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Tidal Influence On Saltwater Intrusion In A Coastal Aquifer System

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Abstract

The quality and quantity of groundwater has been found to deteriorate in many areas of the world due to various human activities and natural causes. Saltwater intrusion is the movement of saline water into freshwater aquifers. In this study four types of experiments were done to know the effect of tide and pumping on saltwater intrusion into a coastal aquifer system. Experiments were conducted in a sand flume, which consists of three compartments. Two reservoirs at both ends containing freshwater and saltwater, representing the landward and seaward boundary, respectively. A middle compartment packed with quartz sand to simulate an unconfined coastal aquifer. A numerical verification of those experiments was done using FEFLOW. The study revealed that the combined effect of both tide and pumping severely affects the aquifer system by saltwater intrusion**.**

I. INTRODUCTION

In coastal areas, the periodic rise and fall of the tide can cause corresponding rise and fall in water levels in hydraulically connected coastal aquifers [1]. Analyzing and describing changes in groundwater levels in coastal aquifers are of important significance for coastal cities relying heavily on fresh groundwater for water supply and for environmental evolution in coastal areas [1]. In this study influence of tidal effects along with pumping is considered for analyzing effect of saltwater intrusion in a coastal aquifer. Oscillations propagate in coastal aquifers, causing groundwater head fluctuations.

This paper describes the tidal effect on the behavior of the saltwater in an unconfined aquifer through both physical and numerical modelling. The tidal influence was examined relative to the forcing of the inland fresh groundwater discharge and density-induced seawater circulation. Kuan et al.,(2012) conducted laboratory experiments and numerical simulations to investigate the influence of tidal oscillations on the behavior of saltwater wedge (Kuan et al.,2012). For the conditions examined, the experiments showed that an upper saline plume formed in the intertidal zone due to tide-induced seawater circulation. The presence of the upper saline plume shifted the fresh groundwater discharge zone seaward to the low-tide mark and restricted the intrusion of the saltwater wedge. Chan Hee Park et al.,2008 [3] studied the tidal effect on saltwater intrusion numerically to evaluate the effect of use of different intertidal zone boundary conditions on the magnitude and the direction of submarine groundwater discharge as well as their effect on saltwater interface profiles. Their findings indicate that the numerical results are sensitive to density difference between the freshwater and seawater phases along with the type of boundary conditions used at the intertidal zone. C.P. Kumar(2001) presents the simulation of seawater intrusion in Nauru Island through Saturated-Unsaturated TRAnsport (SUTRA) model and examine the effect of tidal forcing on the fresh water resources. Peter Neilson (1990) investigated the tidal motions of the water table height inside a sloping beach. Only the movements forced by the tide are considered, so a beach with negligible wave activity was chosen for the field measurements. The data show that even in the absence of precipitation the time average inland water table stands considerably above the mean seal level. Also, the water table at a fixed point inside the beach is far from sinusoidal wave though its variation is forced by a sinusoidal tide. This latter effect is due to the boundary condition along the sloping beach face which acts as a highly nonlinear filter. The observed behavior of the water table is explained in terms of perturbation extensions to the classical deep aquifer solution. One extension deals with the nonlinearity in the interior, the other with the boundary condition at the sloping beach face.

The objectives of the study are to estimate the extend of saltwater intrusion under tidal and non-tidal conditions. To study the effect of pumping on lateral extend of saltwater intrusion with and without tidal effect and numerical verification of tidal effect on saltwater intrusion using FEFLOW

II. METHODOLOGY

A. Physical modelling

A hypothetical study on tidal influence on saltwater intrusion was done by a laboratory experiment. The experimental setup is shown in Fig.1. It consists of three compartments: two reservoirs at both ends containing freshwater and saltwater, representing the landward and seaward boundary, respectively and middle compartment packed with quartz sand to simulate an unconfined coastal aquifer system.

Figure 1. Experimental setup

The landward reservoir was supplied with freshwater at a fixed rate simulating the freshwater flux from the landward boundary and the seaward reservoir was supplied with saltwater at a fixed rate simulating a fixed saltwater flux from the seaward boundary to the aquifer. Tidal effect is created by increasing the water level at seaside with respect to tidal data. Under the non-tidal condition, saltwater was supplied from one tank at a fixed rate (greater than the freshwater discharge rate) and discharged through an outlet to maintain a constant salinity and water level in the near-shore zone. Pumping effect created in the physical model by opening the tap provided in the tank. During the experiments, both the salinity and water level in the near-shore zone were monitored. Scale ratio was determined by using Noda's equation. The parameters used in model are given in Table 1.

TABLE I SCALED PARAMETERS USED IN THE PHYSICAL MODEL

Parameter	Values
Aquifer first layer thickness (cm)	20
Elevation of Groundwater Level Above Mean Sea level (cm)	0.781
Elevation of Land Above Mean Sea level (cm)	1.072
Elevation of Lake Above Mean Sea level (cm)	0.804
Time Taken by Spring Tide for Entering (min)	10.5
Time Taken by Tide for Leaving (min)	10.5
Height of Tide (cm)	0.335

Experiments were conducted in a tank with the dimension of 2.8m length, 0.35cm width, and 0.5m depth. Length of porous media is 2.15m. Experiments were done by filling saltwater and fresh water in two reservoirs simultaneously till it becomes a steady condition. Then adjust the flow rate of water from tank in order to make the water level in the reservoir a constant head of 0.804cm above mean sea-level and for freshwater 0.781m from mean sea-level. Run the experiment till a steady state occurred and note the reading of saltwater head. Repeat the experiment by increasing water level by 0.335 cm. Also, time taken by water to enter in the model was 10.5min and leaving from model is 10.5 min. Then a numerical verification of this hypothetical study had been done using FEFLOW. Concentration of TDS in the fresh water and seawater was 30ppm and 22000 ppm respectively.

Pycnometer is used to determine the specific gravity of soil particles. The specific gravity of sand used in the model is 2.7.

B. Validation of physical model using FEFLOW

Validation of physical model was done using FEFLOW 6.2 which works in one dimension. Model development consists of converting the physical model to a numerical model. Problem setting was shown in Table 2. The model is discretized using triangular units with 786 mesh elements and 438 nodes.

TABLE 2 PROBLEM SETTINGS OF PHYSICAL MODEL IN FEFLOW

Property	**Value**
Dimension	Two dimensional
Type	Saturated media
Projection	Horizontal, vertical
Problem class	Flow transport and mass concentration
Time class	Unsteady flow
Element type	Triangle
Mesh element	786
Mesh nodes	438
Time stepping scheme	Automatic time step contro via predicto corrector scheme- forward AdamsBashforth/ Backward Trapezoid (AB/TR time integration scheme)
Initial time step length	0.0001 min
Final simulation time	30 min
Aquifer type	Unconfined
State	Transient

In the physical model a hydraulic head of 0.804 cm is assigned along the seaside. At fresh water side hydraulic head of 0.781 cm is given. No flow boundary condition is given on the other two sides. Pumping rate is assigned as 0.078 m^3/d. Based on the obtained saltwater head, the model was calibrated. Hydraulic conductivity was estimated. After that model is simulated for different saltwater head under different cases were studied. In the solute transport model, concentration of solute is expressed in terms of total dissolved solids (TDS), since TDS is the main contaminant in the study area. A concentration of 22000 mg/l (Lake TDS) was used along the coastal zone and on fresh water zone, concentration of 30 mg/l was given.

C. Model calibration

Calibration is the process of defining the model representation of the hydraulic properties to achieve a desired degree of correspondence between the model simulations and observations of the saltwater heads (Litang 2015). The calibration procedure consists in modifying the aquifer parameters in order to obtain a model suitable to simulate the groundwater flow within the calibrated target (Litang 2015). In this study calibration of the numerical model is achieved by a trial and error approach by adjusting the zonation and values of key parameter such as hydraulic conductivity. The calibration is stopped when a reasonable match between the observed head and calculated head is obtained (Litang 2015). The calibration plot and root mean square value under different cases are shown in Fig.2. Considering all the cases, the root mean square error values ranges from 0.001058 to 0.00125 and thus hydraulic conductivity value was estimated as 5.5 m/d.

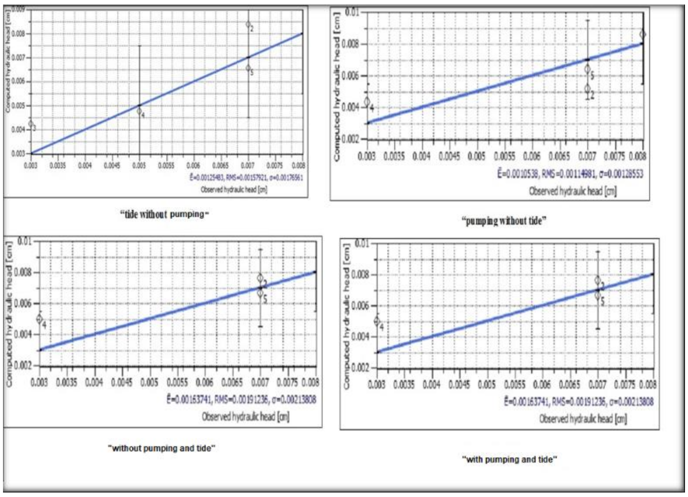

Figure 2. Calibration chart under different cases

III. RESULTS AND DISCUSSION

A. Physical modelling

Experiments were done in the lab using the scaled parameters and the following results were obtained. First experiment was done without tide and pumping rate and estimate the extend of saltwater intrusion. Later the experiment was repeated with increase in sea-level and thus found the effect of tide on saltwater intrusion in a coastal aquifer.

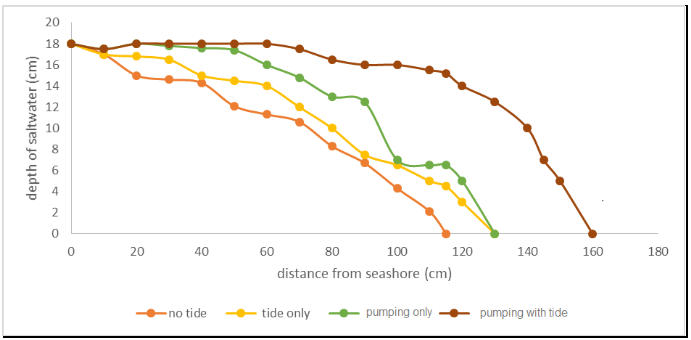

Figure 3. Lateral extend of saltwater intrusion under different cases

Fig.3 shows the profile of saltwater intrusion with and without tide in a coastal aquifer during pumping and non-pumping. It was found that lateral extend of saltwater intrusion under the condition without tide and pumping was 115 cm. But when tide is considered, the lateral intrusion extended to 130 cm. It indicates that about 20 % increase in the lateral extend of saltwater intrusion is due to the effect tide. In the case of pumping, lateral extend of intrusion is obtained as 130 cm. The experiment was repeated with tide and pumping, the lateral extend of saltwater intrusion becomes 160 cm. It revealed that the combined effect of pumping and tide had more effect on intrusion, since the lateral extend of saltwater intrusion is increased to 29%. Thus, the lateral extent of saltwater intrusion found in the actual study area is in between 2.3 km to 2.8 km from seashore.

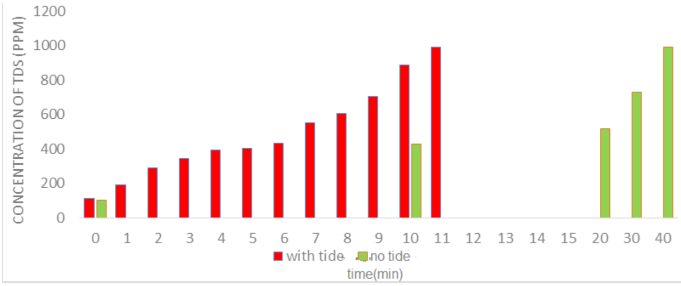

Figure 4. Temporal concentration of TDS under tidal and non-tidal condition during pumping

Fig. 4 shows the concentration of TDS under tidal and non-tidal condition during pumping. In the case of non-tidal case (Green colour), rate of TDS concentration increases slowly when compared to tidal condition (Red colour). Which shows that intrusion occurs faster due to the effect of tide.

B. Numerical modelling

The simulation period for the groundwater flow model in FEFLOW was 30 min and groundwater head at five observation points were used for calibration. The calibrated model was then run during the simulation period to obtain the simulated heads for each minute. The transient simulation of the calibrated groundwater flow model is carried out in the Automatic predictor corrector scheme with a time step length of 0.0001 min and final time as 30 minutes for both steady and unsteady state. The simulated head for all observation points under different cases are shown in Fig.5. The simulation period extends to 30 min.

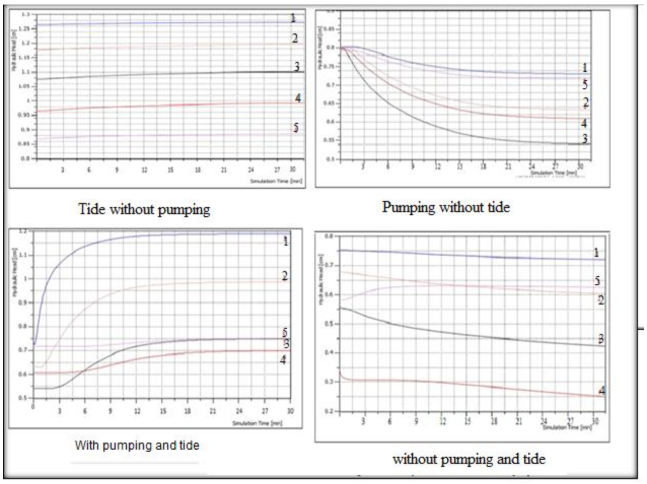

Figure 5. Simulated head under different case

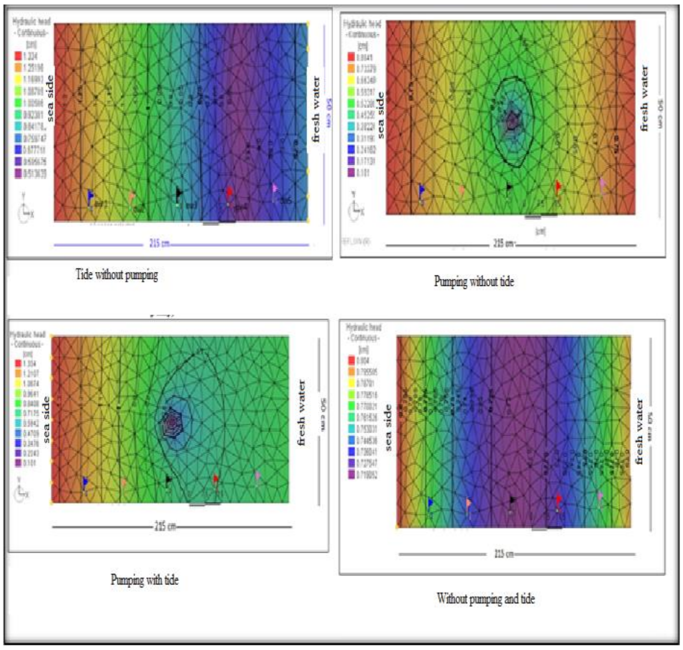

Figure 6. Distributed groundwater head under different cases

Transient simulation of contaminant transport model is carried out using the Automatic predictor corrector scheme with a time step length of 30 minute

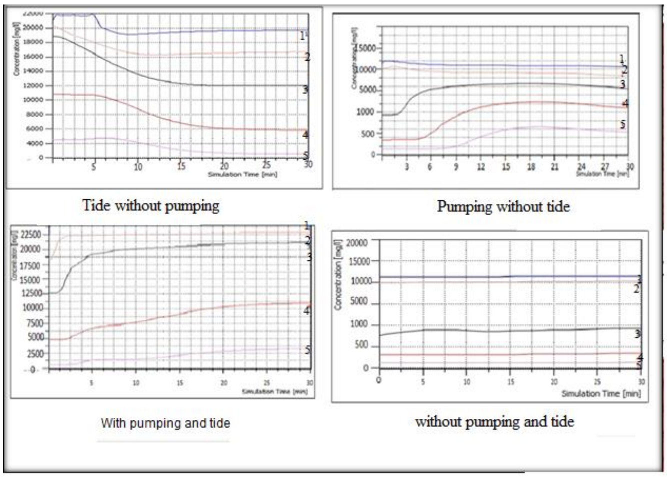

Figure 7. Simulated TDS concentration of different cases

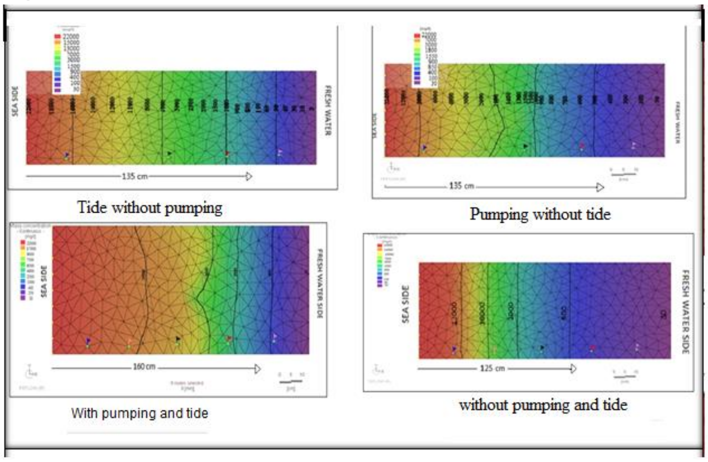

Figure 8. Distributed groundwater head under different cases

The profile of saltwater intrusion with and without tide in a coastal aquifer during pumping and non-pumping. It was found that lateral extend of saltwater intrusion was 125 cm when there is no pumping and tide. But when tide is considered, the lateral extend of salt water intrusion become 130 cm. It shows that about 7.14 % increase in lateral extend is due to the effect of tide. In the case of pumping, lateral extend of intrusion is 130 cm whereas when tide and pumping is considered, the lateral extend of intrusion is increased to 160 cm. From this result it was found that an increase of 21 % in the lateral extent of intrusion occurs due to the combined effect of pumping and tide. The comparison of lateral extend of saltwater intrusion in both physical modelling and numerical modelling are given in Table 3.

TABLE 3 COMPARISON OF LATERAL EXTEND OF SALTWATER INTRUSION

Cases	Lateral extend of saltwater (cm)	
	Physical model	**Numerical model**
Model Without tide and pumping	115	125
Model with Tide	130	135
Model with Pumping	130	135
Model with Tide and pumping	160	160

IV. CONCLUSION

Lateral extend of saltwater intrusion under the influence of tide, non-tide, pumping and their combinations were estimated using a physical model. It shows that

20% increase in the lateral extend of salt water intrusion is due to the influence of tide.

29 % increase in the lateral extend of intrusion is due to the influence of both tide and pumping

A numerical model was developed for the verification of the physical model under the same conditions used in physical model. It revealed that

i. 7.14% increase in the lateral extend of intrusion due to the influence of tide.
ii. 21 % increase in the lateral extend of intrusion due to the influence of tide and pumping

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Thus, the study revealed that the combined effect tide and pumping influences the lateral extend of saltwater intrusion.

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