Impact of Arid Climatic Conditions on Engineered Wetland Design and Performance: Egypt Case Study

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Abstract
Egypt's water resources are becoming increasingly polluted due to the excessive use of these limited resources. The pollution of the Nile River System (main stream Nile, drains, and canals) has increased in the past few decades and caused serious deteriorations of the irrigation and drainage water quality, especially in the Nile Delta. Engineered wetland wastewater treatment technology is gaining wide recognition in Egypt as a prominent and efficient low-cost treatment technology. There are several plans to replicate this new technology in the field of wastewater treatment on the national level. This research aims at investigating and exploring different design and performance aspects of the engineered wetland wastewater treatment. PREWet model is used to simulate the performance of Lake Manzala Engineered Wetland (LMEW) and to carry out a sensitivity analysis (SA) of the critical design factors. The results of this research provide the decision maker with the optimum range of the design factors, which contribute to an efficient wastewater treatment considering the local climatic conditions.
PREWet Model has been calibrated and validated on LMEW for assessing the removal efficiency of four parameters; Total Coliform (TC), Total Nitrogen (TN), Total Suspended Solids (TSS), and Biological Oxygen Demand (BOD). Three design factors have been considered, wetland surface area, average flow discharge and detention time taking into consideration temperature variation between the summer and winter seasons.
Wastewater treatment using the engineered wetland in the Nile Delta is a promising treatment technology, which fits the Egyptian economic and climatic context. This research shows that decreasing the wetland surface area and increasing the average flow rate did not affect its removal efficiency for almost all pollutants. This supports the conclusion that replication of this innovative technology on small scale would achieve a comparable performance to the large scale wetlands such as LMEW. The study also, showed that the effect of temperature variation was pronounced in the increase of the removal efficiency in the summer season, relative to the winter season, for all studied parameters.

Key Words: Engineered Wetlands, Temperature Variation, Removal Efficiency, Sensitivity Analysis

1. BACKGROUND

Egypt's limited water resources are becoming increasingly polluted due to the excessive use of these resources. The pollution of the Nile River System (main stream Nile, drains and canals) has increased in the past few decades and caused serious deteriorations of the irrigation and drainage water quality, especially in the Nile Delta. According to the Egyptian National Water Resources Plan (NWRP) of 2004, the Nile River, from Aswan to the Delta Barrages, receives wastewater discharge from 124 polluting point sources, of which 67 are agricultural drains. Moreover, water quality analysis of drains taken at their confluence to the Nile indicates that out of 43 drains, only 10 drains comply with the standards set by Law 48/1982, while the remainder of the drains exceed the consent standards in one or more of the parameters.

The deterioration of the irrigation and drainage water quality was a result of the absence of wastewater treatment plants for both domestic and industrial effluents. They typically discharged directly or indirectly to agricultural drains, carrying the pollution load resulting from heavy application of the agricultures fertilizers (Abdel Gawad et. al., 2005). These practices create great pressures on the limited water resources, which is intensified by the accelerating urbanization in different places in Egypt. Therefore, the management of the resulting municipal and industrial effluents is becoming a major public health and environmental concern. Increasing environmental awareness and pressing need for sustainable water resources to meet the projected population increase lead to large capital expenditures to treat this water so that it is useful as a supply for non-drinking purposes; i.e. Industrial, commercial, and agricultural activities.

Conventional wastewater management systems in Egypt display an array of problems, such as public health, environmental, and management problems. Technical, financial, institutional, economic, and social constraints are restraining the development of effective wastewater management systems. Recognizing their health and environmental hazards, a number of research initiatives were and/or being carried out to develop innovative waste management practices. These research projects focused on developing low-cost management practices, which in turn achieve the main objectives of these projects, i.e. sustainability. Therefore, low-cost treatment technologies, such as engineered wetlands, gained wide recognition due to their low-cost, low-maintenance, simple and reliable operation, and high removal efficiency characteristics (Economopoulou and Tsihrintzis, 2003). Many programs started in the mid 1980s using the engineered wetlands as a low-cost alternative for wastewater treatment, such as the Tennessee Valley Authority (TVA) (US EPA, 2000). These systems were used for a variety of waste streams (municipal wastewater, acid mine drainage, agricultural wastes and runoff, etc.). The size of the engineered wetlands ranged from on-site single family units to larger municipal systems, which reflects the wide recognition of the advantages of this new treatment approach.

2. ENGINEERED WETLAND

Engineered wetland treatment systems are engineered systems that utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater. They are biological filters that are very effective in removing Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), organic nitrogen, and nitrates (US EPA, 1988).

The design of the engineered wetlands takes advantage of the same processes, which occur in natural wetlands, but under controlled environment. Typically, an engineered wetland is a series of rectangular plots filled with soil or gravel and lined to prevent waste form infiltrating to the groundwater. The plants grown in these plots, not only offer a root mass for filtration, but also provide oxygen and carbon for wastewater treatment. The roots offer attachment sites for microbes, which consume the available oxygen in the process of breaking down pollutants.

Engineered wetlands are classified into two types; (1) Free water surface wetland (FWS) and (2) Subsurface flow wetland (SFS). FWS consists of a shallow basin, soil or other medium to support the roots of vegetation, and a water control structure that maintains a shallow depth of water. The water surface FWS is above the substrata. SFS, on the other hand, consists of a sealed basin with porous substrata of rock or gravel. The water level is designed to remain below the top of the substrata. SFS wetlands are best suited to wastewaters with relatively low solids concentrations and under relatively uniform flow conditions. Therefore, SFS wetlands have been frequently used to reduce the Biological Oxygen Demand (BOD) from domestic wastewater. There are several models used to design engineered wetlands or to calculate the pollutant effluent concentrations. The general model (US EPA, 1988) describing the treatment processes and the effluent pollutants concentration is as follows;

$$\frac{C_e}{C_i} = \exp\left[\left(K_{20}(\theta)^{(T-20)}\right) * \left(\frac{L\ W\ n\ D}{Q}\right)\right] \quad (1)$$

Where,

C_e = Effluent BOD concentration, mg/l
C_i = Influent BOD concentration, mg/l
K_{20} = The rate constant at 20°C
θ = Temperature factor, dimensionless
T = Temperature of liquid in the system, °C
L = Wetland basin length, m
W = Wetland basin width, m
D = Water depth, m
Q = Average flow rate m^3/d

n = Fraction of cross sectional area not occupied by plants (Porosity), dimensionless

The effluent concentration, i.e. treatment process, in the engineered wetland depends on the cell area parameters; length (L) and width (W)), Temperature (T), and average flow rate (Q) as explained by Equation 1. However, the relative contribution of temperature on the removal of each studied parameters is further investigated in the following sections.

3. TEMPERATURE IMPACT ON ENGINEERED WETLANDS PERFORMANCE

Temperature variations affect the treatment performance of engineered wetlands, where it affects both the physical and biological processes in the cell system. The biological reactions responsible for BOD removal, nitrification, and de-nitrification are temperature dependent.

Several biogeochemical processes regulate the removal of nutrients in wetlands, which are affected by temperature, thus influencing the overall treatment efficiency. Kadlec and Reddy (2000) studied the temperature dependence of many individual wetland processes and wetland removal of contaminants in surface flow wetland. They concluded that microbial mediated reactions are affected by temperature; the treatment response was much greater to changes at the lower end of the temperature scale (<15ºC) than at the optimal range (20 to 35 ºC). Furthermore they observed that the processes regulating organic matter decomposition were affected by temperature and then all the nitrogen cycling reactions. Kadlec et al. (2006) pointed out three reasons for the importance of water temperature in treatment wetlands: (1) temperature modifies the rates of several key biological processes, (2) temperature is sometimes a regulated water quality parameter, and (3) water temperature is a prime determinant of evaporative water loss processes.

- **Total Coliform Bacteria (TCB)**

A first-order decay rate is usually used to describe the net loss of TCB, because of death, predation, and settling. The death rate is affected by water temperature, solar radiation in the water column, and salinity, but only the effect of temperature is considered in this research. The effect of temperature is taken into account as explained by the following equation (Thomann and Mueller 1987):

$$K_T = K_{20}(\theta)^{(T-20)} \qquad \text{(2)}$$

Where, K_T = Temperature dependent removal rate constant at T, d^{-1}

- **Biochemical Oxygen Demand (BOD)**

BOD removal occurs through water column microbial degradation, settling of the particulate fraction of BOD from the water column to the sediments, and adsorption to benthic biota. These removal pathways are combined into an overall first-order removal rate, K, (day^{-1}) (Equation2). Observed K, values vary by nearly two orders of magnitude (i.e., from about 0.08 to 5.0) and depend on several factors including the nature of the BOD source. The recommended value for the temperature correction factor for BOD is 1.047 (Thomann and Mueller 1987 and Bowie et al, 1985).

- **Nitrogen removal (N)**

The transformation and removal of nitrogen in wetland involves a complex set of processes and reactions (Lisette et al., 2004). The mechanisms involved in the removal of nitrogen from wastewater depend on the form that is present; nitrate, ammonia, or organic nitrogen. Important processes that transform the basic forms of N in soils and sediments are mineralization, nitrification, denitrification, nitrogen (N_2) fixation, and assimilation (plant and bacterial uptake).

Mineralization is the biological transformation of organic N to $NH4^+$ that occurs during organic matter degradation (Gambrell and Patrick, 1978). The rate of mineralization doubles with a temperature increase of 10 °C, while the optimum temperature of mineralization was found to be between 40 to 60 °C (Reddy and Patrick, 1984), a rare field condition. ***Nitrification*** is the biological oxidation of ammonium-N to nitrate-N with nitrite-N (NO_2^-) as an intermediate product. ***Denitrification*** is the biological reduction of NO_3-N to gaseous N forms such as molecular N_2, NO, NO_2 and N_2O (Novotny and Olem, 1994). Temperature is one of several factors are known to influence the rate of denitrification. Denitrification rate has been shown to increase with temperature, where a 1.5 to 2.0 fold increase will occur with a 10 °C rise in temperature (Reddy and Patrick, 1984).

N content is sometimes referred to as either Total Kjeldahl N (TKN) or total N (TN). Total N is a measure of all organic and inorganic forms and is essentially equal to the sum of TKN, NO_3^- and NO_2^-N (Kadlec and Knight, 1996). The monthly total Nitrogen was calculated, in this research, using the result of laboratory analysis, which includes Nitrate (NO_3) and Ammonia (NH_4) using the following equation;

$$TN = (NO_3/4.42) + (NH_4/1.28) \quad (3)$$

4. RESEARCH OBJECTIVES

Engineered wetland treatment is gaining wide recognition in Egypt as a prominent and efficient low-coast treatment technology. Among these advantages are; high treatment efficiency (especially biological load treatment), relatively low capital investment (provided land availability), easy operation and maintenance and suitability for hot climates. There is a need to gain insights into the technical aspects of their design and performance to provide the decision maker with the sensitive design factors, which contribute to an efficient wastewater treatment. From this point of view, this research focuses on studying the impact of temperature on the design, operation and performance of engineered wetland in the Egyptian climatic conditions.

This research was carried out in the Lake Manzala Engineered Wetland (LMEW) which was financed by the Global Environmental Facility (GEF) through the Cairo Office of the United Nations Development Program (UNDP). The National Executive Agency was the Egyptian Environmental Affairs Agency (EEAA) of the Ministry of State of Environmental Affairs (MSEA). The construction of LMEW was completed in 2004 and transferred to the National Water Research Centre (NWRC) under the Ministry of Water Resources and Irrigation (MWRI) in 2007.

5. STUDY AREA DESCRIPTION

5.1 Lake Manzala Engineered Wetland (LMEW)

Lake Manzala Engineered Wetland (LMEW) is located in the north eastern edge of the Nile Delta, 170 km away from Cairo and 15 km from the city of Port Said as shown in Fig. 1. LMEW is located at the tail end of Bahr El Baqar drain, which constitutes about 25 % of the water inflow to Lake Manzala and 60% of the nutrient load. It carries a mixture of treated and untreated wastewater originating from Cairo and contributing much to the deteriorating water quality of Lake Manzala. LMEW treats 0.8 % of the water load in Bahr El Baqr drain (NIRAS, 2007).

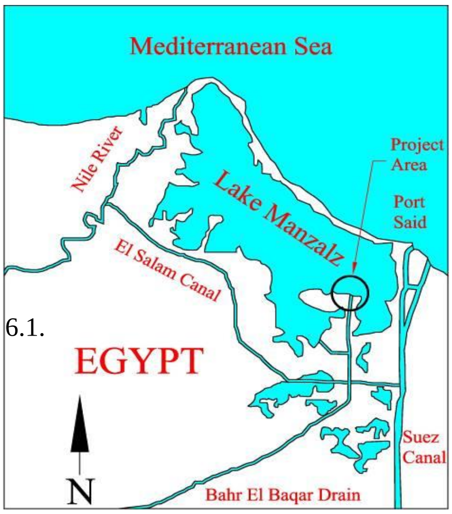

Figure 1: Location of LMEW

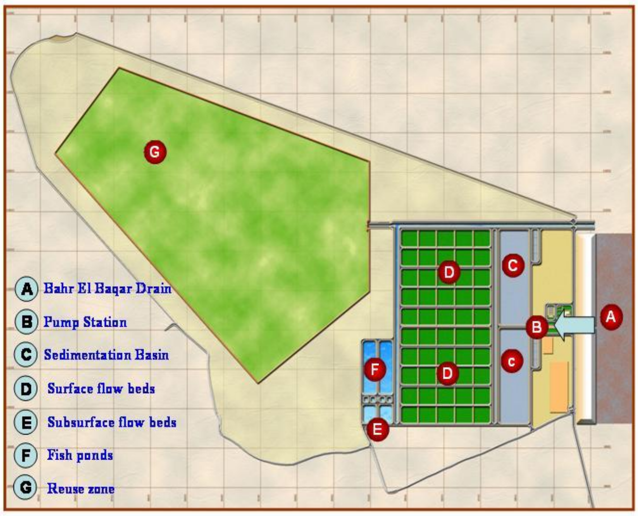

Figure 2: Major Components of LMEW

5.2 Components of LMEW

The total area allocated for LMEW is almost 245 Acres (about 100 hectare), consisting of five major components as shown in Figure 2; **(1) Intake Channel and Pumping Station:** The intake channel selectively withdraws water from the upper half of the Bahr El Baqar Drain (A). Two 12,500 m^3/day screw pumps lift the intake water into the sediment basins. The station is operated by means of two diesel generators (B). **(2) Sediment Basins:** Two 25,000 m^3 sediment basins (C) provide primary treatment. **(3) Surface Flow Treatment Cells:** Effluent from the sedimentation basins flows to ten surface flow cells through distribution canal (D). **(4) Reciprocating Subsurface Flow Treatment Cells:** Two reciprocating subsurface flow cells (E). The cells have a design capacity of 500 m^3/day and treat effluent from the sediment basins. Two pumping stations are used to reciprocate water between the two cells. **(5) Fishery Facility and Fish Farm:** Inflow water to the fishery facility is drawn from the reciprocating treatment system. The fishery includes four hatchery ponds followed by two fingerling production ponds (F). A total area of 60 Acres of fish farm divided into 24 separate ponds of 2.5 Acres (G). **Hydraulic Management of LMEW:** The daily hydraulic load of 25,000 m^3 is pumped from the intake in Bahr El Baqar Drain to the Sedimentation Basin. The flow from the sedimentation basins is distributed into reciprocating subsurface flow cells (500 m^3/day), and with the remaining volume of 24,500 cubic meters to the surface flow cells.

5.3 Climatic Conditions

The study area has a variable climate that is influenced by many local factors. Most of the climatic trends are related to its distance from the coast. Inland areas are characterized by lower annual rainfall, usually below 50 mm, much greater diurnal temperature variation, a predominance of north and northeast wind directions and lower mean wind speeds, as compared to the coast.

The temperature of the study area was collected from the nearest meteorological station at Dakahlia weather station which has is located at (Lat. 31º 03’, Long. 31º 23’, Elev. 7.0 m above mean sea level). The collected data was for the period from August 1997 to March 2010. Simple statistical analysis was carried out to study the variation of the temperature along the study period.

The analysis showed that the daily mean average temperatures over the study area are relatively uniform; ranging from 20º Cº to 22º C. The daily maximum and minimum average temperatures vary over the area, depending on the distance from the coast. The difference between maximum and minimum temperatures varies between less than 5º C and 15º C. Peak average temperatures from 27º C to 28º C are reached in August, while the lowest mean daily temperatures of 14º C to 16º C are obtained in January. The highest absolute recorded temperature is 46º C, occurring in June, while the lowest absolute temperatures of 0º C to 2º C were recorded in February.

5.4 Methodology

Exploring the performance of different engineered wetland designs can be achieved through experimental fields. However, time and financial constraints limit the utility of large scale experimental fields. Mathematical models simulating the engineered wetland performance present reasonable compromise to overcome these constraints. Therefore, PREWet simulation model is used in this research article as an experimental tool to explore the design, operation and performance of the LMEW.

5.5 PREWet Model

PREWet model version (2.5) is a mathematical computer based model for the assessment of free water surface wetland function. This model developed by the U.S. Army Engineer Research and devolvement center in May 2005. The model inputs require the system properties such as length, width, depth, area, volume, and discharge, detention time and water temperature. In addition, the model requires selecting the constituents to be modeled, which are the studied parameters TSS, BOS, TN, and TC and their influent concentration.

The model outputs are three categories; the removal rates, the removal efficiency (RE), and the outflow concentrations of each constituent. The RE depends on the wetland detention time and the removal rate, K (day-1), for the constituent. The removal rates depend on a number of processes, such as microbial metabolism, adsorption, volatilization, denitrification, settling, etc., and ambient conditions, such as water temperature. (Dortch and Gerald, 1995)**.**

5.6 Monitoring program

Investigating the concentration profiles of different pollutants along 10 free water surface cells through the wetland was carried out. An intensive monitoring program was carried out in 2005 to study the performance of the LMEW, where the measurements were carried out twice per month. The monitoring program continued up to date as a routine work of the Drainage Research Institute (DRI) considering the LMEW as a pioneer low-cost biological treatment station in the Middle East.

Five points of interest along the water paths are considered; (1)The intake from Bahr El Baqar drain, (2) the outlet of sedimentation pond, (3) the Inlet of rapid flow free water surface wetland, (4) the outlet of rapid flow free water surface wetland, (5) finally the outlet of the whole system to Bahr El Baqar drain. The selected pollutants for this study are; Total Coliform (FC), Biological Oxygen Demand (BOD), Total Nitrogen (TN) and Total suspended solid (TSS), where the data of 2005 was used for model calibration and for 2008 was used for model verification.

6. RESULTS

6.1 PREWet Calibration and validation

BOD, TC and TN were selected for model calibration and validation. The concentrations of the studied pollutants at the inlet and outlet of LMEW in year 2005 were used for the model calibration where the data was collected to evaluate the performance of LMEW after the construction completion. Model validation was carried out using data of year 2008 (4 years after the completion of the construction) to ensure that the stability of the operations of the LMEW and the treatment process of the different pollutants reached to the equilibrium.

Model calibration focused mainly on the adjustment of the temperature factor for the different pollutants to study the impact of the climatic condition of LMEW area in winter and summer seasons on the removal processes. Also, the comparison between the predicted outflow concentration for the different pollutants using the PREWet model and the actual field measurements of the outflow concentrations using graphical and quantitative (error percentage) methods were carried out.

6.2 Error percentage method

The error percentage between the actual measured outlet concentration of a pollutant (C_m) and its simulated outlet concentration (C_s) was carried out as follow;

$$Diff = C_s - C_m$$

$$Error\% = \frac{\left(\dfrac{\sqrt{\sum (Diff.)^2}}{n}\right)}{\overline{C}_m} \quad \text{……(4)}$$

Where, $\overline{C}_m$ is the average measured outlet concentration of the corresponding pollutant.

6.3 Biological Oxygen Demand (BOD)

Calibration

The model calibration for BOD removal was carried out using the monthly average temperature and the monthly BOD concentrations at the inlet and outlet of LMEW for the year 2005. The default temperature correction factor for BOD removal process (1.047 at 20^o C) was used. The graphical and statistical comparison between the simulated BOD outlet concentration and field measurements showed that there are some differences, where the percent error was equal to 9.9%.

The BOD temperature correction factor was tested using different values such as; 1.047 (default), 1.025, 1.0, 0.95 and 0.9 for summer months where temperature is higher than 20^o C (varied between 21.4^o C and 30.0^o C) and for winter months where temperature is less than 20^o C (varied between 13.7^o and 19.5^o C).

The selected values of the temperature correction values were used to simulate BOD outflow concentrations. The relation between the temperature correction factor and the error percentage of BOD is shown in Figure 3. Decreasing the temperature correction factor resulted in a corresponding decrease in the error percentage.

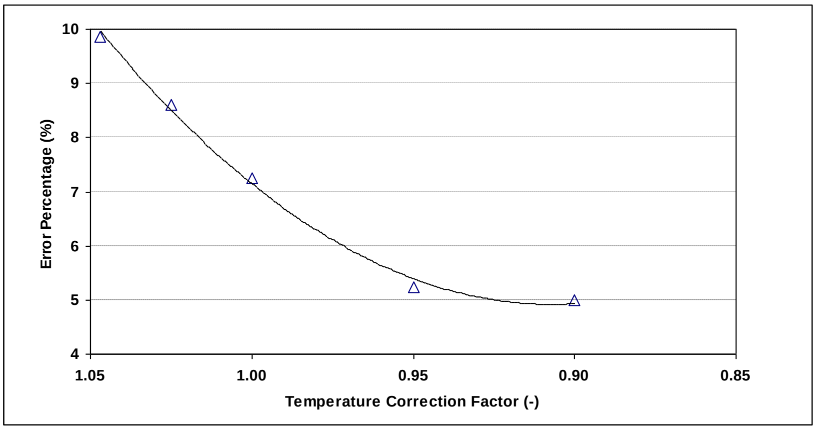

Figure 3: Relationship between the Temperature Correction Factors and Error Percentage between the Simulated and Field Outlet BOD Concentrations.

The model calibration for BOD removal showed that for winter months, where temperature is usually below 20^{o} C, the best value for the temperature correction factor is the default, which is 1.047. In summer months, the optimum temperature correction factor is 0.95.

Validation

Field measurements of the BOD concentrations at the inlet and outlet of LMEW and monthly average temperature for year 2008 were used for the validation process. The adjusted temperature correction factor used for the model calibration (1.047 for temp less than 20 and 0.95 for temp higher than 20^{o}C) were used to simulate the outlet BOD concentration. The graphical comparison between the measured and simulated BOD outflow concentrations as shown in Figure 4 showed a good agreement, which correspond an error percentage less than 4.9%.

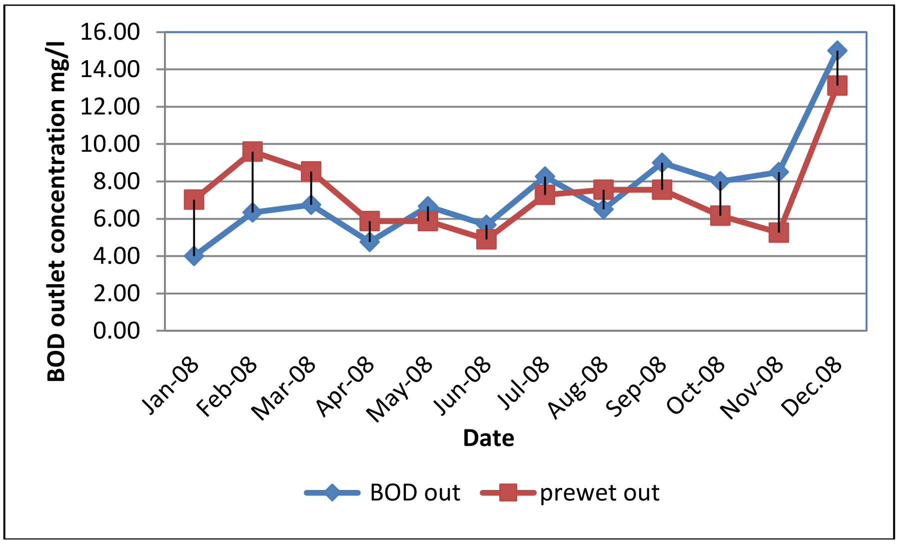

Figure 4: Comparison between the simulated and field BOD outlet Concentration (Verification)

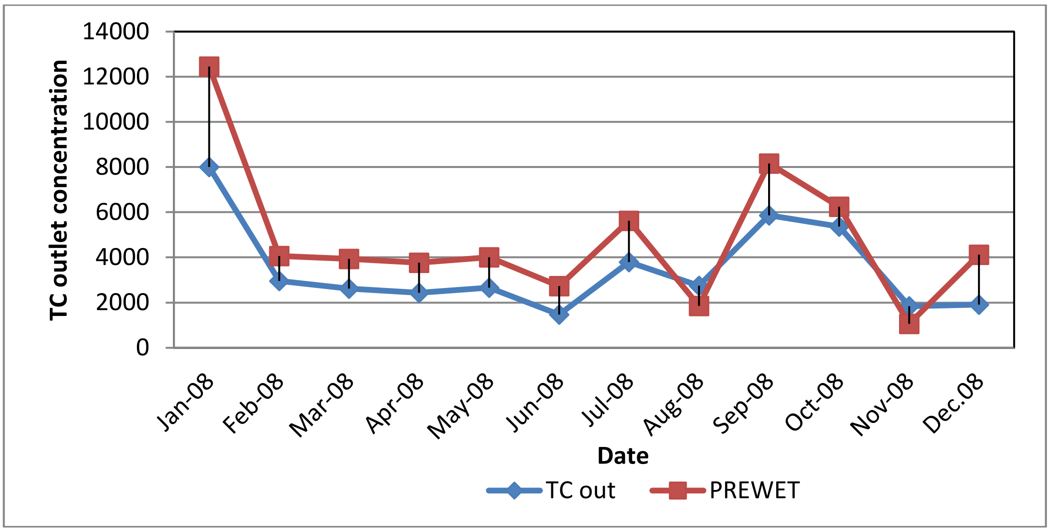

Figure 5: Comparison between the simulated and field TC outlet Concentration (Verification)

6.4 Total Coliform (TC)

Calibration

The model calibration for TC removal is based on the field inlet and outlet TC concentrations and the monthly average temperature of year 2005. The default temperature correction factor (1.07 at 20º C) was used for the TC removal process. The calibration showed that there is a considerable difference between the simulated TC outlet concentration and field measurements, where the error percentage reached 18.9 %.

Different values of the temperature correction factors higher and lower than the default value (1.07) were used to consider the temperature impact on TC removal processes. The analysis showed that the best temperature correction factor for TC removal in the winter season is 0.9. In summer season, the temperature correction factor is 1.17. Both values resulted in a minimal difference between the field and the simulated TC concentrations.

Validation

The field measurements of the TC concentrations at the inlet and outlet of LMEW and monthly average temperature for year 2008 were used For PREWet model validation. The adjusted temperature correction factor resulted from the model calibration (0.9 for the winter season and 1.17 for the summer season) were used to simulate the outlet TC concentrations. Figure 5 shows a good agreement between the measured and simulated TC outflow concentrations. The corresponding percentage error did not exceed 5.2%.

6.5 Total Nitrogen (TN)

Calibration

Similarly, model calibration for the TN removal was based on the results of 2005. Two model parameters, which reflect the impact of temperature on the TN removal processes, were considered; (i) temperature correction factor, and (ii) TN removal rate (vtn) on area basis (m/day) at 20º C. The default temperature correction factor for TN was 1.045 at 20º C and vtn was 0.05 m/day at 20º C. The percentage error did not exceed 11.6%, which is relatively high. Different temperature correction factors and vtn values (higher and lower than the default values) were used to consider the temperature impact on wetland removal processes of the TN. The analysis showed that the best value of the TN removal rate (vtn) for temperature less than 20º C is 0.09 m/day and the temperature correction factor is 0.8. In the summer season (temperature higher than 20º C) the vtn is 0.09 m/day and temperature correction factor is 1.1.

Validation

Similar to the aforementioned parameters, model validation used the TN concentrations for the year 2008 together with the same adjusted temperature correction factor and TN removal rate was carried out.

Figure 6 showed that the percentage error did not exceed 4.9%, reflecting better removal efficiency for the TN.

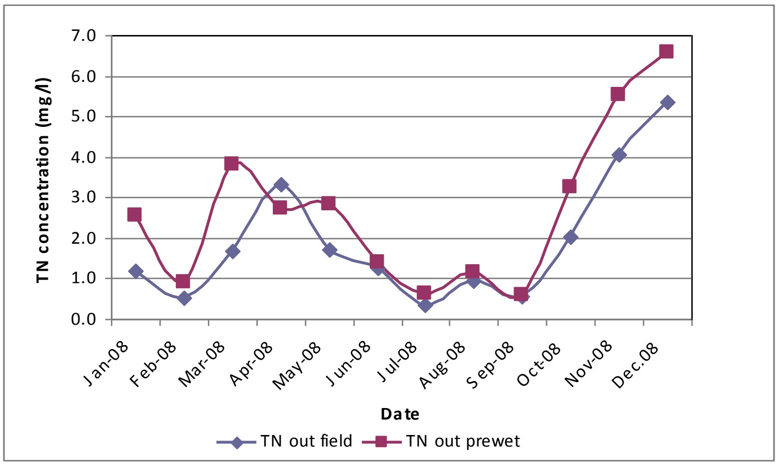

Figure 6: Comparison between the simulated and field TN outlet Concentration (Verification)

6.6 Model Sensitivity Analysis (SA)

Proper hydrological design of engineered wetlands provides the suitable conditions for the chemical and biological processes affecting wastewater treatment. Hydrological conditions can directly modify or change physical and chemical properties, such as soil salinity, pH, sediment properties, substrate anoxia, and nutrient availability, consequently the efficiency of the treatment process. Therefore, sensitivity analysis (SA) is used to determine the effect of main design facors affecting the hydrological conditions in wetland cells. SA was used as an important model validation and assessment tool, which assisted in gaining insights into the constructed wetland performance and the identification of the key hydrological drivers of the system. In general, outcomes of SA are supported by the findings reported in the literature and expert understanding. Therefore, hydrologic detention time, average flow rate, and wetland surface area were selected as the main design parameters for carrying out the SA. Improvements in the removal efficiency of BOD, TSS, TC, and TN are the used SA criteria.

Engineered wetland cells show thermal structure development similar to shallow lakes (Chapman, 1996), i.e. polymictic behavior, which is subject to frequent periods of circulation and mixing leading to a uniform vertical temperature distribution. Thus, design parameter as hydrologic detention time affects the distribution of the temperature on the surface and down to the bottom of the cell, where increasing the detention time provides the suitable conditions for homogeneous distributions of the temperature all over the cell. The same principle applies to the average flow rate which affects the mixing efficiency and consequently the upstream and downstream temperature distributions, (Chapman, 1996). Horizontal temperature distribution, on the other hand, depends on the surface area exposed to the climatic conditions, especially direct sunshine, which is accompanied with rapid drop from the initial thermal conditions to the balance point (Kadlec and Knight, 1996). The observation of Kadlec and Reddy (2000) on the differences in the treatment response between higher and lower temperature ranges was the rational for carrying out the SA for each season to isolate the seasonal temperature effect from the studied design factor.

Detention Time

The choice of the design factors values was based on the literature and the economic limitations, which impose constraints on the aerial expansion of the treatment cells. As a result, values of the hydrologic detention time ranged from 1 day to 2 days, where increase in detention time would result in a consequent increase in the aerial expansion of the treatment cells to accommodate the design treatment volume. Tables 2a and 1b show summary of the SA for the hydrologic detention time in both summer and winter seasons.

Table 2a: Sensitivity Analysis Final Results for Detention Time (Winter of 2008)

		Detention Time (days)			
		1.16(literature)	**1**	**1.5**	**2 (design)**
Removal Efficiency (%)	**BOD**	88.0	83.9	93.6	97.4
	TSS	72.1	66.7	80.8	88.9
	TC	34.5	30.6	42.2	51.8
	TN	4.6	3.9	5.8	7.7

Table 2b: Sensitivity Analysis Final Results for Detention Time (Summer of 2008)

		Detention Time (days)			
		1.16(literature)	**1**	**1.5**	**2 (design)**
Removal Efficiency (%)	**BOD**	98.7	97.6	99.6	99.9
	TSS	72.1	66.7	80.0	88.9
	TC	99.1	98.3	99.8	99.9
	TN	8.8	7.6	11.2	14.6

Increasing detention time to 2 days resulted in a corresponding increase in the removal efficiencies for BOD, TSS, TC and TN. The highest increases, in winter, are by 17.3% and 16.8% for TC and TSS, respectively. In summer, the removal efficiencies are increased by 65.9% and 23.3% for TN and TSS, respectively. The relative highest increase in the removal efficiency is in the TN, in both winter and summer, where doubling the retention time produces a corresponding effect in the removal efficiency. This supports the reported sensitivity of the nitrogen cycle to the temperature effect, as a direct result of increasing the retention time in the treatment cells.

Surface Area

Wetland surface area values were limited to the design surface area of 100,000 m^2 and down to 4000 m^2. Similarly, Tables 3a and b show the SA for wetland surface area in both summer and winter seasons.

Table 3a: Sensitivity Analysis Final Results- Wetland Surface Area (Winter of 2008)

		Surface Area (m^2)			
		100000 (design)	**80000**	**60000**	**40000**
Removal Efficiency (%)	**BOD**	88.0	88.0	88.0	88.0
	TSS	72.1	64.0	53.5	40.0
	TC	34.5	34.5	34.5	34.5
	TN	4.6	4.6	4.6	4.6

Table 3b: Sensitivity Analysis Final Results- Wetland Surface Area (Summer of 2008)

		Surface Area (m^2)			
		100000 (design)	**80000**	**60000**	**40000**
Removal Efficiency (%)	**BOD**	98.7	98.7	98.7	98.7
	TSS	72.1	64.0	53.5	40.0
	TC	99.1	99.1	99.1	99.1
	TN	8.8	8.8	8.8	8.8

Reducing the surface area did not have any effect on the removal efficiency of the studied parameters as the hydrologic detention time, in both summer and winter. The only exception was in the TSS removal efficiency, where area reduction resulted in a corresponding reduction in the removal efficiency. However, this reduction did not result in an equivalent reduction in the removal efficiency, i.e. a 2.5 times reduction in surface area resulted only in 1.8 times reduction in the removal efficiency in winter. The removal efficiencies of the BOD, TC and TN were not affected by the area surface reduction. Due to temperature difference effect, the summer removal efficiencies for BOD, TC, and TN were higher than the corresponding values in winter.

Flow Rate

In the case of the average flow rate, the range tested was from 0.25 of the design flow up to 2 times the design flow. Similarly, Tables 4a and b show the SA for the wetland average flow rate in both summer and winter seasons.

Table 4a: Sensitivity Analysis Final Results- Average flow Rate (Winter of 2008)

		Average Flow Rate (m^3/Sec)							
		0.25 Q	**0.50 Q**	**0.75 Q**	**1.00 Q**	**1.25 Q**	**1.50 Q**	**1.75 Q**	**2.00 Q**
Removal Efficiency (%)	**BOD**	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0
	TSS	99.0	92.2	81.8	72.8	64.0	57.3	51.8	47.2
	TC	34.5	34.5	34.5	34.5	34.5	34.5	34.5	34.5
	TN	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6

Table 4b: Sensitivity Analysis Final Results- Average flow Rate (Summer of 2008)

		Average Flow Rate (m^3/Sec)							
		0.25 Q	**0.50 Q**	**0.75 Q**	**1.00 Q**	**1.25 Q**	**1.50 Q**	**1.75 Q**	**2.00 Q**
Removal Efficiency (%)	**BOD**	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.7
	TSS	99.4	92.2	81.8	72.1	64.0	57.9	51.8	47.2
	TC	99.1	99.1	99.1	99.1	99.1	99.1	99.1	99.1
	TN	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8

A four times increase in the flow rate results in approximately two times decrease in the removal efficiency of the TSS. The sensitivities of BOD, TC, and TN removal efficiencies exhibit similar behavior to the change in the wetland surface area, where changes in their values occur only between winter and summer seasons. Generally, the model indicated that the wetland overall treatment efficiency is highly sensitive to the hydrologic retention time, which directly affects the temperature distribution in the treatment cells. Treatment is not as sensitive to average flow rate and wetland surface area, where the improvement of the treatment efficiency is concentrated in the improvement of TSS removal efficiency.

7. CONCLUSION AND RECOMMENDATIONS

Conventional wastewater management systems in Egypt exhibit a long line of technical and financial problems, which is reflected in well known public health, and environmental concerns. Therefore, engineered wetlands provide better alternative due to their feasible costs, low-maintenance requirements, simple and reliable operation, and relatively high removal efficiency. The pioneer work carried out at LMEW presents a leading field scale experiment in the Middle East. The efficient performance of LMEW in wastewater treatment supports the application of this innovative technology on the national level, as it provides a promising technology that suits the Egyptian climatic conditions.

The results of this research focused on providing the decision maker with the optimum design factors (detention time, average flow rate, and surface area), which should be of high priority in designing similar facilities on the Egyptian land and under similar climatic conditions. The research revealed the importance of temperature effect, which controls the optimum design values by affecting the efficiency of the treatment processes. Generally, the optimum detention time range is from 1 to 2 days, which achieves the highest removal efficiency in both winter and summer seasons. Increasing the surface area does not have significant effect on the removal efficiency for BOD, TC, and TN. Similarly, the average flow rate only affects the TSS removal efficiency, i.e. the overall capacity of the treatment facility. Therefore, climatic conditions, especially temperature, should be considered the governing factor affecting the design and consequently the performance of the engineered wetland.

Simulation results showed that the removal efficiency increases from 10% (for BOD) to 67% (for TN) by doubling the detention time from 1 to 2 days in the winter season. In the summer season, the effect of increasing the detention time affects both TSS (removal efficiency of 23%) and TN (removal efficiency of 66%), while BOD and TC remain unchanged as they are already high due to high temperature in that season. The effect of temperature variation was pronounced in the increase of the removal efficiency in the summer season, relative to the winter season, for all four parameters. Decreasing the surface area and increasing the average flow discharge had no impact on the removal efficiency of BOD, TC, and TN, while TSS removal efficiency decreased from 72.1% to 40.0%, in both winter and summer seasons due to area increasing while TSS removal efficiency decreased from 99% to 47.2% due to discharge increasing..

Wastewater treatment using the engineered wetland in the Nile Delta is a promising treatment technology, which fits the Egyptian economic and climatic context. This research shows that decreasing the wetland surface area and increasing the average flow rate did not affect its removal efficiency for almost all pollutants. This supports the conclusion that replication of this innovative technology on small scale would achieve a comparable performance to the large scale wetlands such as LMEW. The study also, showed that the effect of temperature variation was pronounced in the increase of the removal efficiency in the summer season, relative to the winter season, for all studied parameters.

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