-friendly and low-cost wastewater treatment technique. In this study, the performance of an intermittently operated vertical subsurface flow constructed wetland planted with Amaranthus dubius and the effect of adding oyster shells as a substrate layer in the wetland on its performance were investigated. Major quality parameters such as phosphates, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, Total Organic Carbon and COD in the effluent and influent were monitored and compared. The concentration of these quality parameters was determined by the colorimetric method in the laboratory using a UV-Visible spectrophotometer. The results indicated that the planted vertical subsurface flow constructed wetlands achieved efficient removal of ammonia nitrogen from the wastewater and were effective for nitrification. The addition of oyster shells in the substrate enhanced the total nitrogen removal from the wastewater. The ability of the HYDRUS CW2D model in simulating reactive transport through a vertical subsurface flow constructed wetland was also investigated. A good match between the measured and simulated parameters could be achieved after adjusting certain constructed wetland parameters in the HYDRUS CW2D model. Model validation was performed based on a quantitative statistic known as the ratio of root mean square error (RMSE) to the standard deviation of the observed data - RSR. The RSRvalue for ammonia nitrogen and nitrate nitrogen was less than 0.70, which is satisfactory.

1. Introduction

One of the contemporary global environmental problems is the lack of availability of adequate fresh water. This is a very serious issue in many countries, especially in developing countries. Unscientific water withdrawal patterns, overexploitation of freshwater sources, increase in freshwater demand due to an increase in population and improvement in the standard of

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living, and an increase in wastewater production coupled with the lack of policy regarding and the infrastructure required for efficient wastewater treatment and reuse has compounded the freshwater availability problem further. Among the various causes of deterioration in freshwater quality, the disposal of untreated wastewater into freshwater sources is a major issue. In the course of various developmental activities, major cities produce huge amounts of wastewater every day. However, the capacity of existing urban sewage treatment plants is grossly insufficient to treat all the sewage produced. A large investment is needed to bridge the gap between the actual volume of sewage generated and the treatment capacity of existing treatment plants by constructing new wastewater treatment plants and augmenting the capacity of existing wastewater treatment plants. Among the different causes of water pollution, pollution by nutrients caused by the discharge of wastewaters containing excess nitrogen and phosphorus into water bodies is becoming increasingly frequent. The principal sources of nutrient pollution in water include agriculture, storm runoff, domestic wastewater, etc. Their presence in water bodies causes eutrophication, resulting in conditions that can be toxic to aquatic invertebrates and vertebrates [1]. Thus, it is essential to treat wastewaters containing nutrients before being disposed into freshwater bodies and aquifers. Since conventional treatment requires a high amount of energy, considerable maintenance, and skilled personnel for its proper working, developing decentralized low-cost wastewater treatment systems is essential, particularly in developing countries. It has been reported that constructed wetlands, which are a cost-effective and eco-friendly technique for wastewater treatment, are very effective in removing nutrients such as nitrogen and phosphorus, organic pollutants, and total suspended solids from wastewater [2-4]. Such technology has been adopted in many countries from ancient times onwards [2]. The principal treatment mechanisms in constructed wetlands include various physical, chemical, and biological processes such as sedimentation, adsorption, precipitation, plant uptake, and microbial metabolic activity [5,6]. The main components of a constructed wetland that actively participate in the treatment process include water, substrate, and vegetation. Wetland substrates provide attachment surfaces for microbial communities and act as ingredients for bioreactions [7]. The substrate must have sufficient hydraulic conductivity and good sorptive capacity for treating nutrient-contaminated wastewater [8,9]. Vegetation increases the treatment efficiency by stabilizing the bed surface and increasing the contact time between the wastewater and the plant surface area and filtration [10]. However, some authors have reported that nutrient uptake by plants is only a minor factor in constructed wetlands when compared to the loadings applied [11]. Subsurface flow constructed wetlands (vertical flow type and horizontal flow type) are the most widely adopted type of constructed wetlands in the world [12]. Compared to the horizontal flow type, the vertical flow constructed wetlands require less space and thus provide a better wastewater treatment technique for small communities [13]. In addition to that, vertical flow constructed wetlands provide unsaturated conditions in the wetland environment that enhance the aerobic condition necessary for nitrification. A combination of these types of subsurface flow constructed wetlands could facilitate significant nutrient and organics removal from wastewater. It is made possible on account of the occurrence of aerobic and anaerobic conditions in the vertical and horizontal flow constructed wetlands, respectively [7,14]. The complexity of the internal processes occurring inside the wetland environment necessitates the development of mathematical tools. Numerical models describing the biochemical transformation and degradation processes in a constructed wetland are a good tool to understand the functioning of wetlands. Since the water flow regime in a vertical flow constructed wetland is highly dynamic, it requires a transient variably saturated model. The HYDRUS 2D variably saturated and solute transport model is one of the most widely used numerical models for simulating constructed wetlands [15]. It implements two biokinetic constructed wetland model formulations, namely CW2D and CWM1. The CW2D module describes the biochemical transformation and degradation processes for organic matter, nitrogen, and phosphorus and is used for simulating subsurface vertical flow constructed wetlands [16]. This paper mainly focuses on the performance evaluation of a pilot-scale intermittent vertical flow constructed wetland with respect to the removal of nutrients from domestic wastewater. The effect of vegetation and the addition of oyster shells in the substrate on the removal of nutrients from wastewater are analyzed. The ability of the HYDRUS 2D model to simulate water flow and solute transport through a vertical subsurface flow constructed wetland, without considering the vegetation, is also attempted. The major limitations of the research are the following.

a.The studies were carried out using synthetic wastewater that was freshly prepared in the laboratory before each influent loading.

b.In simulating water flow and reactive transport, only the main treatment layer in the constructed wetland was considered. However, there are layers of smaller depths below and above the treatment layer in a constructed wetland unit that serve as protective layers. It is assumed that these layers contribute only very little to the overall treatment process.

2. Materials and methods

2.1. Experimental setup

The studies were carried out on pilot-scale vertical flow constructed wetlands in the Water Resources Engineering Laboratory of NIT Calicut. The pilot-scale units consisted of two vegetated cells and a non-vegetated cell (control unit). The size of all the cells was 1.83m x 1.22m x 1.22m and made of MS sheet on four sides and transparent acrylic sheet on one side. The constructed wetland units were filled to a depth of 1m with a suitable substrate; this material was washed thoroughly before filling. The main layer in the constructed wetland unit was a depth of 50cm of river sand (1-4mm size). In one of the vegetated units, this layer was composed of river sand and crushed oyster shells in equal proportions. Before filling the substrate, the effluent collection network was laid at the bottom of each unit, and this was protected with a 10cm thick layer of 40mm gravel. To prevent the flow of sand particles into the drainage network, a 20cm thick layer of 6mm gravel was provided immediately below the treatment (main) layer. A layer of 6mm of gravel was provided at the top of each unit. Fresh synthetic wastewater was fed into these units through distribution pipes installed at the top, the rate of flow was controlled with valves. Influent wastewater was pumped into the distribution network using a monoblock pump. The vegetated wetland units were planted with Amaranthus dubius. Amaranthus dubius, commonly known as red spinach, is a locally available tropical edible plant with a branched stem that grows from 30 to 150 cm. It requires well-drained soil for its growth and has the ability to store nitrates in its stems and leaves. The cross-section of a typical wetland unit is presented in Figure 1.

2.2. Constructed wetland operation

The seedlings of the Amaranthus dubius were transplanted immediately after filling the substrate in the pilot-scale units. These were fed with tap water for three weeks to enable their growth and to facilitate their adjustment to the wetland environment. After this period, freshly prepared synthetic wastewater that conformed to the characteristics of typical domestic wastewater was fed to the wetland units. The influent properties were fixed based on the Standard Methods for the Examination of Water and Wastewater (22nd edition, 2012) of the American Public Health Association (APHA). Important quality parameters such as chemical oxygen demand (COD), orthophosphate, total phosphorus (P), ammoniacal nitrogen (NH_3-N), nitrite nitrogen (NO_2-N), and nitrate-nitrogen (NO_3-N) were determined by colorimetric methods. A UV/VIS spectrophotometer was used for the determination of these quality parameters. The constructed wetland units were operated intermittently. The wastewater was supplied for a period of 12h a day, and after that, the supply was stopped for the next 12h. A hydraulic loading rate of 100 litres/m2/day and an organic loading rate of 50g COD/m2/day were maintained throughout the study. This loading was continued until the growth period of vegetation was over. Effluent samples were collected and analyzed weekly for various quality parameters. After the experimental studies, the plant and soil samples were collected and tested in the laboratory to determine their accumulated nutrient concentration.

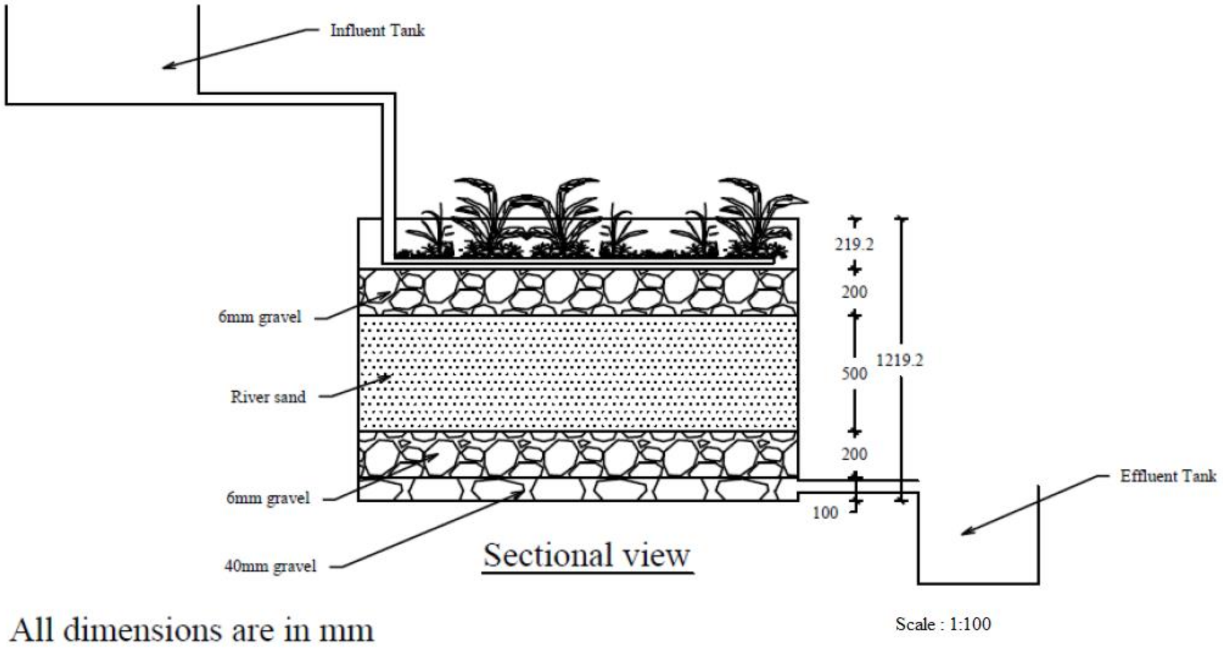

Fig. 1. Cross-sectional view of a typical constructed wetland unit.

2.3. Simulation using HYDRUS 2D

The HYDRUS 2D/ 3D was developed to simulate water flow and solute transport in two and three-dimensional variably saturated porous media. It numerically solves Richard's equation for variably saturated water flow and the advection-dispersion equation for solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots [17]. The water flow model considers prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, and free drainage boundary conditions. The governing flow and transport equations of the model were solved using Galerkin finite element schemes. The CW2D module was developed as an extension of the HYDRUS 2D to model the subsurface flow constructed wetlands. The mathematical structure of CW2D is based on the mathematical structure of the Activated Sludge Model introduced by Henze et al. (2000). CW2D includes 12 components and nine processes. The following components are defined in CW2D: dissolved oxygen (O_2), organic matter (OM) expressed in units of COD divided into readily biodegradable (CR), slowly biodegradable (CS) and inert organic matter (CR), and nitrogen as ammonium nitrogen (NH_{4+}), nitrite nitrogen (NO_2-), nitrate-nitrogen (NO_3-) and dinitrogen (N_2), inorganic phosphorus (IP), heterotrophic microorganisms (XH), and autotrophic microorganisms such as nitrosomonas (XANs) and nitrobacter (XANb). The microbial processes in CW2D are related to the heterotrophic and autotrophic bacteria group. In this model, all the bacteria responsible for hydrolysis, mineralization of organic matter, and denitrification are assumed to be heterotrophic, whereas the bacteria responsible for nitrification are assumed to be autotrophic [16]. In this study, numerical simulation of a vertical flow constructed wetland was performed by considering only the 50cm thick treatment layer of the river sand. The presence of vegetation was not considered in the simulation. The simulation was divided into two steps: simulation of water flow using the standard HYDRUS model and the simulation of degradation and transformation of pollutants using CW2D. In water flow simulation, the single porosity van Genuchten-Mualem soil hydraulic model was employed. Hydraulic parameters such as saturated water content and hydraulic conductivity were experimentally determined. The remaining parameters in the soil hydraulic model were obtained using the Marquardt- Levenberg type parameter estimation technique for inverse estimation of unknown soil hydraulic parameters. In this technique, minimization of the objective function is done by a weighted least-squares approach based on Marquardt's maximum neighbourhood method. It is a local optimization gradient method that requires initial estimates of the unknown parameters to be optimized. During the minimization process, initial estimates of the optimized system parameters are iteratively improved until a desired degree of precision is achieved. The cumulative effluent flow across the boundary was selected to define the objective function to be minimized.

3. Results and discussion

3.1. Experimental studies

Tests were performed on the soil used in the wetland units to determine its gradation and hydraulic conductivity. The hydraulic conductivity of sand was 165cm/day, and the porosity was 0.31. The synthetic influent characteristics were analyzed before supplying it to the wetland units (Table 1). As mentioned previously, the influent was intermittently applied to the wetland units, and the effluent was collected and analyzed weekly. The average concentration of various quality parameters in the effluent and the percentage removal of these quality parameters are presented in Table 2. The performance of the three wetland units employed in this study, w.r.t the removal of some of these parameters, is presented in Figure 2. After completing the experiments, samples of the plants in the wetland units were tested to determine their accumulated nutrient concentration. The results were compared with the nutrient concentration in plants treated with tap water only. The results are presented in Table 3. The soil samples collected from three wetland units were also tested for the residual nutrient concentration, and the results are presented in Table 4.

Table 1. Influent characteristics.

Parameter	Concentration (mg/l)
COD	500
Orthophosphate	5 ± 0.5
Total Phosphorus	6 ± 0.5
Ammonia Nitrogen	60 ± 0.5
Nitrite Nitrogen	0.10
Nitrate Nitrogen	4.7
Total Kjeldahl Nitrogen (TKN)	28.02
Total Organic Carbon (TOC)	203

Table 2. Average effluent concentration and percentage removal of various quality parameters.

Parameter	Control unit		Vegetated unit		Vegetated unit with shells	
	Concentration (mg/l)	% Removal	Concentration (mg/l)	% Removal	Concentration (mg/l)	% Removal
Orthophosphate	0.12±0.12	97.52	0.64±0.81	87.27	0.78±0.81	84.3
Total Phosphorus	1.25±1.05	79.16	1.43±1.43	76.23	2.06±1.63	65.73
Ammonia Nitrogen	3.03±2.47	94.95	2.91±2.85	95.14	1.52±2.99	97.46
Nitrite Nitrogen	8.11±7.01	-	5.42±5.11	-	11.36±14.63	-
Nitrate Nitrogen	11.27±0.34	-	11.29±0.13	-	11.49±0.24	-
Total Nitrogen	4.67	83.33	1.87	93.33	0.68	97.57
COD	89.39	82.12	15.74	96.85	45.9	90.82
Total Organic Carbon (TOC)	0.70±0.64	99.65	1.80±0.82	99.11	1.61±0.1	99.2

Table 3. Nutrient content of vegetation in various constructed wetland units.

Constructed wetland	Total N (g/plant)	Total P (g/plant)
Vegetated unit	3.73	0.45
Vegetated unit with shells	3.87	0.47
Vegetated unit treated with tap water only	0.54	0.054

Table 4. Nutrient content in the sand.

Constructed wetland	**NH_2 N (mg/ kg)**	**NO_3N (mg/ kg)**	**P (mg/ kg)**
Vegetated unit	11.2	22.4	113
Vegetated unit with shells	18.2	18.9	95
Control unit	22.4	13.6	110

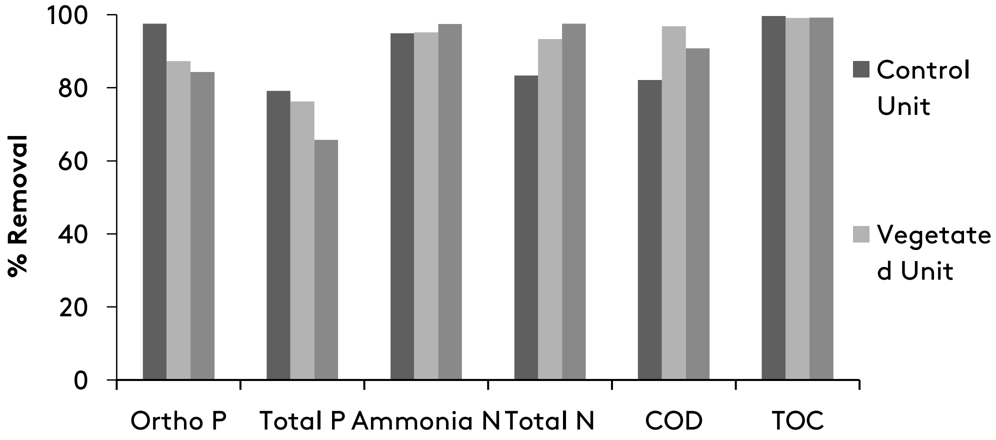

Fig. 2. Comparison of % removal of various quality parameters.

In this study, the performance of the constructed wetland units was evaluated in terms of the percentage removal of various water quality parameters. From the results, it is very clear that vertical flow constructed wetlands performed very well in removing phosphorus, nitrogen, COD, and TOC from the wastewater. The constructed wetland unit planted with red spinach exhibited higher percentage removal of NH_3-N, COD, and TOC from the wastewater than the control unit. The difference in percentage removal of ammonia nitrogen and COD in the constructed wetland unit planted with red spinach and the control unit was 0.19% and 14.73%, respectively, whereas the corresponding difference between the control unit and the vegetated constructed wetland unit with shells was 2.51% and 8.7%, respectively. This clearly indicates that the vegetated constructed wetland unit with oyster shells and without oyster shells performed well in removing ammonia nitrogen and COD, respectively, from the influent. This could be attributed to the presence of the vegetation and crushed oyster shells in the constructed wetland unit. Some studies have reported that the vegetation in a constructed wetland unit plays a major role in the treatment process. The roots of the vegetation retard the flow through the substrate, which in turn enhances the contact time between the substrate medium and the pollutant, thereby facilitating the enhanced removal of the contaminants by adsorption [18]. Oyster shells are a good adsorption medium, and adsorption is the predominant removal mechanism of ammonia nitrogen from wastewater [14]. In addition to the normal nitrification process, some of the ammonia might be adsorbed onto the shell surface. Plant nutrient uptake also enhances the removal of nutrients from the influent. The roots of the vegetation release oxygen and creates an aerobic zone near the roots, thereby facilitating aerobic processes such as aerobic degradation of organic matter and nitrification processes [3,14,19]. The effluent nitrite and nitrate concentration in all the constructed wetland units increased at a higher rate than that of the influent. This indicates that good nitrification has occurred due to the existence of aerobic conditions as a result of intermittent operation of the vertical flow constructed wetland units. Organic carbon is essential for total nitrogen removal, as it acts as an electron donor for denitrification. More than 99% removal of organic carbon was observed in all the constructed wetland units; the increased removal of the total organic carbon indicated that the organic carbon necessary for denitrification was utilized from the organic carbon present in the influent. From the results of the analyses of the plant samples, it is clear that the plants fed with wastewater have a higher nutrient content than those supplied with tap water, which indicates that the plant species play a major role in removing the quality parameters from the wastewater. From the results of the tests performed on the soils, it could be concluded that the soil samples collected from the wetland units with vegetation had a relatively lower concentration of ammonia and a high nitrate concentration when compared to the soil in the control unit. This was due to the better oxygen supply in soils in the wetland unit, facilitated by the presence of plant roots. The highest orthophosphate removal of 97.52% and total phosphorus removal of 79.16% was observed in the control unit than in the vegetated constructed wetland unit. This indicated that the vegetation used in the constructed wetland unit did not have much influence in removing phosphorus from the influent.

3.2. Simulation studies

3.2.1. Water flow simulation

The simulation of a vertical flow constructed wetland was performed using the HYDRUS 2D variably saturated flow and transport model. The time period for simulation was selected as two weeks. The presence of vegetation was neglected, and only a 50 cm thick treatment layer was considered for simulation. The water flow simulation was performed using the van Genuchten-Mualem soil hydraulic model implemented in HYDRUS. The soil properties such as hydraulic conductivity (K_s) and porosity (θ_s) were experimentally determined. And the other properties required for flow simulation, such as residual water content (θ_r), pore connectivity parameter (l), and empirical coefficients affecting the shape of the hydraulic functions (Alpha and N), were obtained using the Marquardt-Levenberg inverse parameter estimation technique. The objective function for the inverse simulation was defined with cumulative effluent flux across the boundary. The results of the inverse simulation are presented in Table 5. The measured and computed cumulated effluent flow before and after inverse simulation were compared (Figure 3). A good match between the measured and computed effluent flow could be achieved after inverse simulation.

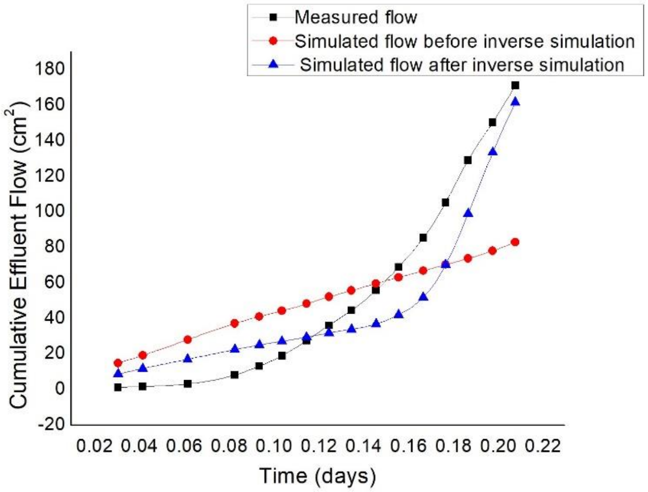

Fig. 3. Comparison of measured and computed cumulative effluent flow.

3.3. Reactive transport simulation

For the reactive transport simulation, CW2D biokinetic module implemented in HYDRUS 2D was employed. Initially, the simulation was performed with the default parameter set. If the measured and computed results did not exhibit a reasonably good match, the parameters influencing reactive transport in the constructed wetland module were adjusted until these results exhibited good agreement with each other.

Table 5. Soil hydraulic parameters after inverse simulation.

Material	$\theta_r[-]$	$\theta_s[-]$	**Alpha [1/cm]**	**N[-]**	$K_s[cm/day]$	$l[-]$
Sand	0.0555	0.31	0.1543	1.624	162	0.2767

In order to fit observed and measured NH_4-N concentrations, the maximum aerobic growth rate and lysis rate constants of Nitrosomonas and Nitrobacter (XANs and XANb) were adjusted. In the case of NO_2-N and NO_3-N concentrations, the maximum denitrification rate and hydrolysis rate constant were adjusted. The simulation was performed at five nodes located 10 cm apart in a vertical direction. The simulated values at the bottom node were used for comparison with the measured values. A comparison of the default and adjusted parameter sets and measured and computed concentrations of water quality parameters in the effluent are presented in Tables 6 and 7, respectively. The simulation results show that after the adjustment of certain CW2D parameters, a reasonably good match between the measured and simulated effluent concentration could be achieved. However, the concentration of inorganic phosphorus did not change much, even after adjusting the parameters.

Table 6. Standard and adjusted constructed wetland parameters.

Parameter description	Standard	Fitted
Hydrolysis rate constant [1/d]	3	1
Maximum denitrification rate [1/d]	4.8	4
Maximum aerobic growth rate of XANs [1/d]	0.90	0.55
Lysis rate constant for XANs [1/d]	0.15	0.3
Maximum aerobic growth rate of XANb [1/d]	1	0.2
Lysis rate constant for XANb [1/d]	0.15	0.1

The validation of the CW2D model was done by applying a quantitative statistic known as the ratio of root mean square error (RMSE) to the standard deviation of the observed data - RSR. The lower RSR indicates a better model prediction, and an RSR ≤ 0.70 is considered as satisfactory. The RSR is calculated by applying Eq. 1.

$$\mathrm{RSR} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right]} \qquad (1)$$

where Y_i^{obs} is the i^{th} observation Y_i^{sim} is the i^{th} simulated value is the mean of observed data

n is the total number of observations

The RSR value obtained for ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen was found to be 0.46, 0.86 and 0.1, respectively. The model validation results showed that the RSR value obtained for nitrite nitrogen was unsatisfactory. Hence, it could be concluded that the CW2D model performs well in simulating ammonia nitrogen and nitrate nitrogen in vertical flow constructed wetlands. Also, the model overpredicted the inorganic phosphorus concentration, which indicated that the model performance was unsatisfactory in simulating the phosphorus in a vertical flow constructed wetland.

4. Conclusions

Based on the studies conducted, the following conclusions could be derived. Intermittently operated vertical flow constructed wetlands effectively treated wastewater containing nutrients such as nitrogen and phosphorus. It was observed that more than a 95% removal of ammonia, nitrogen, orthophosphate, COD, and total organic carbon in the influent could be achieved, as well as a 79% removal of the total phosphorus. Vegetation played an important role in improving the treatment efficiency of constructed wetlands. The relatively high concentration of nitrite and nitrate in the effluent from an intermittently operated vertical subsurface flow constructed wetland occurred because it provided a more oxidized condition, thereby facilitating effective nitrification. The higher removal of organic carbon from the wastewater indicated that the organic carbon necessary for total nitrogen removal was taken from the influent. The addition of oyster shells as a substrate medium improved the overall nutrient removal from the wastewater. The wetland module CW2D in HYDRUS was a good tool for simulating water flow and reactive transport in a vertical subsurface flow constructed wetland. And it gave reasonably good results when simulating nitrogen in the influent.

Table 7. Comparison of measured and simulated concentrations.

Parameter	Influent	Effluent		
	Measured (mg/l)	Measured (mg/l)	Simulated-Default (mg/l)	Simulated-Fitted (mg/l)
NH_3-N	60	4.93	0.032	2.18
NO_2-N	0.1	15.16	0.013	21.26
NO_3-N	4.7	11.27	48.07	17.2
Total N	28.02	4.67	19.99	13.03
COD	500	89.39	59.37	95.61
Inorganic P	6	0.12	6.699	6.699

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