Geologia Croatica | 63/1 | 67–73 | 8 Figs. | Zagreb 2010

Simulation of groundwater mound resulting from proposed artificial recharge of treated sewage effluent case study – Gaza waste water treatment plant, Palestine

Adnan M. Aish

Department of Geology, Faculty of Science, Al Azhar University – Gaza, P.O. Box 1277 Gaza, Palestine; (a.aish@alazhar-gaza.edu)

doi: 104154/gc.2010.04

Geologia Croatica

ABSTRACT

Mounding of the groundwater table beneath recharge sources is of concern as the raised water table approaches closely to near-surface facilities or features. The shape and height of the mound depend on several factors including the recharge rate, hydraulic conductivity and thickness of the aquifer. The objective of this paper is to evaluate the suitability of the study area for a rapid infiltration system of treated wastewater effluent without causing excessive mounding of the water table. A comparison was made between two methods used to estimate ground-water mounding: an analytical approach and a numerical approach. Both approaches incorporate each of the saturated and the unsaturated zones. Results predicted that after 1400 days of groundwater level simulation, the maximum rise of the mound was 18 m in the center of the infiltration pond, and it was almost 17 m at the edges of the pond. As the natural average groundwater level was about 35 m deep in the area of the study, the groundwater mounding caused no problem on the groundwater level. Thus, the planned infiltration was feasible.

Keywords: Artificial recharge, Groundwater modeling, Groundwater mounding

1. INTRODUCTION

Artificial groundwater recharging is one of the most important means required to increase the natural supply of groundwater, and it is an augmentation of the natural movement of the surface water into underground formations by artificially changing natural conditions (CHOUDHARY, 2007). The timing and quantity of recharge reaching the water table has significant consequences for water resources and for the movement of pollutants into groundwater (LEE, 2006). Two types of groundwater recharge are commonly used with reclaimed municipal wastewater: surface spreading or percolation, and direct aquifer injection. Surface spreading is the oldest, simplest, and most widely applied method of artificial recharge. In surface spreading, recharge waters such as treated municipal wastewater percolate from spreading basins through the unsaturated soil and ground vadose zone. Infiltration basins methods are the most favored ones of recharge because they allow efficient use of space and they require only simple maintenance. Infiltration rates are highest where soil and vegetation are undisturbed (TODD, 1980). Advantages of groundwater recharge by surface spreading include: (A) Groundwater supplies may be replenished in the vicinity of metropolitan and agricultural areas where groundwater over-drafting is severe. (B) Surface spreading provides the added benefits of the treatment effect of soils and transporting facilities of aquifers. Direct subsurface recharge is achieved when water is placed directly into an aquifer. In the direct injection, highly treated reclaimed water is pumped directly into the groundwater zone, usually into a well-confined aquifer. Groundwater recharge by direct injection is practiced: (A) where groundwater is deep or where the topography or existing land use makes surface spreading impractical or too expensive. (B) When direct injection is particularly effective in creating freshwater barriers in coastal aquifers against intrusion of saltwater. In arid climates where the practice of groundwater recharge is most imperative, recharge will occur through such means as dry riverbeds and spreading basins, and in most situations there will be an unsaturated zone between the surface and the aquifer (CROOK, 1990). Pretreatment requirements for groundwater recharge vary considerably depending upon the purpose of groundwater recharge, sources of reclaimed wastewater, recharge methods, location, and, more importantly, public acceptance. Although the surface spreading method of groundwater recharge is in itself an effective form of wastewater treatment, some level of pretreatment must be provided to municipal wastewater before it can be used for groundwater recharge (ASANO, 1980). Artificial recharge by spreading waters on a rectangular area is common in practice (WALTON, 1970). The variation of the water table beneath the recharged area is of practical interest. Analytical solutions describing the variation of the water table of an infinite aquifer in response to deep percolation have been reported by GLOVER (1961), MARMION (1962), MARINO (1967, 1974), HANTUSH (1967), BIANCHI & MUCKEL (1970), RAO & SARMA (1983), and LATINOPOULOS (1986). Most of these solutions are based on the assumption of a constant rate of recharge applied continuously or periodically. It is a common assumption to all these solutions that percolation moves vertically downward until it joins the main groundwater body. It is also groundwater flows and takes place in a homogeneous, isotropic, unconfined aquifer with hydraulic properties that remain constant with both time and space. An analytical and numerical solution of the transient groundwater flow is used in this study in order to predict the time-dependent of groundwater response in case of the planned artificial infiltration from Gaza waste water treatment Plant.

2. MATERIAL AND METHODS

2.1. Area of study

Gaza Strip is located to the south-eastern coast of the Mediterranean Sea, between longitudes 34° 2” and 34° 25” East, and latitudes 31° 16” and 31° 45” North. It is an area of about 365 km^2 and it is 45 km long and its width ranges of 6–12 km approximately (Fig. 1). It is located in the transitional zone between a temperate Mediterranean climate in the west and north, and an arid desert climate of the Sinai Peninsula on the east and south.

The population characteristics are strongly influenced by political developments, which have played a significant role in their growth and distribution along the Gaza Strip. The total population is around 1.300.000 (PCBS, 2002). Temperature gradually changes throughout the year; it reaches its maximum in August (summer) and its minimum in January (winter). The average of the monthly maximum temperature ranges between 17.6 C° for January to 29.4 C° for August. The average of the monthly minimum temperature for January is about 9.6 C° and 22.7 for August. The rainfall in the Gaza Strip gradually decreases from the north to the south. The values range from 410 mm/year in the north to 230 mm/year in the south. Gaza topography is characterized by elongated ridges and depressions, dry streambeds and shifting sand dunes. The ridges and depressions generally extend NE–SW direction, parallel to the coastline. Ridges are narrow and consist primarily of Pleistocene-Holocen sandstone (locally named as Kurkar) alternated with red brown layer (locally named as Hamra). In the south these features tend to be covered by sand dunes. Land surface elevations range from mean sea level to about 110 m above mean sea level. The soil in the Gaza Strip is composed mainly of three types, sands, clay and loess. The sandy soil is found along the coastline extending from south to outside the northern border of the Strip, at the form of sand dunes. The thickness of sand fluctuates from two meters to about 50 meters due to the hilly shape of the dunes. Clay soil is found in the north eastern part of the Gaza Strip. Loess soil is found around Wadis, where the approximate thickness reaches about 25 to 30 m. (JURY & GARDNER, 1991). The geology of coastal aquifer of the Gaza strip consists of the Pleistocene age Kurkar group and recent (Holocene age) sand dunes. The Kurkar group consists of marine and Aeolian calcareous sandstone (Kurkar), reddish silty sandstone (Hamra), silts, clays, unconsolidated sands and conglomerates (GVIRTZMAN, 1984). Regionally, the Kurkar group is distributed in a belt parallel to the coastline, from Haifa in the north to the Sinai in the south. Near the Gaza Strip, the belt extends about 15–20 km inland, where it unconformable overlies Eocene age chalks and limestones (the Eocene), or the Miocene-Pliocene age saqiye group, a 400–1000 m thick aquitard beneath the Gaza Strip, consisting of a sequence of marls, marine shale’s and claystones. The Kurkar group consists of complex sequence of coastal, near-shore and marine sedi-

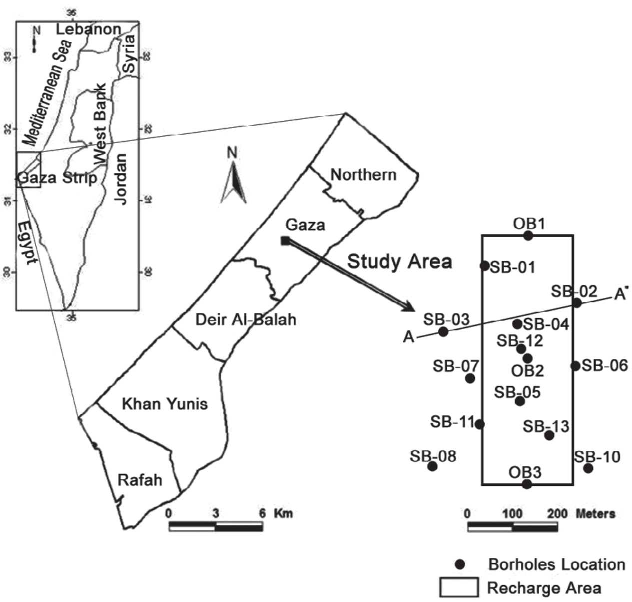

Figure 1: Geographic location of the Gaza Strip with a schematic illustration of the recharge area and drilled boreholes.

ments. The Gaza Strip Pleistocene granular aquifer is an extension of the Mediterranean seashore coastal aquifer. It extends from Askalan (Ashqelon) in the North to Rafah in the south, and from the seashore to 10 km inland. The aquifer is composed of different layers of dune sandstone, silt clays and loams appearing as lenses, which begin at the coast and feather out to about 5 km from the sea, separating the aquifer into major upper and deep sub aquifers. The aquifer is built upon the marine marly clay Saqiye Group (GOLDENBERG, 1992). In the east-south part of the Gaza Strip, the coastal aquifer is relatively thin and there are no discernible sub aquifers (MELLOUL & COLLIN, 1994). The Gaza aquifer is a major component of the water resources in the area. It is naturally recharged by precipitation and additional recharge occurs by irrigation return flow. The consumption has increased substantially over the past years; the total groundwater use in year 2000 is about 145 Mm3/year, the agricultural use about 90 Mm^3/year, domestic and industrial consumption about 51 Mm3/year (METCALF & EDDY, 2000). The groundwater level ranges between 5 m below mean sea level (msl) to about 6 m above mean sea level.

Area of study was the central wastewater treatment plant of the Gaza Strip, which was located to the south-east of Gaza City. In the year 2007, the plant received about 60.000 cubic meters per day. The plant was close to less urbanized and agricultural areas. The specific location within the plant was the infiltration basin with dimensions 200m X 450 m. Figure 1 shows the location of the Gaza Strip and a schematic illustration of the wastewater treatment plant and recharge area as well as the 12 drilled boreholes.

The hydrogeological investigation and laboratory analysis was carried out in the area of study by Palestinian Water Authority where the recharge basin was located to obtain subsurface hydrogeologic properties of the aquifer and unsaturated zone to determine the suitability of the location for artificial recharge. The descriptions and interpretations of the site-specific hydrogeology are based on geological information collected at these locations. The site was covered with a sand layer with a thickness between 3 and 12 meters. In the unsaturated zone, clay lenses were present but there were no information available regarding the extension outside the site. The layers were semi permeable which means that they allowed water to pass through. Analysis of soil samples showed that the hydraulic conductivity of unsaturated zone had an average of 18 m/d. The groundwater level was found at approximately 0.5 m above sea level, which means that the thickness of the saturated aquifer varied from approximately 30 m to 40 m as shown in the geological cross-section A–A⁻. The location of the geological cross-section is shown in (Fig. 2). The pumping test using aquifer test model by means of a Theis-curve fit indicates that the phreatic aquifer has an average hydraulic conductivity of 24 m/d, and a specific yield of 0.24. The recharge area is around 90,000 m^2 and the expected average treatment plant discharge rate is 60,000 m^3/d. This would yield an infiltration rate of 0.67 m/d on average.

2.2. Groundwater mounding analysis

To develop predictions of the mound geometry that may result below an infiltration system, both analytical and numerical methods were employed. Evaluations of these methods were conducted by using data gathered in the field including water-level measurements, and hydrogeological data collected from Palestinian Water Authority.

3. ANALYTICAL MODELING

3.1. Methods

The analytical solution provided by HANTUSH (1967) to predict mounding beneath a rectangular infiltration basin was applied by using a public-domain software program called MOUNDHT (FINNEMORE, 1995). The method assumes that a constant vertical recharge is applied to a rectangular infiltration area of fixed dimension, and that the water table mound remains below the base of the infiltration area at all times. The dimensions of the mound are governed by the basin size and shape, recharge rate and aquifer characteristics. Most solutions are based on the usual assumptions of homogeneous and isotropic aquifers and vertical recharge at a uniform rate. The shape of a mound beneath a rectangular recharge area, expressed by Z_m, is the mound height in function of time and space (Fig. 3), depending upon the artificial recharge flux, the specific yield and hydraulic conductivity of the aquifer.

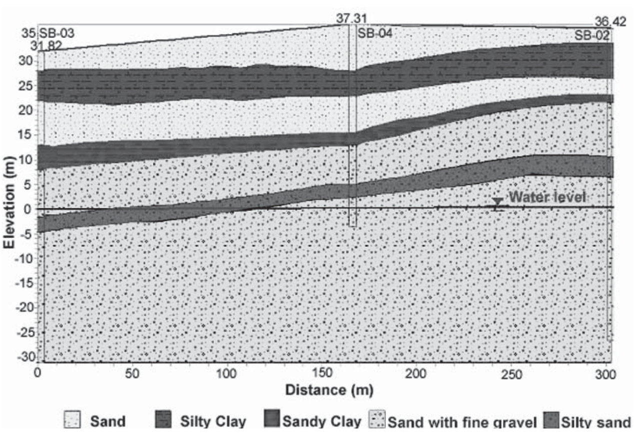

Figure 2: Geological cross-section A–A⁻ in the area of study (Fig. 1).

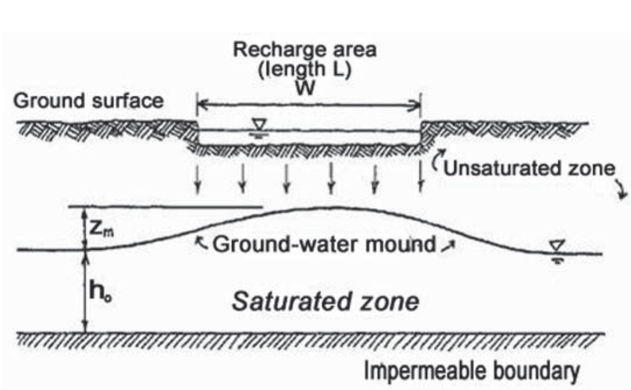

Figure 3: Diagrammatic representation of the groundwater mounding (FINNEMORE, 1995).

From equation of HANTUSH (1967), the maximum height Z_m of the water table at the center of the mound, during water table rise caused by percolation to the water table from a rectangular recharge area, is given by

$$h_m^2 - h_0^2 = \frac{2It\bar{h}}{S_y} S^*(\alpha, \beta) \qquad (1)$$

where h_0 is the initial height of the water table before percolation began, I is the constant rate of percolation, t is the time since percolation began, $\bar{h} = 0.5\,(h_0 + h_m)$, S_y is the specific yield of the aquifer, $S^*(\alpha, \beta)$ is the Hantushs mound function given by

$$\alpha = \frac{L}{4}\left(\frac{S_y}{K\bar{h}t}\right)^{\frac{1}{2}} \qquad (2)$$

$$\beta = \frac{W}{L}\alpha \qquad (3)$$

where L is the recharge area length, W is its width, K is the hydraulic conductivity of the aquifer. Because

$$\left(h_m^2 - h_0^2\right) = \left(h_m + h_0\right)\left(h_m - h_0\right) = 2\bar{h}z_m,$$

where Z_m is the maximum mound height at time t, equation (1) can be rewritten as

$$Z_m = \frac{It}{Sy} S^*(\alpha, \beta) \qquad (4)$$

The convenience and accuracy of equation evaluation provided by the computer, when added to the high prediction accuracy and wide range of applicability of Hantushs method, make this a very attractive means of predicting groundwater mound heights. A computer program named MOUNDHT was applied to calculate groundwater mound in the area of study.

3.2. Input Parameters

Using the data obtained from the hydrogeological study, a recharge value is 0.67 m/d, and a rectangular recharge basin is 200 m x 450 m, hydraulic conductivity is 24 m/d, initial depth of saturated zone is 45 m and specific yield is 0.24. The obtained results are as shown in (Fig. 4). At the center of the basin after 1400 days, the height of groundwater mound rises to about 18 m above the present groundwater table. Therefore, an analytical solution such as the Hantush method is considered an approximation of the field response of the water table.

4. NUMERICAL MODELING

4.1. Methods

To further evaluate the proposed infiltration system, groundwater flow simulations were made by using the three-dimensional numerical model MODFLOW (HARBAUGH & MCDONALD, 1996). A commercial pre- and post- processor software program, Visual MODFLOW, was used to conduct

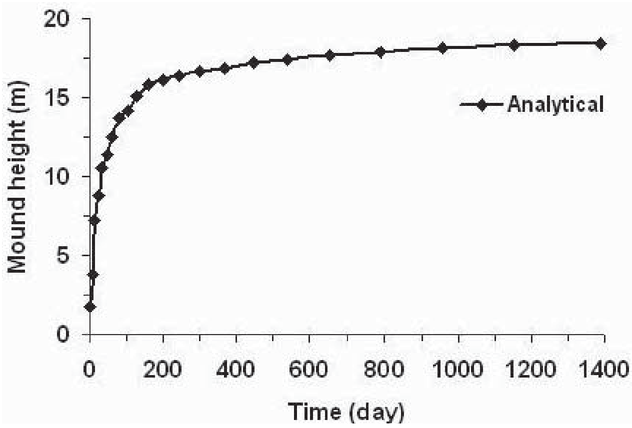

Figure 4: Height of the groundwater mound under the center of the basin.

the modeling. MODFLOW numerically evaluates the partial differential equations for groundwater flow (MCDONALD & HARBAUGH, 1988).

$$K_h \frac{\partial^2 h}{\partial x^2} + K_h \frac{\partial^2 h}{\partial y^2} + K_v \frac{\partial^2 h}{\partial z^2} - W = S_s \frac{\partial h}{\partial t} \qquad (5)$$

where K_h is the horizontal hydraulic conductivity, K_v is the vertical hydraulic conductivity, h is the hydraulic head, $S_{s\ is}$ the specific storativity, W is the source/sink term, t is the time and x, y, z are the space coordinates.

The interface of visual MODFLOW is divided into three modules: the Input Module, the Run Module, and the Output Module. The Input Module provides users with the ability to create a graphical three-dimensional representation of the area of study. The modeler can assign values directly to the area of study and the software creates the appropriate files. The Run Module allows the user to alter the parameters and options that are run specific, such as the solver package, recharge and rewetting applications and the tolerances for convergence. The Output Module provides the user with the ability to display all of the modeling and calibration results. Although Visual MODFLOW graphically represents the area of study, the inputs, and the outputs files are translated and processed by the version of MODFLOW 2000 (HARBAUGH et al., 2000).

4.2. Conceptual model and grid design

The aquifer is considered as unconfined aquifer with a stratigraphy of 7 layers with alternating finer and coarser unconsolidated sediments belonging to the sandstone (Kurkar) formation. The layers are approximately horizontal, with a small inclination towards the sea as shown in Figure 2. The aquifer extends to areas far outside the chosen model domain. The model domain encloses an area of 6.6 x 5.8 km centered on the infiltration area. The grid is chosen to be regular with a cell size of 50 m, with 132 columns and 116 rows. The model boundaries can be described in east of the Gaza Strip as a general head boundary; whereas in the west of Gaza Strip, it is a zero constant head boundary and both north and south are no flow boundary according to the water level contour map. The recharge was calculated with the WetSpass-model (AISH et al., 2008). WetSpass has a flexible structure and is fully integrated within the GIS ArcView, based upon land use, soil type, some meteorological parameters, slope, groundwater depth, wind speed and potential evapotranspiration. WetSpass calculates the spatially distributed groundwater recharge for the model. The spatially distributed recharge output of WetSpass model can improve the prediction of simulated groundwater level and the locations of discharge and recharge areas for a steady state groundwater models. The groundwater abstraction was calculated from agricultural and municipal wells, according to Palestinian Water Authority measurements.

4.3. Input Parameters

Hydraulic property values are assigned based on the hydrogeological investigation and previous studies. The hydraulic conductivity is assumed to be constant for each layer. The horizontal hydraulic conductivity of the sandstone aquifer is 24 m/d, specific storage is 2.2 x 10^{-6} (m^{-1}) specific yield is 0.24 and total porosity is 0.30. The horizontal hydraulic conductivity of the clay layer is 0.2 m/d, specific storage is 3.1 x 10^{-6} (m^{-1}), specific yield is 0.10 and total porosity is 0.45. The vertical conductivity was set to 10% of the horizontal hydraulic conductivity. The measured ground water level used for initial condition

4.4. Model Calibration

Calibration of the model was performed using available of 11 piezometers data. During the calibration the differences between measured and calculated piezometric heads were minimized by trial and error adjustment of the hydraulic conductivities. Figure 5 shows the comparison between the calculated groundwater levels and average measured values. As it appears in (Fig. 5), there is correlation coefficiency of 0.99 between measured phreatic level and simulated phreatic level. Other indicators of the goodness of fit are the root mean square error of 0.114 m and the mean absolute error of 0.099 m. Hence, all tests indicate good correspondence between simulated and measured groundwater levels.

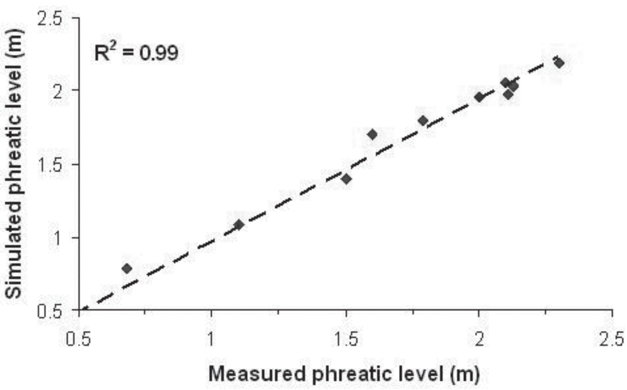

Figure 5: Comparison of measured and calculated groundwater levels.

5. RESULTS AND DISCUSSION

Three observation wells OB1, OB2 and OB3 in the center and at the edges of the recharge area were used for the study of the resulting groundwater mound. Simulation shows that the groundwater mound beneath the center of an infiltration area can be expected to rise around 18 m and to around 16 to 17 m at the edges after 1400 days as depicted in (Fig. 6).

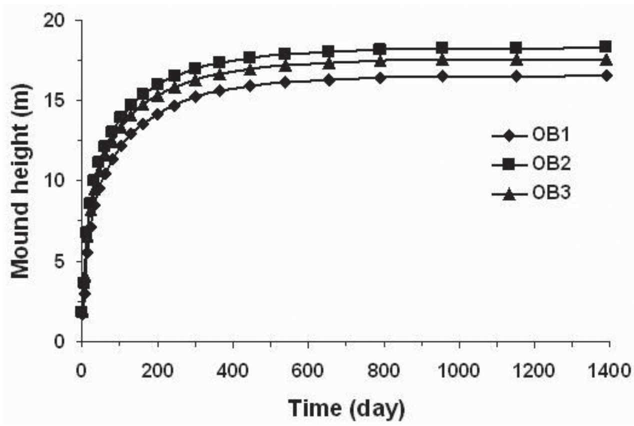

Figure 6: Height of the groundwater mound beneath the recharge basin calculated with the numerical model.

The infiltration will result in a rising groundwater table. The rise will be gradual and the full effect will be seen after 1400 days. Figure 7A shows the groundwater level of initial heads (steady state conditions). Simulated groundwater level with infiltration after 100 days shows mound height of approximately 8 meters (Fig. 7B). Then, after 365 days, it showed mound height of approximately 11 meters (Fig. 7C). Then, after 1400 days of groundwater level simulation, the maximum rise of the mound height of approximately 18 m (Fig. 7D). The model simulations indicate that the water level will increase in the study area due to the infiltration.

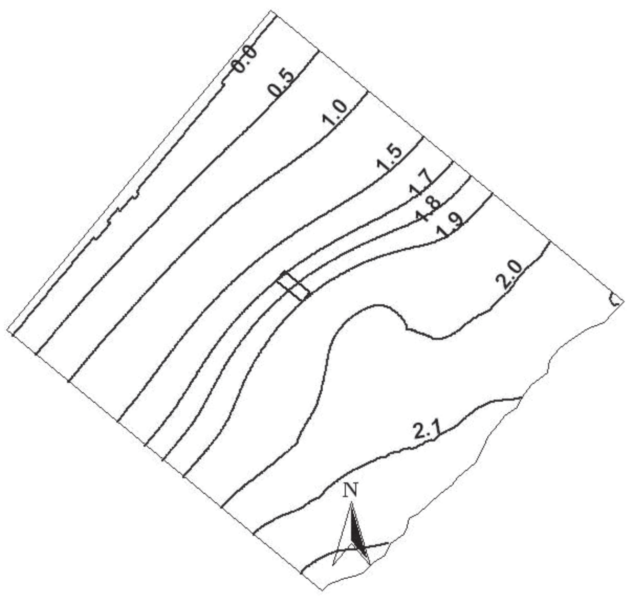

Figure 7A: Simulated groundwater levels in steady state conditions.

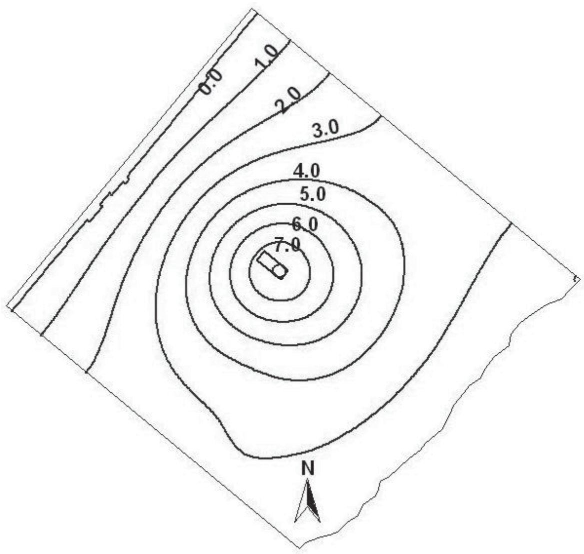

Figure 7B: simulated groundwater levels with infiltration after 100 days

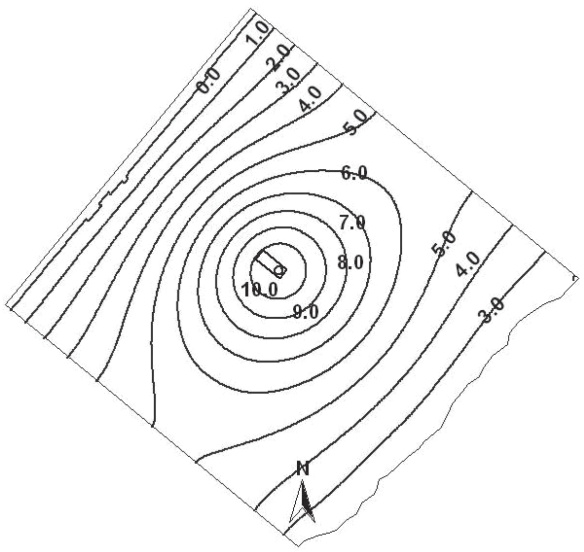

Figure 7C: simulated groundwater levels with infiltration after 365 days

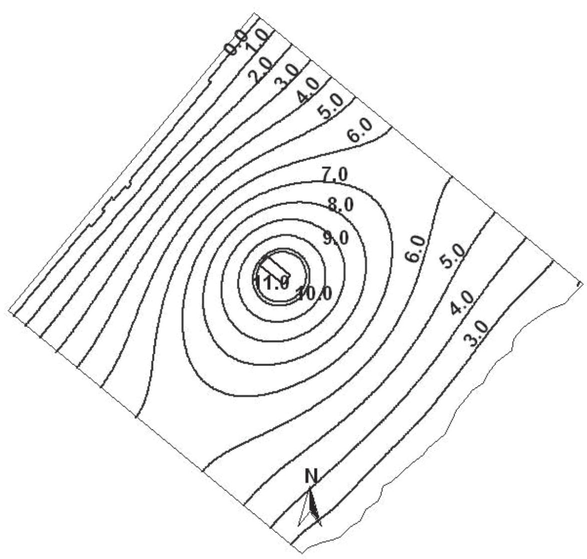

Figure 7D: simulated groundwater levels with infiltration after 1400 days.

When the growth of the groundwater mound obtained with the model simulation was compared to the analytical solution (Fig. 8), one could notice correspondence between numerical and analytical simulation. The small differences can be explained by the assumptions that were made in case of the analytical solution, i.e. a rectangular basin and an average groundwater table elevation to calculate the aquifer transmissivity. Also, in the groundwater model, different ground layers are taken into account. At 1400 days both methods gave similar results, which indicate that the rise of the groundwater mound was about 18 m, which did not cause any problem to the site or surrounding areas.

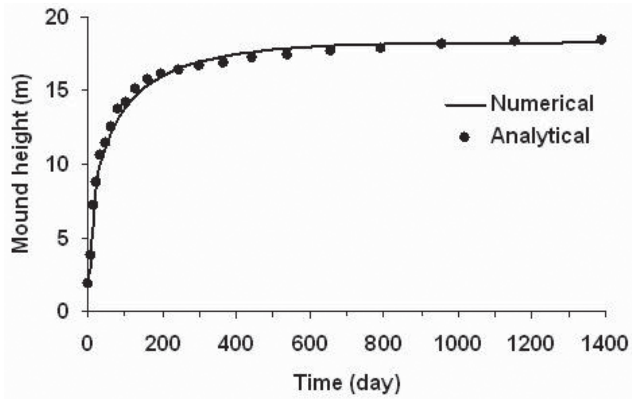

Figure 8: Comparison of numerical and analytical results.

6. CONCLUSIONS

Both analytical and numerical modeling methods were used to predict the mound geometry that may develop in the unconfined aquifer beneath a proposed rapid infiltration system. The hydrogeological field and laboratory analyses were used to develop an analytical and a numerical model of the area of study. A steady-state, average-maximum treatment plant discharge rate of 60.000 m^3/day was used for the analyses. The results of the numerical model simulations were compared with an analytical solution; both were found to be identical. Thus, the groundwater mound would rise to about 8 m after 100 days and to about 11m after 365 days and about 18 m after 1400 days. As the unsaturated zone was about 30 to 40 m thick, the artificial infiltration was considered to be feasible.

REFERENCES

AISH, A., BATELAAN, O. & DE SMEDT, F. (2008): Distributed recharge estimation for groundwater modeling using WetSpass model, case study – Gaza strip, Palestine. Submitting to the Arabian journal for science and engineering (in press).

ASANO, T. & WASSERMANN, KL. (1980): Groundwater recharges operations in California.– J. Am. Water Works Assoc., 72/7, 380–385.

BIANCHI, W.C. & MUCKEL, D.C. (1970): Groundwater recharges hydrology, ARS 41–161, USDA, 62 p.

CHOUDHARY, M. & CHAHAR, B. (2007): Recharge/seepage from an array of rectangular channels.– Journal of Hydrology, 343, 71–79.

CROOK, J., ASANO, T. & NELLOR, MH. (1990): Groundwater recharge with reclaimed water in California.– Water Environ. Technol., 2/8, 42–49.

FINNEMORE, E.J. (1995): A program to calculate groundwater mound heights.– Groundwater, 33/1, 139–143.

GLOVER, R.E. (1961): Mathematical derivations as pertain to groundwater recharge. Mimeographed report, Agricultural Research Service, U. S. Dept. Agriculture, Ft. Collins, Colo., 81 p.

GOLDENBERG, L.C. (1992): Evaluation of the water balance in the Gaza Strip. Geological Survey, Report TR-GSI/16/92 (in Hebrew).

GVIRTZMAN, G., SHACHNAI, E., BAKLER, N. & ILANI, S. (1984): Stratigraphy of the Kurkar group (Quaternary) of the coastal plain of Israel. Geological Survey of Israel, Current Research, 70–82.

HANTUSH, M.S. (1967): Growth and decay of groundwater mounds in response to uniform percolation.– Water Resources Research, 3, 227–234.

HARBAUGH, A. & MCDONALD, M. (1996): User's documentation for MODFLOW-96, an update to the US Geological Survey modular finite-difference groundwater flow model. US Geological Survey, Open-file report, 96–485.

HARBAUGH, A., BANATA, E., HILL, M. & MCDONALD, M. (2000): The U.S. geological survey modular groundwater model-user guide to modularization concepts and the groundwater flow process.

JURY, W. & GARDNER, W. (1991): Soil physics. Fifth edition. ISBN: 0-471-83108-5, 4–18.

LATINOPOULOS, P. (1986): Analytical solutions for strip basin recharge to aquifers with cauchy boundary conditions.– Journal of Hydrology, 83, 197–206.

LEE, L.J.E., LAWRENCE, D.S.L. & PRICE, M. (2006): Analysis of water-level response to rainfall and implications for recharge pathways in the Chalk aquifer, SE England.– Journal of Hydrology, 330, 604–620.

MARINO, M. A. (1967): Hele-Shaw model study of the growth and decay of groundwater ridges.– Journal of Geophysics Research, 72, 1195–1205.

MARINO, M.A. (1974): Water table fluctuations in response to recharge.– American Society of Civil Engineers, Journal of Irrigation and Drainage Division, 100, 117–125.

MARMION, K.R. (1962): Hydraulics of artificial recharge in non homogeneous formations.– Water Resources Center Contribution, 48, Univ. of California, Berkeley, Calif., 88 p.

MCDONALD, M.G. & HARBAUGH, A.W. (1988): A modular three-dimensional finite difference groundwater flow model.– USGS Techniques of water Resources Investigation Report, book 6, ch A1, 586 p.

MELLOUL, A.J. & COLLIN, M. (1994): The hydrological malaise of the Gaza Strip.– Isr. J. Earth Sci., 43/2, 105–116.

METCALF & EDDY (2000): The Gaza Coastal Aquifer Management Plan – Task 3 Appendix A, USAID, Contract No. 294-C-99-00038-00, 64 p.

PALESTINIAN CENTRAL BUREAU OF STATISTICS (PCBS) (2002): Projected population in the Palestinian territory, Establishments report, Ramallah, Palestine, 5 p.

RAO, N. H. & SARMA, P. B. S. (1983): Recharge to finite aquifer from strip basins.– Journal of Hydrology, 66, 245–252.

TODD, D.K. (1980): Groundwater hydrology, 2nd ed. New York, USA, John Wiley & Sons, 535 p.

WELTON, W.C. (1970): Groundwater resources evaluation. Mc Graw-Hill Book Co., Inc., New York, 664 p.

Manuscript received March 12, 2009
Revised manuscript accepted December 08, 2009
Available online February 28, 2010