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Improvement of Water Quality in a Highly Polluted River in Jordan

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ABSTRACT

Zarqa River is considered one of the most important sources of surface water in Jordan. The construction of Al-Samra wastewater treatment plant has caused a considerable deterioration in water quality of that river and pollution of the groundwater of that basin.

This paper aims to study the change in water quality in the river by applying hydraulic and quality models. Samples of wastewater from the inlet and outlet of the plant were collected and analyzed according to the standard methods. The obtained results concerning BOD, NH_4 and DO were used as input to predict water quality in the river. For this purpose, a one dimensional quality model has been developed to simulate pollutants transport in the river. The model was constructed to represent the change in concentrations of such parameters in the river from the treatment plant to the King Talal dam. 296 quality samples and 90 hydraulic samples were taken in order to calibrate the model.

Results indicate that the concentrations of BOD, COD and NH_4 effluent from the plant exceeded the allowable limits according to Jordanian standards.

From the results of simulation, it is found that the model is applied successfully to predict water quality in Zarqa River. Due to self purification, high reduction of pollutant concentrations occur along the river .The concentration of BOD is still higher than the allowable limit until 33 km downstream of the plant, while NH_4 concentration is higher than the standards in all reaches.

KEYWORDS: Modeling, Al-Samra treatment plant, River pollution, Zarqa River, BOD, NH_4, DO.

INTRODUCTION

Jordan has faced the problem of water scarcity for many decades and improved the efficiency of water use is an important part of its effort to deal with the problem.

The increase in water demand in addition to water shortage led to a gowing interest in using treated wastewater in irrigation, indsutries and for recharge of groundwater.

Treated wastwater from the excisting treatment plants is an important water resource component. About 72 MCM/y of treated wastewater are discharged to watercourses or used for irrigation. The Ministry of Water and Irrigation Plans to fully use the wastewater effluent for restricted irrigated agriculture (Barjenbruch and Alzboon, 2008).

In 1985, Al-Samra wastewater treatment plant; the largest natural treatment plant in the Middle East, was constructed to serve the capital Amman, Zarqa City and Rusiefeh town. It serves more than 2 million people and treats 76.0% of the wastewater generated in Jordan. Al-Samra plant is located at 40 km north east of Amman

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near Al-Hashmia village (As'ad, 2006). It consists of three parallel trains, with a total water surface area of 181 ha, each train consists of two anaerobic ponds, four facultative ponds and four maturation ponds, (10) ponds in each train are operated in series. Total design volume of the ponds was originally 2800000 m^3. Approximate total detention time provided by the ponds at the present average flow of (209570) m^3/day is 11 days. The specific design criteria of the plant are illustrated in Table (1) (WAJ, 2006).

Table (1): Design criteria for the plant.

parameter	design criteria
The average daily influent	68000 m^3/d
The maximum daily influent	148000 m^3/d
BOD_5 influent	526 mg/l
Daily organic load (BOD_5 load)	35. 768 tons/d
Daily total suspended solid load	42.024 tons/d
Ambient temperature during Summer Season	25 °C
Effluent BOD_5	30 mg/l
Total fecal coli form count (TFCC)	100 MPN / 100 ml
Nematodes	<1 egg / l

The average daily inflow to the plant was 156746 m^3/d in 1997, and reached 224175 m^3/d in 2006, which equals more than 330% of the average designed flow. The daily BOD_5 loads are about 129 tons/d; equal to a 163% loading increase compared to the design criteria. Also, the total suspended solid load increased from 42.02 tons/d in 1986 to 100 tons/d in 2003 in comparison to 42 tons/d according to the plant design criteria. The overflow rate in addition to the high organic load cause significant deterioration in the plant efficiency (Barjenbruch and Alzboon, 2008; As'ad, 2006).

Treated wastewater from Al-Samra treatment plant is discharged to Wadi Al-Dhulil which meets many tributaries to form Zarqa River where it flows to King Talal Dam (KTD). The total length of the river from the treatment plant to the KTD is about 46 km (Asa'd, 2006). Zarqa River is considered one of the most important sources of surface water because it has wide catchment's areas, and it carries more than 78% of the treated wastewater in Jordan (WAJ, 2006). This study aims to evaluate the change in water quality in Zarqa River and the degree of reduction in contaminants' concentrations.

Governing Equations

In the past century, many researchers showed interest in water quality and many studies have been conducted concerning models in rivers (Crockett et al., 1989; Hiroyuki and Motoyuki,1989; Bedford and Sykes, 1983; Koussouris et al., 1983; Marsili and Giusti, 2008; Wang et al., 2005; Jain et al., 2003; Gelda and Effler, 2000; Paliwal et al., 2007; Rakesh and Khanna, 2007).

Saint –Vennant equation is widely applied to simulate hydraulic parameters in rivers (Oppenheimer et al., 1999; Crossley et al., 2003; Litrico and Fromion, 2006; Evans et al., 2007; Hauke, 2002).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = \pm q \qquad \text{……………….(1)}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + Ag\frac{\partial d}{\partial x} - Ag(S_0 - S_f) = \pm q\frac{Q}{A} \qquad \text{……….(2)}$$

where:

Q : discharge (m^3/s)

A : cross-sectional area

q : lateral inflow into the river (positive) or outflow from the river (negative)

g : acceleration due gravity (m/s^2)

d : water depth (m)

S_0 : slope of the channel

S_f : slope of energy line = $\frac{n^2 v^2}{R^{4/3}}$

R : hydraulic radius $=A/p$

N : Manning roughness coefficient

P : wetted parameter

V : cross-sectional velocity (m/s)

In case of steady-state condition and no lateral flow entering or leaving the water body, equations (1 and 2) can be expressed in terms of velocity and head of water as follows:

$$V\frac{\partial d}{\partial x}+d\frac{\partial v}{\partial x}=0 \qquad \text{……………………(3)}$$

$$V\frac{\partial v}{\partial x}+g\frac{\partial d}{\partial x}-g(S_0-S_f)=0 \qquad \text{………(4)}$$

Pollutants transport in rivers by two processes: advection and dispersion. So, the well-known advection dispersion equation is used to simulate the pollutant distribution in the river. For non-conservative substances, an additional term should be added to the equation as illustrated in equation (5). This additional term ($\sum S$) represents the sources and sinks of pollutants in a defined reach (Hiroyuki and Motoyuki, 1989; Bedford and Sykes, 1983).

$$\frac{\partial C}{\partial t}=V\frac{\partial C}{\partial x}+U\frac{\partial C}{\partial Y}+W\frac{\partial C}{\partial Z}-D_x\frac{\partial^2 C}{\partial x}-D_Y\frac{\partial^2 C}{\partial Y}-D_Z\frac{\partial^2 C}{\partial Z}\pm\sum S \qquad (5)$$

Where C is the pollutant's concentration, D_x, D_y, D_z are the dispersion coefficients in x, y and z directions, respectively, and *V, U, W* are the velocity components in x, y, z directions, respectively.

Zarqa River is very shallow, so that a complete mixing in water body occurs. Because of that, the variation of water quality along vertical direction (z) can be neglected.

For relatively straight streams and rivers, the flow is essentially unidirectional (Aswed, 2000). Zarqa River has a high flow velocity in the longitudinal direction (up to 1.1 m/sec), so it is expected that the velocity component in the lateral direction be very small compared with longitudinal velocity component. For this reason, the effect of velocity in lateral direction (y) can be ignored, and equation (5) is rewritten for steady-state condition and one-dimensional flow as follows:

$$0=V\frac{\partial C}{\partial x}-D_x\frac{\partial^2 C}{\partial x}\pm\sum S \qquad \text{................(6)}$$

Usually, two physical chemical processes cause BOD reduction. The first one is the settling of organic material along the river reaches. Because the river has a high velocity and the density of pollutants is approximately equal to water density, so the effect of settling process on BOD is neglected. The other source is the decay process, where microorganisms consume organic matter. The decay process is assumed as a first order reaction and is involved in equation (6) by the term (k_1L):

$$0=V\frac{\partial L}{\partial x}-D_x\frac{\partial^2 L}{\partial x}-K_1L \qquad \text{.............(7)}$$

Where L is the BOD concentration, and K_1 is the decay rate *(1/d)*.

Equation (6) has been applied for NH_4 model as follows (Kefaya, 2000):

$$0=V\frac{\partial N}{\partial x}-D_x\frac{\partial^2 N}{\partial x}-\beta_1N+\gamma a\mu A_x \qquad (8)$$

Where N: is the ammonium concentration

β_1: is the constant for biological oxidation of ammonium ($1.157*10^{-5}$ -$1.157*10^{-6}$ /s)

μ: is the algae growth rate ($1.157*10^{-5}$ -$3.472*10^{-6}$ /s)

γ: is the fraction of ammonia – nitrogen uptake for algae pool.

A_x: is the algae biomass concentration (mg/l)

a: is the fraction of algae biomass that is nitrogen (0.07-0.09 mg N/mg A_x).

The last term of equation 8 represents the reduction of ammonia concentration by algae biomass.

The governing equation for dissolved oxygen is:

$$0=V\frac{\partial D}{\partial x}-D_x\frac{\partial^2 D}{\partial x}-K_1L+K_2(D_s-D) \qquad (9)$$

Where D: is the dissolved oxygen concentration

D_s: is the saturated dissolved oxygen

and K_2: is the re-aeration coefficient rate *(1/d)*.

The last term of equation (9) represents the effect of the re-aeration process.

METHODOLOGY

Sampling

The total length of the river from the treatment plant to the King Talal Dam (KTD) is about 46 km. During the year of 2002, the hydraulic and quality samples were taken in 12 stations, 10 of which locate along the river and 2 locate on the tributaries which drain in the river.

Dissolved oxygen was measured in 240 samples at 12 stations along the river, while BOD and NH_4 concentrations were measured in 28 samples. Dissolved oxygen was measured by a portable oxygen meter. Using this instrument makes it possible to take alternative readings of the oxygen saturation, oxygen concentration, air pressure and temperature. The measurements of velocity and depth were performed 90 times along the river.

The data obtained during the year 2002 were used for calibration and verification of the model, and an acceptable solution was obtained, so the model is used to simulate the concentration of pollutants for the new sets of data, which are taken during the year of 2006.

Computation of the Constant Parameters

BOD Decay Rate *(K_1)*

Decay rate has been computed by applying Thomas's method on field data collected in 2002. A sample from wastewater influent to the plant was taken, diluted, incubated and analyzed according to the standard method for examination of water and wastewater (APHA, 1998). The decay rate obtained by Thomas's method was = *0.204 /d.*

Re-aeration Coefficient *(K_2)*

There are many equations used to determine K_2, but Owen's equation is recommended for a water depth less than 2 ft, which matches to the case of Zarqa River. Re-aeration coefficient depends on the velocity of water and depth as illustrated in equation (10) (Churchill et al., 1962):

$$K_2(20^{\circ}C) = 5.349\ \frac{V^{0.67}}{H^{1.85}} \qquad \text{……………….(10)}$$

where V and H are velocity and depth of water, respectively. Re-aeration coefficient value is variable and has different values for each reach depending on V and H values.

Dispersion Coefficient

Mahendra's equation is considered the most popular to be used to compute D_x value, so it is applied to determine the dispersion coefficient for this problem as follows (mahendra, 1971):

$$D_x = \frac{V}{KV_s} V H \times 10^{\left[6.5-0.762\ \log\left[-\frac{\rho\rho V}{\mu}\right]\right]} \qquad (11)$$

V: average velocity in the reach $=x/Tp$

X: the length of distance

T_p: time to the peak arrival of the concentration

V_s: effective mean velocity of flow at sampling station$=Q/A$

ρ: mass density of water

K: regional dispersion factor, which varies from one river to another ranging from (1-4)

μ: coefficient of viscosity

D_x: longitudinal dispersion coefficient (m^2/s)

H: depth of river.

The recommended values of the other constants are used, and all these values are tested and calibrated depending on the obtained data in the year 2002.

Formulation and Solution of the Model

The finite differences numerical method is used to find the approximate solution of the hydraulic model. The derivatives appearing in the equations and boundary conditions of the hydraulic model are formulated in finite differences shape, and then are set into a system of linear equations which are solved by Newton-Raphson iteration method.

The quality model is also solved numerically by finite differences where the governing equations are formulated by applying Crank-Niclson methods. In order to reduce the time required to solve the problem, sparse matrix technique is used.

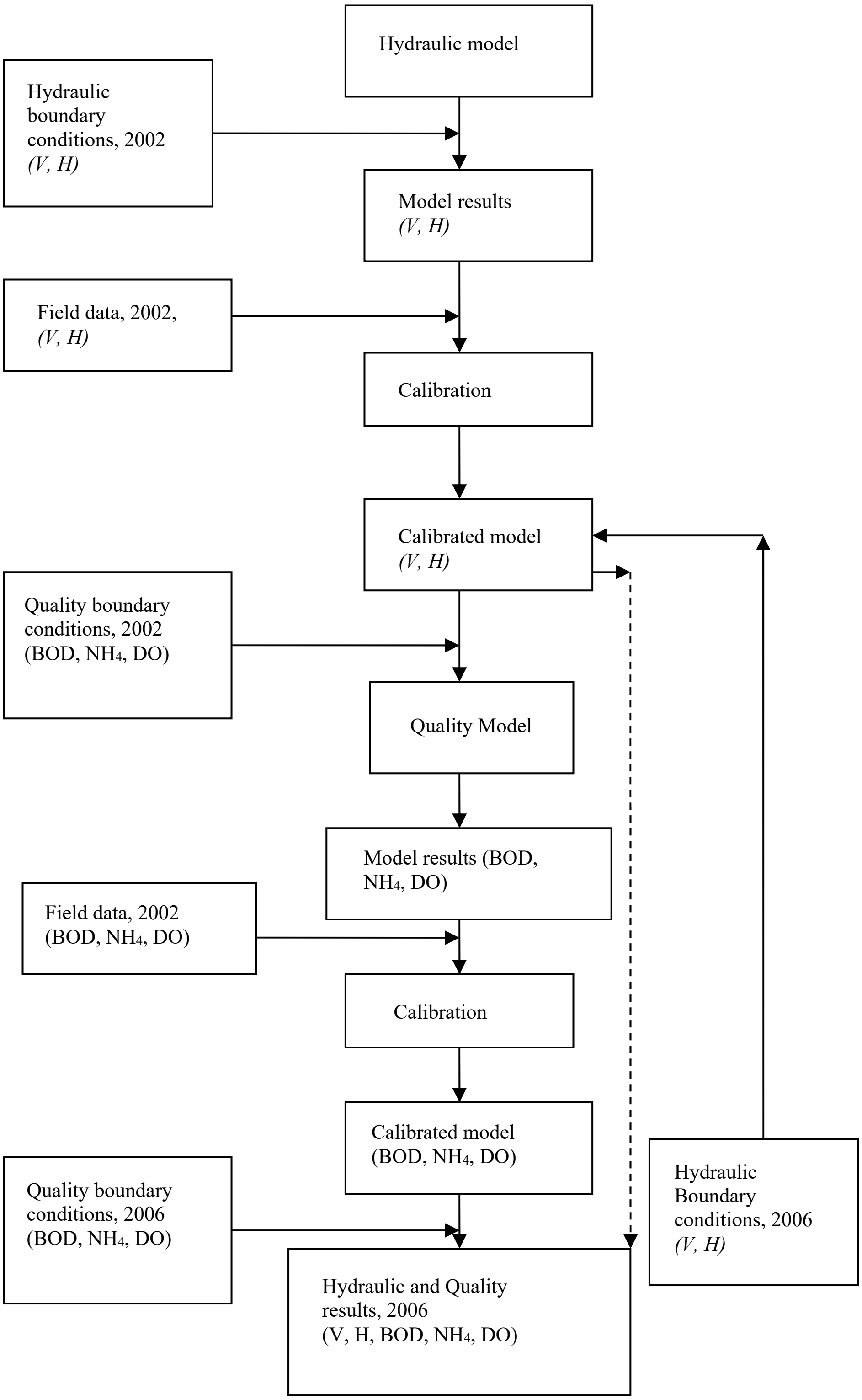

Figure (1): Model flow chart.

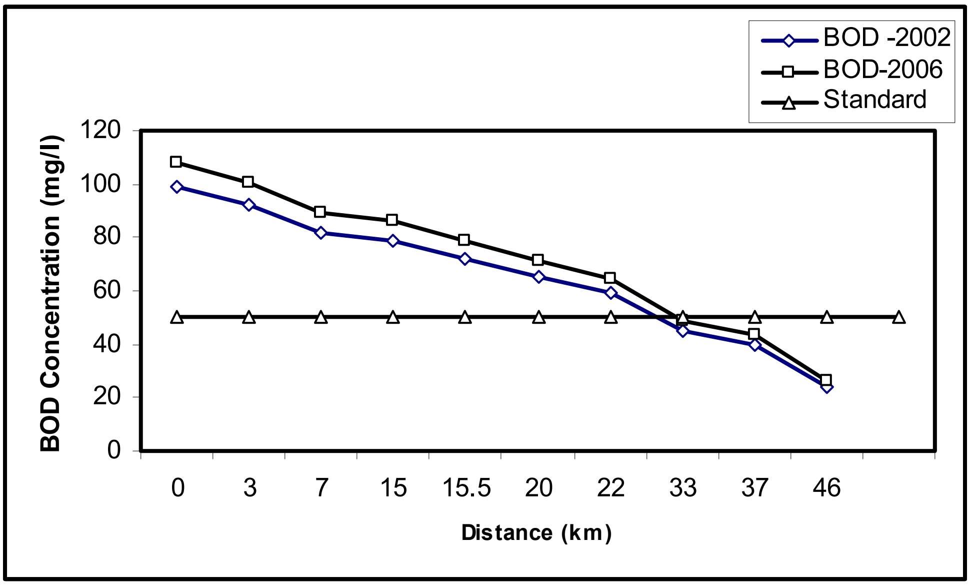

Figure (2): Simulation of BOD concentrations.

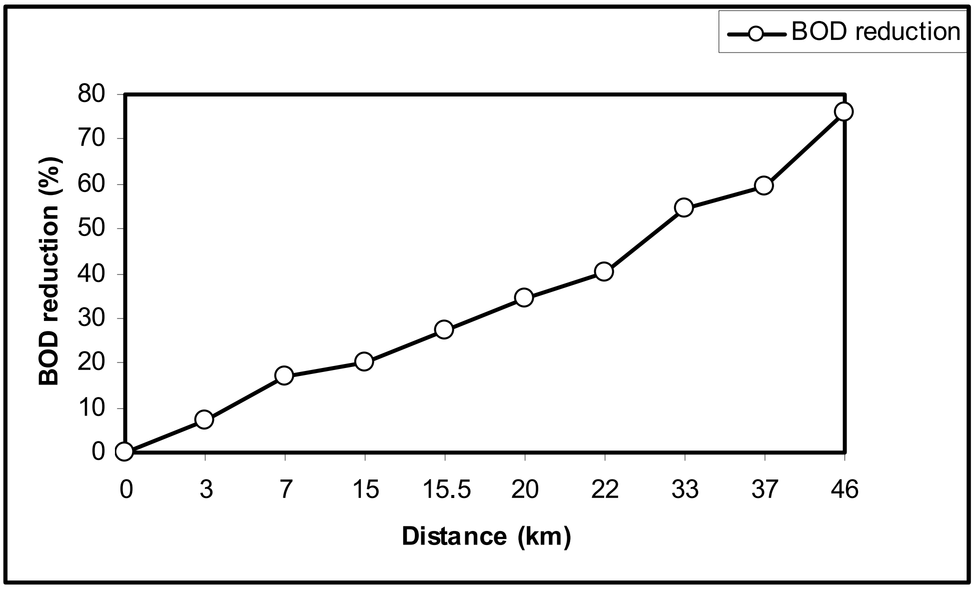

Figure (3): BOD reduction along the river during the year 2006.

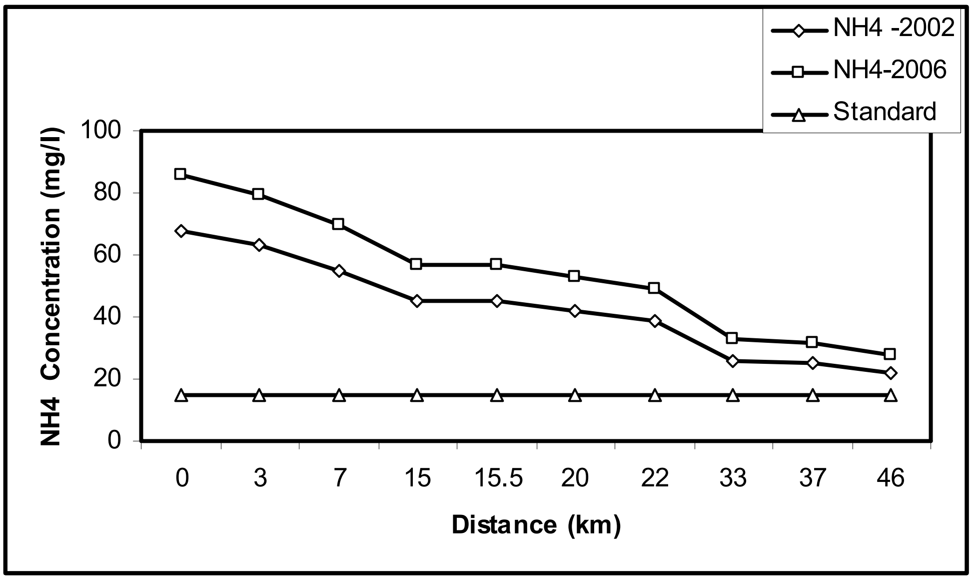

Figure (4): Simulation of NH_4 concentrations.

Figure (5): NH_4 reduction along the river during the year 2006.

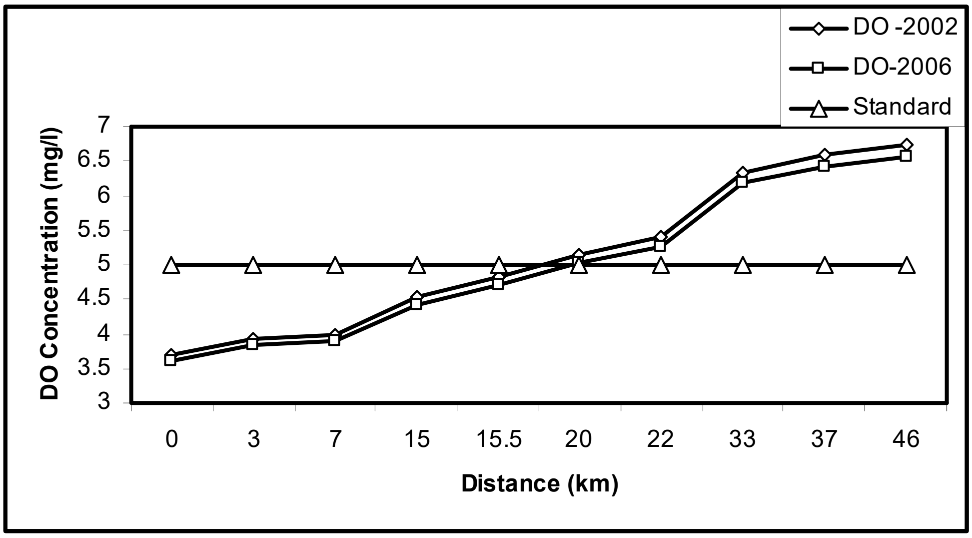

Figure (6): Simulation of DO concentrations.

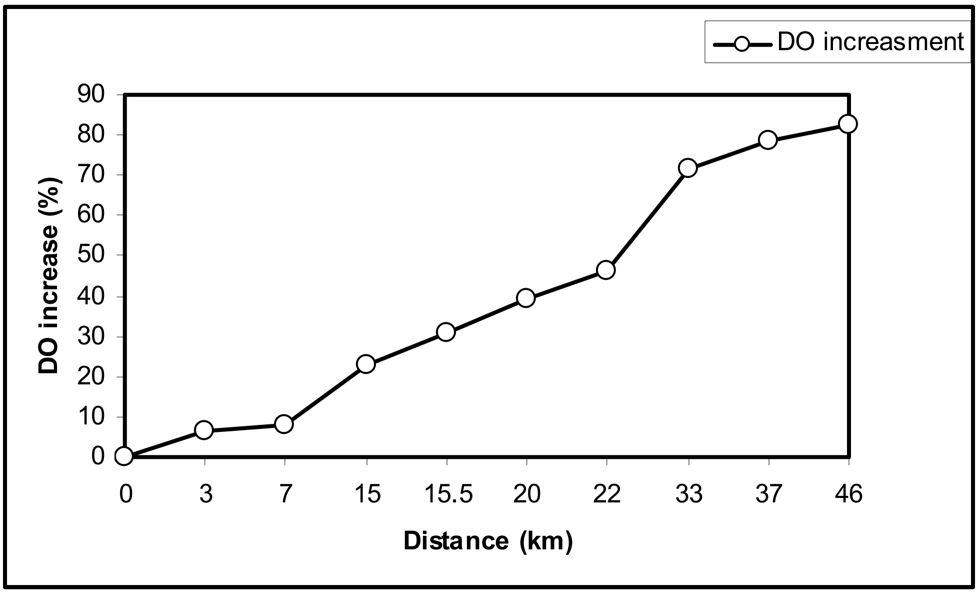

Figure (7): DO increase along the river during the year 2006.

RESULTS AND DISCUSSION

Efficiency of the Treatment Plant

Table (2) illustrates the characteristics of wastewater inlet and outlet of the treatment plant during the year 2006.The obtained data indicated that the average BOD concentration effluent from the treatment plant exceeded the allowable Jordanian standards for wastewater discharged to streams. The similar result for COD and NH_4 parameters is obtained. The plant has a low efficiency regarding to BOD, NH_4 and COD removal because it depends on natural treatment (stabilization ponds) ,so it is affected by seasonal variations of climate parameters such as temperature, pressure and sunshine hours. The plant has not any facility to remove ammonium, so the effluent wastewater contains a high concentration of NH_4. As a result of deterioration in plant efficiency, the effluent concentrations of BOD and NH_4 from the plant in the year 2006 were higher than those in the year 2002.

Table (2): Characteristics of wastewater inlet and outlet of the plant .

Parameter	**Inlet (mg/l)**	**Outlet (mg/l)**	**Removal Efficiency (%)**	**Standards ****
Temperature	23.22	20.216	--------	-----
PH	7.09	7.89	--------	6-9
BOD	552.6	118.08	78.8	50
COD	14416	385	71.25	200
NH4	70.58	86.16	negative	15
TSS	549.9	118	78.0	2000
DO	*	3.64	-------	>2

* Undetected. ** Standards for wastewater discharged to the stream.

Table (3): Accuracy of the model.

Parameters	Average Percentage of Error (%)	MSE
Velocity (V)	6.35	0.0085
Depth of water (H)	7.58	0.0031
BOD	6.27	15.79
NH_4	4.15	22.34
DO	3.23	0.037

Result of the Model

The hydraulic and quality models, which have been designed in 2002, were used to simulate water quality in Zarqa River for the obtained data. Two parameters were used to evaluate the accuracy of the model: the first is the percentage of error and the other is the Mean of Square errors (MSE). Errors in simulations are estimated as the difference between model's predicted values and observed data. The highest relative error, for BOD, was 9% while the average error was 6.27%. Similar agreement for NH_4 and DO results was found, so the results show acceptable errors and good accuracy as illustrated in Table (3).

The calibrated model was used to simulate water quality for the obtained data in the year 2006.

The average concentrations of V,H,BOD, NH_4 and DO effluent from the plant during year 2006 are used as boundary conditions for the model to predict the distribution of pollutants along the river .The output of the hydraulic model is used as input for the quality model as shown in Figure (1).

Figure (2) shows the predicted BOD concentrations along the river from the outlet of the plant to the discharged point at King Talal Dam. It is clear that the outlet treated water contains high concentration of BOD because of low efficiency of the plant. Along the river, the concentration decreases because of biological decay of the organic matter, the presence of algae and shrubs, which consume the organics and the natural re-aeration phenomenon enhancing the oxidation process. Except the effluent from the plant, there is no significant source of BOD drains in the river. All these processes decrease the concentration along the river from 108 to 26 mg/l for the data of 2006. The high re-aeration process is considered as a necessary condition for the natural processes of growth of bacteria and other biological organisms to consume most of the polluting substances. The high reduction in BOD concentration (76%) indicates that an effective self-purification process takes place as shown in Figure (3). In spite of that, until station 8 which locates 33 km downstream the plant, the concentration is still higher than the allowable Jordanian standards (50 mg/l).

NH_4 behavior is similar as BOD where the concentration decreased by 68% (from 86 in the outlet station to 27 mg/l at station 10) for the data collected in year 2006 as shown in Figures (4 and 5). Jordanian standards for wastewater discharged to streams state that the concentration of NH_4 should not be more than 15 mg/l, so that the concentration of NH_4 exceeds the allowable standards in all locations.

The difference in elevation along the river which is about 430 m, in addition to the shallow and turbulent character of water in Zarqa river, result in high re-aeration coefficients and rapid self-purification. These parameters explain the increase in DO concentration between stations 1 and 10, where DO concentration increases from 3.6 to 6.57 mg/l as shown in Figures (6 and 7). Between station 1 and station 6, the DO concentration is less than the Jordanian standards for fish ponds.

The obtained results indicated that the water quality in Zarqa River is affected strongly by treated wastewater effluent from Al-Samra plant. The self-purification process is highly effective in the reduction of pollutants' strength.

CONCLUSION

From the obtained results, it can be concluded that Al-Samra Treatment Plant (ASTP) has low efficiency with regard to BOD, COD and NH_4 concentrations where they do not comply with Jordanian standards. The concentration of BOD decreased significantly along the river stream as a result of biological decomposition and self-purification processes, but is still above the allowable limit until 33 km downstream of the plant. The plant has not any facility for NH_4 removal, so high concentration is discharged to the stream where the concentration is higher than the permitted level according to Jordanian standards. Self-purification process is capable to improve water quality in the river, but the high strength of treated water from the plant has an adverse effect on this process.

The quality model is useful to predict water quality along the river. By using this model, it is unnecessary to measure pollutants in each station along the river, but it is enough to measure them in the effluent point, then these boundary conditions are inserted in the model to determine water quality in the interest point.

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