Extraction Simulations of Fresh Groundwater Artificial Lenses

Kuznetsov, A. Yakirevich and S. Sorek

Abstract Saltwater upconing occurs during pumping of freshwater overlying saline groundwater. Conventional model to simulate pumping considers water and solute withdrawal through point sinks in the flow and transport equations. We compared this approach with two models of water extraction (one assumes distribution of concentration with depth and the other considers full mixing in the well) that explicitly account for the pumping well geometry and temporal variations of water level and solute concentration in it. The water and solute mass balance equations in the well were solved numerically and coupled with the FEFLOW 5.1 code of density dependent flow and transport in the aquifer. The models were applied to simulate axi symmetrical problem of water extraction from the artificial lens of fresh groundwater. Results of simulations indicate the significant effect of seepage face on water salinity in the well. Mixing of water in the pumping well leads to greater solute fluxes towards the well and increase of salt concentration in extracted water in comparison to other cases. A recirculating flow cell is developed near the well after pumping is terminated. This increases the width of the transition zone between saline and fresh water, and widens the saltwater mound. Increasing time of pumping interval while decreasing its rate influences on concentration of the extracted water only at the beginning pumping interval

Index Terms saline groundwater, freshwater lens, mathematical model, density driven flow, pumping.

I. INTRODUCTION

The problem of saltwater upconing during pumping of freshwater overlying saline groundwater has been intensively studied during last decades. Two continuum mechanics approaches are habitually applied to simulate the upconing process: the sharp interface model (Muskat, 1946; Chandler and McWhorter, 1975; Dagan et al, 1998; Motz, 1992), and the miscible displacement model, which is based on density dependent flow and transport (Diersch et al. 1984; Reilly and Goodman, 1987; Panday et al., 1993; Ma et al, 1997; Zhou et al., 2005). Comparison between these two approaches lead to the following conclusion: a transition zone could be considered thin if it is less than one third the thickness of the freshwater zone (Reilly and Goodman, 1987), and the critical pumping rate based on the miscible displacement model is significantly greater than that suggested by the sharp interface model (Panday et al., 1993). The above mentioned differences between the predictions of these two models also depend on the spatial scale of the problem.

Mathematically, pumping is usually simulated by water and solute withdrawal through a point sink when solving axisymmetric or three-dimensional problem. Thus, the actual geometry of pumping well is disregarded and the processes of water fluxes around and into the well are not considered in details. The simulations are also performed for a relatively wide and thick freshwater zone for the problems associated with seawater intrusion or pumping large natural freshwater lenses.

In desert conditions, an artificial lens of fresh groundwater (ALFGW) can be created by infiltrating runoff water collected during precipitation into the saline groundwater (Leshinsky, 1970, Rogovskaya et al., 1986; Mamieva, 1999). The ALFGW has small thickness (3-8 m) and its transition zone between salt and fresh water is narrow (1-2 m), in comparison to the typical spatial scale of the region. Water is extracted from the free surface of an open vertical well crossing the upper or middle part of the ALFGW. Decrease of water level in the well leads to the development of a seepage face in its upper portion. Pumping regime influences the ratio between inflow of brackish water at the lower part of the well and freshwater influxes through the seepage face, thus, affecting the quality of water extracted from the ALFGW. This important part of mass balance is not accounted by conventional models. Therefore, the understanding of the water flow and solute transport processes near and inside the pumping well is important for management of the ALFGW system.

The objectives hereinafter were to compare mathematical models of the water extraction from a well of prescribed geometry; assess patterns of flow and transport involved in mixing of water in the extraction well, and investigate the effect of parameters and pumping regimes on the extracted water quality.

II. THE MATHEMATICAL MODEL

The process of water extraction from the ALFGW was simulated using the FEFLOW 5.1 code (Diersch, 2002) for 2-D/3-D density driven flow and transport in the unsaturated and saturated zones. The non-linear Richards equation and the advection-dispersion equation are coupled through the liquid density, which is assumed as a function of solute concentration. We consider an axi-symmetrical problem of water flow and solute transport for the ALFGW floating on saline groundwater of a phreatic aquifer. Water is extracted

Manuscript received September 2006.

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from a well with prescribed geometry located at the lens (Figure 1). In what follows three different pumping models are developed and implemented.

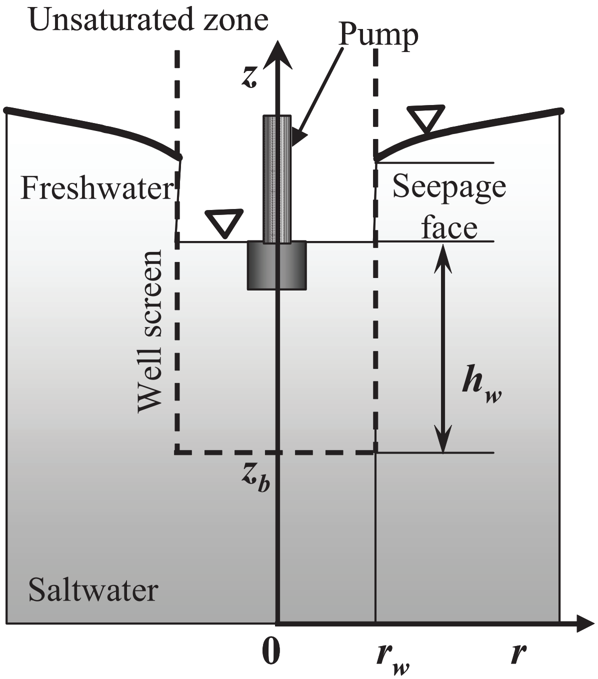

Figure 1. Pumping well configuration.

A. Pumping model 1 (PM 1)

Let us assume that: [A.1] salt concentration varies along well depth; mixing accounts for advection and dispersion processes; [A.2] extraction is from the water free surface and [A.3] water flow within the well is laminar along the vertical direction only.

The temporal water level (h_w) and solute concentration (C_w) in the well are governed by the water and solute mass balance equations, respectively, that read

$$A_w \frac{dh_w}{dt} = Q_w - Q_p \quad (1)$$

$$A_w \frac{\partial c_w}{\partial t} = A_w \frac{\partial}{\partial z}\left(D\frac{\partial c_w}{\partial z} - V_w c_w\right) + 2\pi r_w q_c, \quad z_b < z < z_b + h_w \quad (2)$$

where $A_w = \pi r_w^2$ denotes the well cross-sectional area, Q_p denotes pumping rate, $Q_w = \int_{\Gamma_w} q_w ds$ denotes water flux across the well boundary (Γ_w), q_w denotes the Darcy flux, V_w denotes the evaluated vertical water velocity in the well, q_c denotes the solute flux across the well boundary. We note that (1) and (2) are coupled through boundary conditions that account for the mass exchange through the well bottom and walls, as well as water and solute influx from the seepage face center and pumping from the free water surface in the well.

B. Pumping model 2 (PM 2)

Considering the assumption of full mixing in the well, the water mass balance equation remains in the form of (1) and the solute mass balance equation in the well is simplified to read

$$A_w \frac{d}{dt}\left(C_w h_w\right) = Q_c - Q_p C_w \quad (3)$$

where $Q_{wc} \equiv \int_{\Gamma_w} q_c ds$ denotes solute flux through the well boundary.

C. Pumping model 3 (PM 3)

In this case we implement a conventional approach: the pumping well is presented by a nodal sink in a grid over the domain where the flow and transport equations are solved numerically, pumping rate $Q_p = \sum_{i=1}^{N_p} p_i$ is assembled among nodes representing the well (p_i denotes pumping intensity at the i node) and concentration of the pumped water $C_w = \sum_{i=1}^{N_p} q_{ci} \Big/ Q_p$ is determined as the ratio of total solute flux over total water flux at the sink nodes.

D. *Numerical solution*

Runge-Kutta method of 4th order was applied for the numerical solution of (3) and in the case of (2), the solute mass balance was defined within the domain with the moving upper boundary formed by the water level in the well. To solve (2), we used the Moving Grid Method (e.g., Crank 1987, Segol 1989, Frauhammer 1998) to adjust the finite difference grid to a moving boundary. At each time step the solution for (1)-(2) or (1)-(3) is explicitly coupled with that of the FEFLOW model through the boundary conditions. The case of PM-3 is directly handled by the FEFLOW code and does not require additional treatment.

III. RESULTS AND DISCUSSION

Prior to modeling the ALFGW pumping and to define initial conditions, the simulation of lens formation was performed by Yakirevich et al. (2006). The problem was solved for a homogeneous sand profile (radius of 500 m and 30 m depth) saturated hydraulic conductivity, the longitudinal and transversal dispersivities were 3 m/day, 1 m and 0.1 m, respectively. Initial groundwater level of 15 m and uniform salt concentration of 20 g/L was prescribed. A period of 5 years was simulated assuming that 5000 m3 of freshwater infiltrated through the pond (radius of 25 and 20 m at the top and at the bottom, respectively, and of 3 m depth) during the first month of each year. After 5 years the ALFGW radial extent (concentration less than 5 g/l) was about 45 m and its maximal thickness at the center was 6 m.

We considered a well of 21 m depth and of 1.0 m diameter. Initial water level in the well was 6 m and the salt concentrations in groundwater at the well top and bottom were 0.2 and 5 g/l, respectively. We simulated different scenarios varying by pumping rate (5 - 50 m3/day) and pumping time interval (from 0.25 day for periodical pumping during each 5 days, to continuous pumping). Simulation results for PM-1 to PM-3 are depicted in Figures 2 to 4. Analysis of water and solute balance components in the well for the PM-1 to PM-3 cases reveals that results were practically similar for the PM-1 and PM-2 versions. As the PM-3 case does not account for the seepage of water when water level in the well drops, it affects the concentration of the extracted water. Temporal variation of the pumped water salinity was similar for PM-2 and PM-3 at the beginning of the pumping (Figure 2, 0-10 days period), while it was greater for the PM-2 at the longer times (Figure 2, 80-90 days period). The results for the latter period can be explained in reference to the increase of the average salinity of water in the well since the starting of water extraction leads to sharper decrease of concentration for the PM-2 case in comparison to that of PM-3 during short time because the former model accounts for the freshwater seepage. The PM-2 version predicts that mixing of water in the well leads to the increase of saline water inflow at the lower screen portion while decreasing freshwater inflow at its upper part, thus increasing water salinity in the well. At the beginning of pumping, salinity of extracted water in the case of PM-1 was significantly smaller than that of the PM-2 and PM-3 ones. This can be explained by the fact that PM-1 accounts for the distribution of solute concentration in the well while water is pumped from the free surface where salt concentration is lower than average. Towards the end of the pumping interval, the difference of water salinity between the different models is diminished.

The pumping rate significantly affects the concentration of extracted water at the beginning of the pumping interval. Figure 3 delineates the results of simulations for three pumping rates: 5 m3/day – continuous pumping, 25 m3/day – pumping interval is 1 day, and 50 m3/day – pumping interval is 0.5 day. Increasing pumping rate, while decreasing the pumping interval, leads to an increase of the extracted water salinity because of greater inflow of saline water at the lower screen part in comparison to its upper portion where fresh water is supplied. However, by the end of the pumping period (after 5days) the salt concentrations in the well are similar for all three pumping models. Temporal variations of extracted water salinity are most pronounced for the PM-1 case, which accounts both the seepage face and the distribution of concentration with well depth. During pumping, upconing of saltwater occurs in the vicinity of the well (Figure 4) followed by slow decay of the up-coned saltwater mound when pumping is stopped.

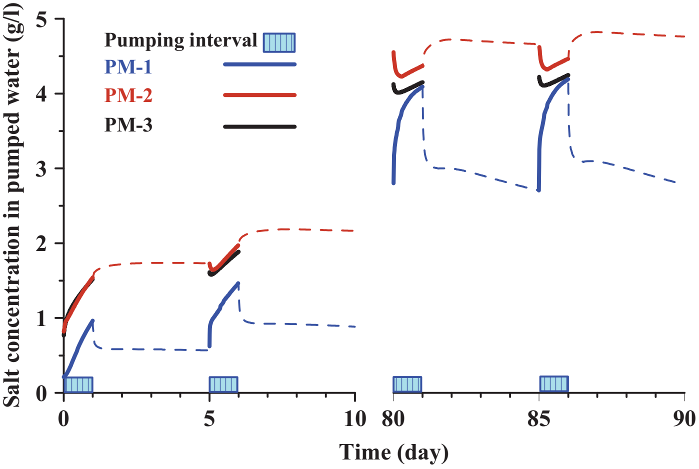

Figure 2. Salt concentration in extracted water predicted by the PM-1 to PM-3 cases: pumping rate is 25 m3/day and pumping interval is 1 day. Dashed lines depict concentrations between pumping intervals.

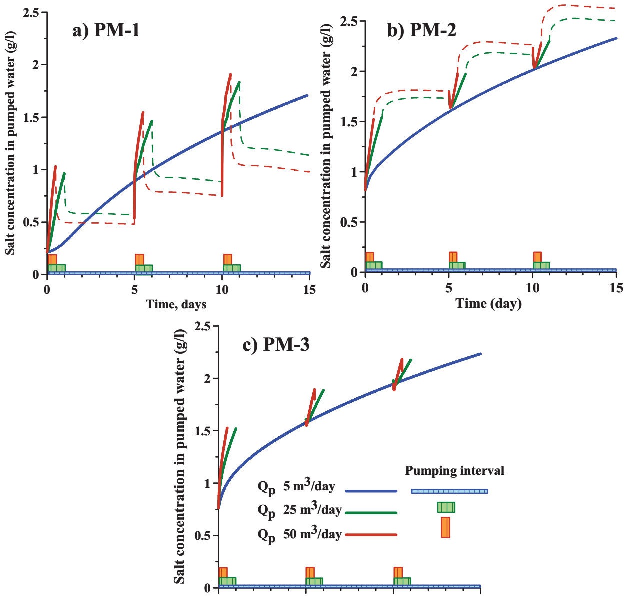

Figure 3. The PM-1 to PM-3 predictions of pumping rate on water salinity extraction: same volume of water (50 m3) is extracted during 5 days period. Dashed lines depict concentrations between pumping intervals.

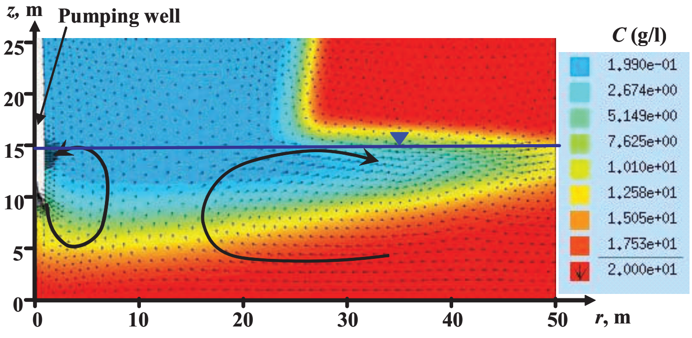

Figure 4. Spatial distribution of concentration and flow patterns after pumping termination

Figure 4 demonstrates that two flow cells were developed recirculating in opposite directions. The clockwise recirculating cell permanently exists at the middle part of the lens and its edge, which leads to an increase of the ALFGW lateral extent and decrease of its thickness with time. The second cell was observed only in between pumping intervals. Termination of pumping and continuation of water influx from the seepage face leads to faster recovery of the water level in the well in comparison with the groundwater level nearby. As a result, flow through the well bottom changes its direction outwards, while at the upper screen portion water flows into the well. Observation of the development of a recirculating flow cell during pumping on a larger scale, which widened the saltwater mound in the horizontal direction, was also reported by Zhou et al. (2005).

Simulations were also carried out to assess the effect of well screen length and location. It was found that shallow well pumping produces water of better quality than that of deep well. However, this limits the rate of production in the former case due to the risk of lowering the well water level below critical depth.

ACKNOWLEDGMENTS.

This research was supported under Grant No. TA-MOU-01-CA20-035 funded by the U.S. Israel Cooperative Development Research Program, Bureau for Economic Growth, Agriculture, and Trade, U.S. Agency for International Development.

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