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Reciprocating Subsurface Wetlands for Drainage Water Treatment A Case Study in Egypt

الأراضي الرطبة الترددية تحت السطحية لعلاج مياه الصرف – حالة دراسية في مصر

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الملخص العربي:

الأراضي الرطبة الترددية تكنولوجيا جديدة طورت بمعرفة هيئة وادي تينيسي لمعالجة ملوثات المياه ، وتتلخص فكرتها في زيادة المحتوى الأكسوجيني للمياه عن طريق تفريغ ثم ملئ خلايا المعالجة الزلطية عدة مرات مما يؤدي إلي تنقية عالية للمياه الملوثة. وقد تم تطبيق هذا الأسلوب في مصر ببحيرة المنزلة كنموذج إيضاحي لمعالجة جزء من مياه مصرف بحر البقر الملوثة بأحمال صرف صحي و صناعي، ويتكون نظام المعالجة من حوض ترسيب يتبعه خليتين ترديتين ذواتا سريان تحت سطحي لمعالجة ١٠٠ م^{٣} يوميا بزمن مكث أفتراضي قدره ٤ أيام. يهدف هذا البحث إلي تقديم وصف دقيق لمسار المياه أثناء معالجتها بتبادلها بين خليتي المعالجة و حتى تمام المعالجة، كما يهدف البحث إلي تقييم أداء هذا النظام في معالجة مياه الصرف و تنقيتها من الحمل العضوي و المواد العالقة و الفسفور و النيتروجين و البكتيريا القولونية و عنصر الحديد، وذلك من خلال تحليل معملي لعينات مياه قبل و بعد المعالجة و استخدام نموذج المسريان كامل الخلط لاستنباط ثوابت معاملات الإزالة للملوثات المختلفة لاستخدامها مستقبلا عند تصميم نظم معالجة ترددية في الأجواء القاحلة أو شبه القاحلة. وقد أوضحت النتائج الكفاءة العالية لذلك النظام في معالجة ملوثات مياه المصرف خصوصا النترات و الأمونيا والتي لا تنجح في معالجتها بكفاءة الأراضي الرطبة الغير ترددية مما سيكون لهذا النظام أثر بالغ في معالجة مياه المصرف و تنقية البحيرة.

Abstract

A new patented constructed wetlands treatment technology for enhanced nutrients reduction has been developed by Tennessee Valley Authority. This new treatment technology is known as Reciprocating Flow Constructed Wetland (RFCW) through increasing oxygen content in the treatment processes. The RFCW has a process of operating two adjacent subsurface flow gravel beds by alternately draining and filling the wastewater on a recurrent basis to achieve tertiary levels of wastewater treatment.

In Egypt, A pilot-scale RFCW was built near Lake Manzala as a demonstration of low cost treatment technology to treat a portion of Bahr El-Baqar drain wastewater that carries drainage water contains domestic and industrial pollution loads. The pilot wetland consists of one sedimentation basin followed by two subsurface flow cells working in fill-empty sequence mechanism. The treatment capacity is 100 m^3 per day. Treatment detention time is 4 days including 2 days in the gravel bed RFCW cells.

Objectives of this paper are to describe operational flow inside the alternate cells, and to evaluate the treatment performance of reciprocating wetland for such polluted drainage water and to estimate removal rate constants (K) of the treated pollutants applying mixed flow reactor model. Water samples were collected from both influent and effluent wetland cells. Samples were analyzed to measure concentrations and loads of DO, BOD, TSS, NH_4-N, NO_3-N, TP, Fe, and FC. Results showed that RFCW managed to polish pollutants of drainage influent especially ammonia and nitrates reaching a limit which it could be used in a safe manner for the agricultural purpose or dumping it into Lake Manzala without negative impacts on its ecosystem.

Key words

Reciprocating wetlands, mixed flow, drainage water treatment, subsurface wetlands.

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1. Introduction

Constructed wetlands are efficient tools for wastewater treatment. It is a competitive treatment technology for the conventional treatment systems due to its minimal requirements of labors, power or spare parts. It is a promising treatment facility for the developing countries due its advantages of saving costs and providing a new unconventional water source. Many of these systems have been utilized in treating wastewater from a number of diversified sources, such as agriculture, municipality, industry, landfill, stormwater runoff, and contaminated surface or groundwater. Such systems offer high performance in removing biochemical oxygen demand (BOD), suspended solids and fecal coliform bacteria (FC). However, the efficiency of nitrogen and phosphorus removal can be quite poor, especially during cold climates. Enhancing oxygen source to the treatment process may help in N and P removal. Cottingham et al. (1999) showed improvement (50%) in nitrification rate by direct aeration of laboratory scale wetlands.

Alternate or tidal vertical flow is not a recent technique in wastewater treatment. Seidel (1978) and Wolverton (1983) started experiments with flood and drain vertical flow wetlands but deep investigations were carried out recently (Tanner et al., 1999. and Sun et al., 1999). The tidal flow treatment wetlands deeply investigated by the Tennessee Valley Authority's (TVA), offering several studies, outstanding treatment performance and a sound design basis. A unique and patented reciprocating RFCW system was developed by scientists at TVA in which paired wetland cells are filled and drained alternately in a rapid (~2 hours per cycle) and recurrent basis (Behrends, 1999). The fill-and-drain cycles helped in the diffusion of oxygen through thin films of water that are surrounding the plant roots and the biofilms on the wetland substrates during the drain cycle and the following re-exposure of the biofilms to anoxic wastewater during the fill period (Behrends et. al., 2001 and Behrends, 2007).

The reciprocating subsurface-flow wetlands could enhance aerobic and anaerobic wastewater treatment processes, oxidize reduced gases, provide environments conducive to enhancing die-off rates of pathogenic micro-organisms, and/or interfere with the life cycle of nuisance insects such as mosquitoes. During the drain cycle, atmospheric oxygen is rapidly supplied to the de-watered and relatively thin (from about one micron to about two millimeters thick) microbial biofilms residing on backfill substrate, promoting growth of aerobic bacteria which are responsible for oxidizing ammonia (nitrification), various heavy metals, and other toxic compounds. During the fill cycle, interstitial water remains anoxic and/or anaerobic, thus creating environments encouraging to reduction reactions such as sulfate reduction, denitrification, and methanogenesis. The combination of aerobic and anaerobic environments, as enabled by the recurrent reciprocation process, provides coupled oxidation-reduction environments that are required for treating mixed wastes and recalcitrant compounds (Zitomer and Speece, 1993).

Egypt has some ongoing plans for the protection of the Mediterranean Sea and the Egyptian natural lakes. For this reason, it is essential for Egypt to seek low-cost wastewater treatment alternatives that are convenient for large quantities of water. An attractive alternative technique appears to be the constructed wetlands for drainage water treatment before reaching northern lakes. A pilot-scale constructed wetland was built in 2000 near Lake Manzala to demonstrate a low cost treatment technology for treating the wastewater of Bahr El-Baqar drain that carries drainage water contains domestic and industrial pollution loads. The pilot wetland included a RFCW designed by the TVA as a new treatment technique in the arid climate regions. The treatment capacity is 100 m^3 per day, after 2 days primary treatment inside a sedimentation basin. In this paper some effort will be concentrated on both RFCW alternate flow description and evaluating its treatment performance for such polluted drainage water and to estimate the removal rate constants (K) of the treated pollutants. These constants may be used in any further RFCW projects design procedures.

2. Lake Manzala reciprocating wetland system

A small scale constructed wetland, project is conducted within Lake Manzala north eastern the Nile Delta, Egypt (32° 7' East, 31° 15' North) in order to reveal a low cost treatment alternative for its influent polluted drainage water. The project is located within El Salam Canal reclamation area west of Suez Canal on the left bank of Bahr El Baqar Drain. The project was established by the Ministry of Environment, funded by the United Nations Development Program and the Global Environmental Facility, and evaluated in cooperation with the Egyptian Canadian NAWQAM (National Availability and Water Quality Management) project through the Ministry of Water Resources and Irrigation.

Bahr El-Baqar drain is the largest and most polluted drain of the seven drains discharging in Lake Manzala (5.5 billion m^3/day), (DRI, 2000) and it was excluded from supplying El-Salam Canal delivering mixed drainage and fresh water to Sinai due to its high level of pollution loads. The drain originates from Cairo collecting agricultural, industrial and sewage water from three other governorates before reaching Lake Manzala with a total length of more than 200 km (TVA, 1998).

A pilot scale project is planned to treat 250 m^3 /day of drainage water before it reaches Lake Manzala. The project main objective is to demonstrate a sustainable economic technique that can protect the lake from pollutants carried by drainage water in order to establish a full scale 250,000 m^3/day wetland project. The project consists of a sedimentation pond for primary treatment stage, followed by 3 free water surface cells (150 m^3/day) and 2 RFCW cells (100 m^3/day) as advanced secondary treatment stages (Rashed et al., 2000). The RFCW is filled with gravel media and planted with common reeds (Phragmites australis) with a plants density of 20 plants/m^2. Reeds are dominant native plant species in the Lake Manzala area. Reeds are fresh harvested (cut at the water surface) every two to three months according to the growing stage and season.

2.1 Reciprocating Wetland Description

Reciprocating wetland system consists of 2 plain concrete lined cells (Table 1).Each cell has a square surface 18*18 m filled with 0.9 m rounded shape gravel divided into 3 layers; each layer is 0.3 m height. Gravel media size of the 3 layers from top to bottom is 6-15, 15-25, and 25 – 50 mm respectively. Primary treated water enters cell 1, (C1) through pipe inlet supplied with a V notch weir to adopt the flow rate on 1.16 l/sec (100 m^3/day). The system is equipped with automatic empting/filling pumps with water level sensors to adopt water levels in C1 and cell 2, (C2) (figure 1).

Table 1- Design parameters for pilot RFCW

Parameter	Units	Value
Flow rate	m^3/day	100
Hydraulic loading rate	m/d	0.154
Detention time	days	--- [a]
Operating depth	m	0.9
Volume of water	m^3	2*100
Surface area	m^2	2*324
Length	m	18
Width	m	18
Bottom slope	%	0
Freeboard	m	1

[a] Detention time value is not theoretically mentioned or practically measured

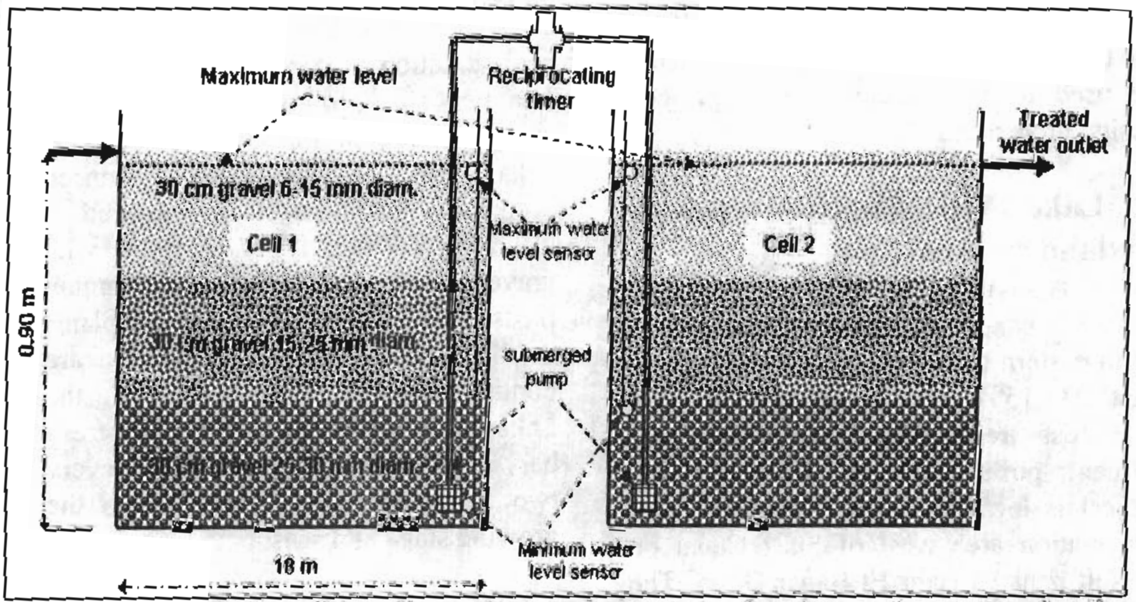

Figure (1) Sketch describing dimensions and elements of reciprocating wetland cells

2.2 Operation and water treatment performance

Water samples were collected at the intake and at the outlet of the pilot RFCW, since the influent water was the primary treated water of Bahr Al Baqar Drain through a 2 days sedimentation pond. Collected water samples were analyzed at the central laboratories of the National Water Research Center to determine TSS, BOD, TP, NH_4-N, NO_3-N, Fecal Coliform, FC and heavy metals such as iron, Fe. All sampling procedures and analysis were carried out according to the U.S. Environmental Protection Agency (USEPA) standard methods. Monitoring continued from September 2003 till March 2005. Dissolved oxygen was measured in the filed using a multi-line prop (WTW®, P4) at C1 entrance and outlets of C1 and C2. Water discharges were measured at the C1 entrance using a V-notch weir which is calibrated and controlled on 1.16 l/sec. Batch effluent water from C2 was measured using ultrasonic currant meter to determine treated water volume. Monitoring continued from September 2003 till March 2005. Pollutant removal efficiency was determined using the following equation (Kadlec and Knight, 1996):

$$RE = \frac{(C_i - C_o)}{C_i}\% \qquad (1)$$

Where: RE = pollutant removal efficiency %, C_i = pollutant concentration at inlet g/m^3, C_o= pollutant concentration at outlet, g/m^3

2.3 Modeling Flow and Pollutant Treatment

Water reciprocating inside RFCW cells enhances the complete mixing processes. The flow may be described as mixed flow since it is definitely not plug flow. Mitsch and Gosselink, (2000) stated that wetland may be conceptually partitioned into a number of equal sized cells, each of which is presumed to be completely mixed and the concentration departing each is equal to the uniform, internal concentration. For N mixing tanks, the relationship between inlet and outlet concentrations could be written as:

$$\frac{C_o - C^*}{C_i - C^*} = \left(1 + \frac{K}{Nq}\right)^{-N} \qquad (2)$$

where: C_i = pollutant concentration at inlet, g/m^3, Co= pollutant concentration at outlet, g/m^3, C^*= background pollutant concentration, g/m^3, K= reaction (removal) rate constant, m/d, q= hydraulic loading rate, m/d, and N= number of equal sized mixing cells.

The removal rate concentrations of any pollutant, (K) may be determined as follows:

$$K = \left\{\left(\frac{C_i - C^*}{C_o - C^*}\right)^{1/N} - 1\right\} * Nq \qquad (3)$$

For each water sampling, measurements and analysis event, pollutant influent and effluent concentrations, C_i and C_o are used in calculating resultant K value. Statistical mean is then calculated for each pollutant. Background concentrations, C^* are calculated based on the actual water quality analysis for different pollutants. The minimum pollutant concentration of pollutant effluent was considered as the background concentrations within the RFCW. There is no reference (in the knowledge of author) of recommended background concentrations for subsurface flow constructed wetlands either in Egypt or in the Middle East semi arid climate.

3. Results and Discussions

3.1 Description of water reciprocation in RFCW

Water Treatment cycle could be described within 48 hours period as shown in figure (2). On time 0 hour, cell C1 has only a thin layer remaining from the previous treatment cycle filling only 5 cm of the 90 cm gravel media in an anaerobic condition after pumping 100 m^3 of semi treated water to C2. About 100 m^3 collected in C2 are treated for 4 hours (from hour 0 to 4) with top aerobic condition and anaerobic condition beneath.

On hour 4, about 66.7 m^3 of C2 partially treated water returns to C1 to be mixed with the new entered 16.7 m^3 of wastewater during the same period raising C1 storage to 83.4 m^3 of a mixture of untreated and partially treated water. Only 33.3 m^3 of C2 water remains in the cell during hour 4 – 8 in aerobic status. On hour 8, C1 total storage reaches 100 m^3 after entering 16.7 m^3 raw water during 4 hours with top aerobic conditions and bottom anaerobic condition. An empting cycle occurs on hour 8 filling C2 with 100 m^3 of C1 water. The C2 filling will push its existent 33.3 m^3 treated water to leave C2 through its outlet. A typical water loop is repeated in the next 8 hours (hour 8: hour 16) producing another 33.3 m^3 of treated water effluent from C2. A similar treatment cycle produces 33.3 m^3 during hours 16 and 24. The daily treated capacity exits from C2 reaches 100 m^3.

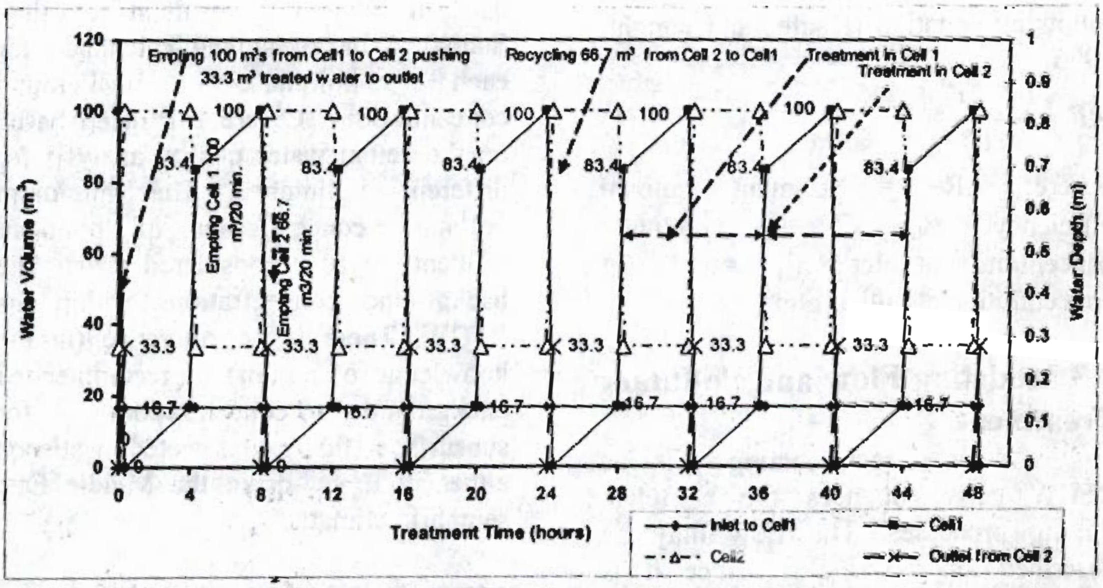

Figure (2) Water volumes and depths in the 2 reciprocating wetland cells during fill and drain treatment cycles

As indicated from Figure (2), treatment processes in C2 is much stable than in C1 due to the continuous influent of untreated wastewater to C1 with a rate of 4.17 m^3/hour. The actual detention time of water could not be exactly estimated in this system since dilution and mixing is continuously repeated between treated and untreated water in C1 and C2. No evidence is found that the effluent 33.3 m^3 from C2 every 8 hours are the same amount of wastewater enters C1, 48 hours earlier. A tracer test may be useful to determine the actual water residence time in such reciprocating system.

3.2 Pollutant treatment through RFCW

Table 2 summarizes the pollutant treatment performance of the RFCW during 2003-2005. For each pollutant, influent and effluent maximum, minimum and mean concentrations are presented. Pollutants removal efficiencies are also presented.

Total Suspended Solids (TSS)

Influent TSS concentrations varied from 15 to 45 mg/l with an average value of 29 mg/l, while it ranged from 4 to 14 mg/l at the outlet of the RFCW cells with an average value of 9 mg/l (Table 2).

Table 2- Removal efficiencies, influent and effluent pollutants concentrations of Pilot RFCW in a comparison with the allowable limits of Law 48 (article 66)

Pollutant	Units	Influent Concentration			Effluent Concentration			Limits of Law 48	Removal Efficiency %
		min.	max.	mean	min.	max.	mean		
TSS	mg/l	14	45	29(1.69)	4	15	9 (0.43)	60	68
BOD	mg/l	15	42	25(1.35)	1	9	4 (0.40)	50	86
NH_4-N	mg/l	2.7	13	6.53(0.55)	0.04	1.9	0.39(0.09)	0.5	93
NO_3-N	mg/l	5.7	35	14.11(1.56)	2	7.2	3.93(0.27)	30	69
TP	mg/l	0.247	1.305	0.69(0.045)	0.119	1.039	0.48(0.044)	1	31
FC	FCU/100 ml	300	24000	3342(1027)	4	850	153 (42)	5000	92
Fe	mg/l	0.123	0.693	0.34(0.028)	0.480	0.310	0.15(0.012)	1	49

n= 33 measured records

Standard error are presented in brackets

Biochemical Oxygen Demand (BOD)

Concentrations of BOD at the RFCW inlet and outlet are shown in Table 2. It also presents the performance of the wetland in removing BOD. Influent BOD varied from 15 to 42 mg/l with an average value of 25 mg/l, while it varied from 1 to 9 mg/l at the outlet of the RFCW cells with an average value of 4 mg/l. The TSS and BOD treatment is much efficient than any conventional secondary wastewater treatment facility (Rashed, 2002).

Nitrate NO3-N and ammonia NH4-N

Influent NO_3-N concentrations varied from 5.7 to 35 mg/l with an average value of 14.11 mg/l, while the effluent ranged from 2 to 7.2 mg/l at the outlet with an average value of 3.39 mg/l. Table 2 describes ammonia (NH_4-N) influent and effluent concentrations of the RFCW and the correspondence removal efficiencies. Influent NH_4-N concentrations varied from 2.7 to 13 mg/l with an average value of 6.53 mg/l, while it ranged from 0.04 to 1.9 mg/l at the outlet with an average value of 0.39 mg/l.

These perfect nitrate and ammonia removals may be explained as effluent NH_4^+ ions in bulk water adsorb to negatively charged biofilms surrounding gravel media. Atmospheric oxygen is drawn down into media pore spaces as the RFCW wetland drains, causing rapid aeration of biofilms (Behrends, 1999, and Austin et. al, 2003) and subsequent nitrification of adsorbed NH_4^+ ions occur. Nitrate in biofilms releases into bulk water in the next flooding cycle. Nitrate is then consumed as a terminal electron acceptor for bacterial respiration of carbon. The water reciprocating helped in nitrate removal by the ammonia sorption/nitrate de-sorption process in flood and drain cycles.

Total Phosphorus (TP)

Influent TP concentration varied from 0.25 to 1.31 mg/l with an average value of 0.69 mg/l, while it varied from 0.12 to 1.04 mg/l at the outlet of the C2 with an average value 0.48 mg/l. The TP treatment efficiency decreased with time during moving from hot summer into the cold winter. The performance of RFCW in removing TP varied from 2% to 81% with an average of 31%. Performance of removing TP decreases with time as the wetland vegetation uptake became slower. Treatment of TP is very sensitive and weak since organic phosphate are not usually available to plants unless transformed to a soluble form. In addition, temperature and water alkalinity have a direct relation with TP release. Biofilm microbes surrounding gravel media are usually able to transform these phosphates into a soluble inorganic form. Phosphate uptake occurs during the growing season, but during the plant senescence in the fall and winter, plant death is followed by its decomposition and TP release (Reinhardt, et al. 2005). Estimates of realistic long term phosphorous removal capacity by plant harvesting is very limited unless plant harvesting will be practiced before the plants senesce, (Kadlec and Knight, 1996). Plant cutting is practiced at regular frequencies which are usually every 2 months in summer and every 3 months in winter.

Iron (Fe)

The concentration of Fe varied from 0.123 to 0.693 mg/l at the intake with average concentration of 0.34 mg/l, while it varied from 0.048 to 0.310 mg/l at the outlet with average concentration of 0.15 mg/l (Table 2). The RFCW cells have a varied performance in the removal of Fe. It ranged from 0% to 86% with an average value of 49%. This performance is due to the sedimentation process and plant uptake. Particulate filtration, sedimentation and plant uptake are the main Fe removal mechanisms which is missing in RFCW due to the fill-drain action in the cells that disturbs the stored particulate Fe.

Fecal Coliform (FC)

The FC influent varied from 300 to 24000 CFU/100ml with an average value of 3341 CFU/100ml, while it ranged from 4 to 850 CFU/100ml at the outlet of the RFCW with average value of 153 CFU/100ml. The performance of FC treatment varied from 55% to 99.9% with an average value of 92%. This high performance is a result of microbial degradation, die-off and predation. Entering intestinal organisms will immediately find themselves in a very hostile environment. Thus die off with time and predation is the primary mechanism in microorganism removal.

Dissolved Oxygen enrichment

Figure 3 presents the dissolved oxygen, DO concentration in the RFCW influent and the effluent from both C1 and C2. The average effluent DO to C1 was 1.29 mg/l while the effluent from C1 during cycling process was 2.48 mg/l. The DO of the treated water effluent from C2 was 7.30 mg/l after 3 cycles of reciprocating as a good indicator comparing with the classical subsurface constructed wetlands. This massive progress in oxygen content was due to air diffusion during the 4 hours aerobic treatment in C2 that produce 1/3 the treatment capacity in 1/3 of the cell gravel depth (Figure 2).

Generally in subsurface treatment wetlands, plants can transport significant amounts of dissolved oxygen to the root zone, thus providing supplemental oxygen for aerobic microbial processes. However, this oxygen is available only for the thin top gravel layer within plants root zone leaving remain media in anaerobic conditions and produces low oxygen content treated water. These boundaries are not existence in the RFCW since there is oxygen pumping to all media layers during the fill-drain cycling, so it is possible to utilize the concept of tide, whereby adjacent cells are alternately drained and filled on a recurrent basis. During the drain cycle, thin water films surrounding the dewatered substrate and attached biofilms are rapidly oxygenated to saturation values.

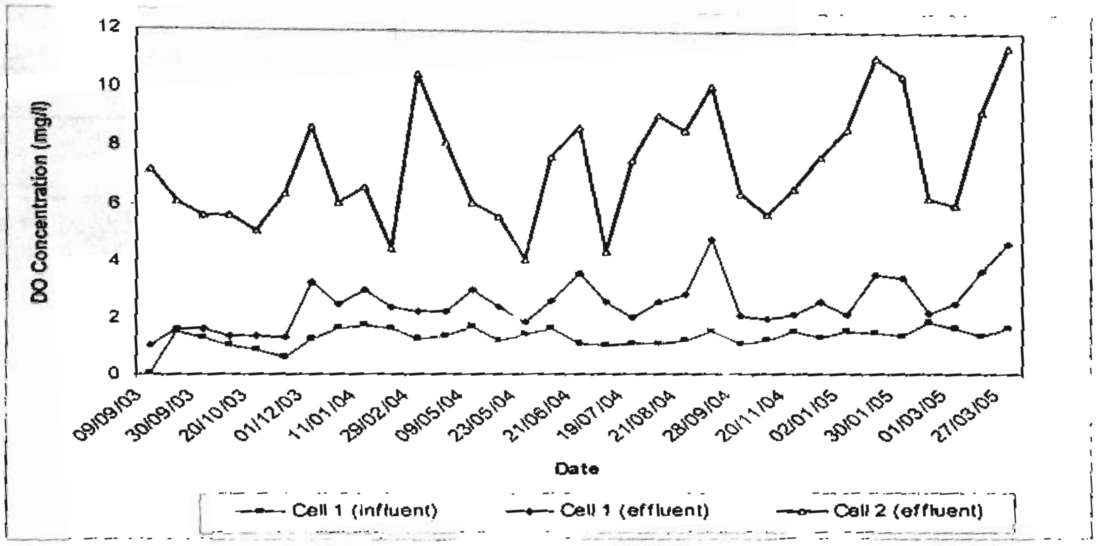

Figure 3. Dissolved oxygen and effluent of RFCW cells and the removal efficiency

Overall performance

The highest efficiency is in removing FC by 98% followed by NH_4-N with an average value equal to 93%. In the middle level of pollutants removal there are BOD (86%), TSS (68%), and NO_3-N (69%). The lower removal efficiencies are 49% for Fe and 31% for TP since those pollutants are mainly attributed to the limited sedimentation and settling processes in RFCW. However the treatment level of these pollutants matches the allowable limits of discharging drainage water into brackish water bodies (Law 48, article 66), (Table 2).

3.3 Estimation of the Pollutant Removal Rate Constant (K)

The first-order, area-based removal constant rate, K is one of the governing factors of pollutant treatment through constructed wetlands. Table (3) presents the estimated pollutants removal rate constants based on collected and measured pollutant concentrations assuming a complete mixing tank reactor in 2 cells (C1 and C2) applying Equation (3).

These K values were compared with the K values referenced in Kadlec and Knight, (1996) which obtained from different climate and physical conditions. There are no similar RFCW in arid or semi arid climate to use its K data in the comparative study. The K values of RFCW are greater than literature K values except for TSS. The huge NO_3-N and NH_4-N removal in RFCW are quite clear when comparing K values with those ordinary subsurface wetlands. A portion of the K values improvements in Lake Manzala RFCW case may be attributed to its hot climate comparing with the climate of referenced K locations. The TSS treatment mechanisms depends mainly on settlement and low water velocity which is not existent in RFCW as the fill-drain process are carried out every 4 hours. The removal of other pollutants is better in RFCW due to the aerobic-anaerobic treatment processes that take place during reciprocating cycles. Pollutant background concentrations presented in Table (3) may be used in similar RFCW design, operation, or performance evaluation.

Table (3) Mean Pollutant concentrations, Background constants, and Removal rate constants

Pollutant	C_i	C_o	C*	K	Ref. K*
	mg/l	*mg/l*	*mg/l*	*m/day*	*m/day*
BOD	24.79	3.52	1	0.662 (0.06)	0.49
TSS	29.39	8.91	4	0.430 (0.03)	2.740
NH_4	6.53	0.39	0.04	1.220 (0.10)	0.093
NO_3	14.11	3.93	2	0.625 (0.15)	0.137
TP	0.69	0.48	0.119	0.160 (0.05)	0.033
Fe	0.34	0.15	0.048	0.291 (0.06)	-----
FC	3342	153	4	1.492 (0.25)	0.260

$Q= 100\ m^3/day$, $q=0.154$ m/day *Standard error are presented in brackets*

**Typical subsurface constructed wetlands since no data available for reciprocating wetlands (Kadlec and Knight, 1996)*

4. Conclusions

- Pilot RFCW with sequential aerobic-anaerobic environments can provide excellent treatment with respect to nitrification-denitrification, heavy metals removal, biological phosphorus removal, and remediation of toxic compounds requiring oxidation and subsequent reduction.
- The treatments of BOD, TSS, NH_4, NO_3, TP, Fe, and FC in effluent water samples are compatible with the law of discharging drainage water in water bodies (Law 48, 1982, article 62 of MWRI).
- The removal rate constant (K) could be determined from the field results using mixed flow model based on pollutant influent, effluent concentrations and its specific background values. These K values may be used in designing RFCW in the arid/semiarid climates.
- Reciprocating treatment wetlands have advantages over constant flow constructed wetlands due to providing cyclical and uniform distribution of nutrient overloaded water to the substrate biofilms during the fill and drain cycles. During the fill cycle, anoxic and/or anaerobic water fills the void spaces between the substrate, and the biofilms are inundated in oxygen-deficient water. Under these conditions, denitrification, phosphorus reduction, and methanogenesis occur. Nitrate reduction provides excellent metals removal, generation of additional alkalinity, and buffering of pH.

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