Simulation of Saltwater Intrusion Caused Electric Conductivity Fluctuations due to Groundwater Pumping in a Coastal Aquifer

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EXTENDED ABSTRACT

The Motooka region in the Fukuoka prefecture in Japan is a coastal area, where groundwater is the main water resource for green house agriculture. Over-exploitation of groundwater in this coastal region has resulted in saltwater intrusion and thus in the contamination of the freshwater aquifer. In addition to the more obvious effects of saltwater intrusion, fluctuations in salt concentrations caused by such intrusion is a crucial problem to address, since even slight changes in salt concentration of the water use for agricultural purposes significantly affect the crop's growth and yield. To the authors' knowledge, research on the salinity fluctuations with groundwater pumping and their effects on seasonal recharge of groundwater in the Motooka region has not been conducted thus far. To this end, a three-dimensional density-dependent finite difference flow model is developed to simulate the saltwater intrusion and salinity fluctuations due to groundwater pumping.

In this preliminary study, the emphasis is on the development of conceptual, mathematical and numerical model of variable density flow and solute transport. The model is based on the "transition zone" approach, which considers the interface as a miscible zone where freshwater and seawater is mixing while maintaining a density gradient across the freshwater/seawater interface. The transition zone approach requires simultaneous solution of the governing water flow and solute transport equations. To this end, the model incorporates three fundamental equations in flow and solute transport, namely Darcy's law, general groundwater flow equation and advection dispersion solute transport equation. The groundwater flow equation and solute transport equation are coupled by the equation of state to produce the salt concentration at each time step for whole flow domain. The finite difference method is used as the numerical technique to solve the partial differential equations of flow and transport under an implicit scheme. The method of characteristics is applied to solve the advection term in the solute transport equation. A non-uniform discretized grid system is adopted in the flow domain allocating relatively small grid sizes to pumping well locations. To achieve reliable results, relevant and important hydro-geological parameters are assigned to the numerical model after considering the hydrological situation of the Motooka region. The initial conditions used in the model are based on land use prior to groundwater development for agriculture when the seawater wedge was in its assumed natural state. Different boundary conditions are assigned considering the dominant hydrological processes that are believed to be in effect in the selected area.

Results of this study demonstrate the effects of variation in pumping and seasonal recharge rates for the years 2001 and 2002 on pumped groundwater under the influence of seawater intrusion. Since the measured pumping rates are not available for these years, pumping rates are assigned by a trial and error procedure by controlling the well drawdown. The results also reveal that model is capable of correctly simulating the physical processes. A comparison of the measured and modeled electric conductivities shows reasonable agreement. The results also hint that the sustainability of the fresh water aquifer and the green house irrigation will be seriously affected, if pumping continues at the present rates.

The present study, in spite of its preliminary nature, is important for the Motooka region in particular and for groundwater hydrology in general, as it not only satisfies a practical environmental purpose but is also helpful to understand the density dependent flow in a porous medium. Future research will update the model for use as a groundwater management tool for the Motooka region through its domain expansion to the whole Motooka coastal aquifer.

1. INTRODUCTION

Rapid urban development, economic growth and intensive population growth in coastal regions of many parts of the world have led to a vast increase in water demand. Inadequacy of surface water supply to fulfill this huge demand tends to increase the groundwater exploitation in coastal regions. Therefore the importance of groundwater has been identified and the usage of groundwater resources has exceeded sustainable limits. Due to overexploitation and environmental pollution, the available drinking water has been drastically threatened. It has been forecasted that in 2025, two thirds of the world population will face a shortage of drinkable water (Oude Essink 2001). As a large proportion of the world population lives in coastal zones, the optimal exploitation of freshwater and control of seawater intrusion are the challenges for present-day and future. Seawater intrusion can be defined as the inflow of seawater in to a coastal aquifer. The major reason for this phenomenon is abstraction of groundwater in exceeded limits.

In the Motooka area in the Fukuoka prefecture in Japan, studied herein, water requirements are fulfilled by river water, irrigation ponds and groundwater. Since a public water supply has become available only recently in this area, groundwater has become the only reliable water supply source for drinking. Basically river water and irrigation pond water are utilized for paddy cultivation. The groundwater is then used as the main drinking water supply. In the Matooka area, groundwater is extracted for greenhouse farming at a rate of approximately 700 m^3/day, for domestic use at 400m^3/day and at about 10 m^3/day for wineries (Tsutsumi et al 2004). The types of pumping are also mostly partially penetrating wells in the aquifer. When a well is pumping freshwater from an aquifer that consists of two sub layers (freshwater and saltwater), the interface between freshwater and saltwater will rise due to the drawdown at the free surface of the freshwater (Lin et al 1998). Due to the continuous exploitation of groundwater, saltwater intrusion has become a significant cause of groundwater problems. Since the slight changes of the salt content in pumped groundwater directly affect the crops, the farmers of Motooka area are keen to know about the salinity variation with groundwater pumping. The up-coning of saltwater in the vicinity of the pumping wells is an especially critical problem that needs to be taken into serious consideration. Construction of a new university in the area may also reduce the groundwater infiltration and create lower groundwater potential and invite significant quantities of saltwater to flow into the freshwater aquifer. As the threat of saltwater intrusion into the groundwater aquifer is becoming more critical, the authors had a keen interest in the study of saltwater intrusion in this area. Due to the distribution of agro-wells and complex geological formations, the application of two-dimensional saltwater intrusion model is not adequate as it cannot simulate the seawater movement to the level which would allow prediction of saltwater intrusion.

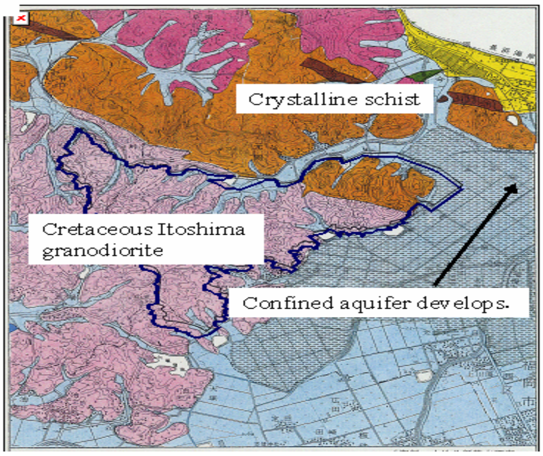


Figure 1. Geology of the area.

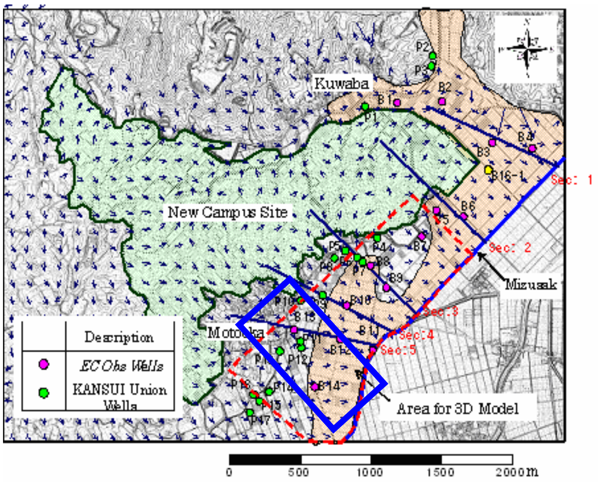


Figure 2. Ground water flow, electric conductivity wells, pumping well distribution and model location.

To fulfill the requirement of precise prediction of saltwater intrusion in the Motooka area under the prevailing complex conditions, development and application of a three-dimensional flow model with variable density is needed. In this paper, the development of a three dimensional numerical model to simulate and predict the spatial and temporal variability in the sea/fresh water interface and saline concentration of groundwater of the selected area is presented.

2. GEOLOGY

The Matooka area is located in the western region of Fukuoka City of Kyushu Island in Japan. The elevation of the ground surface ranges from 0.3 m at the lowest point to about 100 m a.m.s.l at the highest point. The lowland area is an alluvial plain used for agriculture such as greenhouse farming and paddy fields. Under this plain, a shallow unconfined aquifer has been developed and it is partially affected by saltwater intrusion. The thickness of the unconfined aquifer under the lowland is approximately 50 m. There are two geological units consisting of crystalline schist in the north and cretaceous itoshima granodiorite in the south. In the south east low alluvial plain a confined aquifer is being developed (Figure 1). The aquiclude is clayey soil of few meters thick. The hilly areas, which serve as groundwater recharge areas, mainly consist of weathered granite rock at 5 – 10 m depth and un-weathered granite below 40 – 50 m depths. Figure 2 describes the groundwater flow pattern, electric conductivity observation well distribution, pumping well distribution and selected area for the model.

3. METHOD

To simulate the electric conductivity fluctuations due to saltwater intrusion, a three-dimensional density dependent numerical model is developed. The complexity of geology, pumping well distribution, distribution of hourly recharge rate and topography of the selected area emphasize the requirement of a three-dimensional model. In this study, the model is developed for a selected area of the Motooka coastal aquifer, as shown in Figure 2. In the modeling process basically three different flow regions are considered according to the permeability values. These are bed rock, aquiclude and flow dominant areas (Figure 3). The model is based on the finite difference method with a non uniform discretized grid system. The method of characteristics is applied to solve the advection part of the mass transport equation. Fine grids are applied to the pumping well locations to have more precise results for the concentration of pumped water, and larger grid sizes are applied for rest.

3.1. MATHEMATICAL MODEL

The mathematical model consists of partial differential equations that govern the groundwater flow and transport of solute in a coastal aquifer. The numerical model discussed here uses the groundwater flow continuity equation, Darcy's law and the mass transport equation. The X and Z axes are taken as horizontal, while Y axis is considered as vertical.

The continuity equation is given by:

$$\left(C_w + \alpha S_0\right)\frac{\partial h}{\partial t} = -\frac{\partial u}{\partial x} - \frac{\partial w}{\partial z} - \frac{\partial v}{\partial y} \qquad (1)$$

where; C_w is specific moisture capacity, S_0 is specific storage coefficient, α is a dummy number which takes 0 in an unsaturated condition and 1 in a saturated condition, u is pore velocity in X direction (horizontal), w is pore velocity in Z direction (horizontal), v is pore velocity in Y direction (vertical), h is hydraulic pressure head.

Darcy's law is given by:

$$u = -k_x \frac{\partial h}{\partial x} \qquad (2.1)$$

$$w = -k_z \frac{\partial h}{\partial z} \qquad (2.2)$$

$$v = -k_y \left(\frac{\partial h}{\partial y} + \frac{\rho}{\rho_f} \right) \qquad (2.3)$$

ρ and ρ_f are contaminated and fresh water densities, respectively.

The advection dispersion solute transport equation is written as:

$$\frac{\partial C}{\partial t} + \frac{1}{\theta}\left(u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} + v\frac{\partial C}{\partial y} \right) = \frac{1}{\theta}\frac{\partial}{\partial x}\left(\theta D_{xx}\frac{\partial C}{\partial x} + \theta D_{xy}\frac{\partial C}{\partial y} + \theta D_{xz}\frac{\partial C}{\partial z} \right) + \frac{1}{\theta}\frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial C}{\partial z} + \theta D_{zy}\frac{\partial C}{\partial y} + \theta D_{zx}\frac{\partial C}{\partial z} \right) + \frac{1}{\theta}\frac{\partial}{\partial y}\left(\theta D_{yy}\frac{\partial C}{\partial y} + \theta D_{yx}\frac{\partial C}{\partial x} + \theta D_{yz}\frac{\partial C}{\partial z} \right) \qquad (3)$$

where; θ is volumetric moisture content, *Dxx,Dyy, Dzz, Dxy, Dxz, Dyx, Dyz, Dzx, Dzy* are dispersion coefficients, which are dependent on the velocity as shown below:

$$D_{xx} = \alpha_L \frac{u^2}{|V|} + \alpha_T \frac{w^2}{|V|} + \alpha_T \frac{v^2}{|V|} + D_M$$

$$D_{zz} = \alpha_T \frac{u^2}{|V|} + \alpha_L \frac{w^2}{|V|} + \alpha_T \frac{v^2}{|V|} + D_M$$

$$D_{yy} = \alpha_T \frac{u^2}{|V|} + \alpha_T \frac{w^2}{|V|} + \alpha_L \frac{v^2}{|V|} + D_M$$

$$D_{xy} = D_{yx} = (\alpha_L - \alpha_T)\frac{u \cdot v}{|V|}$$

$$D_{xz} = D_{zx} = (\alpha_L - \alpha_T)\frac{u \cdot w}{|V|}$$

$$D_{yz} = D_{zy} = (\alpha_L - \alpha_T)\frac{w \cdot v}{|V|}$$

where; D_{xx}, D_{zz}, and D_{yy} are principal components of the dispersion tensor, D_{xy}, D_{yx}, D_{xz}, D_{zx}, and D_{yz}, are off diagonal terms of the dispersion tensor, α_L is longitudinal dispersion length, α_T is transverse dispersion length, D_M is molecular diffusion coefficient, and $\left|V\right| = \sqrt{u^2 + w^2 + v^2}$ is the magnitude of the velocity vector. When the velocity vector is aligned with one of the coordinate axes, all the off diagonal terms become zero.

The equation of state shows the relationship between fluid density and solute concentration, and is given by:

$$C = \left(\frac{\rho - \rho_f}{\rho_s - \rho_f}\right) \times 100.00 \qquad (4)$$

where C is fluid concentration and ρ_s is seawater density.

3.2. NUMERICAL SIMULATION.

The model discussed here is based on the finite difference approach to solve the partial differential equation of flow and transport. The transient groundwater flow equation (1) is solved by an implicit finite difference method using an iterative successive over relaxation (SOR) technique. The solute transport equation (3) is solved in two step processors. Whereas advection term is computed by the method of characteristic (MOC), the dispersion is calculated by an explicit finite difference method. The method of characteristics is widely used as a high accuracy method to solve the convective-dispersive equation for solute transport in groundwater (Jinno and Ueda 1978, Zheng and Wang.1994). The model domain is divided into unequal discretized grid system for the X and Z directions. For the Y direction, uniform grid size of 2.0 m is used. Small grid sizes are assigned to pumping area and lager grid sizes are assigned to the rest in the X and Y directions. The smallest grid sizes in the X and Y directions are 4.0 m and 5.0 m respectively. Figure 4 shows the grid arrangement of the model: 1053.0 m, 417.0 m and 56.0 m are the length, width and height of the numerical model.

The hydro-geological parameters used in the model are obtained from borehole information, field measurements and literature (Appelo and Postma, 2007). The longitudinal and transverse dispersion lengths are set to 3.6 m and 0.36 m, respectively, while molecular diffusion is 1.0 x 10^{-9} m^2/s. The standard seawater density value of 1025.0 kg/m^3 is used. The density of fresh water is set to 1000.0 kg/m^3, and 1.6 x 10^{-8} m/s, 6.6 x10^{-7} m/s, and 4.6 x10^{-6} m/s are the hydraulic conductivities of bed rock, confined layer and flow dominant region, respectively. Time increment is four hours.

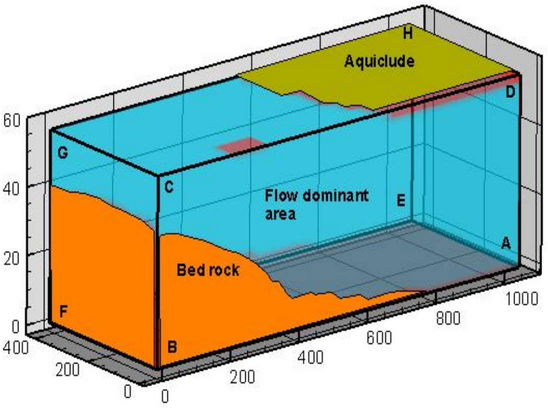


Figure 3. Major geological sections of the model.

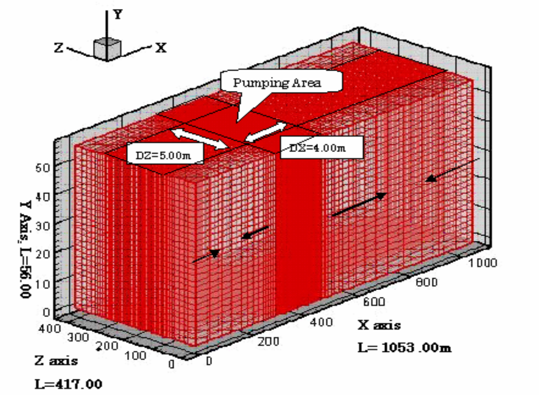


Figure 4. Grid distribution.

Different boundary conditions are applied to simulate groundwater recharge and seaward boundary of the model. In Figure 3, BCGF is the landside boundary while ADHE is the seaside boundary.

Table 1. Boundary conditions for the model. Boundaries are according to Figure 3.

Boundary	Pressure Head	Concentration
ABCD	$h_{ABCD}(t) = H_{ABCD}(t) - y$	$\partial C / \partial y = 0.0$
EFGH	$h_{EFGH}(t) = H_{EFGH}(t) - y$	$\partial C / \partial y = 0.0$
BCGF	$h_{BCGF}(t) = H_{BCGF}(t) - y$	$C = 0.0\ \%$
ADHE	$h_p = (H_s - y) \cdot \frac{\rho}{\rho_f}$	$u > 0, \frac{\partial C}{\partial x} = 0$ $u < 0, C = 100\%$
ABFE	$-k_y\left[\frac{\partial h}{\partial y} + \frac{\rho}{\rho_f}\right] = 0$	$\partial C / \partial y = 0.0$
CDHG	$-k_y\left[\frac{\partial h}{\partial y} + \frac{\rho}{\rho_f}\right] = -\mathrm{Re}(t)$	$\partial C / \partial y = 0.0$

For ABCD, EFGH and ADHE boundaries, time-dependent pressure head boundary conditions are applied. Hourly recharge rate Re(t) is assigned to the CDHG boundary. Different pumping rates are assigned by changing the drawdown of each well. Due to non-availability of pumping rates, a trial and error method is applied to obtain suitable pumping rates.

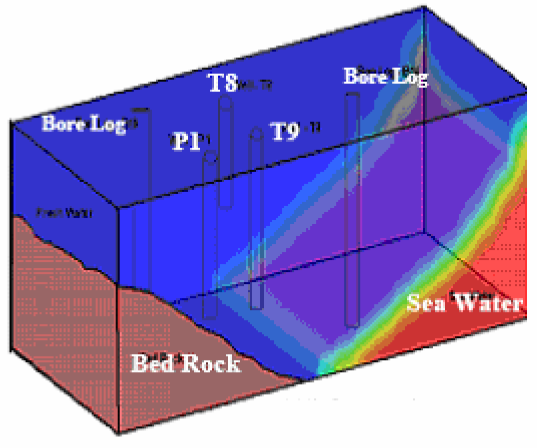
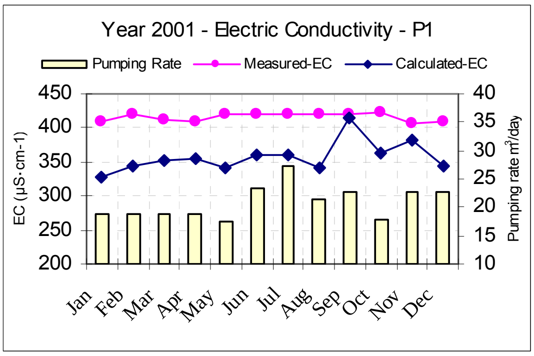


Figure 5. Initial conditions of the model.

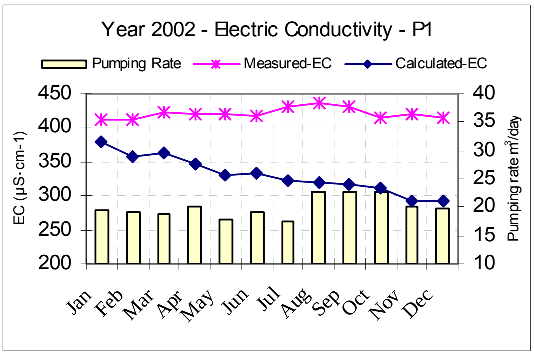
4. RESULTS

Figure 5 shows the initial condition of the model. The interface is assumed to be in a natural state. As shown in Figure 5, there are 3 pumping wells in the model domain. The boring depths of P1, T8 and T9 wells are 40 m, 20 m and 30 m, respectively. The well diameters for P1, T8 and T9 are 100 mm, 100 mm and 120 mm, respectively. Wells P1, T8 and T9 are located at 703 m, 679 m and 647 m from the sea boundary. Even though these 3 wells have been used for a long time, the pumping rate measurements were started only recently; however, electric conductivities have been recorded from year 2000. In this simulation, the main objective is to simulate the electric conductivity variation at pumping wells due to ground water pumping and seasonal groundwater recharge. The initialized model, shown in Figure 5, is run under high but reasonable pumping rates until the salinity levels around the well screening reach observed values. After that, realistic pumping rates are assigned and the results are obtained for the years 2001 and 2002.

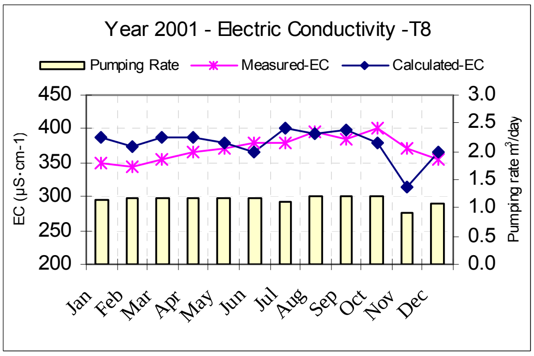
Figure 6 compares the numerical model results with the field observations of electric conductivities of wells P1, T8 and T9. The calculated pumping rates are also shown and it can be seen how the electric conductivities vary with pumping rates.



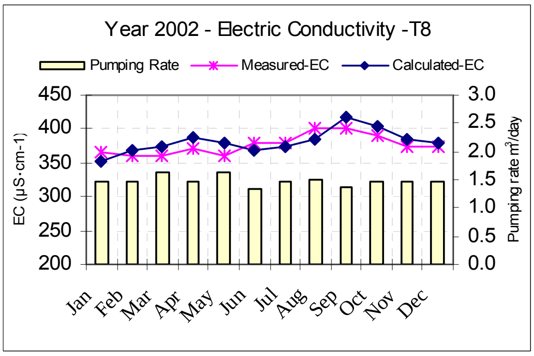
A) Measure and calculated EC variation of well P1 for year 2001



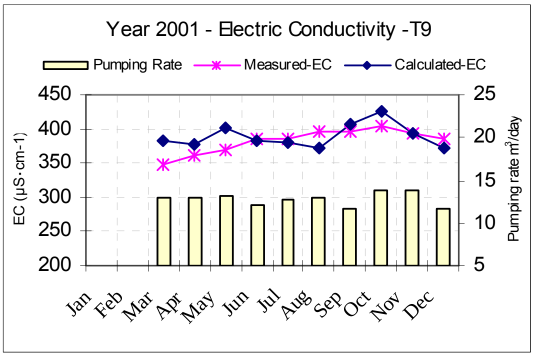
B) Measure and calculated EC variation of well P1 for year 2002



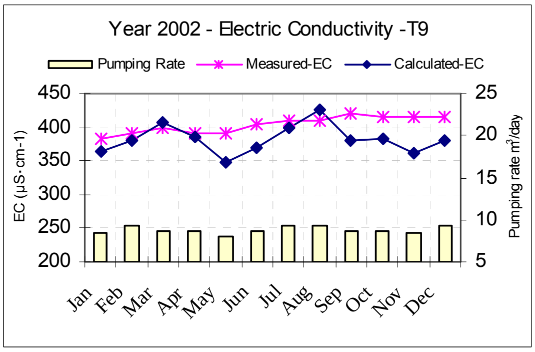
C) Measure and calculated EC variation of well T8 for year 2001



D) Measure and calculated EC variation of well T8 for year 2002



E) Measure and calculated EC variation of well T9 for year 2001



F) Measure and calculated EC variation of well T9 for year 2002

Figure 6. Comparison of numerical results with measured electric conductivities for the years 2001 and 2002.

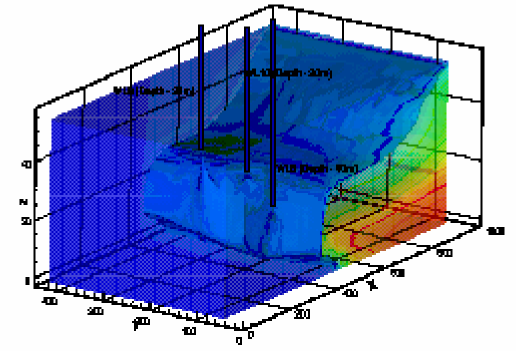


Figure 7. Up-coning at pumping wells

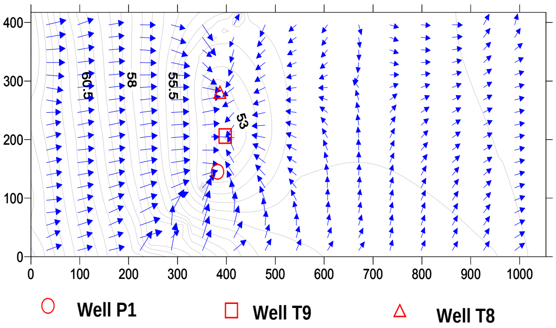


Figure 8. Simulation of groundwater flow pattern at water table and the potential contours.

5. DISCUSSION

Measured electric conductivity values of pumping wells in the selected coastal aquifer show that the present extent of saltwater intrusion is not critical since the electric conductivity values range between 300 μS/cm and 500 μS/cm. However, the fluctuations are more important for agriculture in Motooka. It can be foreseen that, if groundwater exploitation increases more than the present rate, in future this area will be influenced by critical seawater intrusion. The numerical results of well P1 show lower values than the measured electric conductivities. The reason for these lower values may be due to its location (the farthest well in the model domain) and its pumping rates. Its real pumping rate may be larger than the value used in the numerical simulation. Non-availability of pumping rate measurements for the years 2001 and 2002 is certainly an issue in obtaining reliable results for the pumping wells. Contrast to well P1, wells T8 and T9 show good agreements between the measured and the calculated electric conductivity values. For the electric conductivity fluctuations, not only pumping rates but groundwater recharge is influenced. Figure 7 demonstrates the up-coning phenomenon at the tip of the pumping wells. The seawater/freshwater interface movement towards the well is clearly modeled and this up-coning will be a critical problem in future if groundwater extraction continues at high quantities. Hydraulic conductivities are also another factor that affects the results. It seems, however, to control the time scale of the simulated processes. The sensitivity of the simulation results to hydraulic properties of the aquifer is not investigated in this study. Applying suitable boundary conditions, as shown in Table 1, numerical simulation is enhanced to reach the reality. Groundwater flow pattern obtained from the numerical model in figure 8 depicts that the potential distribution of the model is correctly simulated. The flow around the wells directs towards the well points and flow directions are perpendicular to potential lines imply that the model simulates the hydrological processes correctly. One of the significant features of this model is its capability to simulate the relationship between pumping rates and electric conductivity, which is more important to the farmer of Motooka.

6. CONCLUSION

The numerical simulation results of the developed density dependent transport model show satisfactory compatibility with the measured electric conductivities of pumping wells even when the well P1 shows deviation. The general trend of the simulation seems to describe the physical phenomenon quite well. Therefore, this model is capable of simulating electric conductivity fluctuations with different pumping rates, groundwater recharge and variable pressure boundaries. Assigning finer grid sizes is recommended to obtain more reasonable results, since slight changes in electric conductivities are more important to know for the farmers of Motooka. The model can further be updated to be used as a groundwater management tool for the Motooka region by expanding its domain to the whole Motooka coastal aquifer.

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