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MODELLING HIGH RATE P-REMOVAL IN A TWO-STAGE PILOT SCALE ALUM SLUDGE BASED CONSTRUCTED WETLAND SYSTEM

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Abstract

A system dynamics (SD) process-based simulation model was developed using an object-oriented environment to simulate phosphorus (P) transformations in a two-stage pilot scale Dewatered Alum Sludge Cake (DASC) based Constructed Wetlands (CW), which is operated from February 2009 to January 2010 to treat relatively high concentration animal farm wastewater. Structural Thinking Experiential Learning Laboratory and Animation (STELLA v9.1.4) conceived on the principles of SD was used for the development of process-based P model by constructing stock-flow diagrams and carrying out computer simulations using difference equations to integrate stocks and flows. From the model simulation it was found that the major pathways leading to permanent removal of P in a VFCW system in descending order were adsorption, plant uptake and microbial activities. Moreover, the developed model has the ability to simulate the effluent P concentration. Model equations are presented and can be employed in numerical simulation to study optimum design strategies for a specific location with defined environmental conditions. Thus, the P process-based model developed in this study could be used to explain the pilot scale P removal processes and also be used to simulate the fate of P in the animal farm wastewater treated in the DASC-VFCW.

Keywords: actor-network theory, rural tourism, social network analysis, translation process

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1. Introduction

Eutrophication, mainly caused by excess nutrients, poses the highest threat to water quality in Ireland (Archbold et al., 2007). The main threat to surface water quality arises from phosphorus (P) from agricultural sources (manures and fertilizers). Numerous efforts have been made to reduce eutrophication ranging from source control to structural measures. One such effort is the use of dewatered alum sludge cakes (DASC) based constructed wetlands (CW) (Zhao et al., 2011) for removing nutrients, organics, trace elements and other pollutants from wastewater. Tidal flow operation (Zhao et al., 2011) also has been incorporated into the CW system in order to increase the rate of oxygen transfer during the operation. Over the past decade, understanding of (bio) chemical and physical processes involved in CWs has attracted interest with the objective of improving treatment efficiency and operating cost.

Earlier, CW systems are often seen as complex "black box" systems (Rousseau et al., 2004) because a large number of physical, chemical and biological processes occur in parallel and influence each other. Earlier, simple models were developed to address the

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design problems in CWs, but those models have limited understanding of the system (Giraldi et al., 2010). To better understand the processes occurring in CWs, it is necessary to develop numerical models for the improvement of existing design and operation criteria, thus providing insights into the "black box" (Langergraber, 2007). Stein et al. (2007) reported that most of the CW models available in the literature are relevant to horizontal flow (HF) CWs based on simple first-order decay models.

As compared to HF CW models, only a few models can simulate Vertical Sub Surface Flow (VSSF)-CW (Langergraber, 2008) besides CW2D/ HYDRUS (Langergraber and Simunek, 2005). However, it was noted that the importance of process-based modeling was insisted by many authors (Jorgensen and Fath, 2011; Kumar et al., 2011a, 2011b; Malmaeus et al., 2008; Mandal et al., 2009; Mayo and Bigambo, 2005; Nabizadeh and Mesdaghinia, 2006; Ouyang, 2008; Pimpan and Jindal, 2009; Teegavarapu et al., 2005; Zhang and Mitsch, 2005).

In view of the above and considering the importance of process-based models, the system-based software package STELLA v.9.1.4 (Structural Thinking Experiential Learning Laboratory with Animation) was used which is an icon-based simulation tool that uses differential equations represented as stocks and flows (Rizzo et al., 2006).

In the past, a process-based model was developed for the removal of P in the pilot scale four-stage DASC based CWs, and currently the same model structure has been used to simulate the two-stage system with necessary amendments and calibrations. The purpose of this study was to validate the developed model for fate and P removal in a pilot-scale open environmental VFCW system. Furthermore, the study examined the most relevant processes in the P cycle and their ability to treat the animal farm wastewater.

2. Material and methods

2.1. System set up, operation and monitoring

The animal research farm of UCD has a total area of 17,000 m^2 with over 2,000 livestock units of sheep, pigs, cattle and horses. The DASC based CW consisted of a two-stage system with plastic bins as the wetland stage (Fig. 1). The system operated with a Hydraulic Loading Rate (HLR) of 0.56 m^3 m^{-2} d (where m^2 represents the total surface area of the system) and a Hydraulic Retention Time (HRT) of 4 hours in each stage. The total treatment surface area per system is 1.17 m^2. The DASC was a by-product of water treatment facilities that use aluminum salt as a coagulant (Babatunde et al., 2009). The chemical composition of alum sludge has a highly reactive surface and a strong affinity for P (Babatunde and Zhao, 2007; Makris et al., 2005). *Phragmites australis* were planted in stage 1 and stage 2. The system was operated using a tidal flow technique which allowed the system matrices to be filled with wastewater and then to be completely drained to enhance aeration. Owing to the fluctuating characteristics of wastewater generated on the animal farm, careful attention had been given to operate the system by gradually increasing the strength of wastewater to stabilize the reeds growth and the biofilm development on the DASC. Farm wastewater was initially pumped into a holding tank, having a capacity of 10,000 L, and thereafter appropriate dilution was carried out to achieve a desired concentration. Next, the wastewater from the holding tank was gravity fed into an underground tank controlled by a ball-float valve which served as an influent tank.

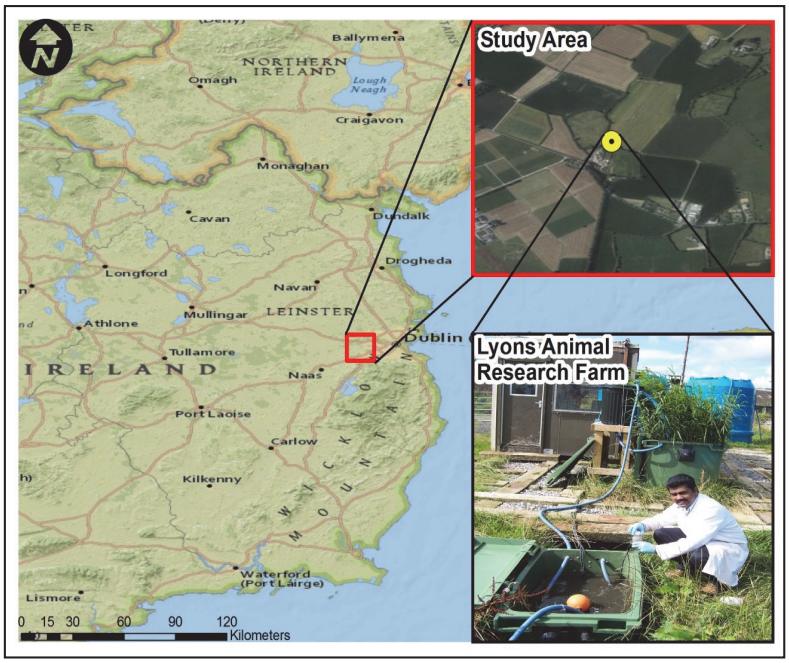

Fig. 1. UCD Lyons Research Farm in Newcastle, Dublin showing DASC based CW described in this study

Afterwards the wastewater was pumped into the DASC based VFCW for treatment. Other detailed system information regarding specific CW set up can be found in Babatunde et al. (2011).

2.2. Employing STELLA modeling tool in two stage VFCW system

STELLA version 9.1.4 modeling tool was chosen to simulate the effluent P concentration for the two-stage CW system. This modeling tool consisting of stock and flow, provides the user a better conceptual understanding of the ecologic system (Rizzo et al., 2006). Stocks represent a reservoir of material such as DISP, ADSP, PLAP, PLBI, DETP. Material flows between stocks or into and out of undefined sources and sinks (represented by 'clouds') at the ends of flow structures. Flows are affected by auxiliary variables, stocks, and other flows through the use of information arrows (Fig. 2). Conceptual diagram of flow, stock and processes for the two-stage pilot scale DASC based CW is shown in Fig. 2.

2.3. Model construction of P processes

A "process based" model was validated in this study to based on previous studies in laboratory-scale DASC based CW (Kumar et al., 2011a, 2011b). Specifically, a P model developed for a four stage (laboratory scale) was used to validate the two-stage system and to simulate the fate of P in the VFCW. P-Model development for the two-stage DASC- CW using STELLA software is shown in Fig. 2. Differential equations and numerous process equations are shown in Table 1. Eqs. (1-5) indicates the differential equations, Eqs. (6-16) explains the process formulations, and Eqs. (17-19) are used to calculate the percentage computation of major P processes. Model symbols and their units are shown in Table 2. Model parameters of the two-stage system are described in Table 3.

The major P transformation processes considered in this study were DASC adsorption, plant and microbial uptake. Adsorption process was described by equilibrium between P in water and P in adsorbent (Kumar et al., 2011b), and was described by Freundlich model. The Michaelis-Menton equation was used to describe the plant P uptake and growth, a two-step process.

The first step explains the uptake of nutrients whereas the second step covers the growth of plants. Microbial P upake was explained using a first order equation. A simple Arrhenius expression was used to represent temperature influence in the model. Overall, the parameter values have been calibrated from the field scale four-stage system to validate the field scale two-stage system.

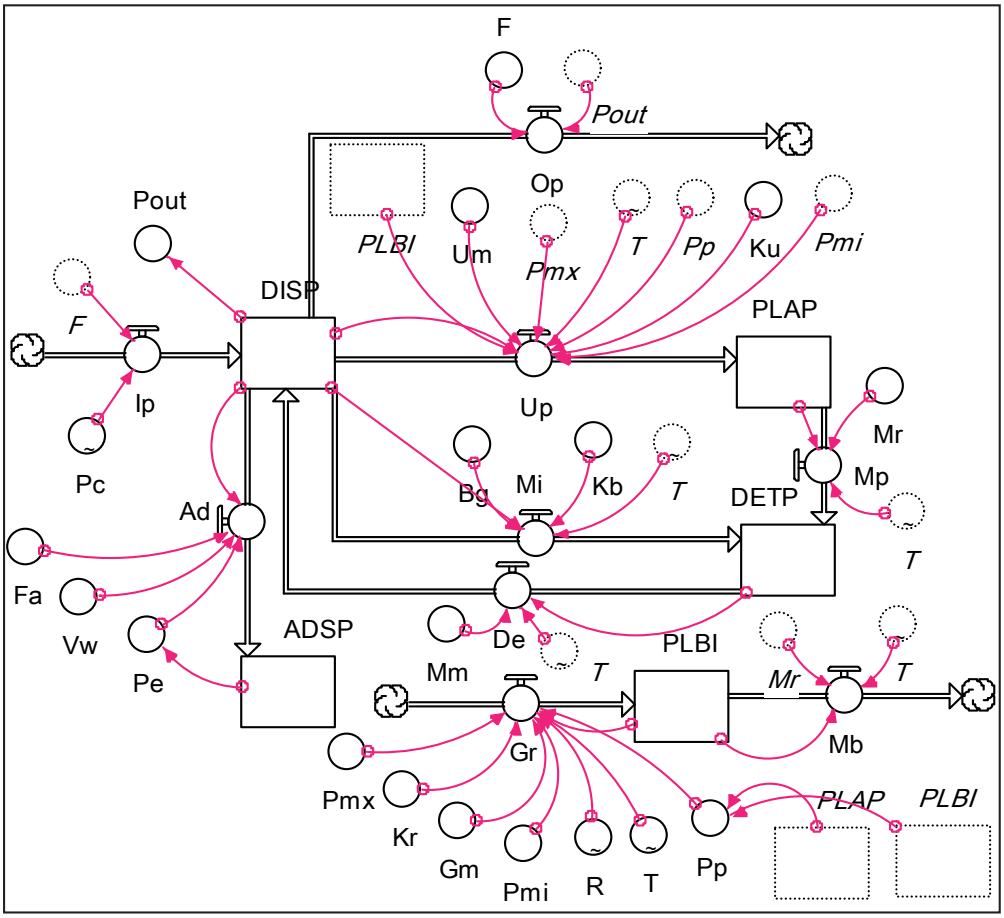

Fig. 2. P- Model development for DASC- CW using STELLA software

Table 1. Model equations for P dynamics in pilot field scale VFCWs

Differential Equations, Process Formulations and Percentage computations		
$\frac{dADSP}{dt} = ADSP + Ad$	(Eq. 1)	Differential Equations
$\frac{dDETP}{dt} = DETP + (M_i + M_p - D_e)$	(Eq. 2)	Differential Equations
$\frac{dDISP}{dt} = DISP + (I_p + D_e - A_d - M_i - O_p - U_p)$	(Eq. 3)	Differential Equations
$\frac{dPLBI}{dt} = PLBI + (G_r - M_b)$	(Eq. 4)	Differential Equations
$\frac{dPLAP}{dt} = PLAP + (U_p - M_p)$	(Eq. 5)	Differential Equations
$Ad = F_a \times (DISP - P_e \times V_w)$	(Eq. 6)	Process Formulation
$Pe = \left(\frac{ADSP}{T_A \times K_F} \right)^n$	(Eq. 7)	Process Formulation
$M_i = \frac{B_g \cdot DISP \cdot 1.05^{(T-20)}}{DISP + k_b}$	(Eq. 8)	Process Formulation
$M_p = PLAP \cdot M_r \cdot 1.07^{(T-20)}$	(Eq. 9)	Process Formulation
$D_e = DETP \cdot M_m \cdot 1.07^{(T-20)}$	(Eq. 10)	Process Formulation
$I_p = F \cdot P_c$	(Eq. 11)	Process Formulation
$O_p = F \cdot P_{out}$	(Eq. 12)	Process Formulation
$U_p = \frac{U_m \cdot PLBI \cdot (P_{mx} - P_p) \cdot DISP \cdot 1.05^{(T-20)}}{(DISP + k_u) \cdot (P_{mx} - P_{mi})}$	(Eq. 13)	Process Formulation
$G_r = \frac{G_m \cdot PLBI \cdot R \cdot (P_p - P_{mi}) \cdot 1.05^{(T-20)}}{(R + K_r) \cdot (P_{mx} - P_{mi})}$	(Eq. 14)	Process Formulation
$M_b = PLBI \cdot M_r \cdot 1.07^{(T-20)}$	(Eq. 15)	Process Formulation
$P_p = \frac{PLAP}{PLBI}$	(Eq. 16)	Process Formulation
$A_{per} = \frac{A_d}{I_p} \cdot 100$	(Eq. 17)	Percentage computation
$U_{per} = \frac{U_p}{I_p} \cdot 100$	(Eq. 18)	Percentage computation
$M_{per} = \frac{M_i}{I_p} \cdot 100$	(Eq. 19)	Percentage computation

Table 2. Model symbols, descriptions and its units

Symbol	***Unit***	***Classification***
ADSP	mg P	State Variable
DISP	mg P	State Variable
PLAP	mg P	State Variable
PLBI	mg P	State Variable
DETP	mg P	State Variable
G_r	mg P d^{-1}	Processes
U_p	mg P d^{-1}	Processes
M_b	mg P d^{-1}	Processes
M_p	mg P d^{-1}	Processes
D_e	mg P d^{-1}	Processes
M_i	mg P d^{-1}	Processes
A_d	mg P d^{-1}	Processes
I_p	mg P L^{-1} d	Table Function/Graph
P_c	mg P d^{-1}	Table Function/Graph
R	J/m^2d	Table Function/Graph
T	°C	Table Function/Graph

V	L	Boundary Conditions
Ct	H	Boundary Conditions
F	L/d	Boundary Conditions
AS	Kg	Boundary Conditions

Table 3. Model Parameters

Symbol	***Values***	***Units***	***Source***
P_{mx}	0.10	g/100g	Estimated
P_{mi}	0.007	g/100g	Estimated
U_m	0.01	d^{-1}	Jorgensen (1998)
K_r	0.002	mg P L d^{-1}	Calibration
B_g	0.6	d^{-1}	Calibration
K_b	0.008	d^{-1}	Calibration
M_m	0.5	d^{-1}	Jorgensen (1998)
P_e	-	mg P L^{-1} d	Calculated
P_p	-	mg/mg	Calculated
M_r	0.006	mg P L^{-1} d	Calibration
G_m	0.81	mg P L^{-1} d	Calibration
K_u	0.20	mg P L^{-1} d	Calibration

3. Results and discussion

3.1. P simulation in two stage system

Performance evaluation was based on monthly averages obtained from the field scale DASC -CW. The mean monthly influent concentration of P was 9.50-32.80 mg L^{-1}, whereas the removal efficiencies were 39 - 87 %. Although the system had previously received numerous applications of high P containing wastewater, it still removed a significant portion of P (Zhao et al., 2011). *Phragmites Australis* grew excellent in the DASC based CWs which confirms the previous findings that alum sludge is not harmful wetland medium for the growth of plants (Babatunde et al., 2009). Model parameters were calibrated for one year with calibrations accomplished by adjusting parameters until the model simulated the P concentration in the effluent as compared to the experimental results. The general performance evaluation of the two-stage field scale CW has been reported in Babatunde et al. (2011). During the study period, wastewater characteristics of the wastewater varied greatly due to farming operations and season change. Regardless, this study successfully demonstrated that the DASC based CW have the capacity to treat the wastewater with high removal efficiencies except for period when there were operational disruptions. This excellent removal efficiency in DASC based CW is due to the fact of using a novel substrate called “DASC” and adopting “tidal flow” operation to enhance more oxygen supply for the better treatment performance. The pH values of the wastewater did not change appreciably across the system and mean value was recorded as 7.5.

The STELLA modeling tool was used to run the P process-based model with a time step of 0.02 h for 12 months. Fig. 3. and Fig. 4. represent the observed and simulated P concentration of both stages in the two-stage CW. The observed effluent P concentration ranged from 4.70 to 13.20 mg L^{-1}, 1.20 to 5.70 mg L^{-1} for stage 1 and 2 of the pilot scale VFCW system respectively whereas the simulated values obtained from the process-based model ranged from 4.62 to 16.60 mg L^{-1}, respectively. The observed mean and standard deviation for stages 1 and 2 ranged from 8.96 ± 3.80 and 3.33 ± 1.56, and from 8.74 ± 3.64 and 4.25 ± 2.29 respectively. The minimum observed effluent P concentration was recorded as 1.20 mg L^{-1} and the maximum was 5.70 mg L^{-1} whereas the minimum simulated P concentration was found as 1.35 mg L^{-1} and the maximum was 8.00 mg L^{-1}. The minimum and maximum effluent P concentration simulated by STELLA is very close to the observed effluent P concentration except few data points. It is interesting to note that there was a trivial deviation in process-based model simulation in stage 1 and stage 2. It has been notified that the simulated effluent concentration values showed slight variations as compared to the observed values. However, the variations captured in the entire study period were minimal. Other authors (Wang and Mitsch, 2000; Ouyang et al., 2007; Ouyang, 2008) used STELLA software to describe the P simulation process in CW, using different kinds of media/substrate.

3.2. Mass balance analysis in P processes

The elimination pathways for P in CWs include precipitation, adsorption, plant uptake, microbial uptake, fragmentation and leaching, mineralization and burial (Babatunde, 2007; Vymazal, 2007). However, the major P transformation mechanisms considered in this study were P adsorption, P plant uptake and P microbial assimilation similar to the previous studies (Kumar et al., 2011a, 2011b). The Adsorption process was estimated using (Eq. 6) and the P_e (Eq. 7) was calculated to describe the P adsorption behavior. From the Freundlich adsorption isotherm experiment it has been found that the relationship between P_e and mass of P adsorbed (alum-sludge) at equilibrium is strong (R^2=0.93). As stated before in previous studies, adsorption was found as a fast process and therefore the delta time (DT) was set as 0.02. It is worth noted that, in both the stages of the VFCWs the P adsorption efficiency was the dominant

process as compared to other processes, likely because of the considerable P adsorption capacity (Zhao and Yang, 2010). Plant uptake and microbial uptake process was explained by lumped models using the Eqs. (8-10) and Eqs. (13-16). Differential equation for the DETP, PLBI and PLAP is shown in Eqs. (2-5). P removed by *Phragmites australis* was explained as a two-step process such as uptake of nutrients and growth of plants (Eqs. 13-14).

The magnitude of P uptake by micro-organism i.e., the amount stored in bio-organisms is very low and it may also depend on the trophic status of the wetland system. Microbial processes were described using Michaelis - Mentons expression in accordance with temperature.

The major P processes and P removal percentage in each stage of the pilot scale system are shown in Table 4. The below mentioned removal efficiencies of P adsorption, P plant uptake and P Microbial uptake was calculated based on the (Eqs. 17-19). In this two-stage study, approximately the maximum influent, 17712.00 ± 3426.00 mg P d^{-1} (mass) was pumped in to the system (Stage 1). Thereafter, the stage 1 effluent concentration was pumped into stage 2 for further treatment. The maximum influent was noted as 1800.9 ± 844.83 mg P d^{-1} (mass). The above mentioned influent mass of P was calculated based on Eq. (12) whereas the mass of effluent P can be calculated using Eq. (12). The research results reveals that the sudden fall in the influent P mass from the source to the stage 1 and then stage 2.

Table 4. Major P processes in 2-stage DASC based CWs

Major P Processes	***Stage 1***	***Stage 2***
P Adsorption (%)	78 – 92	65-76
P plant uptake (%)	8 – 12	6 – 9
P Microbial uptake (%)	3 – 6	2 – 5

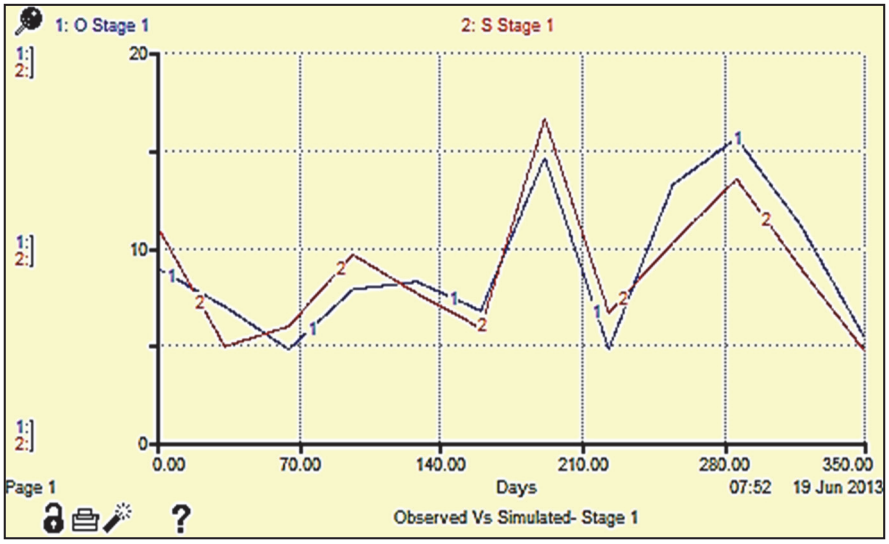

Fig. 3. Stage-1: Observed Vs Simulated P concentration (mgL^{-1}) in two stage VFCW- "1" indicates observed values whereas "2" indicates simulated values

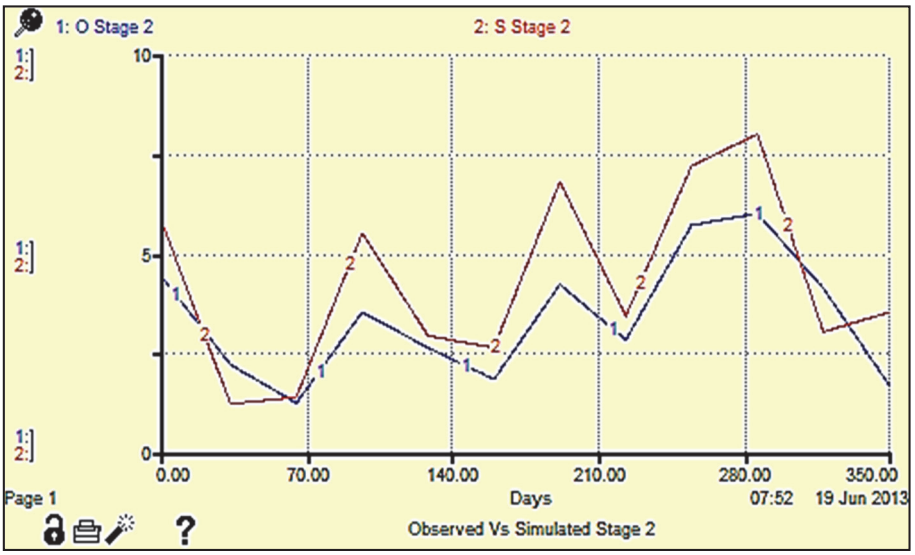

Fig. 4. Stage 2: Observed Vs Simulated P concentration (mgL^{-1}) in two stage VFCW- "1" indicates observed values whereas "2" indicates simulated values

4. Conclusions

The two-stage process-based model proposed in this study was able to simulate P effluent concentration with a reasonable accuracy in both stages of a CW. The following conclusions can be made from the current study: (1) "Pilot scale" DASC based CW has the potential to remove of P in larger extent. (2) A reasonable agreement was made between the simulated P concentration and observed effluent P concentration results. (3) based on the estimation of mass balance analysis, it was found that adsorption plays a major role in the P removal, followed by plant and microbial uptake. Overall the result shows that DASC-based CW is promising and also accepted as a low-cost water treatment system for enhancing P removal efficiencies.

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Nomenclature for P-Model

Abbreviation	Description
ADSP	Adsorbed P in alum sludge
AS	Total amount of alum sludge
DETP	Amount of P found in detritus used by bacteria
DISP	Amount of P dissolved in alum sludge
PLAP	Amount of P found in plants
PLBI	Amount of P found in plant biomass
F	Flow rate
n	Heterogeneity factor
R	Light for plant growth
T	Plant and Microbial activities (temperature)
A_d	P adsorption
A_{per}	Percentage computation for Adsorption
B_g	Growth of Bacteria
Ct	Contact time of wastewater with alum sludge
D_e	Detritus decomposition
G_m	Growth of plants (Maximum)
G_r	P for growth of plants
I_p	Inflow of P
K_b	Michaelis –Menton plant growth rate
K_F	Freundlich constant
K_r	Michaelis –Menton plant growth rate
K_u	Michaelis –Menton plant growth rate
M_b	Mortality of biomass
M_i	Uptake of microbes
M_m	Mineralization (Maximum)
M_p	Mortality of plant
M_{per}	Percentage computation for microbial uptake
M_r	Rate of mortality
O_p	Outflow of P
P_c	P concentration of inflow
P_e	P equilibrium concentration
P_{mi}	P in plants (minimum)
P_{mx}	P in plants (maximum)
P_p	P in plant
T_A	Total amount of adsorbent (g)
U_m	Uptake of P from plants (maximum)
U_p	Removal of P through plants
U_{per}	Percentage computation for plant Uptake
V_w	Volume of waste water

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