Simulation and reaction parameter estimation in subsurface flow constructed wetland for greywater treatment

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Abstract
Subsurface flow constructed wetland (SSFCW) is widely adopted for the removal of BOD5 and TKN from greywater. The design of SSFCW is normally based on thumb rules or using a first-order reaction kinetic model. However, the applicability of this model is system/environment-specific which necessitates the assessment of the potential applicability of other reaction kinetic models. In the present study, experiments were planned on SSFCW during initial and established phases to collect the data on BOD and TKN for assessing the system-specific application of plug flow, K-S* and CSTRs in series models. The reaction rate parameters along the length of SSFCW and overall for the system were estimated. There was no variation in values of rate parameter along the length in an initial phase, but the values increased along the length of SSFCW in established phase. Further, the applicability of these models was assessed for predicting BOD5 in SSFCW based on error analysis. And overall reaction rate parameters were estimated. Based on the average absolute error and RMS error it is concluded that plug flow and K-S* reaction kinetic models are more applicable for BOD5. The volumetric reaction rate parameter is recommended to be 0.612/day (plug flow) and 0.742/day (K-S*) for the design of SSFCW in tropical climate for BOD5 removal. The volumetric reaction rate parameter for TKN removal by plug flow model is recommended to be 0.389/day.

Keywords BOD5 · Canna indica · Constructed wetland · CSTRs in series · Greywater · Plug flow · K-S* model · TKN

Introduction
Subsurface flow constructed wetland (SSFCW) has been widely used to treat domestic wastewater for the removal of BOD5 and TKN. It also offers a reliable and appropriate treatment system in developing countries. The removal mechanisms for BOD5 and TKN are complex due to the contribution of interrelated processes occurring within the SSFCW environment consisting of medium and vegetation. The dominating processes of BOD5 and TKN removal include adsorption, straining, ammonification, nitrification, denitrification, decomposition, and plant uptake. The simplified design approach adopted in general for SSFCW is based on either thumb rules or first-order reaction kinetic model.

The increasing use of SSFCW for the treatment of wastewater under different environmental conditions is a stimulant for assessing the applicability of other potential reaction kinetic models. At present, the models adopted for design of SSFCW include rules of thumb (Wood 1995), regression models (Rousseau et al. 2004), first-order kinetics (Kadlec and Knight 1996; Kadlec 1997; Kallner and Wittgren 2001), retardation model (Shepherd et al. 2001), Monod kinetics (Mitchell and McNevin 2001; Kemp and George 1997) and dynamic compartmental models (Wynn and Liehr 2001). Mrasili-libelii and Checchi (2005) studied combinations of series/parallel CSTRs of unequal volumes in series with a plug-flow reactor for SSFCW. Sonavane and Munavalli (2009) developed lumped distribution model for nitrogen removal from septic tank effluent. Sun and Saeed (2011) studied kinetic modeling of nitrogen and organics removal in vertical and horizontal flow constructed wetland. Abdolmajid et al. (2015) studied efficiency and kinetic modelling of removal of nutrients and organic matter from a full-scale
constructed wetland. Cui et al. (2016) studied nitrogen removal in a SSFCWs and the reaction parameter was estimated using the first-order kinetic model.

A review of literature reaction kinetic/design models for SSFCW shows that the estimated values of reaction rate parameters involved in different kinetic models vary widely. The reported factors affecting variability include a scale of the study, type of wastewater, climatic conditions, a medium used, and type of vegetation. The models based on first-order reaction rate kinetics are popular and most widely used for a variety of field and pilot-scale studies. The reaction rate parameters reported in these studies exhibited wide variability in their values. The use of a proper set of reaction rate parameters for a given SSFCW is required to decide/set design criteria for a given environment. The design criteria developed were based on thumb rules, first-order models and Monod type kinetics. But none of these models is universally applicable. Thus it would be important to test other reaction kinetic models to assess their usefulness and applicability.

The literature cited shows that the studies carried out for tropical climate regions like India are little. The studies on modelling and reaction kinetics of greywater treatment systems have not been reported. Thus, there is a scope to assess the potential of other reaction kinetics models for their usefulness and applicability for greywater treatment. The studies carried out in the present work which contribute to existing knowledge are summarized below:

1. Field-scale experimentation work on SSFCW for BOD$_3$ and TKN removal.
2. Assessment of the applicability of plug-flow, K-S$^*$ and CSTRs in series models for BOD and TKN removal using data obtained from SSFCW.
3. Estimation of reaction rate parameters involved in the above models and assessing the variability of these parameters along the length of SSFCW for initial and established phases.
4. Determination of the best performing reaction kinetic model for BOD$_3$ and TKN removal in SSFCW.

Materials and methods

Field-scale experimentation

The field-scale study was conducted on a working Integrated Onsite Greywater Treatment System (IOGTS) constructed for the hostel of Rajarambapu Institute of Technology at Rajaramnagar (MS) India. Figure 1 shows a schematic sketch of IOGTS. SSFCW which is a part of IOGTS is divided into three compartments by vertical baffles to induce channelized (horizontal) flow. It can be described as around the end vegetated bed baffled reactor. The total length of channelized flow is 30 m (which is divided into three stretches of 10 m each for modelling purposes) with a width of 0.75 m. The channelized flow ensures maintenance of the plug flow conditions within SSFCW as length to width ratio is more than 10. The flow regulation valves are provided at both inlet and outlet structures. Four sampling ports made up of 150-mm perforated PVC pipes are provided in SSFCW for sample collection.

Fig. 1 IOGTS with sampling ports
collection and are shown in Fig. 1. The distance between the two sampling ports is 9.0 m. This modification is made to collect samples along with the flow and to assess spatial/temporal variation of BOD$_3$ and TKN. The area of perforations is more and will not affect the hydraulics of the system at sampling points. Hence the entry/exit effects are not considered in the present study. SSFCW was vegetated with Canna indica in 0.60 m depth gravel medium of size 6–10 mm in month of the January 2015.

The settled greywater was used as a feed to SSFCW and was distributed uniformly by inlet chamber provided with perforated pipe arrangement. The system was operated in continuous mode with an organic loading rate (OLR) of 110 kg/ha day, hydraulic loading rate (HLR) of 110 mm/day and detention time of 1.5 day for a year. The data collected during the operation were used for modelling studies. The experimental study was divided into two phases viz. initial phase (January–April 2015) and established phase (May–December 2015). The initial phase refers to the period required for the proper growth of plants and the development of roots. A fully developed SSFCW referred is as the established phase. The photographic view of SSFCW during these phases is shown in Fig. 2. All the procedures of analysis were referred to APHA (2005) for BOD$_3$ and TKN. The samples of greywater were collected from four ports every hour on each sampling day once a week throughout the year. The composite sample was prepared and used for the analysis of BOD$_3$ and TKN.

**Models used in the study**

In the present study, it is proposed to apply the different reaction kinetic models viz. plug flow, K-S* and CSTRs in series for simulating BOD$_3$ and TKN removal. The models used in the present study are discussed in the following sections:

**Plug-flow model**

The principle of design for SSFCW is based on an assumption of plug flow conditions within SSFCW with biological degradation by first-order reaction kinetics. The basic relationship which is used to describe simultaneously the two components viz. biological degradation and system hydraulics are given as:

$$\frac{dS}{dt} = -k_{app}S$$

where $S$, effluent BOD$_3$ concentration; $S_o$, influent BOD$_3$ concentration; $k_{app}$, apparent reaction rate constant (/day); $\theta$, residence time (day).

**K-S* model**

The modification to Kickuth model to reflect treatment wetland performance data was developed by Kadlec and Knight (1996). The model commonly referred to as K-S* model differs from the original Kickuth equation in two ways: firstly, it is a reversible first-order reaction equation rather than the irreversible equation and secondly, it includes a non-zero background concentration. It is believed that an irreversible first-order model does not satisfactorily describe the removal of pollutants from treatment wetlands because pollutants in the treated water cannot be reduced to zero due to the subsequent release of pollutants from the wetland into the treated water (Kadlec and Knight 1996). Thus the non-zero background concentration represents a release of pollutants resulting from transformation processes within the sediments and sediment–water interactions. These processes are mainly attributed to the production of organics from the decomposition of plant litter and other organic materials as well as endogenous autotrophic processes (IWA 2000; Bavor et al. 1988). Background concentrations of BOD lie in the range of 1–10 mg/L (IWA 2000). K-S* model is written as:

$$\ln \left( \frac{S - S^*}{S_o - S^*} \right) = -\frac{kH_\eta A}{Q} = -\frac{kV}{Q} = -k\theta$$

Fig. 2 Photographic view of SSFCW
k, reaction rate parameter (/day) and $S^*$, non-zero background BOD$_5$ (mg/L).

The values of $k$ and $S^*$ vary from one wetland to another and depend on site-specific factors such as vegetation type and density, the strength of influent wastewater, temperature and hydraulic variable (Kadlec 2000; Kadlec and Knight 1996).

The value of $S^* = 10$ mg/L (IWA 2000) is used in the present study.

**CSTRs in series**

In this model, actual SSFCW is assumed to be replaced by four CSTRs in series and is shown in Fig. 3.

$$\frac{S_4}{S_0} = \frac{1}{1 + \frac{k_{CSTR}}{4} \frac{V}{Q}}$$

$$k_{CSTR} = \left[ \sqrt[4]{\frac{S_0}{S_4}} - 1 \right] \times \frac{4}{\theta}$$

**Table 1** BOD$_5$ and TKN in SSFCW for initial phase

| Month of year 2015 | BOD$_5$(mg/L) | TKN (mg/L) |
|--------------------|---------------|-------------|
|                    | $S_0$ | $S_1$ | $S_2$ | $S$ | $N_0$ | $N_1$ | $N_2$ | $N$ |
| January            | 100   | 90   | 80   | 70  | 14.4  | 12.6  | 11   | 9.6 |
| January            | 120   | 105  | 85   | 75  | 11.1  | 10    | 9    | 8.0 |
| January            | 100   | 90   | 80   | 70  | 12    | 10.5  | 9.2  | 8.1 |
| February           | 110   | 95   | 85   | 75  | 10    | 8.9   | 7.8  | 6.8 |
| February           | 110   | 95   | 80   | 70  | 8     | 7     | 6.2  | 5.45|
| February           | 100   | 90   | 80   | 70  | 11    | 9.7   | 8.5  | 7.50|
| February           | 120   | 105  | 90   | 80  | 14    | 12.3  | 10.8 | 9.5 |
| February           | 100   | 90   | 80   | 70  | 11.1  | 10    | 9.0  | 8.0 |
| February           | 120   | 105  | 90   | 80  | 14    | 12.3  | 10   | 8.8 |
| February           | 120   | 105  | 90   | 80  | 12.5  | 10.8  | 9.4  | 8.2 |
| February           | 100   | 85   | 75   | 65  | 14    | 12.3  | 10   | 8.8 |
| February           | 100   | 90   | 75   | 65  | 11.1  | 10    | 9    | 8.0 |
| March              | 110   | 95   | 80   | 70  | 12    | 10.4  | 9    | 7.8 |
| March              | 100   | 88   | 78   | 66  | 12    | 10.5  | 9.2  | 8.1 |
| March              | 120   | 100  | 85   | 75  | 10.5  | 9     | 7.7  | 6.8 |
| March              | 100   | 85   | 70   | 60  | 11.5  | 9.9   | 8.5  | 7.3 |
| March              | 120   | 100  | 85   | 70  | 10    | 8.9   | 7.8  | 6.8 |
| April              | 110   | 95   | 80   | 70  | 10.6  | 9.30  | 8    | 7.0 |
| April              | 100   | 85   | 70   | 60  | 8.8   | 7.6   | 6.5  | 5.6 |
| April              | 120   | 100  | 80   | 60  | 11    | 9.4   | 8    | 6.8 |
| April              | 110   | 90   | 70   | 50  | 13.6  | 11.5  | 9.8  | 8.3 |
where $S_0$, influent BOD$_5$ (mg/L); $S_4$, effluent BOD$_5$ from system (mg/L); and $k_{CSTR}$, first order reaction rate parameter (/day).

**Results and discussion**

**Results of experimental work used for modelling study**

BOD$_5$ and TKN of greywater collected from various ports in SSFCW for initial and established phases are given in Tables 1 and 2, respectively. These values are used for the estimation of reaction rate parameters.

**Estimation of reaction rate parameters for BOD$_5$**

The computed values of the reaction rate parameter of plug flow and K-S* models for three stretches of SSFCW for the initial phase, established phase and total study period are given in Table 3. Typical computations of $k_{app}$ and $k$ for the month of January are given in Table 4. The results show that the values of $k_{app}$ and $k$ do not vary significantly in the initial phase along the length of SSFCW, but vary significantly in the established phase. The trend of variation for $k_{app}$ and $k$ is the same. The values of parameters increase with length and time in established phase. The reaction rate parameter in the initial phase is less than that for the established phase for all the stretches of SSFCW. This is because of the development of roots and growth of biofilm on roots requires time.

**Table 2** BOD$_5$ and TKN in SSFCW for established phase

| Month of year 2015 | BOD$_5$ (mg/L) | TKN (mg/L) |
|--------------------|----------------|------------|
|                    | $S_0$ | $S_1$ | $S_2$ | $S$  | $N_0$ | $N_1$ | $N_2$ | $N$  |
| May                | 120   | 100  | 75   | 55   | 10    | 8.2   | 6.7   | 5.5  |
| May                | 100   | 80   | 60   | 45   | 13.6  | 11.3  | 9.1   | 6.8  |
| May                | 120   | 90   | 70   | 50   | 11    | 9     | 7.1   | 5.6  |
| May                | 110   | 85   | 65   | 45   | 13.5  | 11.2  | 8.9   | 6.7  |
| June               | 120   | 95   | 70   | 50   | 12    | 10    | 8     | 6.0  |
| June               | 110   | 85   | 60   | 40   | 13.4  | 10.9  | 8.4   | 6.0  |
| July               | 110   | 95   | 80   | 65   | 11.6  | 9.5   | 7.8   | 6.2  |
| July               | 110   | 90   | 75   | 60   | 10    | 8.2   | 6.7   | 5.5  |
| July               | 110   | 95   | 80   | 60   | 11.0  | 9.4   | 8     | 6.8  |
| July               | 110   | 95   | 80   | 60   | 11    | 9.4   | 8     | 6.8  |
| July               | 110   | 90   | 70   | 55   | 12    | 10.5  | 9     | 8.1  |
| August             | 120   | 100  | 80   | 60   | 11    | 9.4   | 8     | 6.8  |
| August             | 110   | 90   | 70   | 50   | 13.6  | 11.5  | 9.8   | 8.2  |
| August             | 110   | 90   | 70   | 50   | 13.6  | 11.5  | 9.8   | 8.3  |
| August             | 120   | 100  | 75   | 55   | 10    | 8.2   | 6.7   | 5.5  |
| September          | 100   | 80   | 60   | 45   | 13.6  | 11.30 | 9.1   | 6.8  |
| September          | 100   | 80   | 60   | 45   | 13.6  | 11.3  | 9.1   | 6.8  |
| September          | 120   | 90   | 70   | 50   | 11    | 9     | 7.1   | 5.6  |
| September          | 110   | 85   | 65   | 45   | 13.5  | 11.2  | 8.9   | 6.7  |
| October            | 120   | 95   | 70   | 50   | 12    | 10    | 8.0   | 6    |
| October            | 100   | 85   | 60   | 40   | 13.4  | 10.9  | 8.4   | 6    |
| October            | 100   | 75   | 60   | 30   | 13.4  | 10.9  | 8.4   | 6    |
| October            | 110   | 80   | 60   | 40   | 14    | 12.3  | 10.8  | 9.5  |
| October            | 110   | 85   | 65   | 45   | 13.5  | 11.2  | 8.9   | 6.7  |
| November           | 100   | 80   | 60   | 40   | 13.5  | 11.2  | 8.90  | 6.7  |
| November           | 110   | 90   | 65   | 40   | 12    | 10    | 8     | 6    |
| November           | 100   | 80   | 60   | 35   | 11.1  | 10    | 8     | 6    |
| November           | 90    | 70   | 65   | 30   | 11    | 9.0   | 7     | 5    |
| December           | 120   | 95   | 70   | 50   | 12    | 10    | 8     | 6    |
| December           | 110   | 85   | 60   | 40   | 13.4  | 10.90 | 8.4   | 6    |
| December           | 120   | 95   | 70   | 50   | 10    | 8     | 6     | 4    |
| December           | 100   | 80   | 60   | 45   | 13.6  | 11.3  | 9.1   | 6.8  |
| December           | 120   | 100  | 75   | 55   | 10    | 8.2   | 6.7   | 5.5  |
Table 3  Computed values of reaction rate parameters ($k_{app}$ and $k$) for three stretches

| Month of year 2015 | Computed values of reaction rate parameter (/day) for Stretch |
|-------------------|---------------------------------------------------------------|
|                   | $k_{app}$ | $k$ | $k_{app}$ | $k$ | $k_{app}$ | $k$ |
| January           | 0.229     | 0.254 | 0.265 | 0.300 | 0.261 | 0.299 |
| February          | 0.260     | 0.289 | 0.274 | 0.309 | 0.258 | 0.297 |
| March             | 0.320     | 0.355 | 0.324 | 0.367 | 0.288 | 0.334 |
| April             | 0.346     | 0.384 | 0.420 | 0.478 | 0.455 | 0.539 |
| Average reaction rate parameter for initial phase | 0.288     | 0.320 | 0.320 | 0.363 | 0.315 | 0.367 |
| May               | 0.475     | 0.529 | 0.547 | 0.629 | 0.651 | 0.790 |
| June              | 0.491     | 0.545 | 0.653 | 0.753 | 0.741 | 0.916 |
| July              | 0.336     | 0.336 | 0.379 | 0.379 | 0.498 | 0.498 |
| August            | 0.382     | 0.423 | 0.506 | 0.576 | 0.635 | 0.757 |
| September         | 0.495     | 0.554 | 0.547 | 0.635 | 0.639 | 0.785 |
| October           | 0.504     | 0.563 | 0.573 | 0.665 | 0.883 | 1.18  |
| November          | 0.449     | 0.506 | 0.618 | 0.726 | 0.970 | 1.25  |
| December          | 0.452     | 0.503 | 0.613 | 0.705 | 0.670 | 0.818 |
| Average reaction rate parameter for established phase | 0.448     | 0.494 | 0.554 | 0.633 | 0.710 | 0.874 |
| Average reaction rate parameter for total study period | 0.394     | 0.436 | 0.476 | 0.543 | 0.759 | 0.705 |

Table 4  Typical computations of $k_{app}$ and $k$ for the month of January

**Plug flow model**

| Month | Stretch 1 | Stretch 2 | Stretch 3 |
|-------|-----------|-----------|-----------|
|       | $S_0$ | $S_1$ | HRT | $S_1$ | $S_2$ | HRT | $S_2$ | $S$ | HRT | $k_{app}$ |
| Jan   | 100   | 90   | 0.5 | 0.211 | 90   | 80   | 0.5 | 0.236 | 80   | 70   | 0.5 | 0.267 |
|       | 120   | 105  | 0.5 | 0.267 | 100  | 85   | 0.5 | 0.325 | 85   | 75   | 0.5 | 0.250 |
| Avg   | 100   | 90   | 0.5 | 0.211 | 90   | 80   | 0.5 | 0.236 | 80   | 70   | 0.5 | 0.267 |
|       |       |       |     | 0.230 |       |       |     | 0.265 |       |       |     | 0.261 |

**K-S* Model**

| Month | Stretch 1 | Stretch 2 | Stretch 3 |
|-------|-----------|-----------|-----------|
|       | $S_0$ | $S_1$ | $S^*$ | HRT | $S_1$ | $S_2$ | $S^*$ | HRT | $S_2$ | $S$ | HRT | $k$ |
| Jan   | 100   | 90   | 10   | 0.5 | 0.236 | 90   | 80   | 10   | 0.5 | 0.308 | 80   | 70   | 10   | 0.5 | 0.267 |
|       | 120   | 105  | 10   | 0.5 | 0.293 | 105  | 85   | 10   | 0.5 | 0.286 | 85   | 75   | 10   | 0.5 | 0.365 |
| Avg   | 100   | 90   | 10   | 0.5 | 0.236 | 90   | 80   | 10   | 0.5 | 0.308 | 80   | 70   | 10   | 0.5 | 0.267 |
|       |       |       |     | 0.255 |       |       |     | 0.301 |       |       |     | 0.300 |

Table 5  Computed values of overall reaction rate parameter for all models

| Month of year 2015 | $k_{app}$ (/day) | $k$ (/day) | $k_{CSTR}$ (/day) | Month of year 2015 | $k_{app}$ (/day) | $k$ (/day) | $k_{CSTR}$ (/day) |
|-------------------|------------------|-------------|-------------------|-------------------|------------------|-------------|-------------------|
| January           | 0.263            | 0.297       | 0.276             | July              | 0.405            | 0.463       | 0.437             |
| February          | 0.269            | 0.303       | 0.282             | August            | 0.508            | 0.586       | 0.560             |
| March             | 0.318            | 0.361       | 0.338             | September         | 0.561            | 0.658       | 0.624             |
| April             | 0.407            | 0.467       | 0.441             | October           | 0.653            | 0.782       | 0.742             |
| May               | 0.558            | 0.650       | 0.621             | November          | 0.679            | 0.828       | 0.774             |
| June              | 0.629            | 0.739       | 0.709             | December          | 0.579            | 0.675       | 0.647             |
| Initial phase     | 0.314            | 0.357       | 0.334             | Established phase | 0.571            | 0.672       | 0.639             |
| Total study period| 0.485            | 0.567       | 0.537             |                   |                  |             |                   |
The biological degradation is supported only by the medium and partially by roots. This is evident in increasing values of parameters with time in the initial phase. Further season/month of the year seems to affect the value of the reaction rate parameter.

The lower values of reaction rate parameters in the starting stretch indicate lesser BOD$_5$ removal. This may be attributed to anaerobic condition existing because of relatively more BOD$_5$ and lower oxygen supply by vegetation. The higher removal rates observed in the latter stretch are due to better oxygen rate leading to the aerobic process. Further, the lower rate parameters are observed due to lesser vegetation growth which is evident in Fig. 2a. The higher values were observed because of the better growth of vegetation (Fig. 2b). The stretch-wise evaluation of parameters is useful in modelling existing SSFCW into step-feed modifications to enhance the performance of the system as removal rate are higher in the latter stages.

The computed values of the overall reaction rate parameter (using influent and effluent BOD$_5$ from SSFCW) applicable for the whole SSFCW for all the three models are given in Table 5. The values of parameters for the initial

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**Table 6** Performance of reaction kinetic models and estimated reaction parameters

| Model            | Average absolute error (mg/L) | RMS error (mg/L) |
|------------------|-------------------------------|------------------|
| Initial phase    |                               |                  |
| Plug flow model  | 5.95                          | 33.05            |
| K-S* model       | 4.60                          | 31.46            |
| CSTRs model      | 27.95                         | 240.00           |
| Established phase|                               |                  |
| Plug flow model  | 6.62                          | 48.63            |
| K-S* model       | 5.53                          | 40.62            |
| CSTRs model      | 41.26                         | 240.00           |
| Total study period|                             |                  |
| Plug flow model  | 11.10                         | 98.00            |
| K-S* model       | 11.07                         | 100.00           |
| CSTRs model      | 35.28                         | 276              |

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**Fig. 4** Computation of overall $K_{app}$ in plug flow model for TKN removal

**Fig. 5** Comparison of observed and simulated BOD$_5$ concentration for plug flow model

The lower values of reaction rate parameters in the starting stretch indicate lesser BOD$_5$ removal. This may be attributed to anaerobic condition existing because of relatively more BOD$_5$ and lower oxygen supply by vegetation. The higher removal rates observed in the latter stretch are due to better oxygen rate leading to the aerobic process. Further, the lower rate parameters are observed due to lesser vegetation growth which is evident in Fig. 2a. The higher values were observed because of the better growth of vegetation (Fig. 2b). The stretch-wise evaluation of parameters is useful in modelling existing SSFCW into step-feed modifications to enhance the performance of the system as removal rate are higher in the latter stages.

The computed values of the overall reaction rate parameter (using influent and effluent BOD$_5$ from SSFCW) applicable for the whole SSFCW for all the three models are given in Table 5. The values of parameters for the initial
phase are less compared to the established phase for the reasons discussed previously.

**Estimation of overall reaction rate parameter for TKN**

**Plug flow**

The reaction rate parameter for TKN removal is calculated by first-order reaction kinetics for initial phase, established phase and the total study period. Figure 4 shows the computation through linearized plots. The overall reaction rate parameter $K_{app}$ for TKN removal for the initial phase, established phase and total study period are 0.459/day, 0.389/day and 0.389/day, respectively.

**Performance of reaction kinetic models for SSFCW**

In this section, an attempt is made to identify the appropriate reaction kinetic model for SSFCW using observed and simulated BOD$_5$ values. The observed values included the data collected from four sampling ports of SSFCW. An appropriate reaction kinetics model is identified based on the goodness of fit between the observed concentrations at the outlet port and the concentration to be computed by various models at the same port. The goodness of fit between two observations is interpreted in terms of average absolute error and root mean square (RMS) of absolute error at each observation. Three reaction kinetics models considered are plug flow, K-S* and CSTRs in series for predicting BOD$_5$. The average absolute error and RMS error are given in Table 6. The applicable models are plug flow and K-S* as the average absolute error and RMS error are minimum. The reaction rate parameters are 0.612/day and 0.742/day for the plug flow and K-S* models respectively to predict BOD$_5$ in the established phase. These values can be used for the design of SSFCW for tropical climate for greywater treatment. The concentration computed by plug flow and K-S* model for this best fit with observed data is shown in Figs. 5 and 6, respectively.

**Comparison of reaction rate parameter reported in the literature and current study**

The comparison of literature reported values and those obtained in the current study for reaction rate parameter is given in Table 7. The comparison is done for parameters (volumetric and area-based) for BOD$_5$ and TKN removal. It shows that the values varied widely and are study specific. In this context, the parameter values of the present study are applicable for greywater treatment in a tropical climate.

**Conclusions**

Experiments were planned and conducted to assess the performance of SSFCW to remove BOD and TKN. The data on performance evaluation were used for estimating reaction rate parameters applicable to tropical climate. Plug flow, K-S* and CSTRs in series models were identified from the literature and applied on data collected. It
was found that the estimated reaction rate parameters by all the models varied spatially and temporally. There was no variation in values rate parameter along the length in an initial phase, but the values increased along the length of SSFCW. The values of these parameters increased in the direction of flow in SSFCW. It is suggestive of anaerobic activity prevailing in the initial stretches and followed by aerobic action in the latter stretches. Based on the average

Table 7  Volumetric and area reaction rate parameter (/day) for BOD$_5$ and TKN removal

| Literature reported values | Present study | Reaction rate parameter $(k)$ (/day) | Present study | Reaction rate parameter $(k)$ (/day) |
|---------------------------|--------------|--------------------------------------|--------------|--------------------------------------|
| **Author**                | **Reaction rate parameter $(k)$ (/day)** | **Present study** | **Reaction rate parameter $(k)$ (/day)** |
| (i) Volumetric based reaction rate parameter for BOD$_5$ removal | | | |
| Crites (1994) | 0.8–1.1 | $k_{app} = 0.612$ |
| Reed and Brown (1995) | 1.104 |
| Tanner et al. (1995) | 0.17 |
| Tanner et al. (1995) | 0.22 |
| Wood (1995) | 1.84 |
| Wood (1995) | 1.35 |
| Wood (1995) | 0.86 |
| Kadlec and Knight (1996) | 0.3–6.1 |
| Liu et al. (2000) | 0.86 |
| Trang et al. (2010) | 0.10–0.24 |
| K-S* | Not Reported | $k = 0.742$ |
| (ii) Area based reaction rate parameter for BOD$_5$ removal | | | |
| IWA (2000) | 0.068 | $k_{app} = 0.208$ |
| Vymazal (1998) | 0.13 |
| Cooper et al. (1996) | 0.06 |
| Cooper et al. (1996) | 0.31 |
| IWA (2000) | 0.17 |
| Arceivala (2005) | 0.17 |
| K-S* | Kadlec (1997) | 0.49 | $k = 0.252$ |
| Brix (1994) | 0.06–0.16 |
| Cooper (1996) | 0.06–0.31 |
| Kadlec (2000) | 0.17 |

Volumetric reaction rate parameter (/day) for TKN Removal

| Literature reported values | Present study | Reaction rate parameter $(k)$ (/day) | Present study | Reaction rate parameter $(k)$ (/day) |
|---------------------------|--------------|--------------------------------------|--------------|--------------------------------------|
| **Author**                | **Reaction rate parameter $(k)$ (/day)** | **Present study** | **Reaction rate parameter $(k)$ (/day)** |
| Tanner et al. (1995) | 0.16 | $k_{app} = 0.389$ |
| Wittgren and Maehlum (1997) | 0.06 |
| Wong et al. (2006) | 4.11 |
| Sonavane and Munavalli (2009) | 0.1834 |
| Sonavane and Munavalli (2009) | 0.355 |
| Trang et al. (2010) | 0.03–0.07 |
absolute error and RMS error it is concluded that plug flow and K-S* reaction kinetic models are more applicable for predicting BOD removal. The volumetric reaction rate parameter for BOD removal by plug flow and K-S* model is recommended to be 0.612/day and 0.742/day respectively for design of SSFCW for tropical climate. The volumetric reaction rate parameter for TKN removal by plug flow model is 0.389/day. The corresponding area-based reaction rate parameter for BOD removal for plug flow and K-S* model is 0.208 m/day and 0.252 m/day.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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