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Investigating the effect of using treated and untreated wastewater in irrigation on groundwater quality

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A R T I C L E I N F O

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A B S T R A C T

In arid and semi-arid regions there are a large gap between water supply and water demand especially in Egypt. This gap can be covered by different techniques including modern irrigation system, rationalization of using freshwater, reuse of agricultural drainage water and wastewater. This study aims to investigate the effect of using untreated and treated wastewater in irrigation on groundwater quality using the finite difference model (MODFLOW). Two scenarios are studied, the first is using untreated wastewater in irrigation and the second is using treated wastewater due to reduction of freshwater by 10, 20, 30, 40 and 50 %. The results showed that using untreated wastewater in irrigation has significant effect in groundwater quality and loss large quantity of freshwater in the aquifer, while using treated wastewater in irrigation is more suitable for protecting groundwater. Also using untreated wastewater in irrigation under the reduction of irrigation water due to climate changes and construction of control structure on the upper Nile River must be considered to protect the groundwater and keeping the human health. The technology of treated wastewater should be extended in arid and semi-arid regions to overcome the shortage of water resource and increase the quality of drink and irrigation water from the groundwater.

Abbreviations

FAO Food and Agriculture Organization
COD Chemical Oxygen Demand
Ppm Part Per Million
Mg/l Milligram per Liter
Mm/yr Mile Meter per Year
M^3/d Cubic Metres per Day
Km^2 Square Kilometre
Q Discharge
R Recharge
w.l Water Level
K_{xx} Hydraulic Conductivity along the x coordinate axe
K_{yy} Hydraulic Conductivity along the y coordinate axe
K_{zz} Hydraulic conductivity along the z coordinate axe
h Potentiometric Head
W Volumetric Flux per unit volume representing sources and/or sink of water
S_S Specific Storage of the porous material
C Groundwater Concentration
D_{ij} Dispersion Coefficient
V Seepage Velocity
q_s Water Flux of sources (positive) and sinks (negative)
C_s Sources or Sinks Concentration
Ө Media Porosity
R_k Chemical Reaction
S_y Specific Yield
S_s Specific Storage
n_{eff} Porosity
n_{total} Total Porosity

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1- INTRODUCTION

Water is essential for life. It is covering two-thirds of the Earth's surface. The supply of fresh water of quality is one of the main environmental challenges during the 21st century. [1]. The world population reached 7 billion after 2010, and by 2045 it is expected that the population will reach 9 billion. Nearly about one fifth of the world's population, do not have safe drinking water, and about half of the World's population does not have adequate sanitation. [2]. The Food and Agriculture Organization (FAO) clarified the water stress classification of the country in view of the percentage of withdrawal where it occurs with a withdrawal of more than 25% of renewable freshwater resources, they suffer from water stress, and when the percentage exceeds 60%, physical water scarcity occurs, and if it exceeds 75%, severe physical water scarcity occurs. [3], [4].

The rapid growth of urbanization and various industries and the increasing use of chemicals for agricultural purposes have led to the destruction of the quality of many rivers, underground reservoirs, and lakes. Many fertilizers, chemicals, and herbicides used to enhance agricultural products have harmful side effects, like industrial pollution. Where these materials are accumulated in aquifers and in natural ecosystems. [2]. Major changes of the Earth's water cycle have arisen in many parts of the planet because of the enormous extension of agriculture over the last decades. Agricultural activities can damage natural vegetation and harm soils, surface water sources and aquifers. Agricultural irrigation causes, a potential risk particularly in arid and semi-arid regions, where the rate of the evapotranspiration is generally high, and rainfall is scarce and greatly varies.[5] . Irrigation and fertilization may have the following impacts in arid zones:(1) salinization of the soil and groundwater beneath fields and (2) increase the concentrations of nitrate in groundwater. Because of higher evapotranspiration, irrigation in arid regions raises salt concentrations in the root zone. Excessive quantities of water are necessary to reduce soil salinization, much more than what crops require. [6]. Water is one of the scarcest resources although it represents about 71% of the earth. Water is abundant in the earth overall, but fresh and healthy water for usage is much less available in the ecosystem. In various countries around the world rivers are the major drinking water supplies. There are several pollutants entering the water when it flows downstream, including human, animal and mining wastes, Agriculture drainage, urban sewage industrial waste, as a result numerous rivers are facing pollution issues or are at risk of pollution. [7]. Groundwater is an essential water resource for agricultural and domestic usage. The main source of groundwater contamination is the discharge of waste disposal from the agriculture, industry, and municipality. Several activities cause a groundwater deterioration. (For example, evapotranspiration salt accumulation, rising water table and water logging, seawater mobilization and subsurface salt/chemical leaching). Furthermore, extensive groundwater abstraction for agricultural purpose has caused depletion and degradation for aquifers. For terms of water quality, pesticides, salinization, and pollution of nutrients are the major global agricultural problems. [1]. The irregularity of agriculture and industrial growth is contributing to increased demand on fresh water supplies leading to the generation of massive volumes of wastewater.

The discharge of contaminated wastewater into ponds, oceans, etc. causes the water deterioration. With the appropriate treatment it may however be used for several beneficial operations, such as industry, agricultural purposes (Fertilization of wastewater), etc. it will contribute to solve water crises. In areas with scarcity of water, the use of wastewater is an option for its low cost. [8].

To face water scarcity, crops are irrigated with untreated wastewater as it is an available source of water and compensates for its scarcity, about 15 million cubic meters per day are used for irrigation. Which leads to contamination of the soil which transmitted through food, as 10% of the world's population gets food from harvests cultivated with wastewater. [4]. When untreated wastewater used for irrigation, this leads to an increase in chemical and biological compounds in the roots of plants, which affects negatively the optimal growth of crops. It reaches the shallow aquifers neighboring to it and affects its quality. It also affects the properties of soil due to leakage of heavy metals.[9]. In arid regions that suffer from water scarcity, farmers use municipal wastewater during long periods of drought when the availability of fresh water is at a minimum. Since long ago municipal wastewater has been used due to the abundance of nutrients and essential elements for crop growth and soil fertility.[10] ,[11]. The physical and chemical properties of water and soil are affected by the discharge of untreated wastewater as it enters the food chain and affects agricultural products and human and animal health. About 4.5 billion people do not have an adequate sanitation system, and globally 2.1 billion people suffer from a lack of clean water. Also, a recent United Nations report mentioned that by 2025, about two-thirds of the world's population may suffer from the problem of water stress.[12]. To profit on wastewater in agriculture in a sustainable manner for both health and the environment, farmers must be aware about the risks and best practices in this operation. Among these practices that reduce the use of fresh water is using the treated wastewater, also it reduces the risks that affect health and the environment. [4]. One of the causes of contamination of the aquifer, especially in confined areas, is the frequent use of fertilizers and the increase in recharge on the contrary, in non-confined areas, groundwater and soil contamination decrease, and this is due to the high recharge rates. Also, groundwater contamination decreases with the increase in pumping, as the contact between the water table and the contaminated fertilizers decreases. The groundwater head can be lowered, and the contamination can be controlled to transmit to groundwater with the construction of a subsurface drainage system. To enhance groundwater quality, the simulation findings recommended constructing a cut-off wall and placing linings in contaminated drains. The study showed a solution for protecting groundwater, lined by geomembranes due to their durability and less costs relative to concrete. [13]. The effects of irrigating with untreated wastewater on groundwater quality were performed by mixing it with treated wastewater or freshwater. The results showed positive effects occurred because of mixing untreated wastewater with treated wastewater. So, the use of treated wastewater might enhance the quality of groundwater used in irrigation and assist to reduce groundwater pollution.[14]. The current study developed to compare between the effect of using untreated wastewater and treated wastewater on groundwater quality using the numerical MODFLOW. This study is applied on a hypothetical case with depth of 100m and square area 4 km^2.

2- Method and materials

2.1 Hypothetical case study

A hypothetical case is studied, with an area of 4 km^2, length and width are 2000 meter and a depth of 100 meter. The total area was divided into several square cells, the area of one cell is 400 m^2, and the area was divided into 100 columns, 100 rows and 20 layers. At 1000 meters from the center, two canals situated on each of the borders of the model, and both are parallel to the main drain which is located at the center of the study area. Also, six wells on each side at 500 m from the center line of the drain as shown in figure (1).

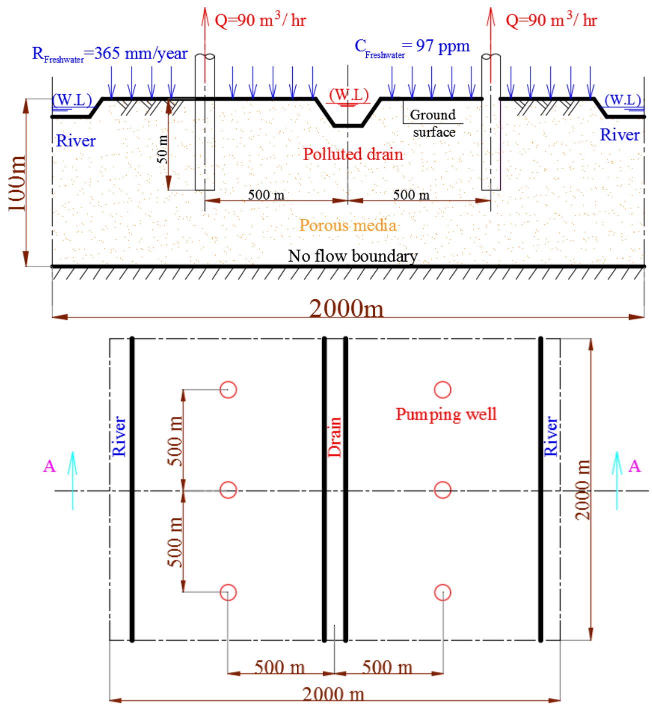


Figure (1): vertical cross section and plan of the case study

2.2 Numerical model

Numerical simulations can be used to evaluate groundwater flow and sault transport in aquifers. MODFLOW is used to estimate the quality and quantity of groundwater for use in irrigation with untreated wastewater. The parameter values and outputs can be visualized in a 2D or 3D model while using the model or presenting the data.

MODFLOW solves the groundwater flow governing equation, which is defined as follows:[15]

$$\frac{\partial}{\partial t}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

In addition, the solute transport model was simulated in 3-D using the MT3D model, the partial differential equation can be written as follows: [16]

$$\frac{\partial c}{\partial t}=\frac{\partial}{\partial xi}\left(Dij\frac{\partial c}{\partial xj}\right)+\frac{\partial}{\partial xi}(ViC)+\frac{qs}{\theta}(Cs)+\sum_{k=1}^{N}(Rk) \quad (2)$$

Where:
K_{xx}, K_{yy}, and K_{zz}: hydraulic conductivity along the x, y, and z coordinate axe (T^{-1}), h: the potentiometric head (L), W: volumetric flux per unit volume representing sources and/or sink of water (T^{-1}), S_S: specific storage of the porous material (L^{-1}), t time (T), C: groundwater concentration (ML^{-3}), D_{ij}: dispersion coefficient (L^2T^{-1}), V: seepage velocity (LT^{-1}), q_s: water flux of sources (positive) and sinks (negative) (T^{-1}), C_s: sources or sinks concentration (ML^{-3}), Ɵ: media porosity [dimensionless] and R_k: chemical reaction term ($ML^{-3}T^{-1}$).

2.2.1 Boundary conditions and hydraulic parameters

Below the ground surface of the water levels are assigned for the main drain, the levels range from 2.5 to 2.8m. On both sides of the model, two parallel rivers were assigned with average water levels ranging from 0.5 to 0.8m and bed levels ranging at depth from 3 to 3.30m below ground surface. The annual recharge rate was set in the first layer of the model and applied at 365 mile per year (mm/yr). Chemical oxygen demand (COD) was identified as a contaminant in agricultural irrigation water, where it was used to recharge untreated sewage water with a constant concentration of 97.4 milligram per liter (mg/l) in Bahr El-Baqar. [17].
Allocating hydraulic parameters to the research area is based on previous experiments and mathematical estimates including horizontal and vertical hydraulic conductivity K_x, K_y= 5, K_z= 0.5 m/d, specific yield S_y= 0.2, specific storage S_s= 27*10^{-7} 1/m, effective porosity n_{eff}= 20%, total porosity n_{total}= 35.[18].

3- Calibration of groundwater flow and solute transport model

MODFLOW code is used to simulate the groundwater flow and the contaminant transport in the study area. The calculation of groundwater head between the river and the drain used the mathematical equation based on Darcy's law as following:[19]

$$K(h^2 - h_0^2) - N * X(L - X) + \frac{K*X}{L(h_0^2 - h_l^2)} = 0 \qquad (3)$$

Where:
h: elevation of water between the river and the drain (L), h_o: the drain elevation located on the west (L), h_L: the river elevation located on the east (L), K: the hydraulic conductivity (L/T^{-1}), N: is the porosity, X: the distance along the aquifer from the drain located on the west (L).

The comparison between calculated head from the numerical model of MT3DS and the observed values calculated by the analytical equation 3. A number of 17 observation well are examined in the current calibration where the residual ranges between (-0.0012 to -0.001 m) with mean equals to -0.004 m and the absolute residual mean is 0.007 m, the root mean square is 0.008 m and normalized root mean square is 13.808% which shown in figure.2.

The vertical cross section for the distributed of COD in the hypothetical base case is presented in figure.3 which indicated that the value is 14.97 ppm. And the high value of contamination is around the polluted drain and the top layer of the soil and decrease by the aquifer depth and the distance from polluted drain. This indicated that the abstraction well must be deep and far from the source of pollution.

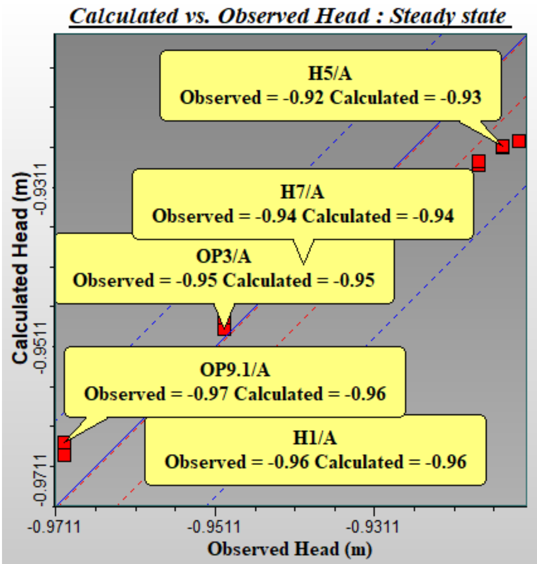


Figure (2): Model calibration

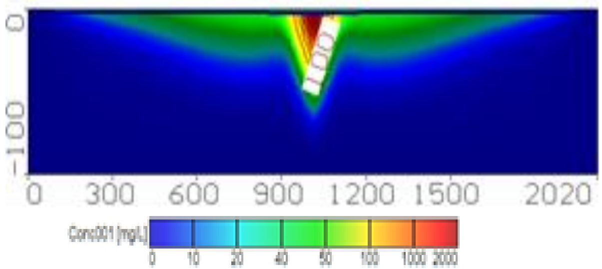


Figure (3): Distribution of contaminant (COD) in the study area (Base case)

Numbers of scenarios were performed to investigate the effect of using untreated wastewater in agriculture, in the first is increasing recharge quantity of untreated wastewater by 36.5, 73, 109.5, 146 and 182.5 mm/yr, while using freshwater recharge values 328.5, 292, 255.5, 219 and 182.5 mm/yr. And for the second is increasing recharge quantity of treated wastewater by 36.5, 73, 109.5, 146 and 182.5 mm/yr while the irrigation water recharge 328.5, 292, 255.5, 219 and 182.5 mm/yr, while the irrigation water recharge 328.5, 292, 255.5, 219 and 182.5 mm/yr. and for the constant pumping rate equals 2160 m^3/d.which are presented in table 1.

Table.1: proposed scenarios for untreated and treated wastewater.

Scenario		Base	Untreated wastewater	Treated wastewater
Pumping rate (m^3/d)		2160	2160	2160
Freshwater	Recharge (mm/yr)	365	328.5	328.5
			292	292
			255.5	255.5
			219	219
			182.5	182.5
	Concentration (ppm)	30	30	30
Mixed water	Recharge (mm/yr)	-	36.5	36.5
			73	73
			109.5	109.5
			146	146
			182.5	182.5
	Concentration (ppm)	-	97.4	52.98

4- RESULTS AND DISCUSSION

The different scenarios of untreated and treated wastewater were considered in the current study including untreated wastewater recharge rates ($R_{untreated}$) (scenario 1). Treated wastewater recharge rates ($R_{treated}$) (scenario 2).

4.1 Impact of using untreated wastewater on groundwater quality

In the first scenario, the impact of using untreated wastewater on groundwater quality were studied using freshwater recharge values 328.5, 292, 255.5, 219 and 182.5 mm/yr and the constant concentration is 30 ppm with untreated wastewater recharge rates equal 36.5, 73, 109.5, 146 and 182.5 mm/yr with constant concentration is 97.4 ppm, while the recharge rates were remained constant by 365 mm/yr. for the pumping rate equals 2160 m^3/d. The distribution of contaminant (COD) is shown in figure.4. The results showed that increasing the use of untreated wastewater recharge rate led to increase the distribution of COD in groundwater and the contamination reached 18.33, 21.69, 25.06, 28.42 and 31.78 ppm at depth equals 25 m (see figure.6). The using of untreated wastewater in irrigation under the reduction of irrigation water due to climate changes and construction of control structure on the Nile River must be considered to protect the groundwater resources and the human health.

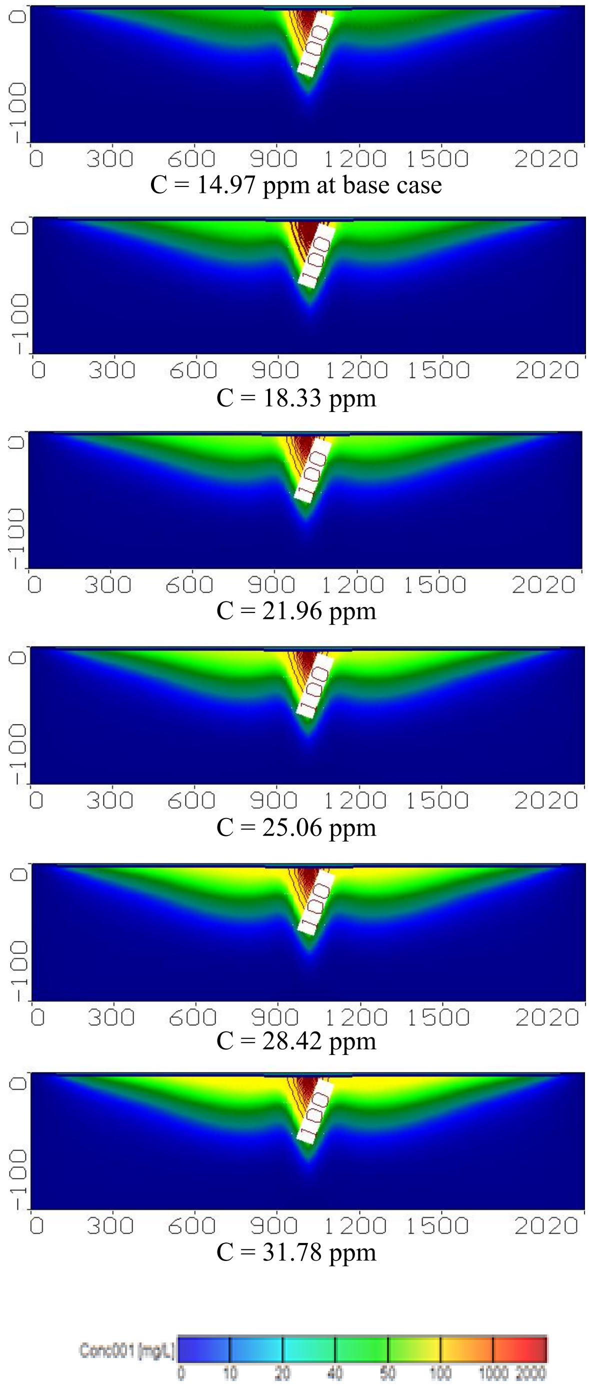
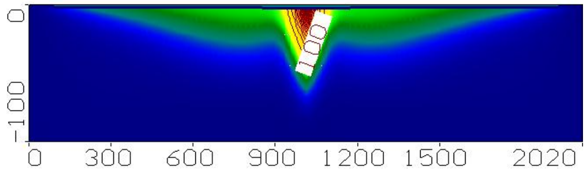


Figure (4): Vertical cross section for the distribution COD contamination using untreated wastewater

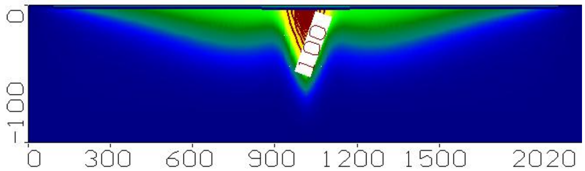
4.2 Impact of using treated wastewater on groundwater quality

In the second scenario, the treated wastewater is used by recharge rates equal 36.5, 73, 109.5, 146 and

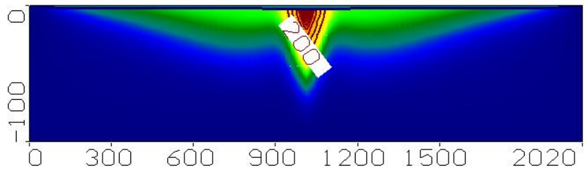
182.5 mm/yr with constant concentration of 52.98 ppm, while the irrigation water recharge 328.5, 292, 255.5, 219 and 182.5 mm/yr and the constant concentration is 30 ppm, and the recharge rates were remained constant by 365 mm/yr. For the pumping rate equals 2160 m^3/d. The distribution of contaminant (COD) is presented in figure.5. The results showed that the distribution of COD in groundwater decreased compared to the value of untreated wastewater and the contamination reached to 16.12, 17.26, 18.41, 19.56 and 20.71 ppm at depth equals 25 m as presented in figure.6 wastewater should be extended in arid and semi-arid regions to overcome the shortage of water resource and increase the quality of drinking and irrigation water from the groundwater.



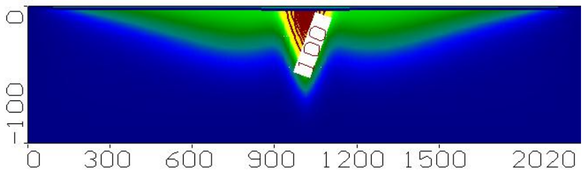
C = 14.97 ppm at base case



C = 16.12 ppm



C =17.26 ppm



C =18.41 ppm

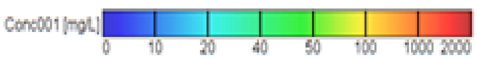


Figure (5): Vertical cross section for the distribution of COD contamination using treated wastewater

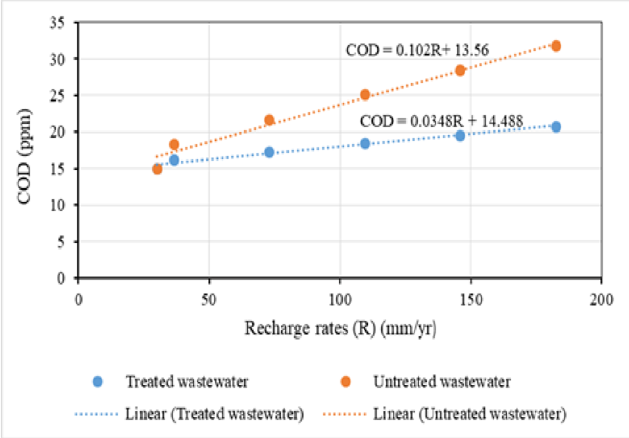


Figure (6): Relation of untreated and treated wastewater recharge rate with COD contamination in groundwater.

The following equation is used to calculate the groundwater contamination using untreated wastewate is

$$COD=0.102R+13.56 \quad (4)$$

While equation is used for calculate the groundwater contamination using treated wastewater is

$$COD=0.0348R+14.488 \quad (5)$$

5- CONCLUSION

The lack of freshwater supplies has led to increase the use of unconventional water resources in high scarcity regions including untreated wastewater. The current study carried out to identify the impact of using untreated wastewater on groundwater contamination in these regions. The numerical model of VISUAL MODFLOW and MT3D were applied on a hypothetical case study dimensions of 2000 m in length and width while the depth is 100 m.

The simulation was done for the base case and two scenarios by decreasing freshwater quantities and increasing the use of untreated and treated wastewater for different recharge quantities and concentration. The result indicated that the concentration reached 14.97 ppm at the base case. Also, the contamination reached 18.33, 21.69, 25.06, 28.42 and 31.78 ppm at depth equals to 25 m by decreasing the freshwater quantities by 328.5, 292, 255.5, 219 and 182.5 mm/yr with constant concentration 30 ppm and increase the untreated wastewater quantities by 36.5, 73, 109.5, 146 and

182.5 mm/yr with constant concentration is 97.4 ppm.

Moreover, the use of treated wastewater quantities by 36.5, 73, 109.5, 146 and 182.5 mm/yr with constant concentration is 52.98 ppm under reduction of the irrigation water recharge 328.5, 292, 255.5, 219 and 182.5 mm/yr and the constant concentration is 30 ppm, the contamination reached 16.12, 17.26, 18.41, 19.56 and 20.71 ppm at depth equals 25 m.

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