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Biological Treatment of Organic Loads in Surface Flow Constructed Wetland Using Convective Dispersion Mixing Flow Model.

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BIOLOGICAL TREATMENT OF ORGANIC LOADS IN SURFACE FLOW CONSTRUCTED WETLAND USING CONVECTIVE DISPERSION MIXING FLOW MODEL

المعالجة البيولوجية للأحمال العضوية في الأراضي الرطبة المشيدة ذات السريان السطحي باستخدام نموذج السريان الخلطي الحملي المشتت

By

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خلاصة:

تعتبر معالجة المياه العادمة باستخدام الأراضي الرطبة المشيدة تفاعل لعمليات طبيعية وحيوية وكيمائية ، ويمكن توصيف تلك العمليات بالسريان الكتلي أو السريان الخلطي أو الاندماج بينهما. تقوم هذه الدراسة على تطبيق مفهوم السريان في الأراضي الرطبة على أنة سلسلة متتالية للأحواض كاملة الخط لتوصيف معالجة الاحتياج الأكسوجيني البيولوجي مع فرض أن كل حوض على حده كامل الخلط و تركيز الملوث الخارج منه مساوي للتركيز الداخلي المنتظم.

في هذه الدراسة تم استخدام نموذج رياضي لتحديد معالجة الاحتياج الأكسوجيني البيولوجي للمشروع التجريبي للأراضي الرطبة المشيدة حرة السطح لمعالجة مياه الصرف الواردة إلى بحيرة المنزلة بشمال مصر. اعتمد النموذج الرياضي علي فرضيتين ، الأولي هي السريان كلي الخلط بالأحواض الداخلية وفيما بينها ، و الثانية تفترض وجود سريان جزئي الخلط أي كلي الخلط داخل الأحواض فقط و سريان كتلي فيما بين الأحواض ، رقد تم دراسة حساسية النموذج المستخدم للمعاملات الهيدروليكية و الهندسية مع دراسة مقارنة بالنتائج الحقلية.

أظهرت الدراسة أن معالجة الاحتياج الأكسوجيني البيولوجي تتحسن بزيادة عدد أحواض الخلط الداخلية و ثابت إزالة الملوث و زمن البقاء الهيدروليكي بينما تتحسن المعالجة بزيادة نسبة الطول للعرض من 1 إلي 2 يليه انخفاض المعالجة بزيادة النسبة أكبر من 2 ، وبمقارنة نتائج النموذج بالنتائج الحقلية أتضح أن النموذج الرياضي متوافق نسبيا مع النتائج الحقلية على طول الحوض بنسبة خطأ مطلق قدره 11.7٪ في حالة السريان الكلي الخلط و 12.5٪ في حالة السريان الكلي الخلط و قد أعطى النموذج قيم الاحتياج الأكسوجيني البيولوجي أقل من نظيرتها المعالجة في الحقل عند مخارج الأحواض.

ABSTRACT

Wastewater treatment through constructed wetland is a combination of physical, biological and chemical treatment processes. These processes are described by plug flow, mixed flow or by the plug – mixing flow combination. The concept for describing removal of organic loads biologically with treating the wetland as a series of completely stirred tanks reactors is practically

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applied (Chen et al, 1999). Each of stirred tank reactors is presumed to be completely mixed and the concentration departing each is equal to the uniform, internal concentration.

A model is used to assess the BOD removal through free water surface (FWS) constructed wetland in a pilot scale project treating drainage wastewater before dumping at Lake Manzala on the North of Egypt. Two assumptions are used in the model application; the fully mixing stirred tank reactor with fully dispersion and diffusion inside and between the wetland subsystems. The other assumption is proposed as a new idea based on the fully mixed flow assumption; namely: the partially mixing stirred tank reactor with fully dispersion and diffusion inside and a plug flow between the wetland subsystems. Sensitivity analysis of the two assumptions is presented as well as a comparison between the BOD treatment results and the corresponding results obtained from field data.

Sensitivity results shows that for both model assumptions, BOD treatment improves with increasing number of internal mixing tanks, removal rate constant, and hydraulic detention time and with decreasing the aspect ratio (length/width). In both model assumptions the BOD concentration values were nearly comparable with the corresponding measured BOD values along the wetland length with a mean absolute error of 11.7% for the case of fully mixed flow and 12.5% the case of partially fully mixed flow.

Keywords: Wetland, drainage water, plug flow, mixed flow, and pollutants.

INTRODUCTION

The spectrum of wetland types is widely used; it ranges from constructed wetlands in a greenhouse (living machine), to natural wetland systems passing through constructed wetlands for treatment purposes, polishing wetlands, and combined sewers overflow ponds, reconstructed wetlands, and so on (BRIX 1998). The wetland is alive with micro-organisms that convert chemical compounds from one form to another. A large fraction of these organisms are attached to plant stems and litter and to sites throughout the soil and plant root complex. The physical removal of BOD is believed to occur rapidly through settling and entrapment of particulate matter in the void spaces of vegetations. Soluble BOD is removed by microbes attached to plant roots and rhizomes (USDA, 2002).

Constructed wetlands are currently designed based on the assumptions of plug flow hydrodynamics neglecting any dispersion in the system as all the fluid particles have a uniform detention time traveling through the system. The plug flow concept may not be practical at constructed wetlands since there is internal mixing. The complete internal mixing at wetland cells may be described as a series of internal sub cells (tank reactors) through which flow moves and stirred from wetland inlet to outlet. Others, (Kadlec and Knight, 1996 and Reed, 1995) concluded that flow and mixing at FWS wetland follow a pattern described as plug flow with dispersion, tank in series and a small number of series, and parallel continuous stir tank reactor (CSTRs).

In this study, a small scale constructed wetland located at Lake Manzala is evaluated against measured BOD treatment data with the considered models. Two models for describing the flow through FWS wetland cells are presented. The first model considers fully mixing flow at wetland cells with a number of continuous stirred tank reactors, (CSTRs) is assumed based on the theoretical model of Chen et al., (1999). The other model which is a special case of the mixed flow model at N=1, considering a partially mixing flow between the internal wetland cells as separate stirred tank reactors in which a fully mixing is assumed at each cell. The overall objectives of this study are:

- To assess the sensitivity of models for both fully mixed and partially mixed flow assumptions.
- To apply the mixed flow procedure model with the two separate assumptions.
- To evaluate the BOD removal of the constructed wetland by comparing the models outputs with the measured effluent concentrations.

BOD MODELS

Many mechanisms can describe the BOD removal rates through constructed wetlands depending on the pollutant behavior and the different treatment processes. Theses mechanisms include convection, diffusion, dispersion of pollutants and the zero or first order production or decay of pollutant. The general partial differential equation that relates these factors for a one-dimensional pollutant transport can be written as (Hayami, 1951):

$$R\frac{\partial C}{\partial t} = D_s\frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x} - K_T C - r_1 \quad (1)$$

where: C= the pollutant concentration, M/L^3, D_s = dispersion coefficient, L/T, *u*= pore water velocity, L/T, R= retardation factor (ratio between non polluted water velocity and polluted water velocity) $R \geq 1$ (dimensionless), K_T= constant rate of first order decay T^{-1} , and r_1= constant rate for zero-order production.

When R=1 and r_1=0, Eq. (1) reduced to the steady state condition and it reads:

$$D_s\frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x} - K_T C = 0 \quad (2)$$

Chen et al. (1999) proposed a new concept, to describe solute-transport process in a more accurate procedure. Equation (2) can be used to describe flow through constructed wetland as a series of fully mixing cells depending on the assumptions of convective dispersion with a uniform detention time traveling through the system.

Wastewater pollutant enters a constructed wetland with an initial concentration C_i then it is treated and discharged from the wetland outlet with a concentration C_o. Assuming the flow through wetland is a mixed flow and divided into several continuous stirred tanks reactors, CSTRs, (Levenspiel, 1972) or subsystems. These CSTRs subsystems are in series and the mass balance principles can be applied to each subsystem separately. For the nth subsystem the Nth CSRT pollutant concentration, they derived a solution for obtaining pollutant effluent concentration as follow:

$$C_N = \frac{C_i}{\left(1+\tau' K_T\right)^N}\left[1 - e^{-\left[\frac{(1+\tau' K_T)}{\tau'}\right]t}\sum_{i=0}^{N-1}\left(\frac{1+\tau' K_T}{\tau'}t\right)^i (i!)^{-1}\right] \quad (3)$$

where: C_i = influent concentration, mg/l , C_n = effluent concentration from subsystem n, mg/l, K_T = removal rate constant of first order decay (1/d), τ' = hydraulic detention time d, *u* = flow velocity m/d, t = W. d. x. τ / *u*, ε = porosity of wetland vegetations (%), W = wetland width, m, N= number of CSTR (subsystems), i = symbol of subsystem No. 1, x = length of CSTR , (m) from impulse.

For the first subsystem (N=1), the effluent concentration C_1 is obtained as:

$$C_1 = \frac{C_i}{1+\tau^{\cdot} K_T}\left(1 - e^{-\left[\frac{(1+\tau^{\cdot} K_T)}{\tau^{\cdot}}\right]t}\right) \quad (4)$$

For the second subsystem (N = 2)

$$C_2 = \frac{C_i}{(1+\tau^{\cdot} K_T)^2}$$

$$\left[1 - e^{-\left[\frac{(1+\tau^{\cdot} K_T)}{\tau^{\cdot}}t\right]}\left(\frac{1+\tau^{\cdot} K_T}{\tau^{\cdot}}t\right) - e^{-\left[\frac{(1+\tau^{\cdot} K_T)}{\tau^{\cdot}}t\right]}\right] \quad (5)$$

FULLY MIXING FLOW (FMF) ASSUMPTION MODEL

Mixing in constructed wetlands exists due to several causes. Vertical and lateral mixing can be happened when flow around submerged plants stems causes turbulence. Turbulence and mixing may be generated by the action of wind-driven waves and recirculation exists in large scale wetlands especially in the deep zones. In addition, water moves more slowly in the plant litter layer, and more rapidly in surface waters in unobstructed channels. Consequently, some water elements move quickly to the wetland outlet, others are delayed and arrive after much longer travel times Fig. (1).

The net effect is velocity profile mixing at the wetland outlet. There is a direct relation between growing patterns of wetland vegetation and patterns of water movement. The modeling process for each internal CSTR can be tested using Eq. (3).

PARTIALLY MIXED FLOW (PMF) ASSUMPTION MODEL

An idea based on the FMF model, Eq. (4) for N=1, is introduced to provide pollutant removal within the constructed wetland. The flow can be treated as a partially mixed flow not as CSTR. This consideration copes with some previous studies which describes flow through wetland as plug flow with dispersion small number tanks in series.

The wetland is considered to be divided into a number of subsystems (cells) with equal cell length, plant porosity and flow discharge. The mixing flow is assumed only within each cell but not between adjacent cells. Flow between cells takes the plug flow description. A schematic diagram of the partially mixed flow pattern within constructed wetland is presented in Fig. (2). The inflow pollutant concentration of the first cell (subsystem) is C_{in1} while the effluent concentration is C_1. The inflow concentration of the second cell (subsystem), is C_{in2} which equals the first cell effluent concentration C_{o1} ($C_{i2} = C_{o1}$), while the effluent concentration is C_{o2} etc.

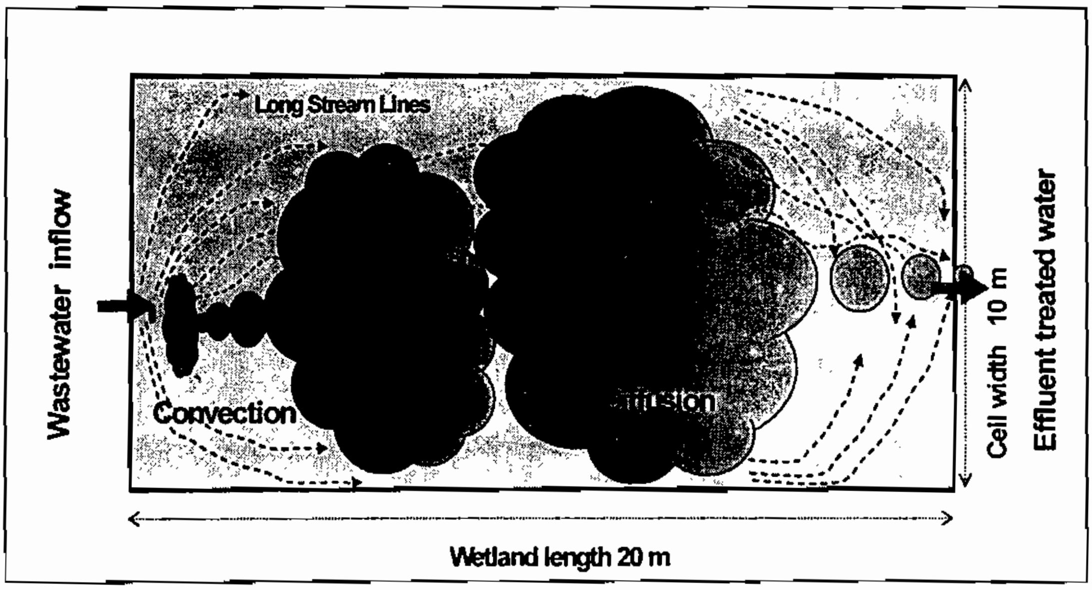

Figure 1. Sketch Describes Fully Mixed Flow between Wetland Sub-systems of N numbers.

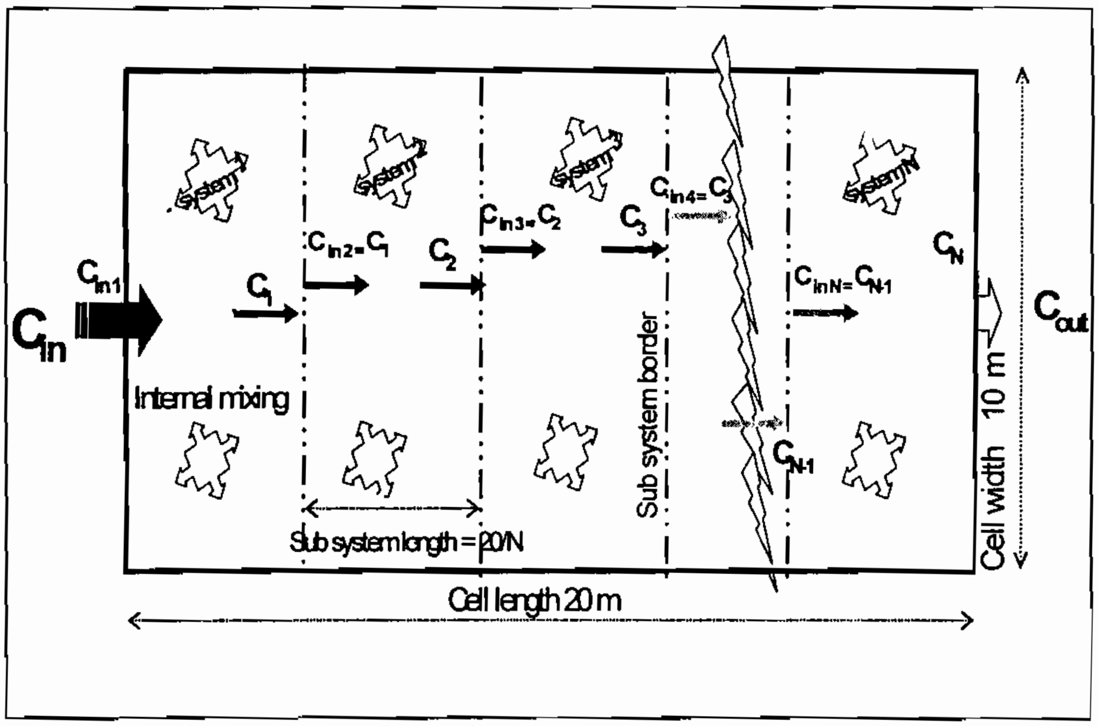

Figure 2. Sketch Describes Partially Mixing Flow between Wetland subsystems of N Numbers.

STUDY AREA

A demonstration scale constructed wetland project is constructed at Port Said Governorate part of El Salam Canal newly reclaimed lands to treat a mixture of agricultural industrial and domestic wastewater from Bahr El-Baqar before it reaches Lake Manzala. The treatment capacity is 250 m^3 /day of the drain water that retained at a sedimentation pond for two days as a primary treatment process prior to entering the wetland (Rashed et al. 2000 and Rashed et al. 2004).

The wetland consists of 3 parallel cells each cell treats 50 m3/day. Dimensions of each cell are 20 m length, L 10 m width, W and 0.5 m water depth, h with a Hydraulic Detention Time, τ of 2 days, Fig. (3). The wetland is planted with common reeds (*Phragmites Australis*) that makes a water porosity of 0.8. Field researches were carried out for two years to evaluate the treatment efficiency of constructed wetland through influent / effluent analysis. Results shows that the treatment efficiencies were 71 % for BOD, 63 % for TSS 95% for NH_4, 74 % for NO_3, and 98 % for both TC and FC bacteria. The removal rate aerial based constants were 0.748, 0.55, and 1.66 day^{-1} for BOD, TSS, and TC respectively.

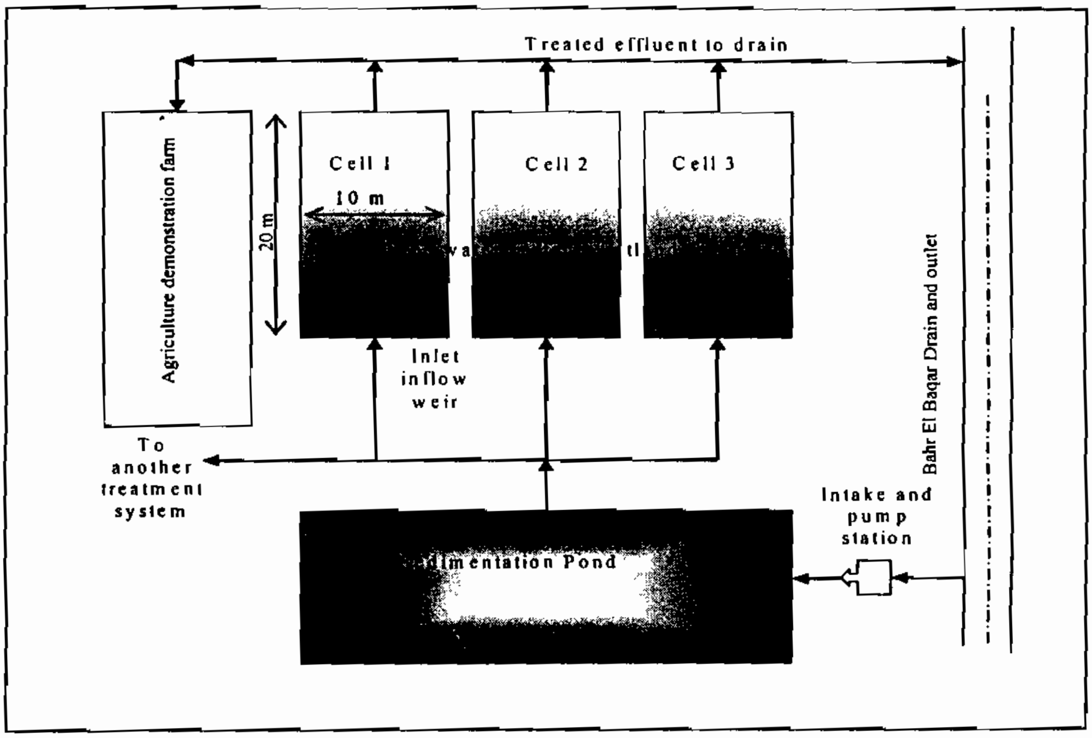

Figure 3. Sketch Describes Components of The Constructed Wetland

The BOD removal may be explained as; gravity produced settling is categorized as discrete and flocculent. Both of which are influenced by particle size, specific gravity, shape, and the viscosity of the fluid. The stems of emergent plants (reeds) have an important role in BOD removal. The plant surfaces in the water column which are coated with an active biofilm may by interception and adhesion remove particulate matter and BOD. Soluble BOD is removed by microbes on the plants surfaces and those attached to plant roots and rhizomes penetrating the bed. On the other hand, oxygen generated by submerged plants, as well as nitrogen oxides and nitrogen gas from denitrification may enhance the BOD decrease. Table 1 presents the statistical summary of the BOD concentrations of water samples collected from the 3-wetland cells. Fig. (4) presents the BOD concentrations of the wetland cells at its inlet, middle and outlet in mg/l and the removal efficiencies as well. The mean BOD in cell1 decreased from 28.59 mg/l at inlet of to 13.55 mg/l at cell 1 middle and to 7.91 mg/l at outlet.

Table 1. BOD Concentration at the Inlet, Middle and Outlet of 3 Wetland Cells

Location	$N_{St.}$	Minimum	Maximum	Mean	Std. Deviation
INFLOW	22	17	42	29	6.17
FWSM1	22	3	24	14	5.48
FWSM2	22	6	22	15	4.36
FWSM3	22	8	20	15	3.17
FWSO1	22	2	12	8	3.32
FWSO2	22	1	16	8	4.18
FWSO3	22	2	15	9	3.60

SENSITIVITY ANALYSIS of MODELS

The results of the testing and validation of model are evaluated here to provide confidence in the model and in the system dynamics modeling process. The behavior of different hydraulic parameters in wetland cells is examined to provide a better understanding of the dynamic nature of contaminant removal. The parameters considered in sensitivity analysis are;

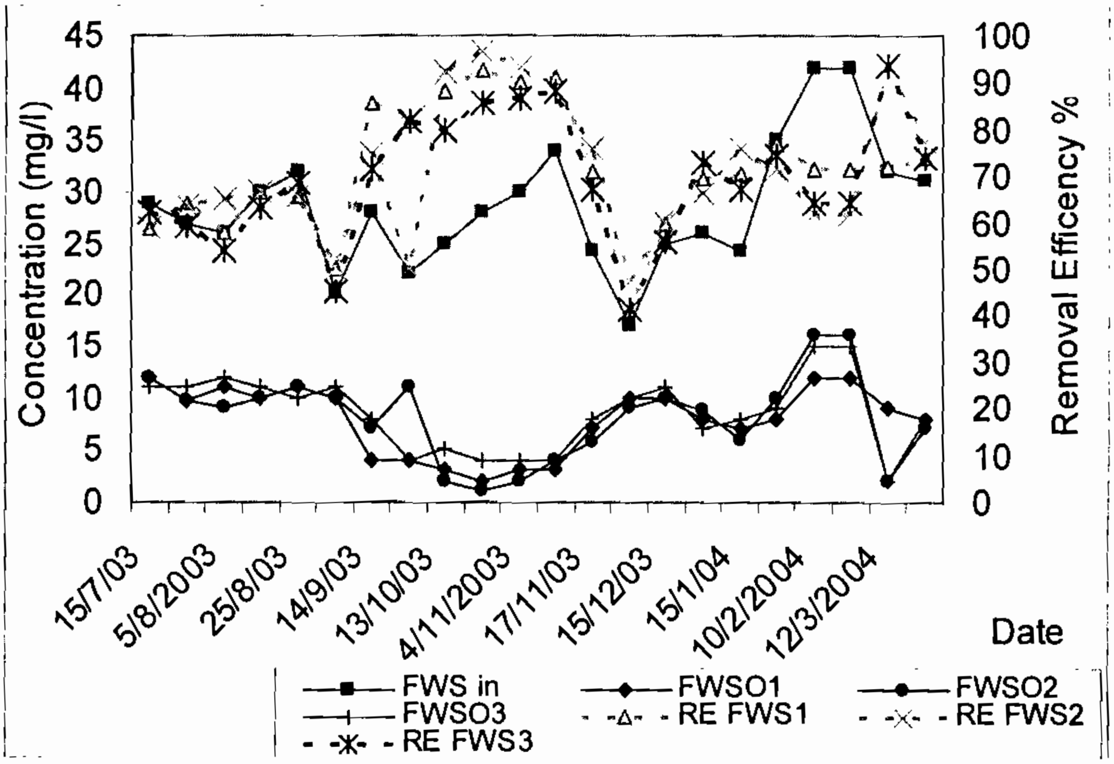

Figure 4. BOD Concentrations and Removal Efficiencies of Wetland

number of CSTR, N, aspect ratio, L/W, hydraulic detention time, τ, removal constant rate, K_T. The wetland physical and engineering features that are used in the model are: Q= influent discharge, L=total wetland length, W=wetland width, N= number of CSTR (subsystems), K_T= constant rate of first order decay, τ= hydraulic detention time, C_i = influent concentration. The output is the BOD concentrations, C_i at several distance measured from wetland inlet.

Table 2 presents a summary of the above sensitivity study of both model. The table indicates each calibration item, its range of application and the relationship of each item on pollutant treatment along the constructed wetland cell length. Conditions of application and change value of each calibration item are also presented. The treatment efficiency improved with increasing each of number of CSTR, N, removal rate constant K_T and hydraulic detention time, τ. The length to width ration (aspect ratio) takes a reverse trend as for the same distance from wetland inlet; the treatment deteriorates with increasing the aspect ratio.

Table 2 Summary of Calibration Both of Fully Mixed Flow and Partially Mixed Flow Models and Its Parameter Range Application.

Calibration item and Symbol	Range of Model application	Effect of increasing item on pollutant removal	Conditions
L=20m, W=10m, h=0.5m, τ=2days, Q=50 m^3/d, K_T= 0.748 1/d			
CSTR subsystems N	1-20	Direct	Fixing other design parameters
L=20m, W=10m, h=0.5m, τ=2days, Q=50 m^3/d, N=8			
Removal rate constant K_T (day^{-1})	0.25-0.90	Direct	Fixing other design parameters
W=10m, τ=2days, Q=50 m^3/d, N=8, V K_T= 0.748 1/d			
Aspect ratio (length/width)	1-10	Reverse	Constant ,τ, w and varied depth
L=20m, W=10m, h=0.5m, N=8, K_T= 0.748 1/d			
Hydraulic detention time τ (day)	1 – 5	Direct	Discharge increases with τ decrease

Figs. (5) to (8) presents the characteristics of the hydraulic parameters that considered in this study, along the wetland length against to BOD concentration. These characteristics are number of CSTR (N), removal rate constants (K_T), hydraulic detention time (τ), and aspect ratio (L/W).

Effects of N on BOD treatment is shown in Fig. (5) and proves that the BOD improves of increasing N and the mixing inside wetland. There are no differences between the model assumptions in case of small N (N=1 and N=2) while the difference increases at N greater than 2. The PMF assumption shows better treatment than the FMF at N=4 and N=8 CSTR since mixing is greater in case of the FMF that may retard biodegradation of pollutants. Effects of K_T on BOD treatment are presented in Fig. (6), which indicate that treatment improves with increasing K_T. The PMF assumption shows better BOD treatment of BOD for all values of K_T (0.25 to 0.90 m/day).

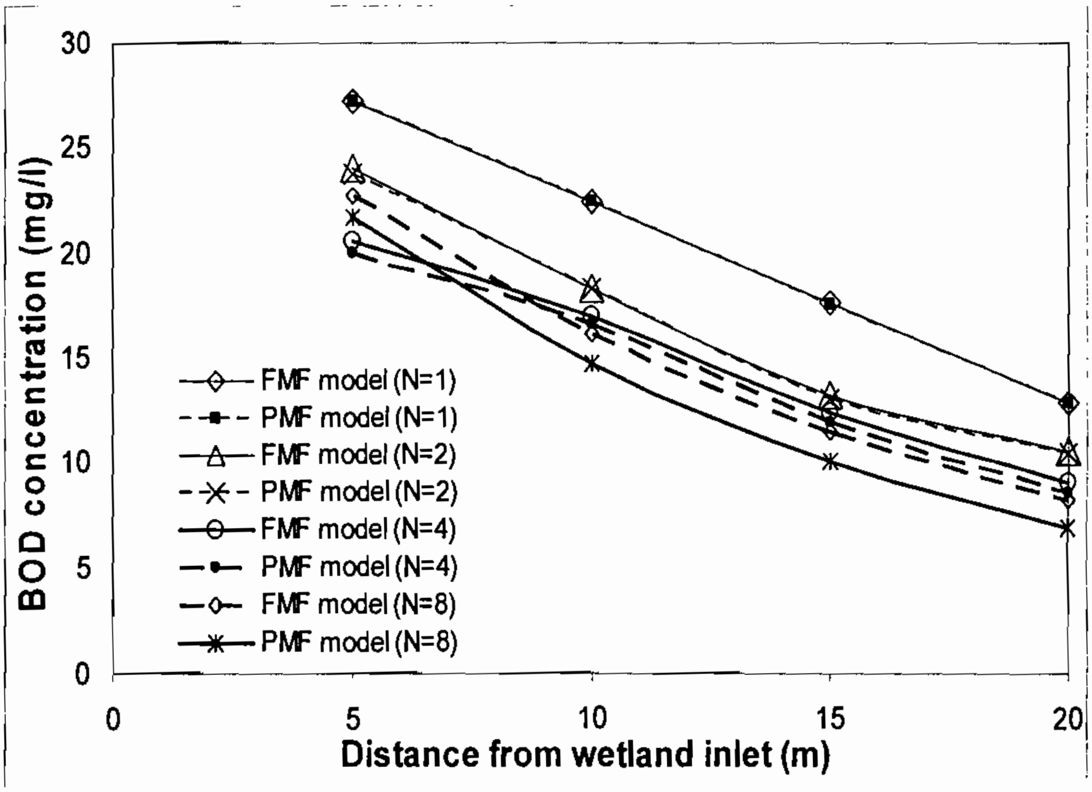

Figure (5) Comparison between the FMF and PMF models for number of CSTR impact on BOD removal.

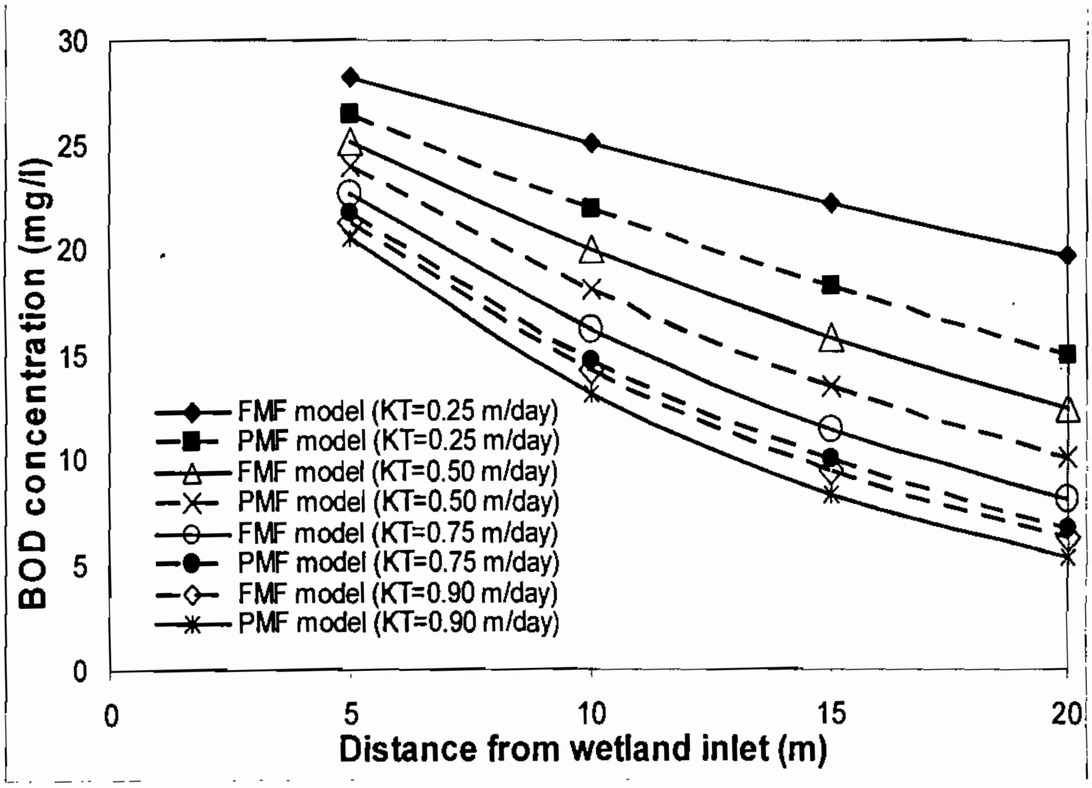

Figure (6) Comparison between the FMF and PMF models for the removal rate constant impact on BOD removal.

Hydraulic detention time τ, results are shown in Fig. (7). The BOD removal is better in the case of PFM than the FMF when τ = 1 while the two assumptions shows the same BOD treatment when τ became greater than 1 day (τ =2 to 4). It is obvious that increasing τ shows better BOD treatment.

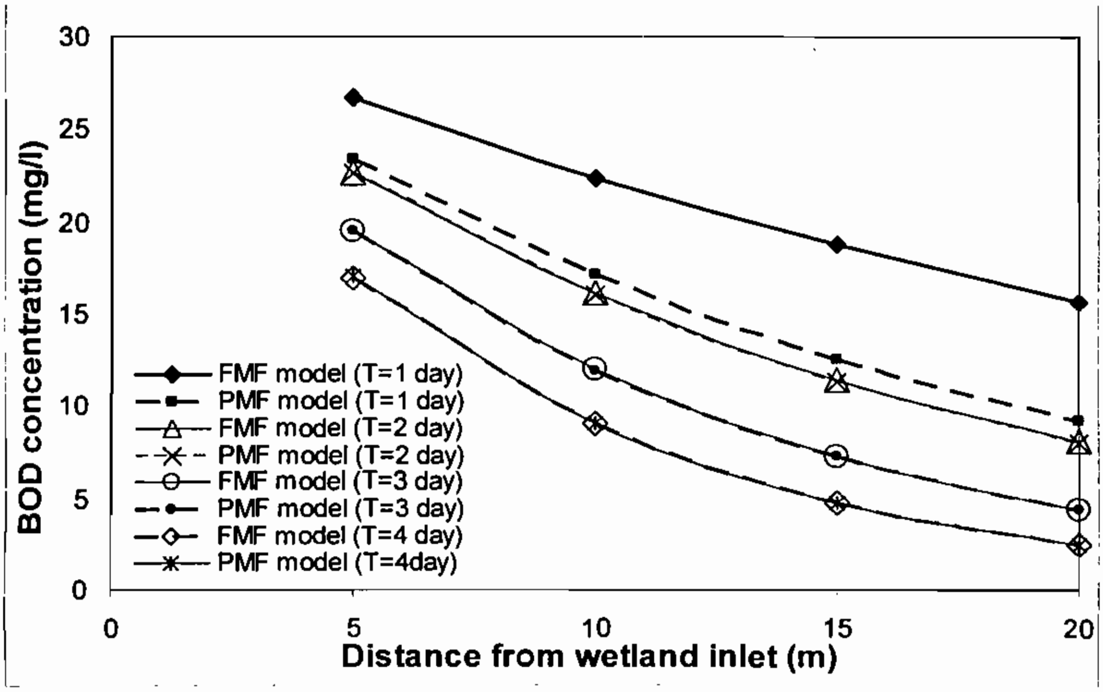

Figure (7) Comparison between the FMF and PMF models for hydraulic detention time impact on BOD removal.

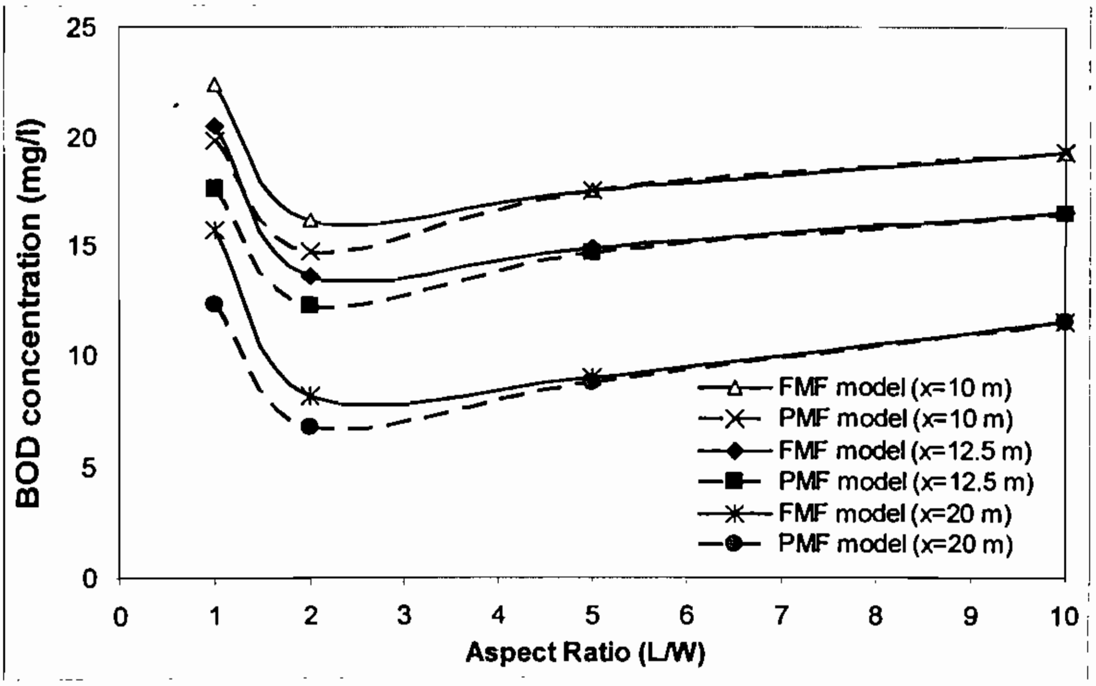

Figure (8) Comparison between the FMF and PMF models for aspect ratio impact on BOD removal.

The aspect ratio impacts are shown in Fig. (8). The comparison is between BOD concentrations at certain distances measured from wetland inlet since the wetland length is varied when changing the aspect ratio from 1 to 10. Increasing the aspect ratio from 1 to 2 will cause a sharp improvement in BOD treatment while the BOD removal slightly decreased with increasing the aspect ratio from 2 to 10. In all aspect ratio values, the PFM shows better BOD treatment than the FMF.

APPLICATION of FWS MODELS on BOD TREATMENT

Nine groups of BOD data are collected from the field and analyzed in the lab. The mean and standard deviation values of these data groups are used to test models, Table 3. A comparison between the field and predicted BOD mean values using the FMF and PMF models is presented in Table 3 and plotted in fig. (9).

Table 3. Comparison Between Field BOD Concentrations and The Values Obtained from Mixing and Partially Mixed Flow Model

Distance (m)	0	2.5	5	7.5	10	12.5	15	17.5	20
					Measured filed data				
Mean field	32.33	25.67	19.89	15.89	12.89	12.44	11.89	10.78	10.00
Stand. Deviation	4.21	3.64	2.80	1.17	0.93	1.13	1.17	0.83	0.87
					Computed models results				
Mixed flow model	32.00	26.36	22.67	19.14	16.13	13.59	11.45	9.65	8.13
Relative error	0.01	-0.03	-0.14	-0.20	-0.25	-0.09	0.04	0.10	0.19
Mean abs. error									0.117
Partially mixed flow Model	32.00	26.40	21.70	17.90	14.70	12.20	10.00	8.25	6.80
Relative error	0.01	0.03-	0.09-	0.13-	0.14-	0.02	0.16	0.23	0.32
Mean abs. error									0.125

L=20m, W=10m, h=0.5m, τ=2days, Q=50 m^3/d, K_T= 0.748 1/d Deviation = (field BOD– model BOD) / field BOD

Results presented in table 3 and fig. (9) show that both field and model data have the same descending trend with close values. The simulation is carried out depending on the actual pilot wetland characteristics. The input data of BOD model are flow Q = 50 m3/day, length, L = 20 m, width, W = 10 m depth, h = 0.5 m, removal rate constant, K_T = 0.748 1/day, detention time, τ = 2 days, inflow concentration C_i = 32 mg/l.

As for the mixed flow model the estimated BOD concentrations are relatively greater than the filed BOD in the first half cells with less treatment. The estimated BOD concentrations at the last half cells of the wetland have a better treatment. This is due to that, the actual BOD removal rate constant, K_T is greater than the K_T value of mixed flow model at the first half while the opposite happened 0n the last half of cells.

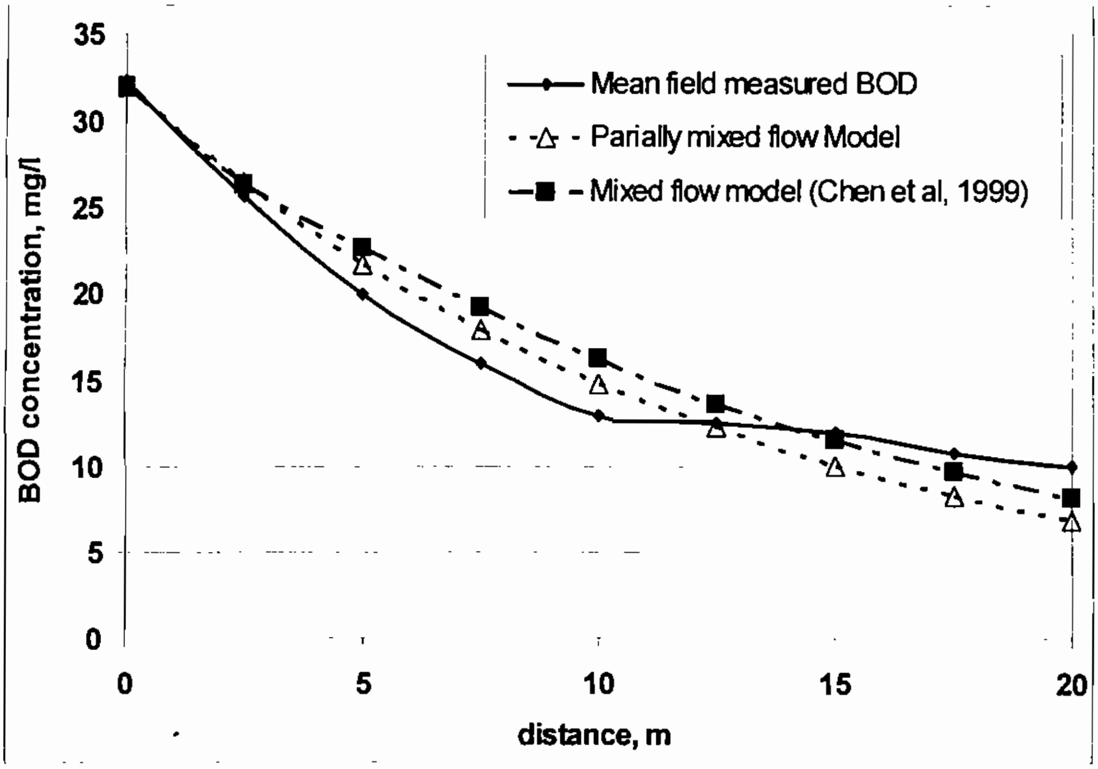

Figure 9. Variation of Model Results With Field Measured BOD Through Wetland

As for the partially mixed flow model the estimated BOD concentrations are closer to the field data than the mixed flow model in the first wetland half, while the BOD concentrations deviated from field data more than the mixed flow model in the last wetland half.

The statistical F-test shows that there are significant differences between the field and the two models results at a confidence level greater than 95%. Carrying out a Kruskal-Wallis non parametric test on results medians shows that the mean rank of field results is lower than that of both two FMF and PMF models the at 15 meters from wetland inlet and higher than the two models at the last 5 meters of wetland length. The median equality test of field and two models data can be rejected at a probability values higher than 0.433.Although the FMF model gave BOD treatment results that have large error at the middle part of wetland, it gave a comparable results at the last wetland quarter especially at the outlet than the values of PMF model.

CONCLUSIONS

From this paper it is concluded that:

- The first order convective-dispersive equation could be simplified into a one-dimensional pollutant transport under steady state flow conditions. It could be simplified using continuous stirred tank reactor theory at free water surface constructed wetland.
- The sensitivity of both models was tested against wetland hydraulic parameters as well as the wetland dimensions changes. Results showed that:
  a) The pollutant removal improved with increasing number of continuous stirred tank subsystems and the BOD had a good removal with increasing the removal rate constant.
  b) The estimated pollutant removal could be improved by increasing τ with respect to decreasing Q and vise versa and consequently the longer detention time would enhance enough time for the microbes to degrade the contaminant.
  c) The BOD treatment could be affected with decreasing the aspect ratio (L/W). At the same distance from wetland inlet, the longer wetland had smaller pollutant removal than the shorter one with constant width value. Increasing the aspect ratio from 1 to 2 will cause a sharp improvement in BOD treatment while the BOD removal slightly decreased with increasing the aspect ratio from 2 to 10. In all aspect ratio values, the PFM shows better BOD treatment than the FMF.

   d) When the aspect ratio became less than 1, chances of short circuiting might increased and this might be corrected after using several parallel wetland cells.

- The FMF model showed that the estimated BOD concentration values were comparable with the corresponding field data along the wetland cells with mean absolute error of 11.7 % .
- The pollutant removal of BOD by the PMF model presented an agreement with the field data at the first mid wetland and did not agree with field data at the outlet. However The model has relatively comparable results with the FMF along the wetland length.

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NOTATIONS

The following symbols are used in this paper:

BOD = biological oxygen demand

C_i= influent concentration, mg/l

C_n=effluent concentration from subsystem n, mg/l

CSTRs = continuous stirred tank reactors

H = wetland water depth

K_T = removal rate constant of first order decay (1/d)

PMF = partially mixed flow

TC = total coliform bacteria

U = flow velocity m/d

W= wetland width, m

τ' = hydraulic detention time of each subsystem, d

FWS = Free Water surface

ε = porosity of wetland vegetations

W=wetland width, m

Q = flow m3/day

FMF = fully mixed flow

N= number of CSTR (subsystems)

TSS = total suspended solids

FC = fecal coliform bacteria

x= length of CSTR , (m) from impulse

L = wetland length, m

i = symbol of subsystem No. i