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Nutrient Removal Abilities of Horizontal Subsurface Flow Constructed Wetland

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Abstract
With the rapid urbanization, the production of wastewater is increasing day by day. Direct discharge of wastewater in the water bodies/land causes environmental pollutions. Hence, treatment of the wastewater is must, prior to the disposal. Treatment of wastewater through constructed wetlands (CWs) require low cost, less energy consumption, easy construction, and simple operation/maintenance. So, CWs can be the better option for the developing countries such as Nepal.
Main objective of the study was to determine the nutrient removal abilities of nitrogen (N), phosphorous (P), and potassium (K^+) in the horizontal subsurface flow (HSSF) CW. The study was carried out in the CW having gravel as substrate material and common reed (narkat, *Phragmites karka*) as macrophyte. The CW treated domestic wastewater at an average flow rate of 8.64 $m^3.d^{-1}$.
The first order removal rate constants were 0.015 m^{-1} (0.200 d^{-1}) for total N, 0.035 m^{-1} (0.484 d^{-1}) for total P, and 0.004 m^{-1} (0.052 d^{-1}) for K^+. The influent concentration of total N, total P, and K^+ ranged from 60-100, 11-13, and 34-48 $mg.l^{-1}$ respectively; effluent concentration from 35-55, 1-3, and 31-38 $mg.l^{-1}$ respectively. Average removal efficiencies of total N, total P, and K^+ were 50.5, 75.5, and 15.0 % respectively. CW will be a promising option for wastewater treatment.

Keywords
Wastewater, Horizontal Subsurface Flow Constructed Wetland, Nutrient Removal, Common reed, Gravel

1. Introduction

Direct discharge of wastewater into environments causes several environmental problems such as waterborne infectious diseases, eutrophication, and decrease in dissolved oxygen (DO) of environmental waters. Therefore, it is necessary to treat wastewater prior to discharge into environments. The wastewater treatment process which is simple, easy to operate and maintain, and low cost will be applicable in most of the developing countries including Nepal [1].

Constructed wetlands (CWs) are artificial engineered systems, designed and constructed to treat wastewater by utilizing the natural processes involving macrophytes, substrate, and microorganisms [2, 3]. CWs can remove organic matter, suspended solids, nutrients, and heavy metals from wastewater. CWs are low energy-consuming, environment-friendly 'green' technique [4, 5], low cost, land-intensive, and less-operational and maintenance-requiring in comparison to conventional treatment systems. Therefore, CW is a suitable wastewater treatment option for small and poor communities in remote locations or decentralized areas [5, 6, 7].

The main objective of this study was to determine the nutrient removal abilities of horizontal subsurface flow (HSSF) CW from domestic wastewater, for different nutrients such as nitrogen (N), phosphorous (P), and potassium (K^+). Determination of nutrient removal abilities will add a rational design approach of HSSF CWs treating domestic wastewater.

2. Materials and Methods

2.1 Design Considerations

The CW was designed and constructed at Pulchowk Campus, Institute of Engineering, Tribhuvan University in 2010, with the assistance of KOICA (Korea International Cooperation Agency). Design

Table 1: Design input parameters for the Horizontal Subsurface Flow Constructed Wetland

S.No.	Input Parameter	Quantity	Units
1	Design Discharge (Q)	8	$m^3.d^{-1}$
2	Influent BOD (C_i)	200	$mg.l^{-1}$
3	Effluent BOD (C_e)	50	$mg.l^{-1}$
4	Reaction Rate Constant at 20 ^oC (K_{20})	0.6	per day for BOD removal
5	Hydraulic Conductivity for gravel (K_s)	500	$m.d^{-1}$
6	Porosity (η)	40	%
7	Bed Slope (S)	0.5	%
8	Average temperature of effluent in winter for proposed location (T)	9	^oC
9	Correction Factor (θ_{20})	1.06	

Table 2: Detailed description of the CW

Components	Dimensions (m)	Remarks
Settling tank	4.20 × 2.55	Brick masonry
Horizontal bed	42.00 × 7.00 × 0.45	Single bed
Inlet	110 mm ϕ perforated pipe	
Media Inlet and outlet apron Filter media	 40 mm - 80 mm size gravels 20 mm - 30 mm size pebbles	 150 mm compacted clay, lined with PVC geo-membrane sheet and 50 mm sand filling
Effluent tank	4.90 × 2.20	Brick masonry
Outlet pipe	110 mm ϕ HDPE pipe	
Inspection ports	110 mm ϕ vertical PVC pipe at an average c/c spacing of 1.25 m	

input parameters and detailed description of the CW are shown in Table 1 and Table 2, respectively [8].

Schematic diagram of CW is shown in Figure 1.

2.2 Wastewater Flow Regulation

In this study, domestic wastewater from the nearby community was initially collected and allowed to settle in settling tank. Wastewater flow was regulated and fixed to be 8.64 $m^3.d^{-1}$ throughout the experimental period, considering the average flow in the dry season. Detention time in the CW (Eq. 1) for the flow was calculated to be 3.06 days.

$$t = \frac{\eta L W d}{Q} \tag{1}$$

where,

η = Porosity = 40 %

L = Bed Length = 42 m

W = Bed Width = 7 m

d = Depth of flow = 0.225 m (average depth)

Q = Discharge = 8.64 $m^3.d^{-1}$

2.3 Collection and Analysis of Sample

This study was started from January, 2017 for 6 months. Samples were taken twice a week from the inlet, port number 1, 2, 4, 9, 12, 15, 18, 21, 23, 24, 25, 29, 30, and 31 (distance 0.7, 1.9, 4.35, 11.1, 15.1, 18.7, 22.5, 26.35, 28.9, 30.1, 31.2, 35.7, 37.3, and 38.65 m from the inlet), at least 10 intermediate ports in each sampling time. Samples were stored in refrigerator at 4 ^oC and analyzed in IOE laboratory in accordance with the Standard Methods for the Examination of Water and Wastewater [9]. The pH was measured in laboratory, after each sampling by standard pH meter (Auto Deluxe pH Meter LT-10). Concentrations of total N and total P were measured by using Ultraviolet Spectrophotometric Screening Method and Persulfate Digestion Method, respectively (UVmini – 1240, UV-VIS Spectrophotometer, Shimadzu Co. Ltd., Japan). The K^+ was measured by Compact K^+ Meter B-731 (LAQUAtwin K^+ HORIBA Scientific).

2.4 Nutrient Removal Kinetics

Previous studies suggested the use of first order kinetics model for the design of HSSF CW treatment

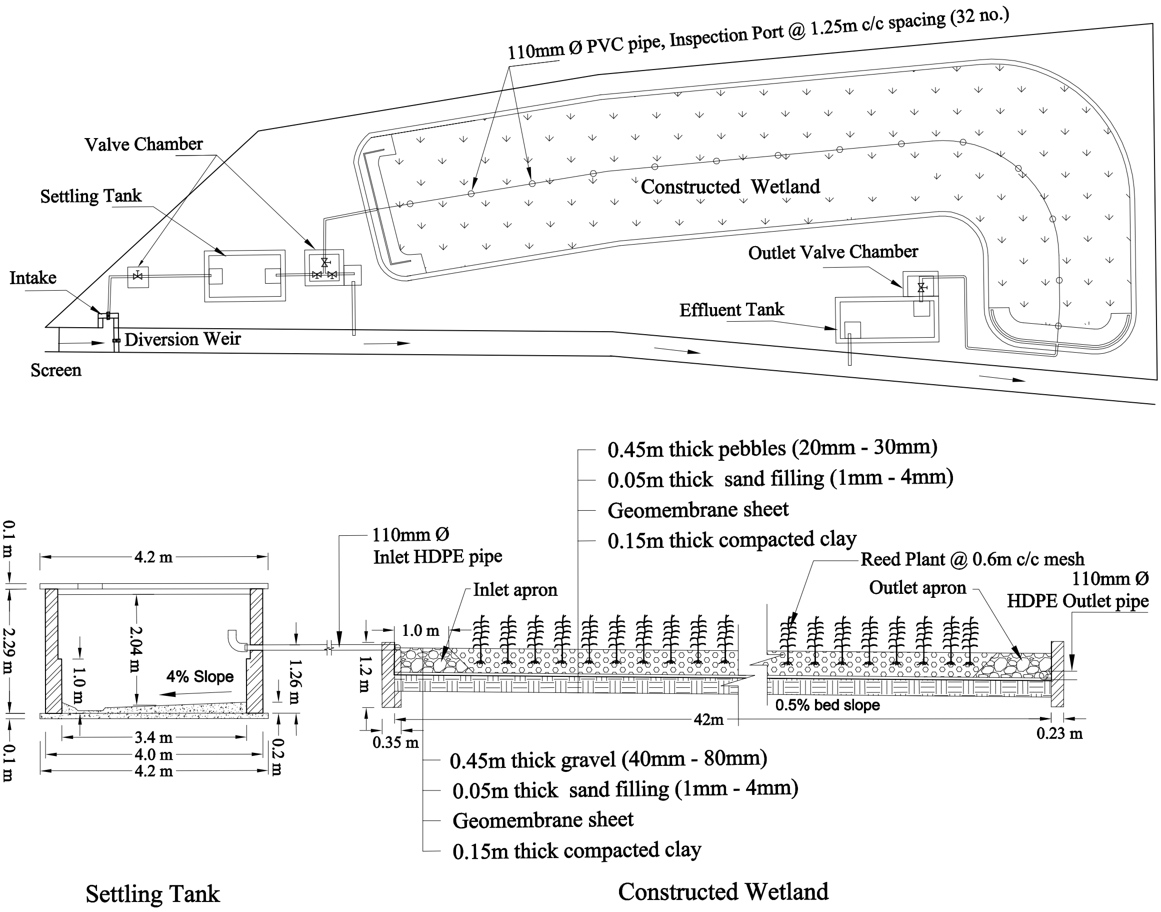

Figure 1: Schematic diagram (plan - top and section - bottom) of HSSF CW, constructed in the IOE premises

systems [10, 11]. So, the nutrient removal rate (K) of total N, total P, and K^+ in the HSSF CW were calculated based on the assumption that the nutrient removal follows first order kinetic reaction. First-order kinetic reactions for plug flow reactor is described by Eq. (2) [12].

$$\frac{dC}{dt} = -K.C^1 = -K.C \tag{2}$$

After integrating and simplifying, Eq. (2) reduces to Eq. (3).

$$C_t = C_o e^{-Kt} \tag{3}$$

where,

C_t = nutrient concentration at time, t

C_o = initial nutrient concentration

t = time of flow

3. Results and Discussion

The performance of CW was measured in terms of total N, total P, and K^+ for the determination of their respective first order removal rates.

3.1 Total Nitrogen Removal

Total N concentration ranged from 60 to 100 mg-N.l^{-1} in influent and from 35 to 55 mg-N.l^{-1} in effluent. Average removal efficiency of total N was 50.5 %. Since average pH of the influent was 7.7, the ammonium nitrogen removal by volatilization was insignificant [13]. Total N variation pattern with respect to the length of CW is shown in Figure 2.

Concentration of total N was found to be gradually decreasing up to 30 m length of flow, which decreased at high rate afterwards. The first order removal rate constant of total N was 0.015 m^{-1} (Figure 2) or 0.200 d^{-1} (Figure 3).

In the first 5 m length of CW, total N removal was less. Afterwards, the wastewater might have received oxygen from the roots of the reed plant for nitrification, and simultaneous denitrification occurred at the bottom of the CW, decreasing the total N concentration, though the digestion of total N is not

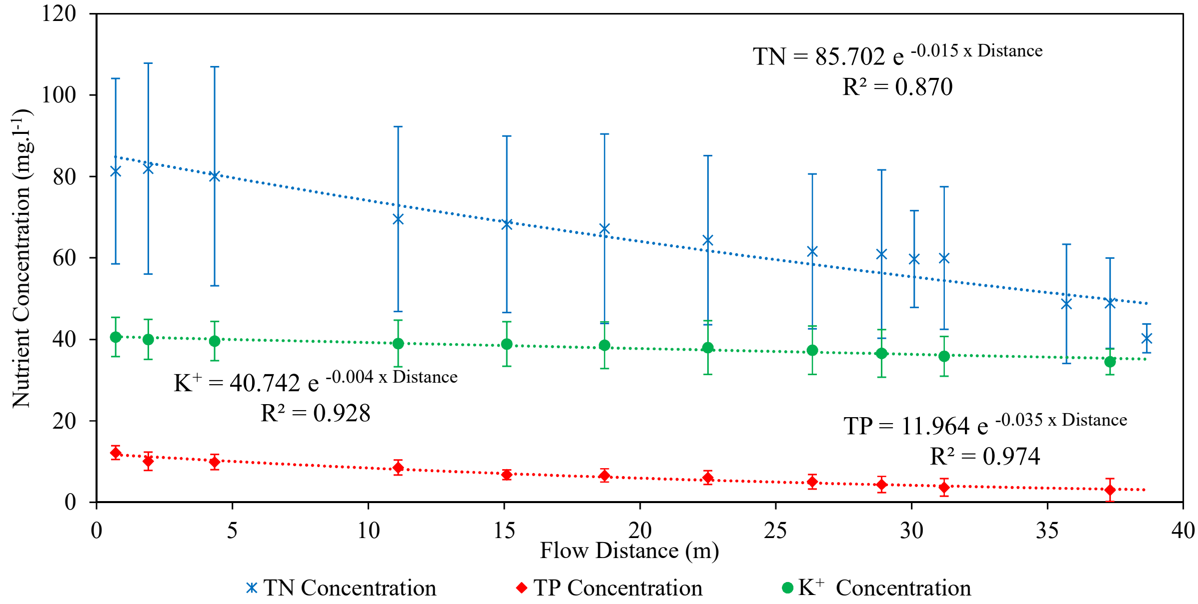

Figure 2: Nutrient concentration variations with respect to flow distance. Values represent means and the error bars indicate the standard deviations of the data

complete within the length of the CW.

3.2 Total Phosphorous Removal

Concentration of total P in influent ranged from 11 to 13 mg-P.l^{-1} and in effluent ranged from 1 to 3 mg-P.l^{-1}. Average removal efficiency of total P was 75.5 %. HSSF CW have high potential for total P removal via adsorption and precipitation but washed gravel has very low capacity of sorption and precipitation [14]. During long term operation of the CW, soil and other debris deposited over the gravel. This might have even decreased the sorption capacity of gravel.

Concentration of total P was found to be gradually decreasing up to 19 m length of flow, which decreased at high rate afterwards. Total P variation pattern with respect to the length of CW is shown in Figure 2.

The first order removal rate constant of total P was 0.035 m^{-1} (Figure 2) or 0.484 d^{-1} (Figure 3).

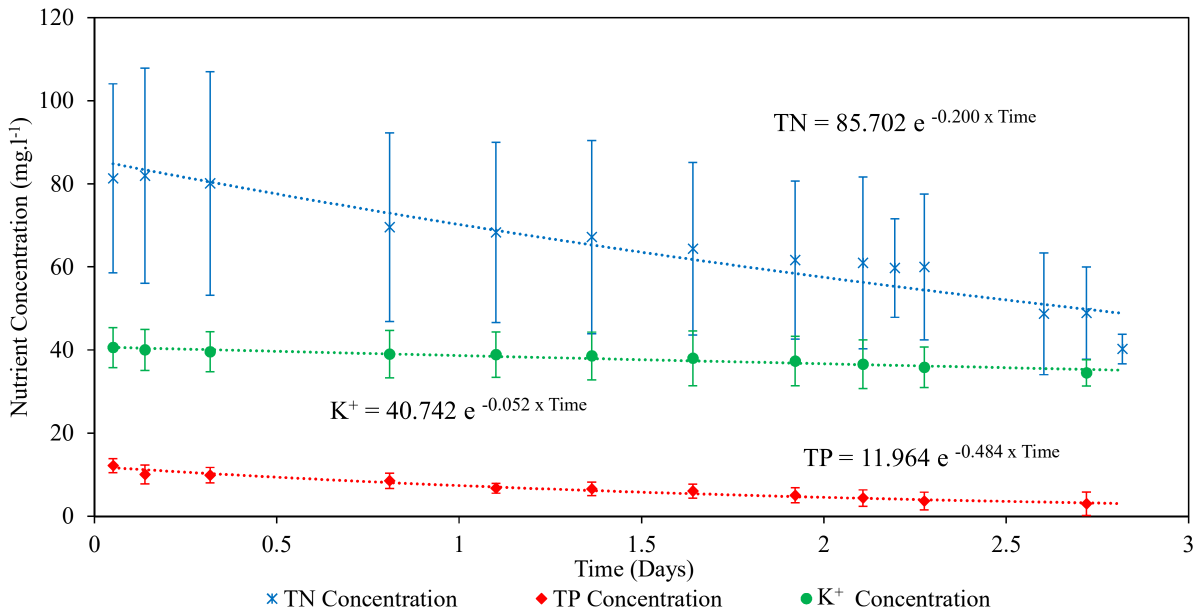

Figure 3: Nutrient concentration variations with respect to time. Values represent means and the error bars indicate the standard deviations of the data

3.3 Potassium Removal

Potassium is an alkali metal required for the growth of plants and microorganisms. Influent concentration of K^+ ranged from 34 to 48 mg.l^{-1} and effluent from 31 to 38 mg.l^{-1}. Average removal efficiency of K^+ was 15.0 %. K^+ variation pattern with respect to the length of CW is shown in Figure 2.

Concentration of K^+ was found to be gradually decreasing up to 18 m length of flow, which decreased at high rate afterwards. The first order removal rate constant of K^+ was 0.004 m^{-1} (Figure 2) or 0.052 d^{-1} (Figure 3). The K^+ removal rate or efficiency in CW was less in comparison to other studied parameters. Design of CW systems has not yet targeted K^+ and removal efficiency is also very low [15]. Adsorption of K^+ on the gravel (substrate) and plant uptake could be the K^+ removal mechanism in wetlands. The length of the CW seems to be insufficient for the K^+ removal and also may have been affected by decreased plant density in the CW.

4. Conclusions

The variation pattern of the nutrients (N, P, and K^+) with respect to the flow length or time of flow in the CW was investigated.

The first order removal rate constants were 0.015 m^{-1} (0.200 d^{-1}) for total N, 0.035 m^{-1} (0.484 d^{-1}) for total P, and 0.004 m^{-1} (0.052 d^{-1}) for K^+. Concentration of total N ranged from 60 to 100 mg-N.l^{-1} in influent and from 35 to 55 mg-N.l^{-1} in effluent with an average removal efficiency of 50.5 %. Concentration of total P in influent ranged from 11 to 13 mg-P.l^{-1} and in effluent ranged from 1 to 3 mg-P.l^{-1} with an average removal efficiency of 75.5 %. Similarly, concentration of K^+ ranged from 34 to 48 mg.l^{-1} in influent and from 31 to 38 mg.l^{-1} in effluent, with an average removal efficiency of 15.0 %. Nutrient removal rate constants in HSSF CW will be necessary for a rational design of CWs.

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