



NUMERICAL SIMULATION OF CHANGE IN FLUX DYNAMICS OF A COASTAL AQUIFER DUE TO SALINE WATER PUMPING

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ABSTRACT

Sea water intrusion is the landward incursion of seawater in a coastal area, which primarily causes reduction in the availability of palatable water quantity. This natural phenomenon which occurs, due to the density difference between fresh water and sea water, is accelerated in recent years owing to increase in inland pumping rate. Preventive measures to curb intrusion is to be devised for sustainability of coastal groundwater. Pumping of saline ground water using vertical wells for desalination plants, has been found successful in 'refreshing' the aquifer and hence could be regarded as one of the remediation measures to seawater intrusion. The aim of the present study is to investigate the implications of simultaneous pumping of fresh water and saline ground water, on flux dynamics of a saltwater intruded aquifer. A numerical model is developed for a case study, using the finite difference model, SEAWAT, to assess the effect of pumping parameters on interface movement. The quantifying parameters for dynamics of interface, namely, toe position, width of mixing zone, salt and fresh water flux are obtained in response to pumping from the aquifer. Performance analysis with regard to change in well salinity is analyzed using a case study. The case study shows the quantification of change in flow rates and flow patterns due to pumping, within the aquifer.

Keywords: Numerical simulation, coastal aquifer, Seawater intrusion, pumping, SEAWAT, interface

INTRODUCTION

Excessive pumping of fresh groundwater from coastal aquifers, accelerate the intrusion of seawater further inland, causing reduction in the availability of palatable water quantity. To tackle this issue, various technical solutions were presented in the literature like regulating pumping patterns, direct artificial surface recharge, combination of injection extraction methods and subsurface barrier etc. (Todd, 1974; Luyun et.al,2011). All these methods even though reduces the intrusion, but suffer from some disadvantages in economical and operation point of view (Abd-Elhamid, et.al, 2017). Another promising method is the pumping of brackish and saline ground water (SGW) near the shoreline, which has proven to be a feasible remediating measure to 'refresh' a distressed phreatic aquifer (Sherif & Hamza, 2001). Recent studies emphasis effective and economical use of this pumped saltwater as a feed for desalination plant (Stein, et.al,2019). For coastal and arid zones where fresh water supply is limited, desalination is a promising solution to looming water crisis.

The changes due to near shore pumping for desalination plants and its effects on salinity of coastal aquifer needs to be further investigated. In the present study an attempt to understand this change in dynamics of coastal aquifer, is accomplished. The dynamic behavior of the aquifer could be explained in terms of change of amount of fresh and salt

water fluxes and their relative contribution in deciding the salinity of the aquifer. Fresh water from the coastal aquifer moves towards sea due to hydraulic difference between land and sea. Sea water flux owing to higher density moves towards aquifer and gets mixed with terrestrial fresh water, causing a reduction in its density and is flushed back to sea. This entire process makes a convective circulation, which is responsible for the transfer of dissolved nutrients and contaminants to the sea. For analyzing the dynamic behavior, the key quantifying parameters contributing to this circulation needs to be found out.

For quantification, intruded seawater is reasonably assumed to take the shape of a wedge, the geometry of the three sides being the sloping freshwater-saltwater interface, the vertical seaward seepage faces, and the base of the aquifer extending from the saltwater boundary, which is regarded as the length of the intrusion of toe. The change in transient location of interface of toe of this wedge, change in amount and direction of salt mass flux causing circulation and the amount of groundwater discharged into the sea need to be known for every hydrological stress condition (Smith, 2004). In this study, pumping of saline water from the aquifer is taken as the stress condition and transient changes in the parameters are found out by simulating numerically using dispersive interface approach.

METHODOLOGY

To understand the effect of simultaneous pumping of fresh water and salt water on flux dynamics, a case study is chosen which represents a vertical cross section of a regional coastal aquifer system, similar in dimensions to conceptual aquifer considered by Motz & Sedighi, (2009). The finite difference model, SEAWAT 2000, which

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combines MODFLOW and MT3DMS through a density coupling relationship was used to numerically simulate scenarios of saline ground water pumping.

Governing equations

Ground water flow equation in MODFLOW is modified in terms of equivalent fresh water head and fluid density and is as shown below (Langevin and Guo, 2006):

$$\nabla \cdot \left[-K_f \rho \left(\nabla h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z \right) \right] = \rho S_{sf} \frac{\partial h_f}{\partial t} + n \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \rho_s q'_s \quad (1)$$

where S_{sf} is the fresh water specific storage defined as the volume of water released from storage per unit volume per unit decline of fresh water head, C is the concentration of solute mass per unit volume of fluid, ρ is fluid density (fluid density and concentration are related by an equation of state which could be expressed in linearized form as $\rho = \rho_f + \frac{\partial \rho}{\partial C} C$), K_f is the hydraulic conductivity tensor, q'_s is the source/sink of fluid, z is upward coordinate direction aligned with

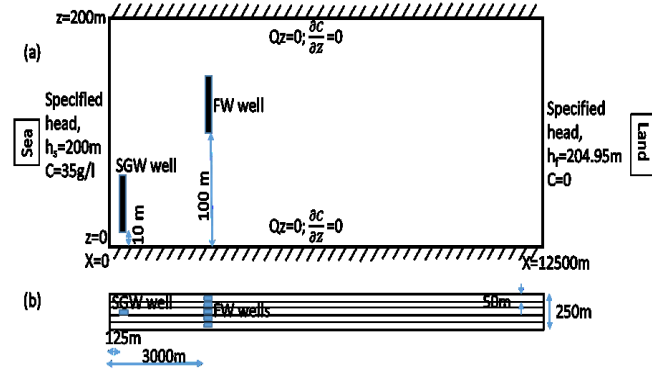


Fig. 1: Conceptual model of the regional aquifer showing boundary conditions assumed in the study (a) vertical cross-section and (b) plan view (note that one saline ground water (SGW) well is representing a group of wells)

gravity and h_f is the equivalent fresh water head (which is the dependent variable) and is defined as $h_f = \frac{p}{\rho_f g} + z$, where p is the pressure and g is the acceleration due to gravity. Specific discharge, q is obtained from the Darcy's equation modified for variable density flow and is given as

$$q = -K_f \frac{\mu_f}{\mu} \left(\nabla h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z \right) \quad (2)$$

The solute transport in MT3DMS uses the conventional advection-dispersion equation of a single species and is governed by the equation as given below:

$$\frac{\partial (nC)}{\partial t} = \nabla \cdot (nD \cdot \nabla C) - \nabla \cdot (qC) - q'_s C_s \quad (3)$$

where D is the hydrodynamic dispersion coefficient tensor and C_s is the source or sink concentration. The flow and

transport equations are coupled using a synchronous time stepping approach (Guo and Langevin, 2002).

Numerical model development

The geometry of the numerical model chosen was 12,500m in length, 250m in width and 200m in depth, which is discretized as 50 columns, 5 rows and 40 layers respectively. A uniform grid size of $\Delta x = 250m$ and $\Delta y = 5m$ was employed resulting in 10000 cell mesh and grid Peclet number

$$Pe_g = \frac{v \Delta L}{D_m + \alpha_L v} \cong \Delta L / \alpha_L = \frac{250}{125} = 2 \quad (4)$$

For all simulations, the boundary conditions considered are illustrated in Fig.1, where top and bottom boundaries were taken as impermeable, i.e. normal flux and concentration along top and bottom were not considered. Seawater intrusion was first simulated by forcing specified head at land and sea boundaries (hydraulic head difference be 4.95m) and the model was run until a steady state was achieved.

Three distinct stress conditions were simulated, to compare and evaluate the flux dynamics of the system. In the first case, pumping from the wells were not considered, seawater intrusion was simulated only due to fluid density variation. This was considered as the base case, to which all other simulations were compared. After simulating SWI for 50 years, for the second case, one well was introduced which is at 125m from the shoreline and 10m above the base of the aquifer, which started pumping saline ground water, till it reached steady state. This simulation was done to understand and compare the role of saline ground water pumping alone in the transient change in flux dynamics. In the third case, five fresh water wells were introduced in a line perpendicular to and 3000m distant from the shore line and at depths of 100m from the base. SWI was simulated by pumping these fresh water wells for 50 years, after which both the fresh water and saline ground water wells were pumped simultaneously till it reached steady state which would replicate the condition of aquifer refreshing along with the regular fresh water pumpage of aquifer.

In order to understand the effect of rate of pumping on flux dynamics, seven different SGW pumping rates of 2.5, 5, 10, 15, 20, 25, 30-million-meter cube (Mm^3/yr) were tested. These values were considered for a similar study to understand the feasibility of SGW pumping in aquifer refreshing (Stein et al., 2019). Also as adopted in the same study, one SGW well adopted here was representing a battery of wells and was simulated by 'WELL boundary' in SEAWAT and pumping rate was distributed into 5 nodes. Fresh water wells were pumping at a constant rate of 14 Mm^3/yr , which were also simulated as 'WELL boundary' and are distributed into 25 nodes. The parameters used for all the three sets of simulations were enlisted in the Table.1.

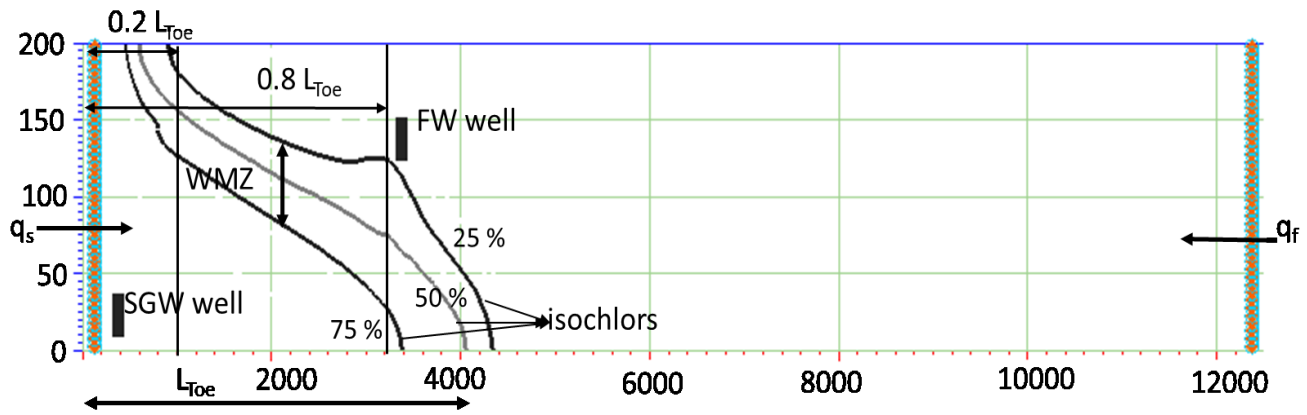


Fig. 1 : Illustration of the method by which quantifying variables (Length of penetration of Toe (L_{Toe}), Width of mixing zone (WMZ) and saltwater flux(qs)) are measured [as defined in (Abarca, et.al., 2007)]

Table 1: Parameters taken for numerical simulations

Parameter	Unit	Value
Horizontal hydraulic conductivity (K_H)	m/day	50
Vertical hydraulic conductivity (K_V)	m/day	0.5
Longitudinal Dispersivity(α_H)	m	125
Transverse (Vertical) Dispersivity(α_V)	m	1.25
Porosity(η)		0.30
Density of fresh water	kg/m ³	1000
Density of saltwater	kg/m ³	1025

RESULTS AND DISCUSSION

The three sets of simulations were run and variables of interest such as interface location (L_{Toe}), average width of mixing zone (WMZ) and saltwater flux (q_s) were measured. The description of the variables is as per Fig.2.

Dimensionless interface location (L_D)

Interface location is measured as the length along X-axis from the coastal line to the point where 50% isochlor touches the base of the aquifer (L_{Toe} as given in Fig.2), which is made dimensionless(L_D) by dividing by the thickness of the aquifer, 'd'(Abarca, et.al., 2007). Fig.3. shows the variation of interface location for different pumping rates. For the base case, interface location moves towards land with increasing time, dimensionless interface toe location value varied from 9.3(for 25 years) to 20.3(for 150 years). For the second case of only SGW pumping, a general trend of decrease of interface location is obtained which indicates the movement of interface towards SGW well, the effect being more pronounced at higher pumping rates (15.96 for 2.5 Mm^3/yr and 13.37 for 30 Mm^3/yr). For the simultaneous pumping of FW and SGW wells, L_D value

decreased from 20.825 to 18.52 for SGW pumping rate of $2.5\text{Mm}^3/\text{yr}$ and $30\text{Mm}^3/\text{yr}$ respectively.

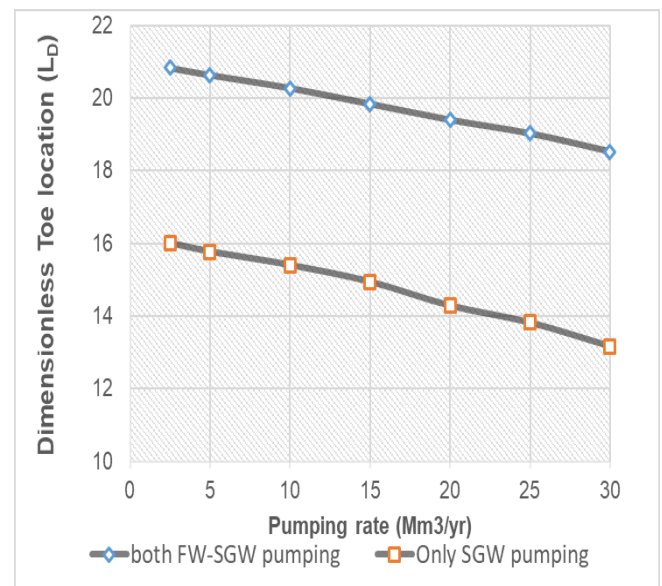


Fig.2 : Variation of interface toe location (dimensionless) with pumping rates

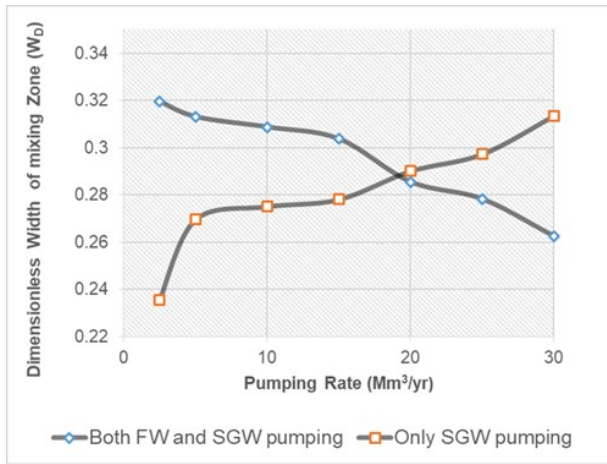


Fig. 3 : Pattern showing the change in width of mixing zone(dimensionless) with pumping rates

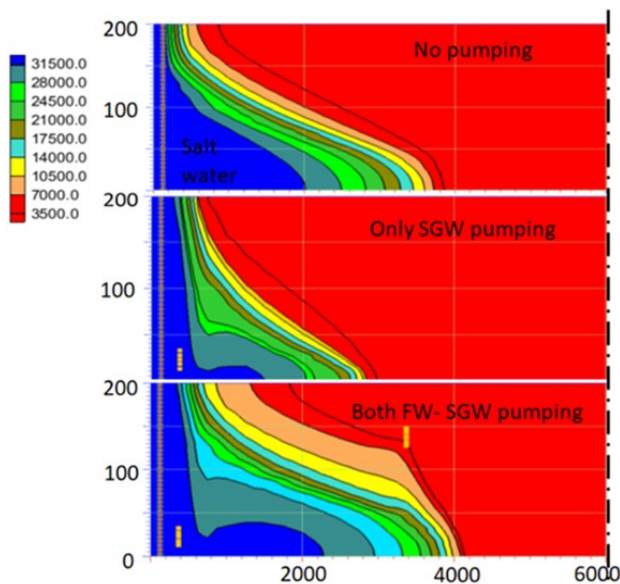


Fig.5 : Cross section illustrating dispersed interface for (i) no pumping (ii) only Saline ground water (SGW) pumping and (iii) simultaneous SGW and Fresh water(FW) pumping. (note the cone of depression near the SGW well) Half of the longitudinal cross section is shown for brevity.

Pumping rate is showing less influence (11% decrease) in interface location for this simultaneous case, compared to second case (17% decrease), in which, as SGW wells pumps saltwater coming from sea rather than that from aquifer. Similar trend was also obtained for the study (Stein et al., 2019). The location of SGW pumping wells further inland may cause more extraction of saltwater from land and may further reduce interface location.

Dimensionless average width of mixing zone (W_D)

WMZ is calculated for all the cases, as the average vertical width between 25% and 75% isochlor measured between horizontal distance of $0.2 L_{Toe}$ and $0.8 L_{Toe}$ (Abarca, et.al., 2007). This value is made dimensionless (WD) by dividing

by 'd' and variation is compared and presented in Fig.4. The value of WD for no pumping was obtained as 0.285, for only SGW pumping, 0.26 to 0.3 and for simultaneous pumping it decreased from 0.320 to 0.262. A cone of depression towards SGW well was observed as shown in Fig.5. But for simultaneous pumping case, width of transition zone was increased and interface toe location increased towards the base of the aquifer.

Dimensionless saltwater flux(R_D)

R_D is calculated as the ratio of volumetric salt water rate of seawater (q_s) entering into the system from seaside boundary to the corresponding fresh water rate(q_f) from the land side. For no pumping scenario, the R_D value obtained was 1.034, whereas for pumping scenarios, it showed an increasing trend, with simultaneous pumping case an average increase of 30% over only SGW pumping case (refer Fig.6). This was expected, as more salt water will be drawn to the system, but it showed less intrusion of saltwater to inward land side.

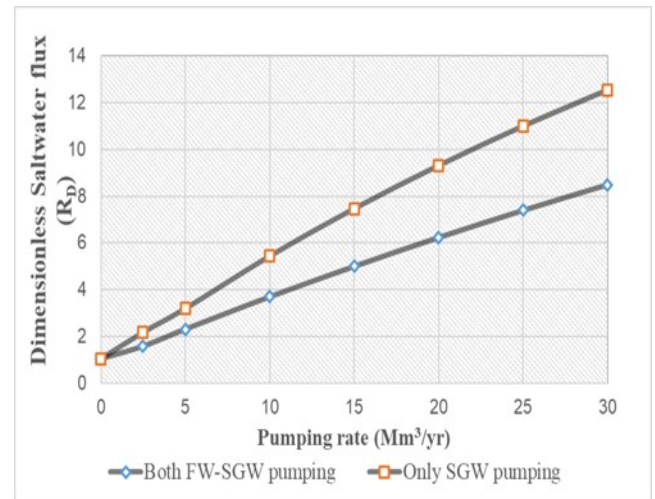


Fig.6 : Saltwater flux entering into the system at steady state with respect to fresh water entering to the aquifer

CONCLUSIONS

To determine the impact of simultaneous FW and SGW well pumping on refreshing a saltwater intruded aquifer, three scenarios of pumping from a regional scale aquifer were simulated and quantifying parameters were derived. Saline cone of depression was obtained when SGW well alone was pumping and while a more dispersed transition zone near to that cone of depression was observed for simultaneous pumping of FW and SGW wells. The obtained quantified variables proved reduction in salinity intrusion further inland. This pumped water could be used as a feed for desalination plants, which is a double advantage. However, more scenarios could be tested by changing location of pumping wells, and aquifer parameters to understand the sensitivity of these parameters on the refreshing effect. Further studies on knowing the dispersion effect due to pumping are also required. It would throw light in devising an optimal solution for remediating a saltwater intruded aquifer.

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