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Design Curves Development for Full Scale Engineered Wetland Based on Parameters Estimation of Reed and K-C first-order Kinetic Models

A. M. Aboulfotoh

Department of Environmental Engineering, Faculty of Engineering, Zagazig University, Zagazig, 44519, Egypt

: aseaf_1@yahoo.com; asalem@zu.edu.eg;

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aseaf_1@yahoo.com,
asalem@zu.edu.eg
Phone: +201111784499;

Abstract

Constructed wetland treatment systems are engineered systems that proved to be effective in removing of nutrients and suspended solids from polluted streams, mathematical models have been frequently used for sizing of engineered wetlands systems (EWs) because they are more accurately represent the liquid behavior in these reactors, among these models the first order models Reed and K-C* (Kadlec) models has already been used in the prediction of organic matter removal in EWs, but kinetic parameters estimation, calibration, and validation of these models have been little explored in the literature. In the present work, the operation data from a full scale EWs was used to develop design curves in order to be used as a tool for the prediction and control of wetland performance, this was done by estimating the kinetic parameters for Biochemical oxygen demand (BOD), Total suspended solids (TSS), Ammonia nitrogen (NH4-N) and Total Phosphor (TP) for the two 1st order models, this estimation was validated using the least square method. The two model's implementation using the estimated kinetic parameters provide a comprehensive description of the organic removal processes as the model predicted the behavior of the tested sets of data with considerable accuracy, the prediction of the two models were almost identical for all tested constitutes types and values.

1. Introduction

Water resources in Egypt are limited (**Figure 1**), conventional water resources in Egypt are The Nile River inflow, the groundwater, as well as the rainfall. However, seawater desalination and the use of wastewater (treated or partially) represent the non-conventional water resources [1]. Egypt is characterized by a dry climate, scarce rainfall, the desert covers most of the land, and its water supplies are uncertain [2].

Non-conventional water resources utilization became essential based on the fact that water demand is larger than the conventional supply. With the importance of reusing drainage water, there are limiting factors of this reuse as the excessive reuse causes the accumulation of salts in the agricultural land, and the seepage of drainage water may include toxic pollution and chemical elements that cause harm to aquifers [3].

The purpose of drainage and wastewater treatment is to remove solids (suspended, colloidal and floated), biodegradable organic matters, nutrients and elimination of pathogenic microorganisms. Water quality criteria for irrigation generally take into account characteristics such as crop tolerance to salinity, sodium concentration, and phytotoxic trace elements. It is important to reuse both drainage and treated wastewater in order to blocking the gap in water needs [4, 5].

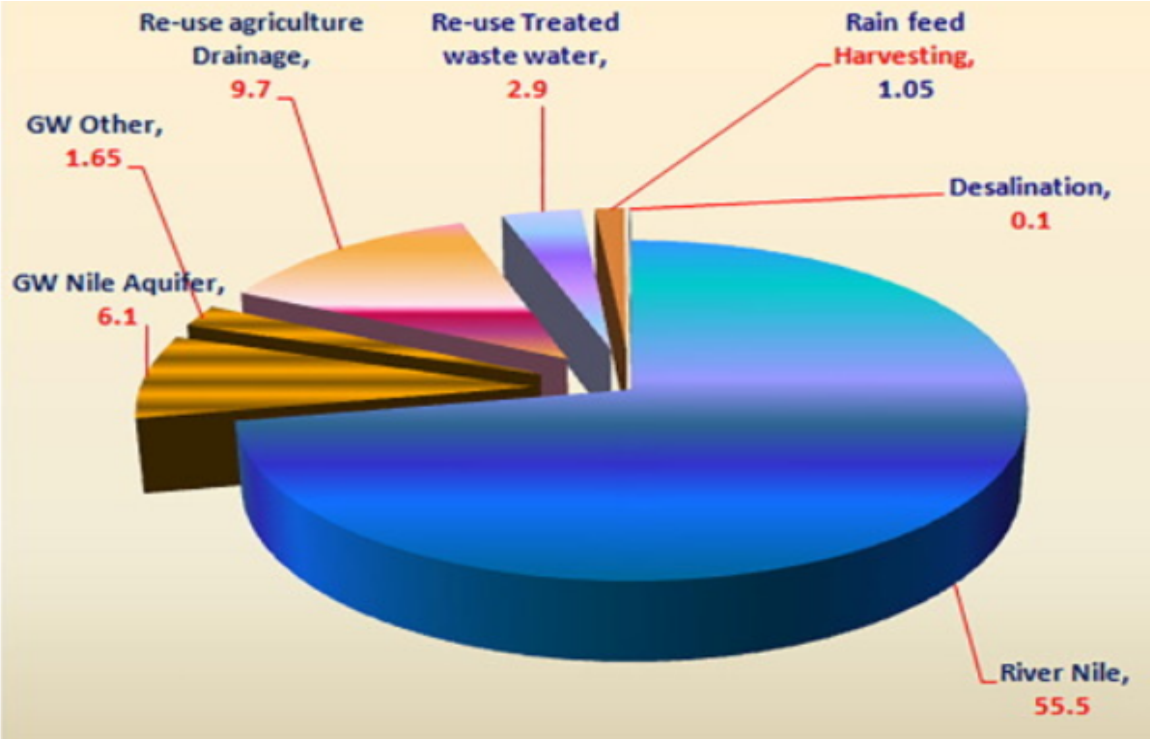
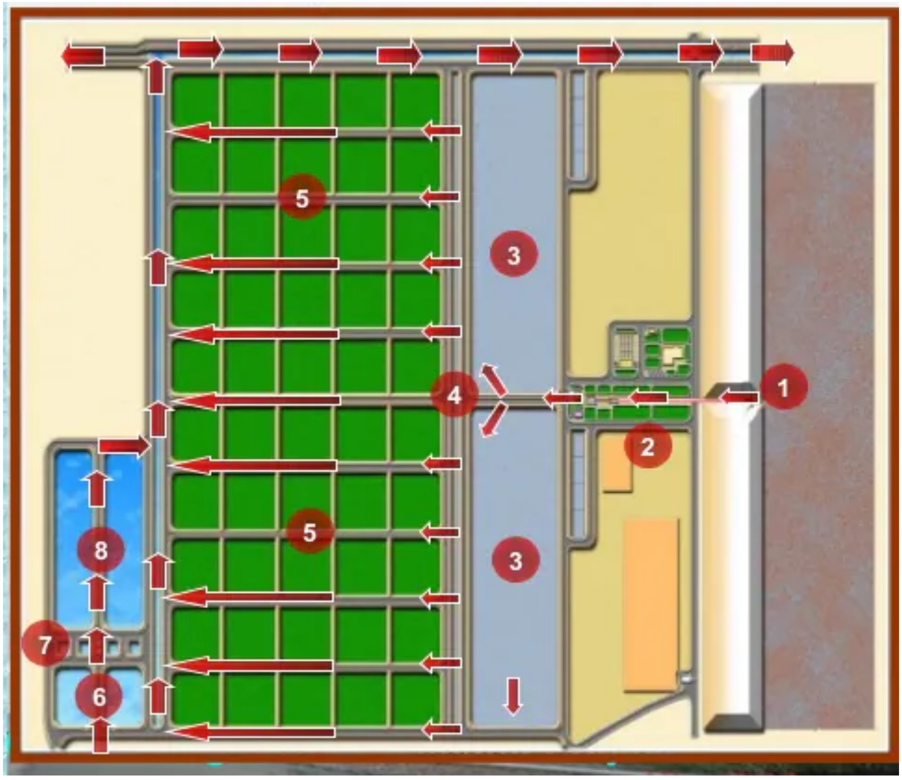
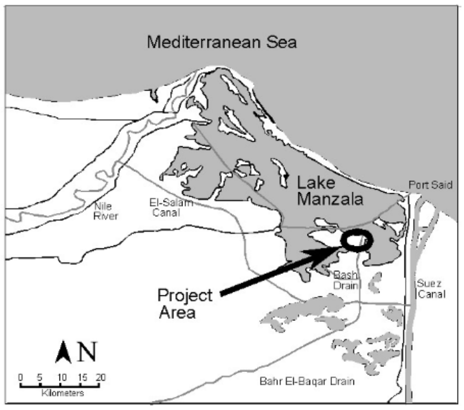


Figure 1. Availably of water supply in Egypt (billion m^3) [6]

Natural treatment systems such as Engineered wetland systems (EWs) are characterized by low-maintenance, simple and re-liable operation and high removal efficiencies. These systems are highly favored in small to medium communities, where the resources and the skilled personnel required for the operation of conventional systems are often limited [7, 8]. EWs consist of impermeable excavated basins, which use engineered structures to control the flow direction, liquid retention time and water level. Water is fed and retained during a specified time in these systems, which depends on the inflow rate and the volume of the basin. EWs are planted with aquatic macrophytes, typical from natural wetland areas. According to the way water circulates through the basins, they can be classified as either Subsurface Flow Wetlands (SSF EWs) or Surface Flow Wetlands (SF EWs). In the first case, water circulates underground through the porosity of a granular medium, whereas in SF CWs water circulates in contact with the atmosphere [9-14].

Location and layout of Manzala WEs project are displayed in **Figure 2,** It is situated in the northeast frontier of the Nile Delta, Egypt (the center of the wetland is 31.164329 N and 32.19441 E for), The average diurnal temperature in the study area is 21 ± 1 ºC, the full capacity of the system is 25,000 $m^3.d^{-1}$. Firstly, the flow is discharged from "Bahr El-Baqar" drain, in continuous operation, to two sedimentation basins with a nominal design hydraulic retention time (HRT) of 78 h. Subsequently, the primary effluent is distributed via a channel and pipes to ten surface flow cells, which planted with reeds common to the Lake Manzala area such as Phragmites australis, Typha and other species. The wetland system was designed as free water surface flow to provide adequate treatment and enhance water quality, each bed has 250 m length and 50 m width with an average depth of 0.5 m. Each wetland is subjected to daily flow 2,500 m^3 with hydraulic loading rate of 0.20 m. d^{-1} and average residence time of 60 h. Then, part of the treated effluent 4,000 $m^3.d^{-1}$ is reused for hatchery ponds followed by fingerling ponds. The remaining portion is dumped into the drain which discharges its water into "El-Manzala" Lake, then the Mediterranean Sea [14-16].





Project Components

Bahr El-Baqar drain
Intake pump station
Sedimentation lagoon
Distribution channel
Free surface flow wetland
Hatchery ponds
Fingerling ponds
Disposal

Figure 2. Manzala EWs project location and main components

The wastewater treatment system for reducing organic matter concentration in EWs is often represented by first-order kinetic models based on ideal flow regimes. However, possible inadequacies of these models, especially for the removal of heterogeneous organic material, have been frequently reported in the literature [12, 13, 17-21]

There are several models used to design EWs or to calculate the pollutant effluent concentrations, such as the Reeds first-order plug flow model [10, 11], the plug flow K–C* model [12], and the tank in series model [13], the present study was aimed to develop design curves based on the kinetic parameters estimation of two of the most used first order models (Reed and K-C*) for the modeling of full scale EWs at Manzala.

2. Methodology

2.1 Reeds first order model

Reeds [10, 11] proposed that EWs can be considered to be attached-growth biological reactors, and their performance can be estimated with first-order plug flow kinetics for BOD, TSS, ammonia nitrogen, and phosphorus, for both FWS and SSF wetlands. The basic relationship for plug-flow reactors is given by **Eqn. 1**:

$$C_e = C_i * e^{-K_R * t} \qquad \textbf{Eqn. 1}$$

$$K_R = K_{R.20} * \theta_R^{T_w - 20} \qquad \textbf{Eqn. 2}$$

Where C_e = outlet constituent concentration (mg/l), Ci = inlet constituent concentration (mg/l),

t = hydraulic residence time (d), K_R = Reed's temperature-dependent, first-order reaction rate constant (d-1), $K_{R.20}$ = Reed's reaction rate constant at 20ºC (d^{-1}), Θ_R = Reed's temperature coefficient at 20°C, T_w=Average water temperature in wetland during period of concern (°C).

2.2 K-C* model

Kadlec and Knight [12] defined the K–C* model based on the first-order areal plug flow model. This model considers background concentrations from ecosystem to water. The general form of this model is defined by **Eqn. 3** for surface flow and subsurface flow wetlands, **table 1** shows the reference kinetic parameters for reed and K-C* model.

$$C_e = C^* + (C_i - C^*)e^{-K_K/q} \quad \textbf{Eqn. 3}$$

$$K_K = K_{K.20} * \theta_K^{T_w-20} \quad \textbf{Eqn. 4}$$

$$q = \frac{Q}{A} \quad \textbf{Eqn. 5}$$

Where C* = Background constituent concentration (mg/l), q = hydraulic loading rate (m/d), K_k = Kadlec's temperature-dependent rate constant (m.d-1), such that $K_{K.20}$ = Kadlec's reaction rate constant at 20°C ($m.d^{-1}$), Θ_K = Kadlec's Temperature coefficient at 20°C, Q = Average flow rate ($m^3.d^{-1}$), A = Wetland surface area (m^2).

Table 1. Reference kinetic parameters values for Reed's and K–C* model [10-13, 15, 22-24]

Parameters	Reed		K-C*		
	$K_{R.20}$ (d^{-1})	Θ_R	$K_{K.20}$ ($m.d^{-1}$)	C* (mg/l)	Θ_K
BOD	0.678	1.06	0.3025	3	1.057
TSS	NA	1.00	0.1186	6	1.00
NH4-N	0.218	1.048	0.0932	0	1.05
TP	0.04	1.00	0.0249	0	1.097

2.3 Least square method

Least Square method or the mean square error of prediction (MSEP) is probably the most common and reliable estimate to measure the predictive accuracy of a model, MSEP (Equation [6]) consists of the difference between observed values (Yi) and model-predicted values (f (X1,...., Xp)i) [25]:

$$MSEP = \frac{\sum_{i=1}^{n}(Y_i - f(X_1,\ldots,X_p)\quad i)^2}{n} \quad \textbf{Eqn. 6}$$

Where Yi is ith observed value, X_j are the variables used in the model to predict Y_i, f $(X_1,\ldots, X_p)_i$ is the i^{th} model-predicted value using X variables, n is number of data points.

2.4 Selected data set

Most of the published results on Manzala EWs in the references were based on the average removal rates of different pollutants and they cannot be relied upon to determine the kinetic parameters. Therefore, the results published by Nasr [16] were used as they represent a measure of the inlet and outlet concentration of the BOD, TSS, NH_4-N and TP for an extended period.

2.5 Parameter estimation

In order to estimate the values for each kinetic parameters, a basic parameter search routine was implemented such that different values were proposed for each parameter starting from the values mentioned in **Table 1**, then the sum of squared errors between the predicted and measured values was calculated, taking into consideration that for the K-C* model two different approaches was tested; the 1st approach involved changing the KK values with using the reference value for C*, the 2nd approached involved using the reference value for K_K with changing the values C* After determining of the kinetic parameters from the previous step a validation process was performed by comparing different data set to the model. The effect of temperature was neglected as the average temperature in the study area is around 20°C.

3. Results and Discussion

3.1 Assessment of data set

The descriptive statistics of the selected data set that was employed in this study are described in **Table 2**, the inlet concentration of BOD, TSS, NH_4-N and TP ranged between 83.49 - 96.77 mg/l, 64.36 - 73.34 mg/l, 6.85 - 9.24 mg/l and 4.75 - 5.94 mg/l respectively, while the average removal ratio of these pollutants were 70%, 54%, 51% and 46% for BOD, TSS, NH4-N and TP respectively, these values comply with [9-15, 26, 27] for raw water source and treatment performance.

Table 2. Descriptive statistics for the selected data set

Descriptive statistics	Inlet constituent concentration (mg/l)				Outlet constituent concentration (mg/l)			
	BOD	**TSS**	**NH_4-N**	**TP**	**BOD**	**TSS**	**NH_4-N**	**TP**
Mean	89.74	67.97	8.16	5.23	27.11	31.47	3.95	2.80
Standard Error	0.97	0.66	0.15	0.08	0.72	0.51	0.06	0.06
Median	87.98	67.68	8.25	5.15	27.95	32.65	3.86	2.84
Standard Deviation	4.22	2.86	0.65	0.34	3.13	2.24	0.28	0.27
Sample Variance	17.79	8.16	0.42	0.12	9.82	5.04	0.08	0.07
Range	13.28	8.98	2.39	1.19	9.79	7.10	0.90	0.96
Minimum	83.49	64.36	6.85	4.75	21.65	26.96	3.44	2.26
Maximum	96.77	73.34	9.24	5.94	31.44	34.06	4.34	3.23
Count	19	19	19	19	19	19	19	19

3.2 Estimated kinetic parameters

Table 3 shows the estimated values for the kinetic parameters that gives the least value of MSEP, all kinetic parameters for Reed model were different from the reference values while for the K-C* model, the BOD kinetic parameter remain constant as the reference value while C* changed and the remaining kinetic parameters were different than the reference values.

Table 3. Estimated kinetic parameters values

Parameters	Reed		K-C*		
	KR.20 (d-1)	**ΘR**	**KK.20 (m.d-1)**	**C* (mg/l)**	**ΘK**
BOD	**0.50**	1.06	0.3205	**11**	1.057
TSS	**0.31**	1.00	**0.18**	6	1.00
NH4-N	**0.29**	1.048	**0.15**	0	1.05
TP	**0.25**	1.00	**0.125**	0	1.097

Bold numbers represented the values that diverted than references values

Table 4 shows the descriptive statistics for actual outlet values and the models expected results, the statistics results show that the mean and the median of actual and predicted outlet concentration values of BOD, TSS, NH_4-N and TP are extremely close which confirmed by **Figure 3**, the two models' prediction was almost the same for all tested values, and the two models provide a comprehensive description of the organic removal processes that take place within EWs.

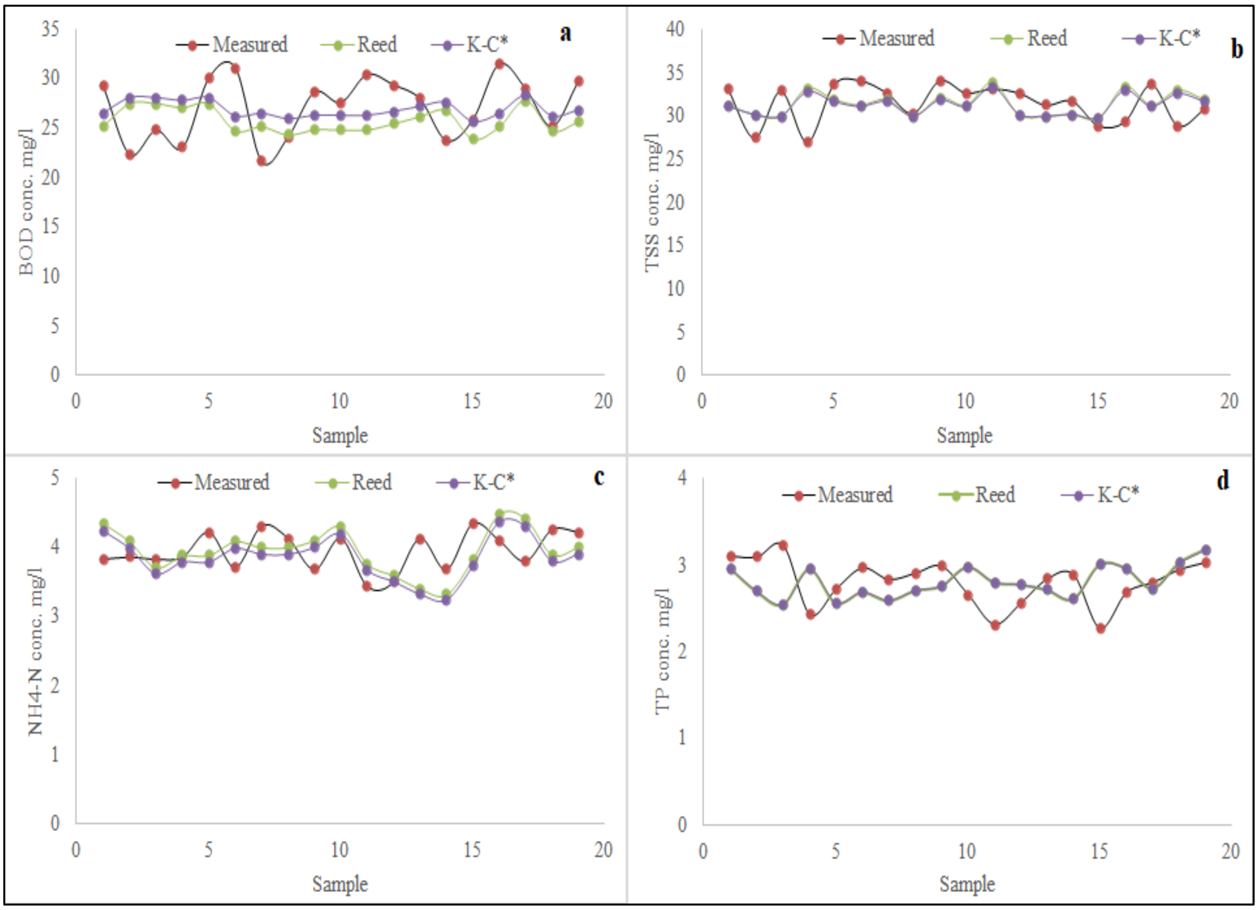


Figure 3. actual and predicted outlet concentrations for a) BOD, b) TSS, c) NH_4-N and d) TP

Table 4. Descriptive statistics for actual outlet values and the models expected values

Descriptive statistics	BOD-Out	BOD-Reed	BOD-K-C*	TSS-Out	TSS-Reed	TSS-K-C*
Mean	27.11	25.71	26.86	31.47	31.32	31.20
Standard Error	0.72	0.28	0.19	0.51	0.30	0.27
Median	27.95	25.21	26.51	32.65	31.18	31.08
Standard Deviation	3.13	1.21	0.85	2.24	1.32	1.16
Sample Variance	9.82	1.46	0.72	5.04	1.73	1.35
Range	9.79	3.80	2.67	7.10	4.14	3.65
Minimum	21.65	23.92	25.60	26.96	29.65	29.73
Maximum	31.44	27.73	28.28	34.06	33.79	33.38
Count	19	19	19	19	19	19
Descriptive statistics	**NH4-Out**	**NH4-Reed**	**NH4-K-C***	**TP-Out**	**TP-Reed**	**TP-K-C***
Mean	3.95	3.95	3.86	2.80	2.80	2.80
Standard Error	0.06	0.07	0.07	0.06	0.04	0.04
Median	3.86	4.00	3.90	2.84	2.76	2.76
Standard Deviation	0.28	0.32	0.31	0.27	0.18	0.18
Sample Variance	0.08	0.10	0.09	0.07	0.03	0.03
Range	0.90	1.16	1.13	0.96	0.64	0.64
Minimum	3.44	3.32	3.24	2.26	2.54	2.54
Maximum	4.34	4.48	4.37	3.23	3.18	3.18
Count	19	19	19	19	19	19

3.3 Validation of the models

Validation of the model was done by testing the estimated kinetic parameters from the previous step against measured data through the EWs length, change in wetland length changed residence time from 0 to 2.50 d and hydraulic loading rate from 1 to 0.20 m. d^{-1}. **Figure 4** shows the actual and predicted outlet concentrations through the bed length for two sets of data represented the low values (L) and high values (H). also, these results shows that the two models provide a comprehensive description of the organic removal processes that take place within EWs.

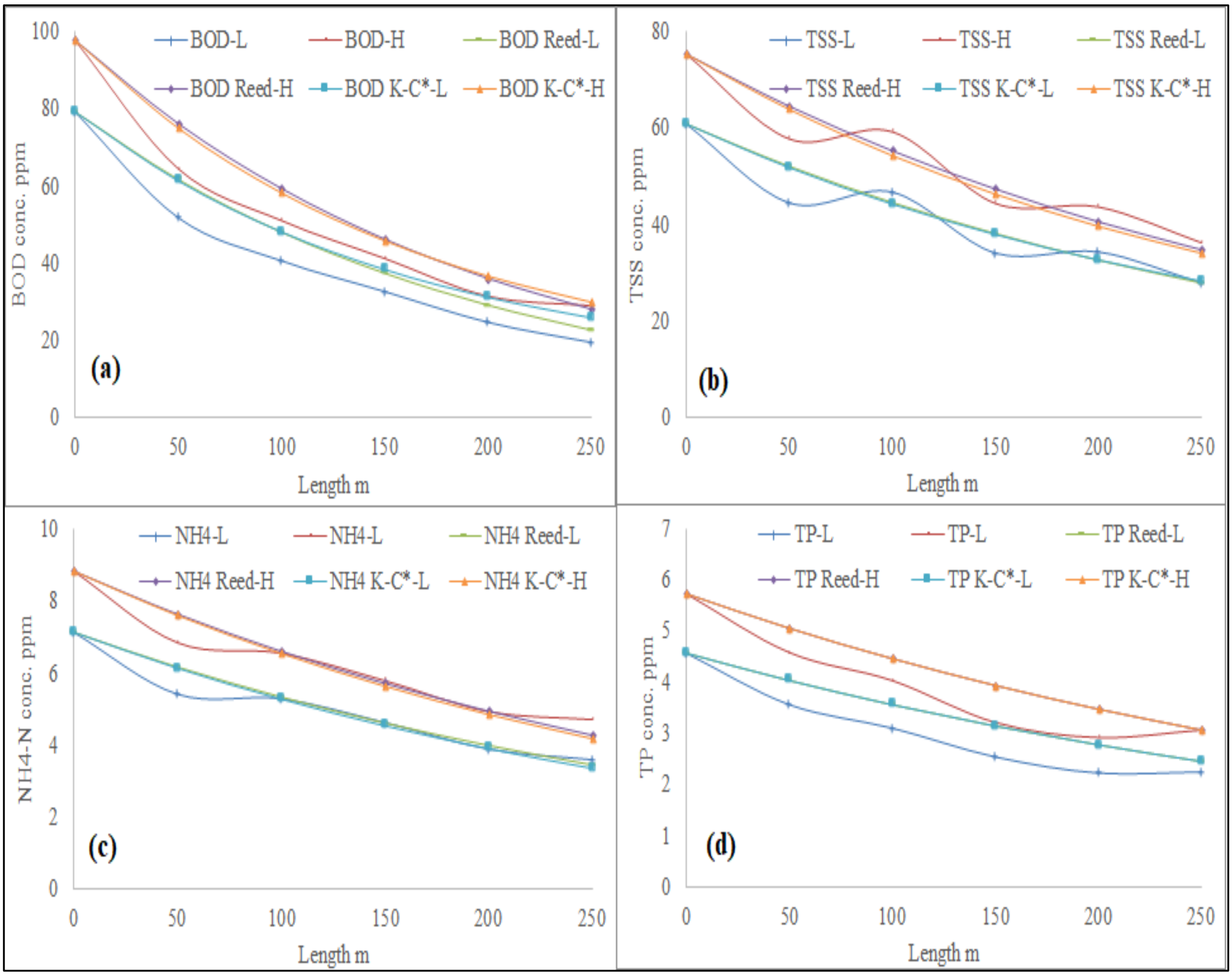


Figure 4. actual and predicted concentrations for a) BOD, b) TSS, c) NH_4-N and d) TP along wetland length

3.4 Extension of the models (design curves development)

The updated kinetic parameters were used to develop the following design curves be a used as a tool for the prediction and control of wetland performance, **Figure 5** shows the expected removal rates for different pollutants based on Reed's model and **figure 6** shows the expected removal rates for different pollutants based on K-C* model, from these figures and based on the required removal ration of pollutants the required residence time and hydraulic loading rates could be determined then being used to calculate the EWs volume, depth and area.

According to Egyptian law 48/1982, the required effluent concentration of the BOD, TSS, NH_4-N and TP is 40 mg/l, 50 mg/l, 3 mg/l and 1 mg/l respectively, with required removal rates of 55%, 26%, 63% and 81% with the same order; therefore from **figures 5 and 6** it will be found that the removal of TP will be the limiting factor with a residence time and hydraulic loading rate of 6.6 days and 0.08 m/d, the expected cross ponding removal rate of the BOD, TSS, NH_4-N and TP will 96%, 87%, 85% and 81% respectively, these results complies with [28, 29] who recorded at residence time of 11 days and hydraulic loading rate of 0.03 m/d a removal ratio for BOD, TSS, NH_4-N and TP of 91%, 92%, 84% and 63 % respectively, also [30] reported a removal ratio of 91%, 97%, 94% and 4% for BOD, TSS, NH_4-N and PO_4-P respectively. The model predictions also comply with [16] expected results but the used models in the current study is more simple, easy and applicable.

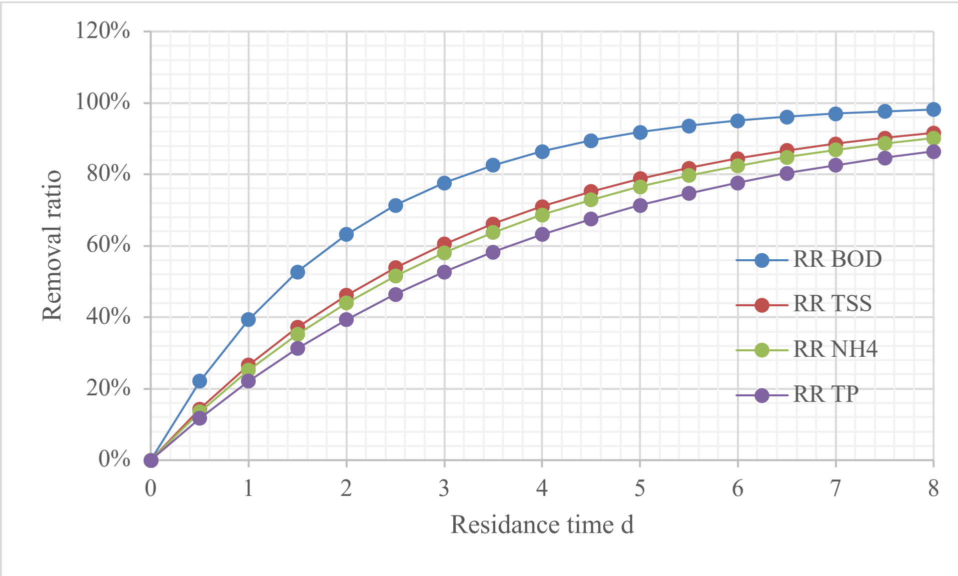


Figure 5. Expected removal rates for different pollutants based on Reed's model

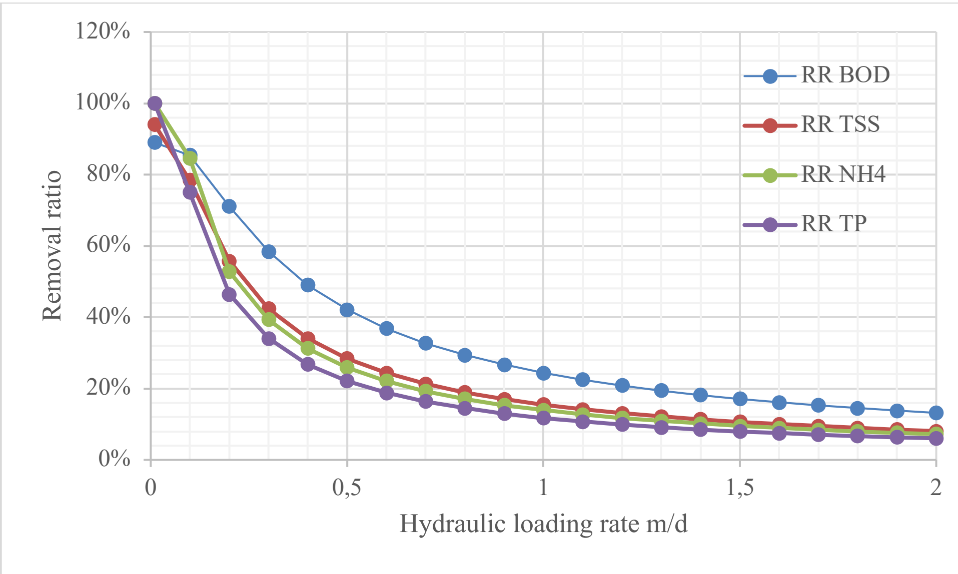


Figure 6. Expected removal rates for different pollutants based on K-C* model

Conclusion

The present study was aimed to develop design curves based on the kinetic parameters' estimation of two of the most used first order models (Reed and K-C*) for the modeling of full scale EWs at Manzala, the following points summarizes the conclusion of this study:

- Operation data from a full scale EWs were used in order to develop design curves based on kinetic parameters estimation for the first order models (Reed and K-C*).

- The test constitute related to this reach were Biochemical oxygen demand (BOD), Total suspended solids (TSS), Ammonia nitrogen (NH_4-N) and Total Phosphor (TP).
- Least square method used to determine the best fit kinetic parameter.
- The two model's implementation using the estimated kinetic parameters provide a comprehensive description of the organic removal processes that take place within EWs for the as the model predicted the behavior of the tested sets of data with considerable accuracy.
- The prediction of the two models were almost identical for all tested constitutes types and values,
- Simple design curves had been developed to be a used as a tool for the prediction and control of wetland performance.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest. *Compliance with Ethical Standards:* This article does not contain any studies involving human or animal subjects.

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