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Groundwater Abstraction: A Model for Saltwater Intrusion of Coastal Fresh Water

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Abstract
The knowledge of salinity level and intrusion of saltwater into freshwater aquifer is necessary for groundwater monitoring and prediction in the coastal areas. In this work, an advection-dispersion saltwater intrusion model is used to study and simulate saltwater intrusion in a typical coastal aquifer. The aquifer portion was divided into grid with elements and nodes. Map of the study area indicating well locations was overlain on the grid system such that these locations coincide with the nodes. Chlorides at these wells were considered as initial nodal salinities. Results showed a highest and lowest increase in simulated chloride of 37.89 mg/L and 0.8 mg/L respectively. It also revealed that the chloride concentration of most of the considered well may climb unacceptable level in the next few years, if the current abstraction rate continues unabated.
Keywords: Saltwater Intrusion, Coastal aquifer, Nodal salinity, Chloride concentration

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Introduction
The most worrisome water quality predicament associated with coastal aquifer is saltwater intrusion. It is the movement of saline water into freshwater aquifers, which can lead to contamination of drinking water sources and other consequences (Post and Abarca, 2009). Freshwater quality and availability remain a critical environmental and sustainability issues of the twenty first century (UNEP, 2002). Saltwater intrusion occurs naturally owing to the hydraulic connection between groundwater and seawater. Human activities such as groundwater abstraction or overexploitation are the major cause of saltwater intrusion (Custodio, 2015). The extent of saltwater intrusion also depends on the characteristics of the groundwater flow in the aquifer region, the nature of groundwater management as well as on climatic conditions (Narayen et al, 2007).

The thickness of the transition zone between fresh and saltwater can vary from a few meters to hundreds of meters and is controlled mainly by the geologic heterogeneities and physical structure of the aquifer, recharge rate and freshwater extraction through pumping (Bobba, 1993). The Ghyben–Herzberg principle, gives the relationship between the

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freshwater and saltwater pressures. It gives an approximation to the depth of the saltwater–freshwater interface.

$$h_s = \left(\frac{\rho_f}{\rho_s - \rho_f}\right) h_f \qquad (1.0)$$

$$h_s = 40\, h_f \qquad (2.0)$$

Where h_s and h_f are the piezometric heads for saltwater and freshwater respectively. ρ_f is density of freshwater and ρ_s represents the density of saltwater.

Two approaches exist in modeling saline water intrusion. They are the variable density approach and the sharp interface assumption. The former assumes that both freshwater and saltwater do mix while the latter assumes that there exist stagnation point where there is no mixing. By using two sets of pressure data obtained from both fresh water and salt water zones in a single borehole, Kim et al.,(2007) estimated the interface depth. Other methods for determining the location of the freshwater - saltwater interface in coastal zones using hydraulic heads have been discussed by Xun Zhou (2011).

Methodology

The mathematical model consists of partial differential equations that govern both groundwater flow and solute transport in coastal aquifer. The equation for the conservation of mass of fluid written as:

$$\frac{\partial(\varepsilon p)}{\partial t} = -\nabla(\varepsilon p v) + Q_p \qquad (3.0)$$

Where $p(x, y, z)$ is the fluid density, Q_p is the fluid mass source, $v(x, y, z, t)$ is the fluid velocity, ε is the porosity and t is the time. Darcy's Law is expressed as

$$u = -k_x \frac{\partial h}{\partial x}, \quad w = -k_z \frac{\partial h}{\partial z} \qquad v = -k_y \left(\frac{\partial h}{\partial y} + \frac{\rho}{\rho_f}\right) \qquad (4.0)$$

The solute transport equation is obtained by considering a unit aquifer matrix in which saltwater is transported. The rate of solute transport into this aquifer is assumed to be by molecular diffusion, advection as well as dispersion. Processes within aquifer matrix are also considered. Using Fick's Law the contribution of diffusion is $-D(\nabla c)$, advection is ∇c and dispersion is $\nabla(\theta c)$.

$$\frac{\partial(\theta_w c_w)}{\partial t} = \frac{\partial}{\partial t}\left[D_{xx}\frac{\partial}{\partial x}(\theta_w c) + D_{xy}\frac{\partial}{\partial x}(\theta_w c)\right] + \frac{\partial}{\partial y}\left[D_{yx}\frac{\partial}{\partial x}(\theta_w c) + D_{yy}\frac{\partial}{\partial y}(\theta_w c)\right] - \left[\frac{\partial}{\partial x}(v_{wx} c) + \frac{\partial}{\partial y}(v_{wy} c)\right] - \frac{\partial}{\partial t}(\rho_b K_d c_w) - \lambda(\theta_w c_w + \rho_b k_d c_w) \qquad (5.0)$$

Application

Samples of water collected from both boreholes and hand dug wells were analyzed to ascertain the initial groundwater condition. Target aquifer portion was divided into grid with elements and nodes. Map of the study area showing well locations was overlain on the grid system such that these locations coincide with the nodes. Chlorides values at these well were assumed to represent the initial nodal salinities and simulations were performed at each node for ten time steps at $\Delta t = 400$days. A recharge of 1532mm/yr was assumed, transverse and longitudinal dispersion coefficients were taken as 0.25 and 0.75 m/day, transmissivity

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and velocity of groundwater as 2200m^2/day and 0.025m/day respectively. Porosity was 0.5, and the average measured temperature of 29.2^{o}C was used. Outputs were then obtained and interpreted.

Results

Figure 1 shows the simulated chloride contour after 4000 days. Figure 2 is the graph of simulated chloride at each time step of 400days.Figure 3 show a sample of simulated nodal salinity highest increase of 37.89 mg/L was observed at Node 8 after 4000 days. This may be because of the current as well as projected high relocation of people to this area in the next few years. Node 35 has the highest initial but simulated output after 4000days gives an increase of about 2.6 mg/L. Generally results show a progressive rise in the value of chloride at all nodes and at every time step. It further reveal that more than half of the well considered may have in the next decade attain a salinity level that is well above the WHO acceptable standard and hence will be very injurious to the health of coastal inhabitants. Table 1 is a part result of simulated chloride in the study area for a period of 4000 days

Figure 1: A 3-D Chloride simulation contour at t=4000days

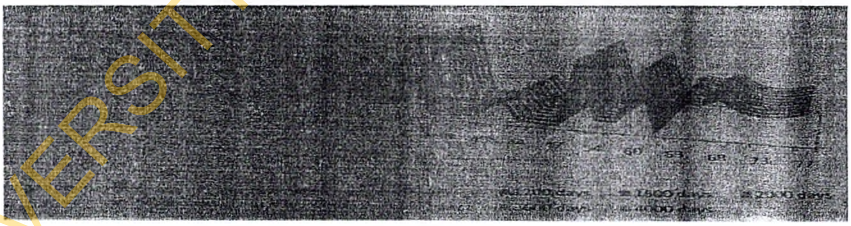

Figure 2: Variation of simulated nodal chloride for each time step from t=0 to t=4000 days

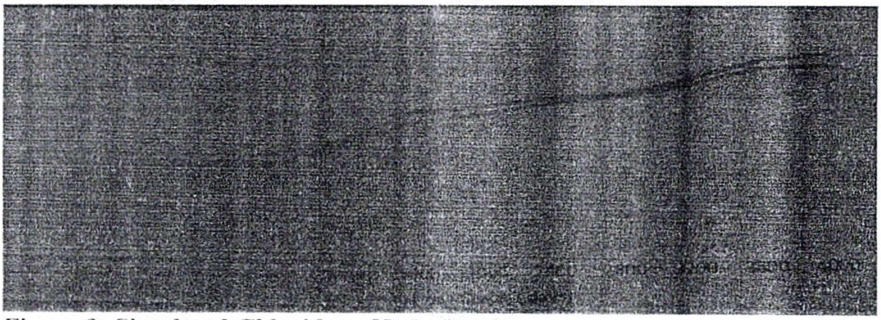

Figure 3: Simulated Chloride at Node 51

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Table 1: Result of simulated chloride in the study area for a period of 4000 days

Time Steps (days)	Node1	Node2	Node 4	Node 5	Node 8	Node11	Node 16	Node 18	Node 35
0	91.801	7.100	205.211	198.505	335.010	251.901	21.700	108.822	779.610
400	92.810	7.261	205.610	198.720	339.800	251.321	21.901	108.961	779.856
800	93.501	7.410	205.801	198.921	347.301	251.605	22.312	109.403	780.310
1200	95.312	8.121	205.991	199.450	354.110	251.819	24.509	109.610	780.593
1600	98.112	8.520	206.167	199.712	355.523	252.026	25.002	109.981	780.910
2000	99.220	8.720	206.510	199.909	359.701	254.101	25.911	110.112	781.222
2400	100.601	9.101	206.711	200.155	362.312	254.781	26.102	111.303	781.546
2800	101.310	9.707	207.121	200.413	366.100	254.998	26.711	113.207	781.778
3200	101.811	9.981	207.331	200.721	370.121	256.013	26.997	113.442	781.978
3600	103.101	10.121	207.458	200.821	372.058	256.601	27.187	113.728	782.145
4000	105.500	10.501	207.806	201.121	372.901	256.821	27.524	113.998	782.234

Conclusion

Models are veritable tools in detecting and predicting saltwater intrusion in coastal aquifers. It has been shown that wells closer to the coast experience high salinity because of the population density and the consequent heavy abstraction of fresh coastal water.

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