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Three dimensional solute transport numerical modeling of salinity fluctuations in a coastal aquifer

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Abstract: Over-exploitation of groundwater in coastal aquifers is one of the major reasons for saltwater intrusion. Saltwater intrusion contaminates the freshwater resource in coastal aquifers by increasing the salinity levels of the groundwater. A small quantity of saltwater is enough to contaminate the large quantity of freshwater in a coastal aquifer. Therefore, saltwater intrusion should be considered seriously. Numerical models are needed to enhance the understanding of saltwater intrusion and its related phenomena extensively. The Motooka region in the Fukuoka prefecture in Japan is a coastal area, where groundwater is the main water resource for green house agriculture and domestic use. 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 salinity caused by such intrusion is a crucial problem to address, since even slight changes in salinity of the water use for agricultural purposes significantly affect the crop's growth and yield. So far, a research on the salinity fluctuations with groundwater pumping and their effects on seasonal recharge of groundwater in the Motooka region has not been conducted. Therefore, in this study a three-dimensional density-dependent solute transport flow model is developed to simulate the salinity fluctuations due to groundwater pumping.

In the present numerical study, the emphasis is on the development of conceptual, mathematical and numerical model of variable density flow and solute transport and its application to simulate the salinity fluctuation due to groundwater pumping at different rates. The model is based on the "transition zone" approach, which considers the interface as a miscible zone where freshwater and saltwater is mixing while maintaining a density gradient across the freshwater/saltwater interface. The transition zone approach requires simultaneous solutions 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 the 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. Different boundary conditions are assigned considering the dominant hydrological processes those are believed to be in effect in the selected area.

The numerical results obtained from the model demonstrate the salinity variation due to groundwater pumping and seasonal recharge rates from year 2001 to 2007 under the influence of saltwater intrusion. 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.

Keywords: *Coastal aquifer, density dependent flow, numerical model, salinity, saltwater intrusion*

1. INTRODUCTION

Approximately 50% of the world population lives within 60 km of the shoreline (Essink, 2001). According to the World Meteorological organization, only 2.5% of the total water volume in the earth is freshwater and the availability of surface water is limited in many areas of the world (Ranjan et al., 2006). As a consequence of increasing demand of water in coastal areas, substantial falls of freshwater heads can be observed. Fall of freshwater head in the coastal aquifer invites saltwater to move into the freshwater zone of the aquifer and this phenomenon is technically named as saltwater intrusion. Saltwater intrusion can have severe impact on costal groundwater systems due to its irreversible nature. Severe saltwater intrusion may cause the abandon of the aquifer from further use. The areas which are affected by saltwater intrusion result high salinity levels in their pumped groundwater. The extent of the intrusion depends on climatic conditions, the characteristics of the groundwater flow within the aquifers and the nature of groundwater management in that particular area (Narayan et al., 2007). The complex geological formations, irregular pumping well distributions and regional hydro-geologic conditions raise the necessity of complex numerical models to simulate the seawater intrusion phenomenon. Many researchers have conducted numerical simulations of the saltwater intrusion (e.g. Andersen et al., 1988; Rivera et al., 1990; Ghassemi et al., 1993; Essink, 2001; Christian and Weixing, 2006; Lin et al., 2008). However, the studies on the salinity fluctuations due to groundwater pumping and seasonal recharge are not much highlighted in the field of hydrological numerical simulations. A numerical study on salinity fluctuation is valuable for costal aquifers where groundwater is used for agriculture, especially in the green house farming. Not only the high salinity levels but also the changes in salinity levels in pumped groundwater critically influence the growth of crops and their yields. In some cases, mild salt effects might go entirely unnoticed because of a uniform reduction in growth of crops across an entire field (Ayers and Westcott, 1985). When soil salinity exceeds a plant's tolerance, growth reductions occur. As salt concentration increases, water becomes increasingly difficult for the plant to absorb. A plant would die from water stress or drought in a moist soil if the salt concentration becomes high enough (Blayock, 1994). In the present study, an attempt has taken to simulate the salinity fluctuations due to groundwater pumping in a coastal aquifer which is affected by saltwater intrusion. A three dimensional density dependent solute transport model is developed for the selected area of the Motooka coastal aquifer.

2. WATER USE AND GEOLOGY OF THE STUDY AREA

The Matooka area is located in the western region of Fukuoka City of Kyushu Island in Japan (Figure 1). The water requirements of the area are fulfilled by river water, irrigation ponds and groundwater. The elevation of the ground surface ranges from 0.3 m at the lowest point to about 100 m above mean sea level 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. Until recently, a public water supply was not available in this area. Therefore, groundwater was the only reliable water supply source for drinking that time. Still the groundwater is an invaluable water resource for this area. Basically river water and irrigation pond water are utilized for paddy cultivation. The groundwater is then used as the main water supply for drinking and greenhouses. In the Matooka area, groundwater is extracted at a rate of approximately 700 m^3/day for greenhouse farming, 400m^3/day for domestic use and about 10 m^3/day for wineries (Tsutsumi et al., 2004). The types of pumping are also mostly partially penetrating wells in the aquifer. 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. Construction of a new university in the area may also reduce the groundwater infiltration and creates 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 saltwater movement to the level which would allow prediction of salinity fluctuation. 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 2). 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 3 describes the distribution of monitoring wells for electric conductivity, pumping well and selected area for the model.

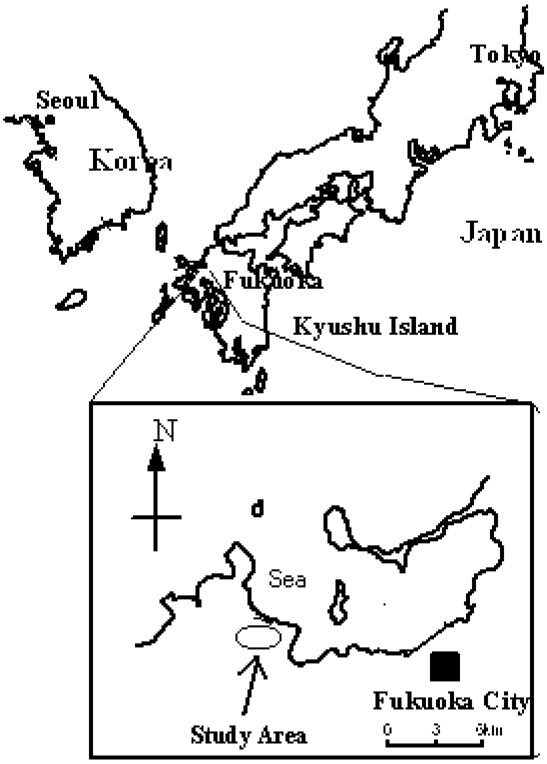

Figure 1. Location maps of the study area.

3. METHODOLOGY

To simulate the salinity 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 3.

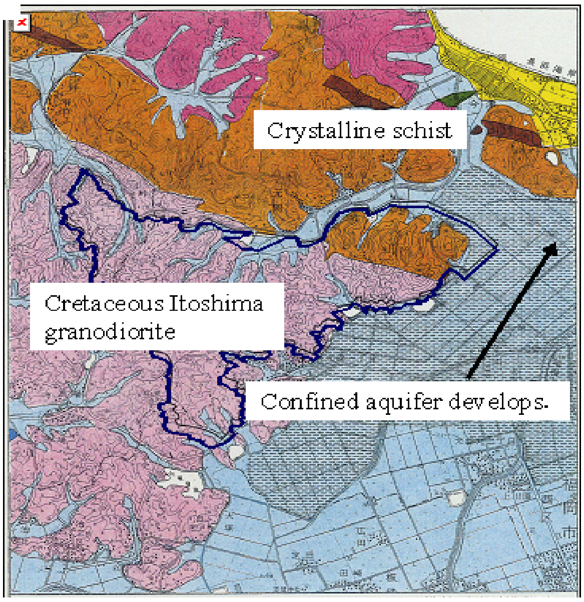

Figure 2. Geology of the area

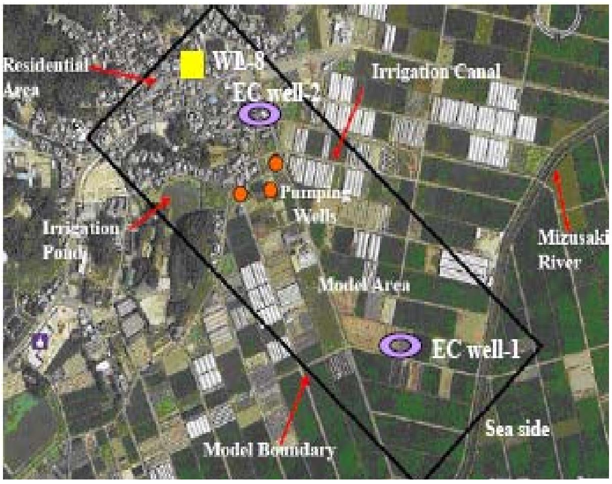

Figure 3. Detailed information about the model area – pumping wells, water table observation well (WL 8) and salinity observation wells (EC well -1 & 2). The minimum distance between the pumping wells inside the model area is 90 m and the maximum distance is 165 m.

3.1. Mathematical Model

The mathematical model consists of partial differential equations those 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:

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

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, *w* is pore velocity in *z* direction, *v* is pore velocity in *y* direction, *h* is hydraulic pressure head.

Darcy's law is given by:

$$u=-k_x\frac{\partial h}{\partial x}\qquad(2.1);\qquad w=-k_z\frac{\partial h}{\partial z}\qquad(2.2);\qquad v=-k_y\left(\frac{\partial h}{\partial y}+\frac{\rho}{\rho_f}\right)\qquad(2.3)$$

ρ and ρ_f are contaminated and fresh water densities, respectively. The advection dispersion solute transport equation is written as:

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

where θ is volumetric moisture content, D_{xx}, D_{yy}, D_{zz}, D_{xy}, D_{xz}, D_{yx}, D_{yz}, D_{zx} and D_{zy} are dispersion coefficients, which are dependent on the real flow velocities as shown below:

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

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

$$D_{yy}=\alpha_T\frac{u'^2}{|V|}+\alpha_T\frac{w'^2}{|V|}+\alpha_L\frac{v'^2}{|V|}+D_M\qquad(4)$$

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

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

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

where u^1, w^1 and v^1 are the components of real pore velocities in x, z and y directions. D_{xx}, D_{zz}, and D_{yy} are principal components of the dispersion tensor, D_{xy}, D_{yx}, D_{xz}, D_{zx}, D_{yz} 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 $|V|=\sqrt{u^2+w^2+v^2}$ 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 it is given by:

$$C=\left(\frac{\rho-\rho_f}{\rho_s-\rho_f}\right)\times 100.00\qquad(5)$$

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). 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 *z* directions. The smallest grid sizes in the *x* and *z* directions are 4.0 m and 5.0 m respectively. Figure 4 shows the grid arrangement of the model. 1053.0 m and 417.0 m are the length and width of the numerical model. 56.0 m is the height at seaside boundary while the maximum height at the landside boundary is 66.0 m.

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 saltwater density value of 1025.0 kg/m^3 is used. The density of fresh water is set to 1000.0 kg/m^3. In the modeling process basically three different flow regions are considered according to the hydraulic conductivities. These are bed rock, aquiclude and flow dominant area as shown in Figure 5. The hydraulic conductivities of bed rock, aquiclude and flow dominant region are 1.6 x 10^{-8} m/s, 6.6 x10^{-7} m/s, and 4.6 x10^{-6} m/s respectively. Time increment is four hours. Different boundary conditions are applied to simulate groundwater recharge and seaward boundary of the model. In Figure 4 and 5, ADEF is the landside boundary while BCHG is the seaside boundary. For ABCD, ADEF and EFGH boundaries time dependent pressure head boundary conditions are applied. Those boundary conditions and the time dependent seasonal groundwater recharge are obtained from the regional groundwater flow and recharge model developed by Tsutsumi et al., 2004. The initial conditions used in the model are based on land use prior to groundwater development for agriculture when the saltwater wedge was in its assumed natural state. Figure 6 shows the measured average pumping rates for the pumping wells located in the selected model area for the year 2007. In the calculate year 2007 pumping rates are assigned for the years 2002 to 2006 also assuming same pattern of water use from year 2002 to 2007. Figures 7, 8 and 9 show the simulated results for electric conductivity and monthly average pumping rates during 2002 to 2007 for the wells P1, T8 and T9 respectively. In Figure 4, the locations of pumping wells are also illustrated.

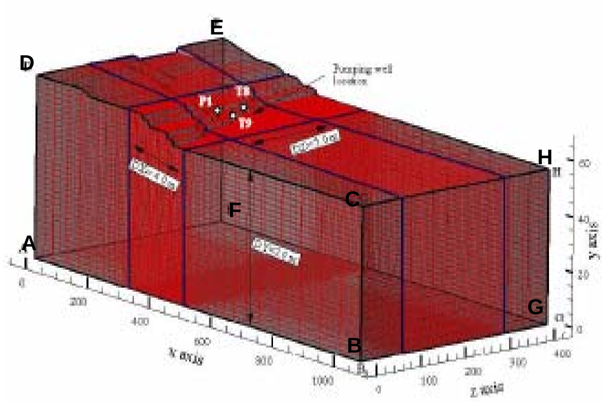

Figure 4. Grid arrangement of the numerical model

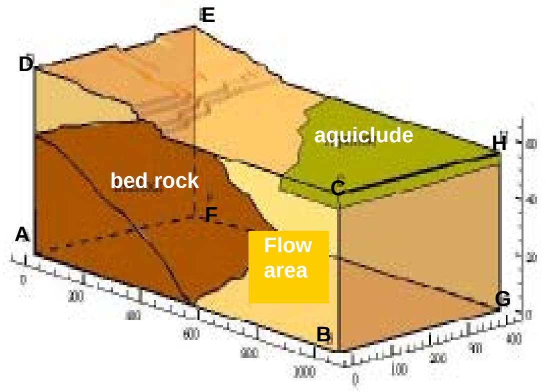

Figure 5. Geological regions of the model

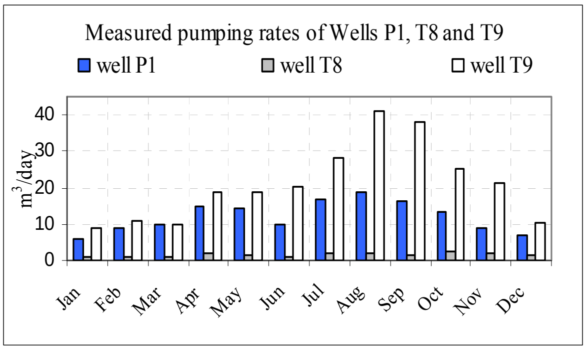

Figure 6. Monthly average pumping rates for the year 2007

Table **1.** Boundary conditions for the model (According to Figure 4 & 5)

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

4. DISCUSSION AND CONCLUSIONS

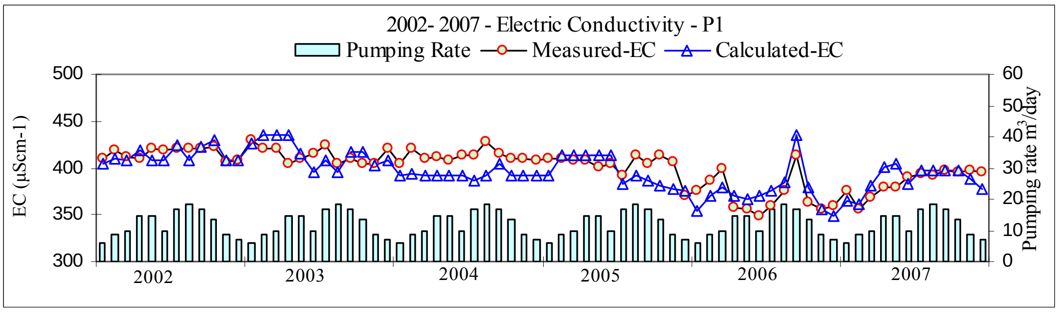

Figure 7. Measured and calculated EC variation of well P1 for year 2002 and 2007

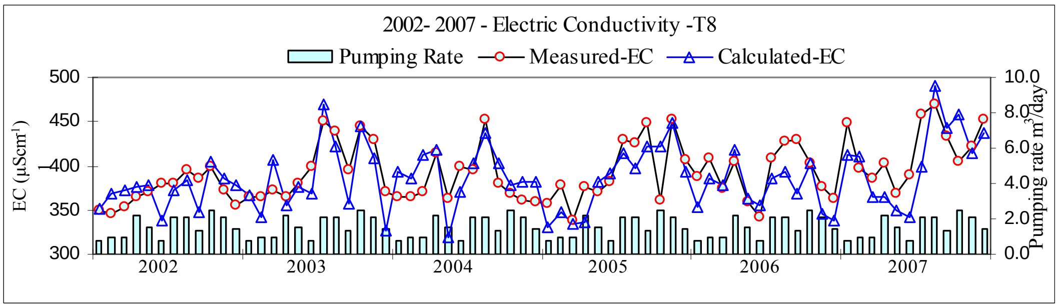

Figure 8. Measured and calculated EC variation of well T8 for year 2002 and 2007

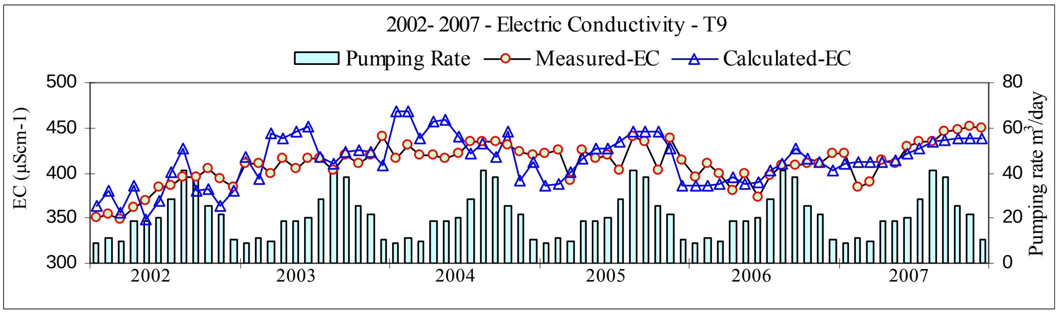

Figure 9. Measured and calculated EC variation of well T9 for year 2002 and 2007

In the numerical results, salinity is represented as electric conductivity of the pumped groundwater. The variation of electric conductivities of the three pumping wells is caused by the pumping rates and seasonal recharge rates. In this model, seasonal recharge is considered and time-dependent boundary conditions are assigned.

According to the observed and calculated results, pumping well T8 shows larger fluctuations of electric conductivity than the other two wells, although its pumping rates are smaller than that of the others. The reason for this is the screen depth of the well T8. Even if the pumping rates are low, the well screen is deep and, thus, the possibility of gaining high salinity water is high. Therefore, the well screen is also an important factor which causes fluctuations. For year 2007, well T8 and T9 show salinity increments compared to year 2006. These two wells are located closer to the seaside boundary than the well P1. From years 2005 to 2007, good agreements between simulated and observed electric conductivity values are obtained for the wells P1, T8 and T9 than the simulation period between the years 2002 and 2005. The reason may be the assumed pumping rates for the years between 2002 and 2005.

Measured electric conductivity values of pumping wells in the selected coastal aquifer show that the present extent on saltwater intrusion is considerably not critical since the electric conductivity values range between 300 μS/cm and 500 μS/cm. But 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 saltwater intrusion. For the electric conductivity fluctuations not only the pumping rates, but the groundwater recharge is also influenced. Applying suitable boundary conditions, as shown in Table 1, the numerical simulation is enhanced to reach the reality. In this model one significant feature is the capability of simulating relationship between pumping rates and salinity or the electric conductivity fluctuation which is more important to the farmers. 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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REFERENCES

Appelo, C.A.J. and Postma, D. (2007), Geochemistry, groundwater and pollution, 2nd Edition, A.A. Balkema publishers, Leiden.

Andersen, P.F., Mercer, J.W. and White, H.O. (1988), Numerical modeling of seawater intrusion at Hallandale Florida. Groundwater, 26, 619-630.

Ayers, R.S. and Westcott, D.W. (1985), Water quality for agriculture, irrigation and drainage. PaperNo. 29, Food and agriculture organization of the United Nations Rome.

Blayock, A.D. (1994), Soil salinity, soil tolerance and growth potential of horticultural and landscape plants. Cooperative extensive service, Department of plants, soil and insect sciences, College of agriculture, University of Wyoming.

Christian, D.L. and Weixing, G. (2006), MODFLOW/MT3DMS – based simulation of variable-density groundwater flow and transport. Groundwater, 44(3), 339-351.

Essink Gualbert H. P. O. (2001), Density dependent groundwater flow. Academic publishing of Utrecht University, Utrecht, 12-50.

Ghassemi, F., Chen, T.H., Jackeman, A.J. and Jacobson, G. (1993), Two and three dimensional simulation of seawater intrusion: Performances of the SUTRA and HST3d models. AGSO J Aust Geol Geophys, 14(2-3), 219-226.

Jinno, K. and Ueda, T. (1978), On the numerical solutions of convective dispersion equation by shifting particles. Trans JSCE, 10, 126-129.

Lin, J., Snodsmith, J.B., Zeng, C. and Wu, J. (2008), A modeling study of seawater intrusion in Alabama Gulf coast, USA. Envion Geol, DOI 10.1007/s00254-008-1288-y.

Narayan, K.A., Schleeberger, C. and Bristow K.L. (2007), Modeling seawater intrusion in the Burdenkin delta irrigation area, North Queensland, Australia. Agricultural Water Management, 89,217-228.

Ranjan, S.P., Kazama, S. and Sawamoto, M. (2006), Effects of climate and land use changes on groundwater resources in coastal aquifers. Journal of Environmental Management, 80, 25-35.

Rivera, A., Ledoux, E. and Sauvagna, S. (1990), A compatible single-phase/two-phase numerical model: 2. Application to a coastal aquifer in Mexico. Groundwater, 28(2), 215-223.

Tsutsumi, A., Jinno, K. and Berndtsson, R. (2004), Surface and subsurface water balance estimation by the groundwater recharge model and a 3-D two-phase flow model, Hydrological sciences, 49(2), 205-215.