IMPACTS OF TREATED WASTEWATER REUSE IN IRRIGATION ON GROUNDWATER: CASE STUDY OF SADAT CITY – EGYPT

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ABSTRACT

Groundwater is becoming an essential water resource in Egypt due to the deficit in water balance. It is planned to increase withdrawal in 2017 to 7.5 BCM and 3.5 BCM from renewable and non-renewable groundwater aquifers, respectively. In recent years there have been efforts to protect this water resource. The main objective of this paper is studying the impacts of reusing treated wastewater in irrigation after natural attenuation through the vadose zone. Hydrogeological data were collected to characterize the aquifer in Sadat City. A field program was conducted to identify the saturated hydraulic conductivities of the aquifer and the contaminant concentrations in groundwater. Field investigations were conducted by drilling five boreholes in the study area and five monitoring wells were installed. Groundwater flow and solute transport were simulated by VISUAL MODFLOW and MT3D. Four contaminants of concern were selected for simulation: magnesium, chloride, iron and nitrates. Seven irrigation scenarios were tested: primary treated wastewater, secondary treated wastewater, oxidation pond wastewater, tertiary treated wastewater, tertiary for double field water duty, irrigation with two-year rotation (primary treated wastewater and groundwater) and in the last scenario the study area is divided into 3 zones and irrigated with tertiary treated wastewater, oxidation pond wastewater and groundwater. The simulation results of the seven scenarios were presented and compared to the initial concentrations in groundwater. The results show that the contaminants of concern concentrations depend on initial concentrations in groundwater and the quality of the infiltrated water from the vadose zone.

Keywords: Wastewater, groundwater, vadose zone, MODFLOW.

1. INTRODUCTION

The overall objective of this work is to assess the impacts of treated wastewater (TWW) reuse in irrigation on the groundwater aquifer in the study area in Sadat City after vadose zone attenuation. In this research, groundwater numerical models were developed to simulate groundwater flow and transport of the contaminants of concern (COC). Previous vadose zone model results (Abu-Bakr et al. 2015) were used as a basis for MODFLOW recharge fluxes at the water table and for COC concentrations following natural attenuation in the vadose zone.

Numerous studies discussed the solute transport simulations in groundwater and vadose zone, and reuse of treated wastewater in irrigation. Pakorajac (2000) developed a numerical groundwater model (GROW) to assess the problem of high concentration of coliform bacteria in two production wells in Bosnia. The results indicated that the source of pollution was domestic septic tanks upstream of the well field. The research recommended long term monitoring and sewerage system construction. Hai long et al. (2006) simulated wastewater transport and attenuation in a soil aquifer on the Chongming island of China using MODFLOW and MT3DMS to assess the soil infiltration treatment system and interaction between surface water and groundwater. Jovanovic et al., (2008) simulated nitrogen transport in the unsaturated zone using HYDRUS-2D and in groundwater using VISUAL MODFLOW. Candela et al., (2007) evaluated the impacts of treated wastewater utilization on soil and groundwater aquifer in Girona, Spain. The results indicated that the soil and aquifer chemical characteristics of the area were affected by irrigation water quantity and quality. Bekele et al., (2011) applied a soil aquifer treatment approach on infiltrated secondary treated wastewater from the Subiaco wastewater treatment plant in Western Australia. They concluded that the reductions in average concentrations were 30% for phosphorous, 66% for fluoride, 62% for iron and 51% for total organic carbon with a treated wastewater infiltration rate of 17.5 L/ min and residence times of four days in the vadose zone and two days in the aquifer.

These studies guide us to understanding the impacts of treated wastewater reuse on groundwater through (1) developing numerical groundwater models, (2) wastewater transport and attenuation in soil aquifer simulation (3) interaction between surface water and groundwater and through applying soil aquifer treatment approach and (4) the reductions in concentrations through the vadose zone.

2. MATERIALS AND METHODS

2.1 Site Description

The study area is located in Sadat City, Egypt and is shown on Figure 1 an area of 49.4 km^2. The region includes oxidation ponds, a wooded area irrigated with treated wastewater from the oxidation pond, another area irrigated with groundwater and a non-cultivated area.

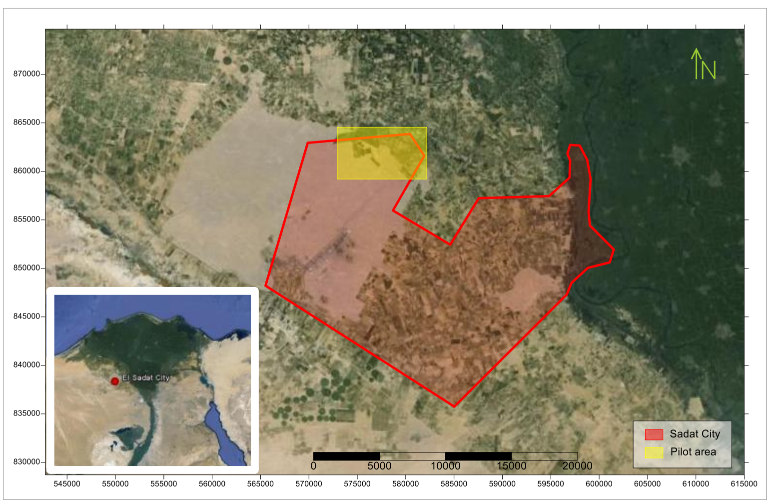

Figure 1. Study Area and Location Plan

2.2 Study Area Hydrogeology

The key hydrogeological formation in the study area ranges in age from Tertiary to Quaternary (Shata et al. 1962 and Said 1962). Tertiary is subdivided into Miocene and Pliocene while Quaternary is subdivided into Holocene and Pleistocene as shown on Figure 2.

There are three main aquifers in the study area; Nile Delta, Moghra and Wadi el Natrun as shown on Figure 3 (RIGW/IWACO 1992). The Nile Delta aquifer is predominantly sand and gravel and can be several hundred meters thick; this aquifer is highly productive with high permeability values ranging from 35 to 75 m/day. The second main aquifer is the Moghra aquifer, characterized by coarse sand and gravel. The Moghra aquifer is also highly productive with permeability values ranging from 15 to 25 m/day. These two aquifers are connected hydraulically to the east of the Wadi El Natrun depression (RIGW/IWACO, 1992). The Wadi el Natrun aquifer is a Pliocene aquifer consisting of sand and clay layers. The Wadi el Natrun aquifer is underlain by the Moghra aquifer, separated by clay layers of

Lower Pliocene age. The aquifer is in hydraulic contact with the overlying Nile Delta aquifer, north of the Wadi el Natrun depression. Figures 4a and 4b show hydrogeological cross-sections at the Sadat City area.

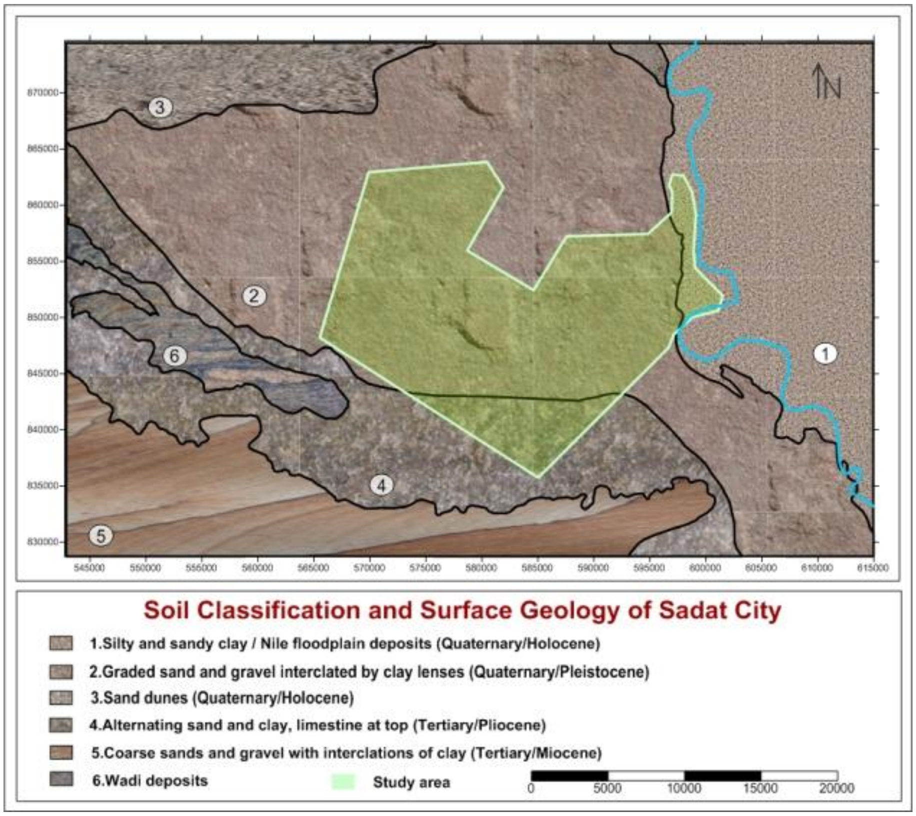

Figure 2: Soil classification and surface geology of the study area

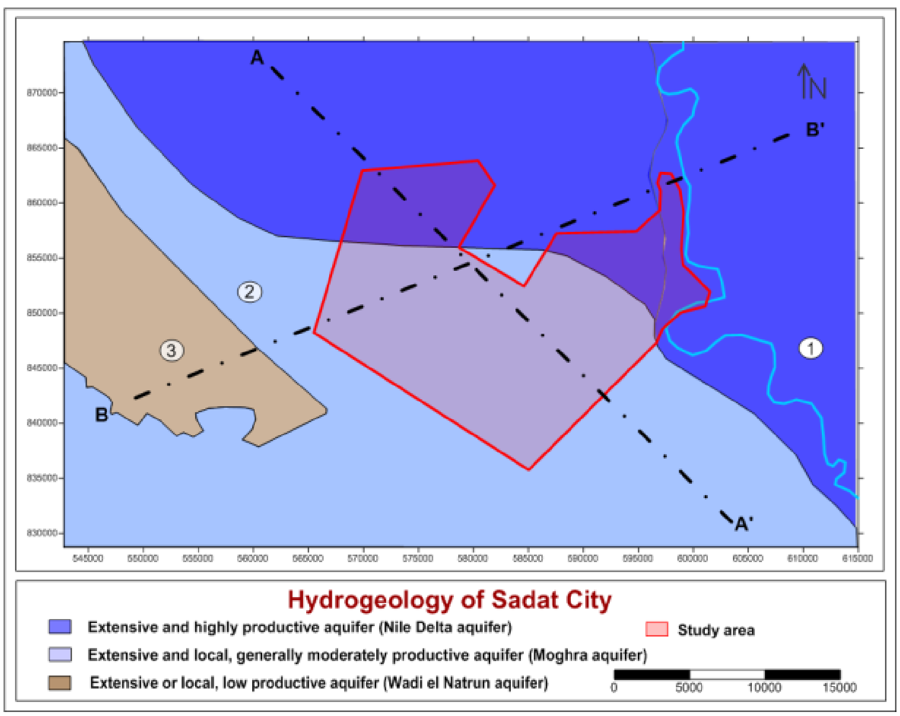

Figure 3: The aquifer system of Sadat City

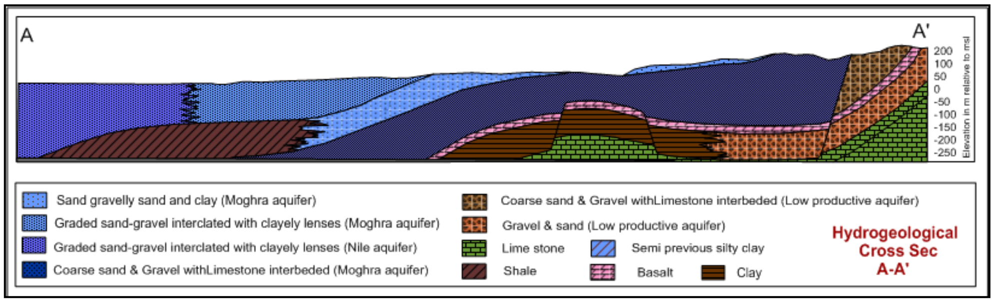

Figure 4.a: Hydrogeological cross-section A-A'

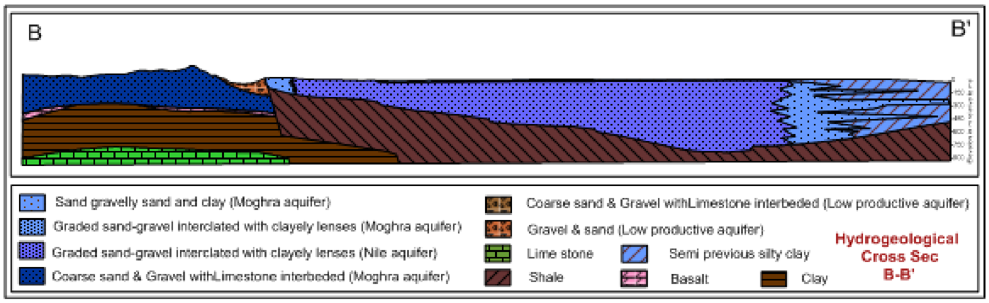

Figure 4.b: Hydrogeological cross-section B-B'

2.3 Hydrogeological Conceptual Model

A hydrogeological conceptual model (Figure 5) was developed to simulate groundwater flow and solute transport and to predict impacts of treated wastewater infiltrated from the vadose zone to the groundwater aquifer. January 1992 was chosen to calibrate the model under equilibrium (steady state) conditions and data from years 1992-2014 were chosen to verify the calibrated model under non-equilibrium (transient) conditions.

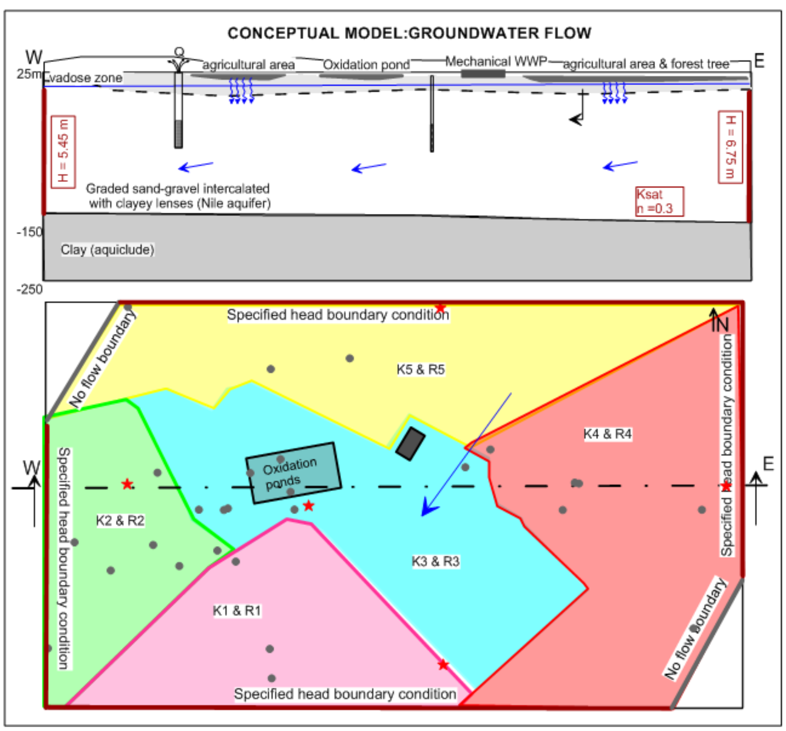

Figure 5: Schematic presentation of the conceptual model

The model domain covers an area of about 49.4 km^2. The grid size is taken as 250m × 250m. The vertical discretization (5, 20, 50 and 100m) is shown in Figure 6. The study area is modelled as one hydrogeological layer, which represents the young quaternary aquifer consisting of graded sand and gravel with thickness ranging from 160m to 200m. At the base of this aquifer is an impervious clay layer. For solute transport, four contaminants of concern (COC: Mg, Cl, Fe, and NO_3) were selected for simulation based on the findings of previous studies (Abu-Bakr et al. 2015).

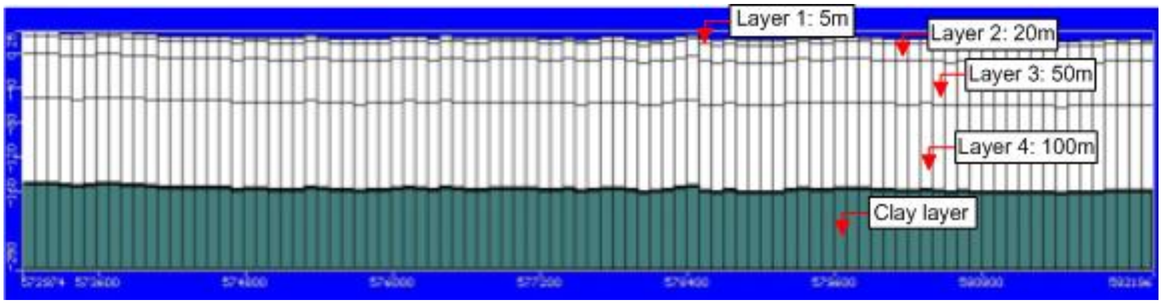

Figure 6: MODFLOW model cross-section showing vertical discretization

2.4 Groundwater Sampling

Five boreholes were drilled and equipped with monitoring wells in the study area. Borehole/monitoring well locations were selected to provide areal coverage of the three types of irrigated lands (land that was irrigated with effluent, land that was irrigated with groundwater and land proposed to be irrigated with treated wastewater) as shown in Figure 7. Groundwater samples were collected to assess the initial condition of groundwater quality. Two groundwater samples were collected from each borehole in August 2014 and May 2015. The laboratory analysis of groundwater samples followed the standard methods for the examination of water as described by the American Public Health Association (1998). Table 1 summarizes the COC average concentrations for the groundwater samples.

Table 1. COC average concentrations in groundwater (mg/l)

Parameter	Mg	Cl	Fe	NO3
Borehole1	17	50	0.7	1
Borehole2	18	43.98	0.964	1
Borehole3	16	60.99	0.5	5
Borehole4	29.25	200	0.36	21.8
Borehole5	37	335.3	0.33	10.1

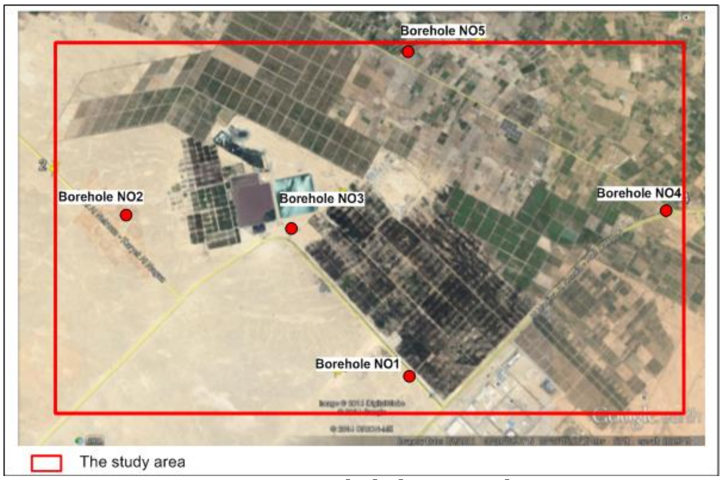

Figure 7: Borehole location plan

3. RESULTS AND DISCUSSION

3.1 Groundwater Flow Simulation with VISUAL MODFLOW

A numerical groundwater model constructed and run with VISUAL MODFLOW code is used for flow and solute transport simulation for the aquifer system. The model is used to evaluate the impacts of reuse of treated wastewater in irrigation on the groundwater after the vadose zone natural attenuation.

Year 1992 is selected as a steady state year because significant changes in water use in Sadat city began in 1992, including substantial increases in groundwater withdrawal and decreases in water supplied to agricultural use. According to 1992 data the groundwater flow direction in steady state is from the northeast to southwest in 1992 (Figure 8). According to 2002 and 2014 data, groundwater flow direction changed slightly over time and was trending north to south. No flow boundary conditions are considered to exist at the southeastern and northwestern boundaries of the model domain. The northern boundary is simulated as a variable general head boundary with time (1992, 2002 and 2014) according to field investigations and groundwater monitoring data. The lower boundary of the aquifer system is treated as a no flow boundary or aquiclude (impervious clay layer). Finally, the upper boundary is defined as a recharge boundary which is obtained from HYDRUS-1D simulations as per (Abu-Bakr et al. 2015) as input in VISUAL MODFLOW. The recharge rates R1, R2 R3, R4 and R5 in areas surrounding the five boreholes (B1, B2, B3, B4 and B5) are summarized in Table 2.

Table 2. Output bottom flux values obtained with HYDRUS-1D for the period from 1992 to 2042 and used in VISUAL MODFLOW (mm/yr)

Parameter	R1	R2	R3	R4	R5
time=0 to 3650 days	190.0	0.00	100.0	1000	900.0
time=3650 to 8030 days	842.0	667.0	917.0	917.1	708.0
time=8030 to 18250 days	928.6	785.7	928.6	892.9	696.4

According to Abu-Bakr et al. (2015), the values of the coefficient of permeability are measured using a permeability test for each linear vertical meter along each of the five boreholes. The average values of saturated hydraulic conductivity are 15, 24, 17, 16 and 32 m/d for boreholes B1, B2, B3, B4 and B5, respectively.

The calibration process relied on a number of observation wells providing head data in the study area. The model is calibrated against the available average annual groundwater heads in January 1992 under steady state conditions. The model is then run under transient conditions from 1992 to 2014 using measured heads at 2002 and 2014. Figure 8 shows calculated groundwater levels at 1992 and Figure 9 shows the calibration curve.

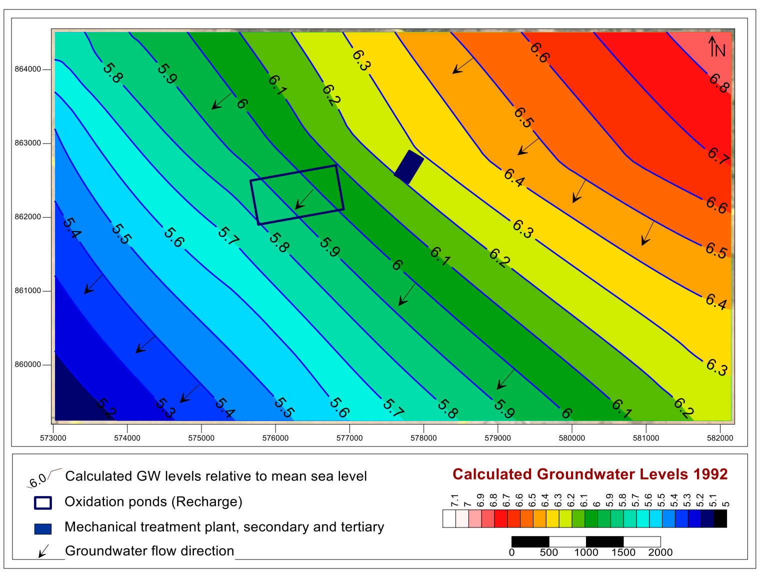

Figure 8: Calculated groundwater levels 1992

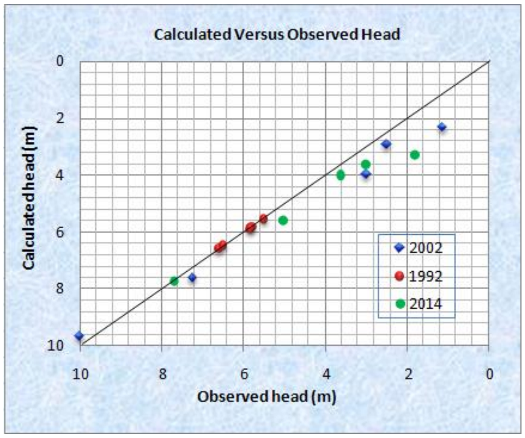

Figure 9: Calculated versus observed heads for years 1992, 2002 and 2014

3.2 Solute Transport Simulation and Irrigation Scenarios

MT3D is used to simulate the transport of the COC (Mg, Cl, Fe and NO_3) for a simulation period of 10220 days from August 2014 to August 2042. The initial contaminant concentrations in groundwater were assigned according to groundwater sample analysis results in August 2014. The values of COC concentrations in recharged water were taken from HYDRUS-1D as per Abu-Bakr et al. (2015).

Seven irrigation scenarios were developed to simulate flow and transport. These scenarios are:
(1) Primary treated wastewater;
(2) Secondary treated wastewater;
(3) Oxidation pond;
(4) Tertiary treated wastewater;
(5) Tertiary treated wastewater for double the field water duty;
(6) Irrigation with two year rotation (primary treated wastewater and groundwater); and,
(7) Dividing the study area to 3 zones and irrigation with tertiary treated wastewater (area surrounding B1&B2), oxidation pond water (area surrounding B3) and groundwater (area surrounding B4 & B5).

Model simulations have been completed to predict the changes in groundwater quality after irrigation for each scenario. The predicted COC concentrations were compared to World Health Organization (WHO) drinking water standards and to Food and Agriculture Organization (FAO) irrigation water standards. The comparison between COC concentrations in groundwater for the seven scenarios at five locations in the aquifer (i.e., the five boreholes) in August 2042 with groundwater initial concentrations is summarized in Figure 10 and discussed below.

3.2.1 Magnesium (Mg)

The highest Mg concentration occurs at the north area surrounding boreholes B3, B4 and B5.
- For B1 concentration decreases for all scenarios except scenarios 6 and 7.
- For B2 concentration increases for all scenarios except for scenario 5.
- For B3 concentration increases for all scenarios except for scenario 5.
- For B4 concentration decreases for all scenarios.
- For B5 concentration decreases for all scenarios except for scenario 7.

These results are most likely due to Mg concentrations in the vadose zone bottom flux due to irrigation being less than the initial Mg concentration in groundwater.

3.2.2 Chloride (Cl)

The highest Cl concentration occurs at the north area surrounding boreholes B3, B4 and B5.
- For B1, B2, B3 and B4 concentration increases for all scenarios because Cl concentrations in wastewater were greater than Cl concentrations in groundwater.

- For B5 concentration decreases for all scenarios except for scenario 7 because the Cl concentration in B5 was greater than the Cl concentration in wastewater.

These results are most likely due to Cl concentrations in the vadose zone bottom flux due to irrigation being greater than initial Cl concentration in groundwater except in the area which surrounds B5.

3.2.3 Iron (Fe)

The highest values of Fe concentration occur in proximity to boreholes B1, B4 and B5. Fe concentration increases with time in all irrigation scenarios except for scenario 3, most likely because Fe concentrations in the vadose zone bottom flux due to irrigation water were greater than initial Fe concentrations in groundwater.

3.2.4 Nitrate (NO_3)

The highest NO_3 concentration occurs at the north area surrounding boreholes B3, B4 and B5. NO_3 concentration increases with time, most likely because NO_3 concentrations in the vadose zone bottom flux due to irrigation water were greater than initial NO_3 concentrations in groundwater.

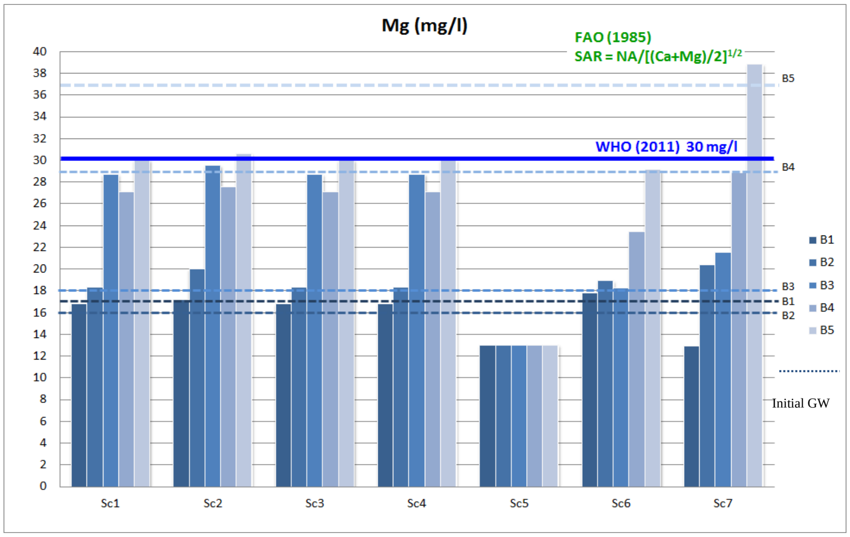

Figure 10.a: Comparison between Mg concentrations in groundwater from GW models results for the seven scenarios for five boreholes at January 2042 with initial groundwater concentrations, FAO and WHO guidelines

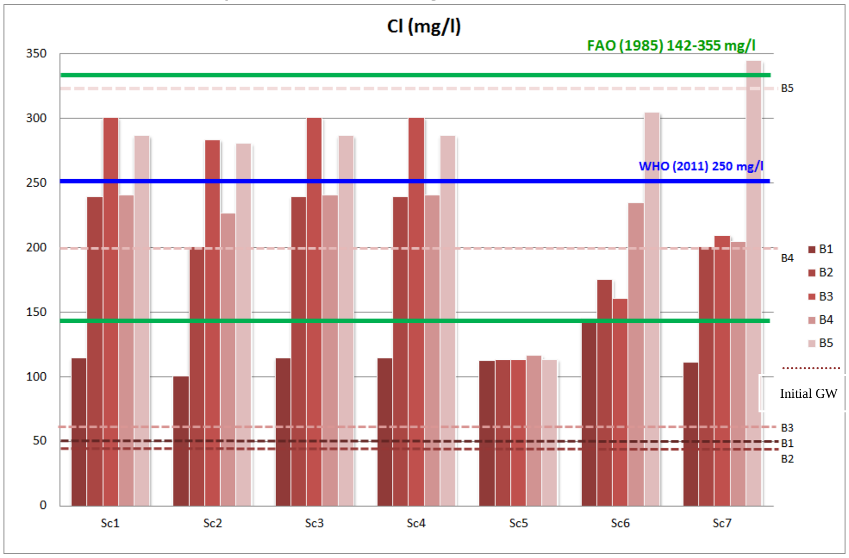

Figure 10.b: Comparison between Cl concentrations in groundwater from GW models results for the seven scenarios for five boreholes at January 2042 with initial groundwater concentrations, FAO and WHO guidelines

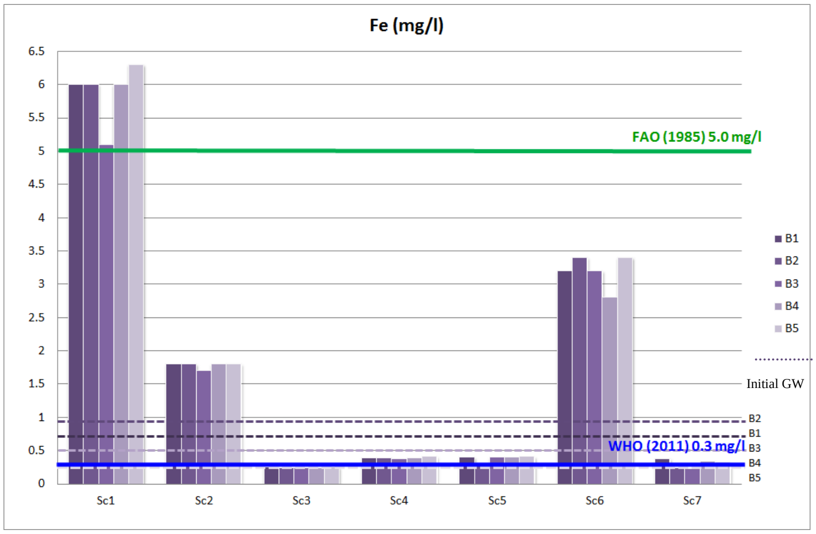

Figure 10.c: Comparison between Fe concentrations in groundwater from GW models results for the seven scenarios for five boreholes at January 2042 with initial groundwater concentrations, FAO and WHO guidelines

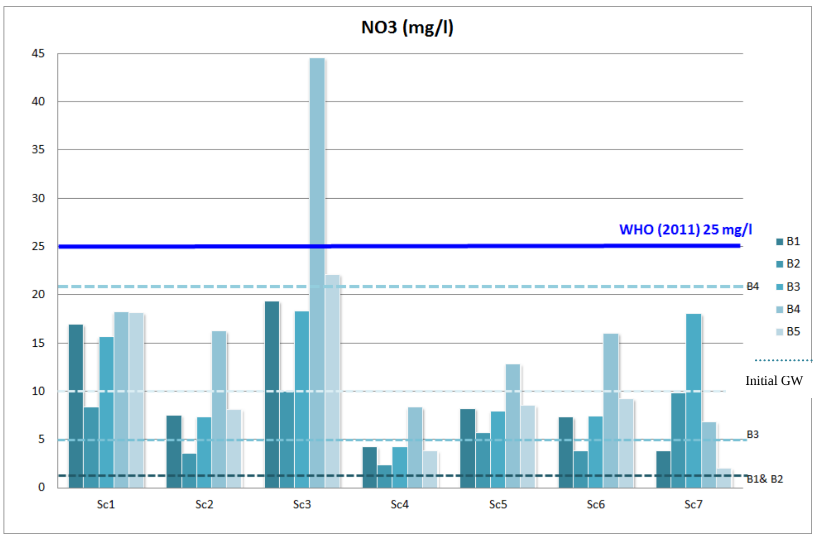

Figure 10.d: Comparison between NO3 concentrations in groundwater from GW models results for the seven scenarios for five boreholes at January 2042 with initial groundwater concentrations, FAO and WHO guidelines

4. CONCLUSION

This paper presents the feasibility of reusing treated wastewater in irrigation and the impacts on a key groundwater aquifer for the study area in Sadat City, Egypt. The study area covers 49.4 km^2. The region includes oxidation ponds, a wooded area irrigated with treated wastewater from the oxidation pond, another area irrigated with groundwater and a non-cultivated area.. Groundwater samples were collected from five boreholes. Four contaminants of concern (COC) were selected for analysis and simulation: Magnesium (Mg), Chloride (Cl), Iron (Fe) and Nitrate (NO_3). A regional groundwater model was developed using VISUAL MODFLOW and MT3D. The rate of recharge and COC concentrations in the water percolating into the groundwater aquifer were obtained from HYDRUS-1D (Abu-Bakr et al. 2015) and used as inputs for VISUAL MODFLOW.

Seven irrigation scenarios were selected to simulate groundwater flow and transport according to quality of irrigation water and irrigation rate. According to groundwater simulation results, the highest predicted concentrations of Mg, Cl and NO_3 concentration in year 2042 are at the north area in close proximity to boreholes B3, B4 and B5; however, the highest predicted concentrations of Fe occur in close proximity to boreholes B1, B4 and B5. The results indicate that COC concentrations were highly affected by the initial soil and groundwater concentrations, irrigation water quality, irrigation rate, bottom flux (and concentration) from the vadose zone, soil contaminant transport parameters, reaction parameters, longitudinal dispersivity, diffusion coefficients, adsorption isotherm coefficient, nitrification and denitrification rate constants. Considering WHO and FAO standards and the irrigation scenario simulation results, the three recommended scenarios are 4: irrigation with tertiary treated wastewater, 5: irrigation with tertiary treated wastewater doubling the infiltration rate: and 7: zonal irrigation with tertiary treated wastewater, oxidation pond and by groundwater.

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REFERENCES

Abu-Bakr, H.A., Elkhedr, M., Ghanem, A., and Bazaraa, A. 2015. Evaluation of Treated Wastewater Quality Changes through the Vadose Zone. *Civil and Environmental Research Journal*, 7(7): 111-125.

American Public Health Association for Standard Methods for the Examination of Water and Wastewater 2005.

Asano, T. and Cartruvo. 2004. *Groundwater Recharge with Reclaimed Municipal Wastewater: Health and Regulatory Considerations*, Water Research, California, United States, 38 (8): 1941-1951.

Bekele, E., Toze, S., Patterson, B., and Higginson, S. 2011. Managed Aquifer Recharge of Treated Wastewater: Water Quality Changes Resulting from Infiltration Through the Vadose Zone, *Water Research Journal*, Elsevier, 45: 5764-5772.

Candela, L., Fabregat, S., Josa, A., Suriol, J., Vigues, N., and Mas, J. 2007. Assessment of Soil Groundwater Impacts by Treated Urban Wastewater Reuse, A Case Study Application in a Golf Course (Girona, Spain), *Science of the Total Environment*, 374 (1): pp. 26-35.

Davis, S. N, and Dewiest, R. J. M. 1966. Hydrogeology, Wiley, New York.

Delleur, J. W. 1991. *The Handbook of Groundwater Engineering*, CRC press, New York.

Freeze, R. A., and Cherry, J. A. 1979. *Groundwater*, Prentice Hall Inc., Englewood Cliffs, New Jersey.

Hai-long, Y and Zu-xin, X. 2006. Numerical Modelling of Wastewater Transport and Degradation in Soil Aquifer, Journal of Hydrodynamics, 18 (5): 597-605.

Icekson, N., and Blanc, R. 1997. Wastewater Treatment and Groundwater Recharge for Reuse in Agriculture-Dan Region Reclamation Project –Shafadan, *International Conference on Water Problems in the Mediterranean Countries*, Israel, 509-513.

Jovanovic, N. Z., Hon, A., Israel, S., Le Maitre, D., Rusinga, F., Soltau, L., Tredoux, G., Fey, MV., Rozanov, A., and Van der Merwe, N., 2008 . *Nitrate Leaching From Soils Cleared of Alien Vegetation*, Water Research Commission Report No K5/1696.

Kumar, C.P. 2001. Common Groundwater Modeling Errors and Remediation, *Journal of Indian Water Resources Society*, 21(4): 149-156.

Mercer, J. W., and Faust, C. R. 1981. Groundwater Modelling, An overview, *Groundwater journal*, 18: 108-115.

Pokrajac, D. 2000. Interrelation of wastewater and groundwater management in the city of Bijeljina in Bosnia, *Urban Water*, 1: 243-255.

RIGW/IWACO. 1992. *Hydrogeological Map of Egypt*, scale 1:2,000,000.

Said, R. 1962. *The geology of Egypt*, Elsevier, Newyork.

Shata, A. 1962. *Remarks on the Geomorphology, Geology and Groundwater Potentialities of the Southern Entrance to the New Valley, the Lower Nubia Area, Egypt*, pp. 273-299.

Zheng, C. E., and Benett, G. D. 2002. *Applied Contaminant Transport Modeling*, 2nd edition, Wiley, New York.