IMPACT ASSESSMENT OF SOLUTION MINING ON GROUNDWATER RESOURCES IN KAZAN TRONA FIELD, ANKARA-TURKEY

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ABSTRACT
This study presents the hydrogeological impact assessment of the Kazan Trona project area, Turkey, where solution mining will be used to extract the source. Geological, hydrogeological and hydrogeochemical data are used to define hydrogeological units and flow conditions in the area. Three aquifers systems were identified and interactions between them were conceptualized into a site hydrogeological model. A finite difference groundwater flow model was developed to represent aquifer systems and the flow conditions. The model has been calibrated under steady state and transient conditions. Model outputs have shown good agreement between the observed and simulated heads, and flow conditions. The volumetric budget of the system was continuously checked with estimated groundwater budget components. Results confirmed the accuracy of the numerical groundwater flow model and verified the conceptual understanding of the area. The resulting model was used in conjunction with a three dimensional transport model to simulate the impacts of the solution mining of trona deposit on groundwater resources in the area. The results demonstrate that pilot well solution-mining of trona deposit will not have significant impact on quality of groundwater resources in the overlying aquifers.

1. INTRODUCTION

The discovery of a trona ore deposit by Rio Tinto in Eocene deposits of the Kazan Basin, 30 km northwest of City of Ankara-Turkey, has led to a detailed hydrogeological and hydrogeochemical characterization of the groundwater resources in the area with the ultimate aim to assess the potential impacts of the solution mining on groundwater resources. A numerical ground water flow model of the study area has been developed to understand the groundwater flow patterns in the area, to determine the extent of the interaction between various aquifer systems in the study area, and to verify the conceptual hydrogeological understanding of the study area. The resulting model is used to assess the potential impacts of solution mining on groundwater resources within the scope of the environmental impact assessment regulations and to develop a monitoring program to be implemented during mining and post-mining periods.

The numerical MODFLOW (Harbaugh and McDonald, 2000) model, which uses a finite difference approximation method, was used to simulate ground water flow in the project area (Figure 1). The geological, climatic, topographic, hydrogeological, and hydrogeochemical site data that were collected as part of the baseline studies were analyzed to develop a conceptual understanding of the site conditions which is briefly reviewed herein.

The numerical model which is postulated on conceptual site model was calibrated under steady-state and transient conditions. The good fit between simulated and measured water levels, inferred flow directions, and groundwater budget components estimated by other approaches confirmed the accuracy of the numerical groundwater flow model and verified the hydrogeological conceptual understanding of the site. The resulting numerical model coupled with MT3D (Zheng and Wang, 1999) is then used to predict the solute mass transport in three-dimensional groundwater flow system to assess the potential impacts of the solution mining of trona on groundwater resources within the scope of the environmental impact assessment regulations.

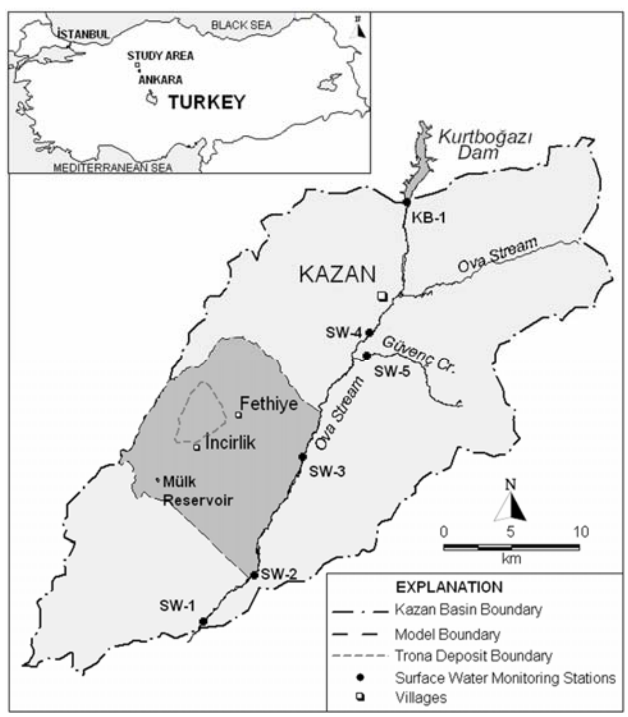

Figure 1: Location map of the model area

2. CONCEPTUAL MODEL

The ground water flow regime within the study area can be conceptualized schematically as shown in Figure 2. The water bearing units from bottom to top consist of a deep ground water aquifer system in fractured bedrock (i.e., fractured zones of İncirlik, Asmalıdere and Fethiye), a middle system at the base of the Neogene, and a shallow system in the Quaternary Alluvium and the uppermost fractured and weathered Neogene units. The Akpınar Formation acts as an aquitard where it exists. The fractured bedrock aquifer system is mainly recharged along zones that outcrop in the ridges on the western side. The flow in this system is mainly controlled by the shear and fracture zones. This is particularly obvious upon the review of the potentiometric map of the deep aquifer. The linear NW-SE trending ridge or mound in the heads of the deep aquifer system suggests that in addition to recharge through the outcrop zones, the fractured system is also recharged by line sources such as faults. However, the main direction of flow in the deeper fractured system appears to be towards the southeast. The deeper fractured aquifer system, having a greater potentiometric surface than the middle Neogene and upper alluvial system, also sets up an upward gradient; thereby, recharging them in downgradient areas. The decrease in the intensity of fractures in the bedrock aquifer downgradient acts as a barrier to the ground water flow. This forces the flow to take place toward the upper aquifers. Elevated concentrations measured in downgradient alluvium wells suggest the seepage of deeper groundwater into the alluvium in these areas.

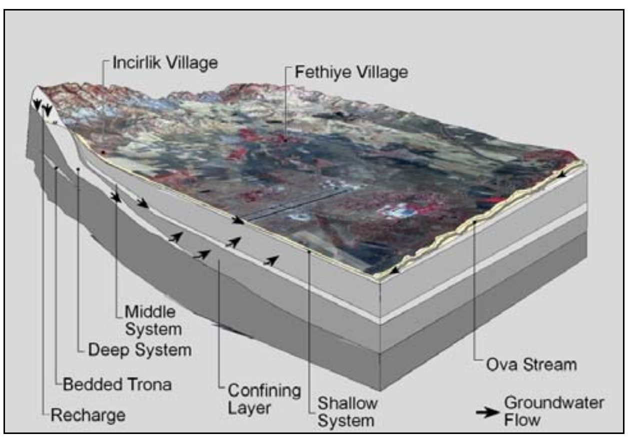

Figure 2: Conceptual Hydrogeological Model

3. GROUNDWATER FLOW MODEL

The model grid consists of 143 rows and 137 columns with a total of 14,536 active cells. Each cell represents 10,000 m^2 with a distance of 100 m on a side. The aquifer system was discretized vertically into 11 layers. The lateral boundaries of the model layers are shown in Figure 3.

The northwestern boundary of the model coincides with the present-day Kazan Basin boundary where a NE-SW striking thrust fault provides recharge to the basin (Figure 3). This boundary was modeled as a flux boundary, the magnitude of which has been determined during calibration. The southeastern boundary of the model is defined by the perennial Ova Stream where variable constant head boundary conditions were used. The northeastern and southwestern boundaries of the model are defined as no-flow boundaries. The lateral boundaries of layers correspond roughly to the contact between hydrogeologically defined units. The upper boundary was simulated as a free-surface and the lower boundary was designated as a no-flow boundary at an altitude where the İncirlik Member was assumed to be unfractured and non-water bearing.

Surface runoff in ephemeral creeks and three main springs discharging water from Alluvium were simulated as drains in the model. Two main internal faults that transect the ground water basin were simulated as partial barriers to ground water flow (Figure 3). The Horizontal Flow Barrier (HFB) package (Hsieh and Freckleton, 1993) was used to simulate these faults as horizontal flow barriers. Two wells (K-17 and K-27) are used by Fethiye villagers for domestic purposes (Figure 3). These wells discharge water from all water-bearing formations and are incorporated into the model with the total discharge of 487 m^3/day.

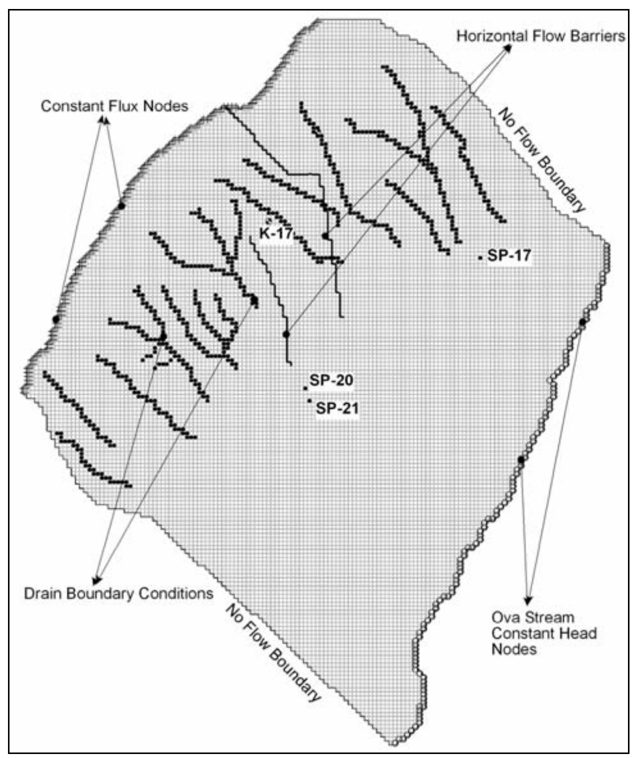

Figure 3: Model grid and boundary conditions

Using information collected through pump tests, packer tests, water levels, and discharge measurements, model calibration under steady-state and transient conditions was carried out until a good match is obtained between measured and simulated groundwater levels. The steady-state model was calibrated with root mean square error equal to 11.9 m. The correlation coefficient between the simulated steady-state hydraulic head and the measured water levels for average conditions equals 0.96 (Figure 4). During the process of calibration a continuous check was maintained on the water budget of the system. The groundwater budget components obtained from groundwater model were consistent with earlier estimates made using more conventional methods (SRK, 2003).

The transient state model was calibrated using the water level data from monitoring wells for the period of 2001-2003. The general agreement between the temporal variations in simulated and observed water levels at 18 wells has resulted in a successful transient calibration of the model (SRK, 2004).

4. SOLUTION MINING IMPACT ASSESSMENT

Solution-mining method using horizontal wells is planned to extract the trona ore because of its depth and low-grade. This would require the injection of hot, pressurized water through a vertical injection hole connected to a 500 m long horizontal well drilled along the base of the trona bed. The injected fluid would dissolve the trona and produce a production fluid that would then be recovered through a vertical production well connected to the end of the horizontal well. Initially, a single pilot well is planned to be operated for a period of 2.5 years before proceeding with the full scale development. The groundwater flow model developed for the project area was used to predict the effect of solution-mining of pilot well on groundwater resources during operation (2.5 years) and post-operation periods.

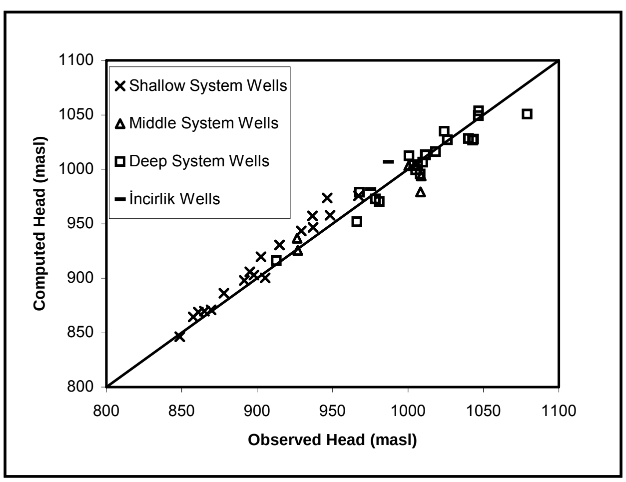

Figure 4: Calculated and observed water levels at monitoring wells

4.1 Operation Period

Process of solution mining will create a 500 m long cave in underground, filled with brine solution. With a 30% trona tenor, the volume of the cave is estimated to be 135,000 m^3. The solution filling this cave will have significant concentrations of sodium, chloride, bi-carbonate and carbonate ions in addition to others. The predicted ion concentrations of the brine in the solution cavity during operation and post-operation periods are given in Table 1. Because the system is pressurized, there is possibility of transport of the brine solution from the solution cavity towards the overlying aquifer systems. A transport model was constructed and run to predict these impacts.

Parameter	Operation Period	Post-Operation Period
Sodium, Na (mg/l)	118,000	112,000
Chloride, Cl (mg/l)	7,300	7,300
Bicarbonate, HCO_3 (mg/l)	100,000	44,000
Carbonate, CO_3 (mg/l)	99,000	119,000

Table 1: Predicted ion concentrations in the brine at the solution cavity.

Mass transport in three dimensions (MT3D) is used for simulation of advective and dispersive transport of solutes in three-dimensional groundwater flow system (Zheng and Wang, 1999). The model is used in conjunction with the finite difference groundwater flow model developed for the project area. Model was run for the operation period of 2.5 years under transient flow and transient transport conditions. Recharge and discharge conditions for the period between February 2001- August 2003 were used in the model simulations. Moreover, the pressure of the injection fluid which is expected to vary from 4800 kPa to 1370 kPa through the solution cavity was converted into equivalent head of water and added to the calibrated heads through the solution cavity in the model simulations. In order to simulate the worst conditions hydraulic heads throughout the solution cavity was assumed to be constant for 2.5 years of operation period. Groundwater flow model was run for 2.5 years with monthly stress periods to determine the flow conditions in the model area. Flow simulated in the model area is then used to simulate transport of non-adsorbed and non-reactive solute with a constant source concentration of 100 units in the solution cavity by using MT3D model. In order to analyze effect of transport from solution cavity better, initial concentration of “0” was assigned to the rest of the model domain.

Because no experimental work was carried out to determine the field dispersivity values, representative value corresponding to 100 m length of model cell was selected from literature (Neuman, 1990). However, model was also run for dispersivity values of 10 m and 30 m in order to see how predicted concentrations change with the dispersivity. Transverse dispersivity for all cases was assumed to be 1/10 of the longitudinal dispersivity.

Concentration distribution at the end of the operation period (2.5 years) is presented in Figure 5, both in vertical section and x-y plane along the solution cavity. As it can be seen from Figure 5 solution with 1 unit concentration is transported only about 100 m from the solution cavity. Maximum concentration at the deep aquifer system overlying the solution cavity was calculated as %0.00025 at the end of the operation period. This means, for example, an ion with 100,000 mg/l concentration at the solution cavity will increase the concentration in the deep aquifer system by 0.25 mg/l.

The estimated concentrations of some ions in the brine at the solution cavity during the operation period are given in Table 1. Sodium ion has the highest concentration with 118,000 mg/l; however, it will contribute only 0.3 mg/l to the deep aquifer system. The existing Na, Cl, K, HCO_3, B, Li concentrations and TDS values in the deep aquifer system overlying the solution cavity is given in Table 2. Very high concentrations of these ions put this groundwater in Class III (Highly Contaminated Groundwater) type according to the classification scheme provided by the Ministry of Environment and Forestry (MOEF 2005). Consequently, there will not be a significant impact from the solution-mining operation to the low quality deep aquifer system groundwater.

Predicted concentrations in deep aquifer system overlying the solution cavity for dispersivity values of 10 m and 30 m are 0.00010 % and 0.0004 %, respectively. Sodium ion with 118,000 mg/l concentration at source will contribute to the deep aquifer system 0.12 mg/l for dispersivity value of 10 m and 0.5 mg/l for the dispersivity value of 30 m. So the model results have shown that even for different dispersivity values deep aquifer system is not significantly impacted by the solution mining operation.

Parameter	Concentration (mg/L)	MOEF (2004) Groundwater Quality Class
Total Dissolved Solids (TDS)	7,000	III
Sodium (Na)	4,000	III
Bicarbonate (HCO_3)	3,500	-
Carbonate (CO_3)	1,000	-
Chloride (Cl)	1,000	III
Potassium (K)	20	-
Boron (B)	150	III

Table 2: Groundwater quality of the deep aquifer system above the solution cavity.

The above model simulations were conducted using calibrated vertical hydraulic conductivity of $6X10^{-6}$ m/day for the less permeable (aquitard) zone between solution cavity and deep aquifer system. However, it is possible that the vertical hydraulic conductivity of this zone may increase due to subsidence associated with the solution cavity. Unfortunately, it is not possible to predict the increase in vertical hydraulic conductivity of the aquitard layer above the solution cavity for the Kazan project. Increase in hydraulic conductivity may be determined by permeability tests and monitoring of groundwater levels, which can be conducted before and during the operation period. However, in order to assess the effect of increase in hydraulic conductivity of the aquitard layer on groundwater quality of the deep aquifer system several simulations were conducted. Vertical hydraulic conductivity of the aquitard layer between deep aquifer and solution cavity at the subsidence impact area predicted by Agapito Associates Inc. (2002) was increased by 5, 20 and 50 times of the calibrated base value and the effect of Na ion (with highest concentration of 118,000 mg/l) was predicted at deep aquifer system. As it can be seen from Figure 6 when the vertical hydraulic conductivity increased by 50 times, Na ion concentration increases to 58 mg/l from 0.3 mg/l. The existing Na concentration in the deep aquifer system groundwater is 4000 mg/l (Table 2). If vertical hydraulic conductivity increases by 50 times, the increase in Na ion concentration in deep aquifer system will only be 1.45 % of the existing concentration. This increase is even less than acceptable level (5 to 10%) for analytical errors of chemical analyses. Thus, it can be concluded that even 50 times increase in vertical hydraulic conductivity of the aquitard layer due to subsidence will not have a significant impact on groundwater quality of the deep aquifer system.

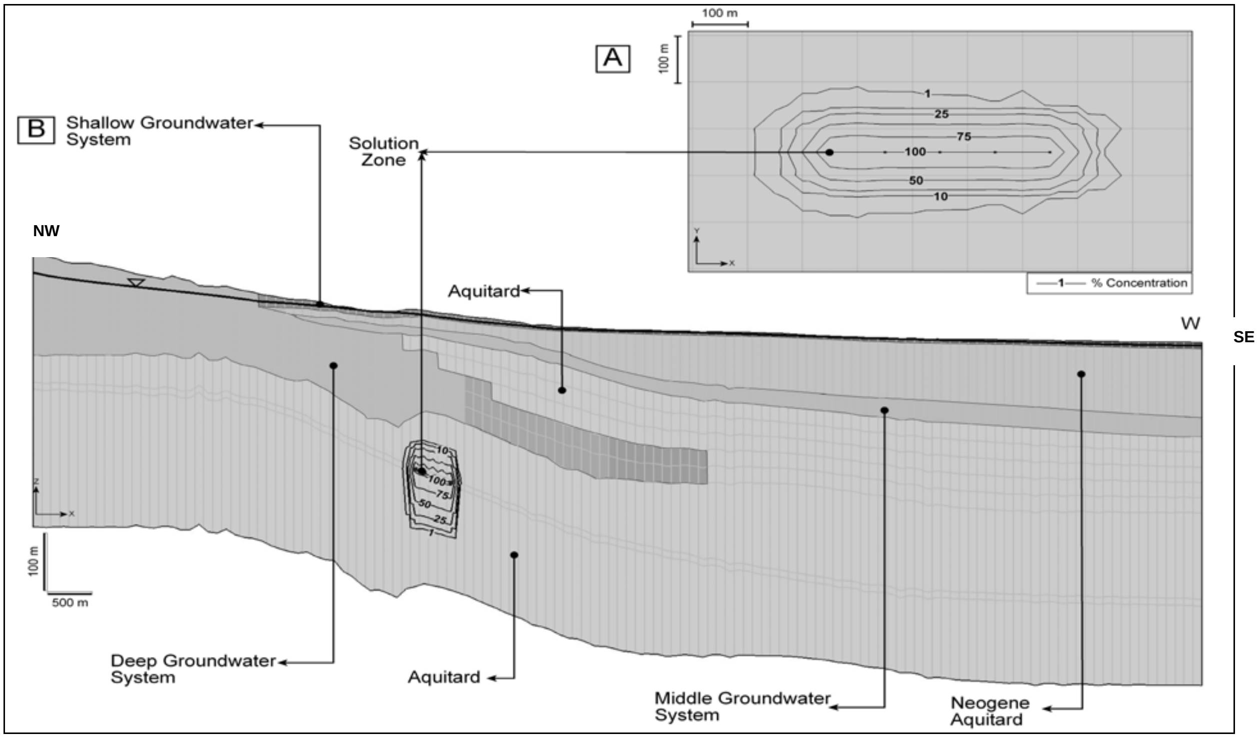

Figure 5: Concentration distribution at the end of operation period (2.5 years)

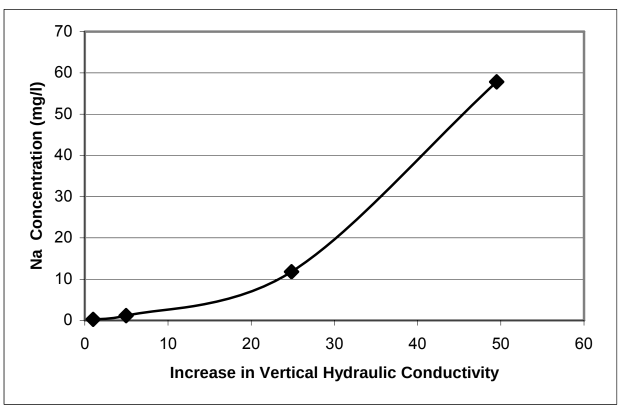

Figure 6: Increase in Na with increase in vertical hydraulic conductivity of the aquitard

4.2 Post Operation Period

MT3D model developed by Zheng and Wang (1999) was used in conjunction with the groundwater flow simulation model MODFLOW in order to simulate the effects of solution mining after mine closure on groundwater quality. The simulations were performed for 1000 years after mine closure. Concentrations calculated at the end of 2.5 years of operation period were used as initial concentration distribution. Transient flow simulation after mine closure has shown that water levels reach to steady-state conditions in 20 months after mine closure.

Consequently, simulations were conducted under steady-state flow conditions and 1000-year transient transport conditions. Model was run with dispersivity values of 10, 20 and 30 m in order to see how resulting concentrations change with dispersivity.

The predicted concentration distributions in vertical section and x-y plane at the end of 1000 year are presented in Figure 7 for the dispersivity value of 20m. Predictions show that 1 unit concentration will spread about 150 m horizontally and vertically. Initial concentration of 100 units at the source (solution cavity) is decreased to 85 units. Predictions have shown that concentrations will increase at the deep aquifer system at the end of 1000-year period. For example, % 0.00025 predicted concentration at the end of operation period increased to % 0.019 at the end of 1000 year at the deep aquifer system. However, it should be noted that possible chemical reactions, crystallization and precipitation at the solution cavity were not considered during simulations. In this case, additional concentration created by an ion with 100,000 mg/l concentration at the solution cavity will be 19 mg/l at the deep aquifer system. Na and CO_3 ions with highest concentrations (112,000 mg/l Na; 119,000 mg/l CO_3) will create 21-23 mg/l additional concentrations at the deep aquifer system 1000 year after mine closure. Present Na and CO_3 concentrations in the deep aquifer system were observed as 4000 mg/l and 1000 mg/l, respectively (Table 2). Thus, model results have shown that the effect of solution cavity to present concentrations will be 5‰ of present Na concentration and 23‰ of present CO_3 concentration. Factors which are not considered during model simulations such as possible chemical reactions, crystallization and precipitation at the solution cavity will reduce these impacts further.

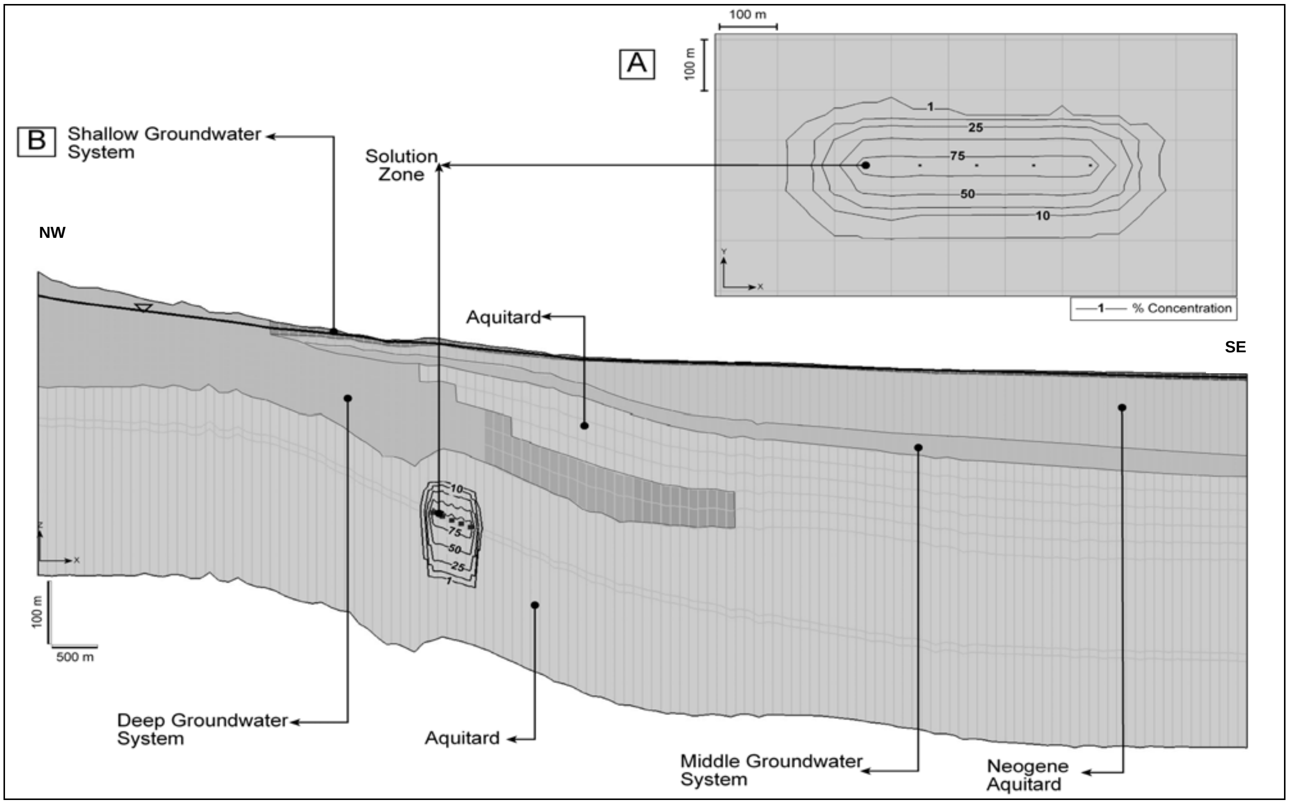

Figure 7: Concentration distribution at the end of 1000 years after mine closure

In order to assess the effect of increase in vertical hydraulic conductivity of the aquitard between deep aquifer system and solution cavity due to subsidence several simulations were conducted. Vertical hydraulic conductivity of the aquitard at the subsidence impact area was increased by 5, 20 and 50 times, as it was done for the operation period. Transport simulations for 1000-year were conducted to analyze the changes in Na and CO_3 concentrations based on increase in vertical hydraulic conductivity of the aquitard (Figure 8). If the vertical hydraulic conductivity increases (from $6X10^{-6}$ m/day to $3X10^{-4}$ m/day), Na and CO_3 ion concentrations increase from 21-23 mg/l to 193-205 mg/l at the deep aquifer system. Results have shown that effect of 50 times increase in vertical hydraulic conductivity will be 4.8 % of present Na concentration and 20 % of present CO_3 concentration at the end of 1000 year. Results show that even 50 times increase in vertical hydraulic conductivity will not have a significant impact on poor quality water bearing deep aquifer system. Factors which are not considered during model simulations such as possible chemical reactions, crystallization and precipitation at the solution cavity will eventually decrease the impacts.

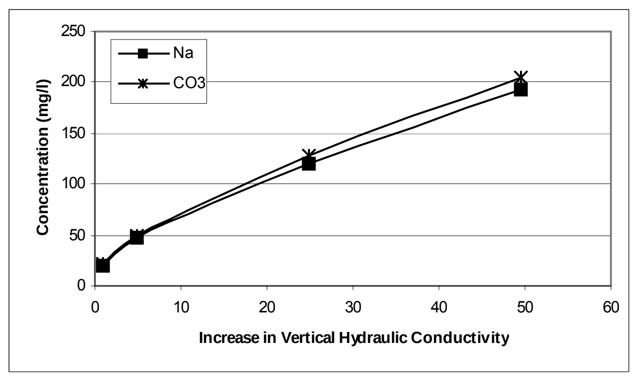

Figure 8: Increase in Na and CO_3 with increase in vertical hydraulic conductivity of the aquitard

5. SUMMARY AND CONCLUSIONS

The geological, climatic, topographic, hydrogeological, and hydrogeochemical site data that were collected as part of the baseline studies at Kazan trona project area were analyzed to develop a conceptual understanding of the site hydrogeological conditions. A numerical model postulated on conceptual site model was calibrated under steady-state and transient conditions. The good fit between simulated and measured water levels, inferred flow directions, and groundwater budget components estimated by other approaches confirmed the accuracy of the numerical groundwater flow model and verified the hydrogeological conceptual understanding of the site. The resulting numerical model coupled with a three dimensional solute transport model was then used to assess the potential impacts of the solution mining of trona on groundwater resources during operation and post-operation periods. The results show that pilot well solution-mining of trona deposit will not have significant impact on the quality of groundwater resources in the overlying aquifers.

Modeling results rely on field studies and subsurface geology obtained from drillings. Most of the data used in the models have an uncertainty due to stochastic nature of the state parameters and recharge conditions. Consequently, in order to minimize the environmental risks, appropriate measures should be considered. Twelve pumping/monitoring wells at upstream and downstream from the solution-mining well are recommended to monitor groundwater quality periodically during operation and post-operation periods (Figure 9). These wells will be used for both monitoring and pumping wells to capture the brine if any seepage is detected.

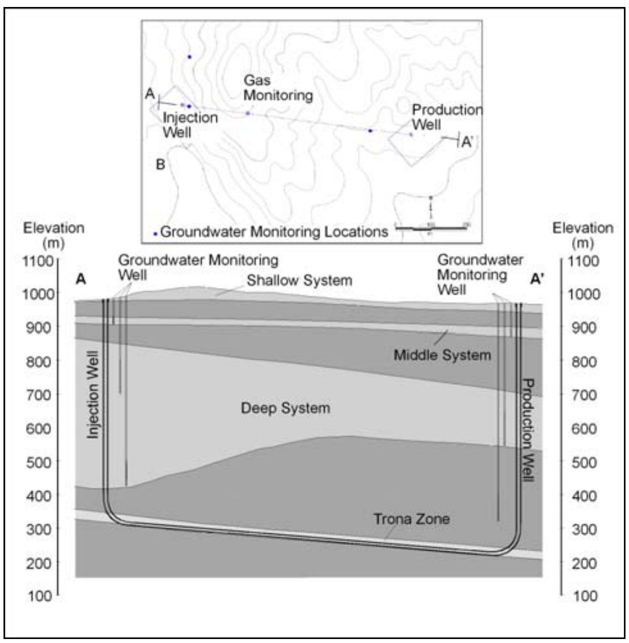

Figure 9: Groundwater Monitoring Wells

6. ACKNOWLEDGEMENTS

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References

Agapito Associates Inc., 2002, Subsidence evaluation for the Kazan Project, Rio Tinto. Grand Junction, Colorado, U.S.A.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Process By: U.S. Geological Survey Open-File Report 00-92, 121 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chap. A1, 576 p.

MOEF, 2004, Water Contamination Control Regulations. Ministry of Environment and Forestry, *Official Gazette* No: 25687, 2004, Ankara, Turkey.

Neuman, S.P., 1990, Universal scaling of hydraulic conductivities and dispersivities in geologic media. *Water Resources Research*, 26(8): pp. 1749-1758.

SRK, 2003, Water Supply Assessment, Kazan Trona Project. Ankara, Turkey.

SRK, 2004, Hydrogeological Modeling, Kazan Trona Project, Ankara, Turkey.

Zheng C. and Wang P.P., 1999, MT3MS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. University of Alabama, U.S.A.