Sains Malaysiana 39(4)(2010): 525–532

A Numerical Modelling of Seawater Intrusion into an Oceanic Island Aquifer, Sipadan Island, Malaysia

(Pemodelan Berangka Kemasukan Air Laut ke dalam Akuifer Pulau Lautan, Pulau Sipadan, Malaysia)

MOHD HARUN ABDULLAH, SARVA MANGALA RAVEENA*
& AHMAD ZAHARIN ARIS

ABSTRACT

The primary source of water on many small islands is the fragile freshwater lens that floats on saline water in its shallow aquifer. The management of such a limited groundwater resource on these islands is seriously constrained by the occurrence of seawater intrusion. Sipadan Island, the renowned and only oceanic island in Malaysia, had experienced in the over-extraction of its groundwater for more than ten years to cater for freshwater demand associated with tourism activities. This paper discusses the output of modelling of seawater intrusion into the island's aquifer using SEAWAT*-2000. The findings indicated that the island's coastal aquifer has been encroached by seawater. The infiltration of isochlor (chloride concentration) of 2.5 and 45% of seawater and freshwater mixing ratios has moved 63.4 m and 12.7 m inland from the coastline, respectively. The upconing event at the pumping well, as simulated by the three-dimensional model, showed that 14.5% of seawater-freshwater mixing ratio took place below the bottom of each well. Intensive and unregulated exploitation of groundwater from such an unconfined aquifer of the island by pumping wells contributed to the upconing. In order to protect the fresh groundwater resources in the study area from seawater intrusion, adjustment of groundwater pumping rate is needed. This study showed that the model is useful in demonstrating the mechanism and movement of freshwater-seawater interface in the island, and thus provide a powerful management tool for such an aquifer.*

Keywords: Groundwater; numerical modelling, oceanic island; seawater intrusion

ABSTRAK

Sumber air primer bagi pulau-pulau kecil adalah lensa air tawar bawah tanah yang terapung di atas air masin di dalam akuifer. Pengurusan sumber air bawah tanah yang terhad di pulau-pulau ini dibebani oleh penyerapan air laut. Pulau Sipadan merupakan pulau yang terkenal dan satu-satunya pulau lautan di Malaysia, mengalami pengekstrakan air bawah tanah secara berlebihan lebih dari sepuluh tahun bagi menampung permintaan air bawah tanah yang dikaitkan dengan aktiviti pelancongan. Makalah ini membincangkan output model kemasukan air laut ke dalam akuifer pulau menggunakan SEAWAT*-2000. Peresapan isoklor 2.5 dan 45% (kepekatan klorida) nisbah percampuran air laut dan air tawar, masing-masing adalah 63.4 m dan 12.7 m dari laut ke daratan. Pembentukan* upconing *di setiap telaga pengepaman seperti yang disimulasi oleh model menunjukkan nisbah percampuran air laut dan air tawar adalah sebanyak 14.5% yang berlaku di bahagian bawah telaga pengepaman. Pengunaan air bawah tanah secara intensif dan tidak terkawal dari akuifer pulau ini menyebabkan pembentukan* upconing. *Usaha untuk melindungi sumber air bawah tanah di kawasan kajian daripada kemasukan air laut memerlukan pengubahsuaian kadar pengepaman. Kajian ini menunjukkan model tersebut adalah berguna dalam menerangkan mekanisme dan pergerakan antara muka air tawar dan air laut pulau serta sebagai alat pengurusan yang berguna bagi jenis akuifer seperti ini.*

Kata kunci: Air bawah tanah; kemasukan air laut; model berangka; pulau di lautan

INTRODUCTION

Small islands have limited options when developing their freshwater resources. Groundwater is the only main source of freshwater on these islands (Abdullah et al. 2008; Aris et al. 2008). The optimal development of that resource is essential to the long-term future of these small islands. Perhaps the notion of carrying capacity is more meaningful with respect to small islands. It may be that the current concept of groundwater sustainability can be rendered operational by the study of the optimal groundwater resources development of small islands (Falkland 1991). According to Mao et al. (2005) in Ardeer off Scotland, seawater intrusion occurs in two ways: one is the advancement of the seawater at the bottom of the aquifer resulting from the density difference between seawater and freshwater. The other way is the infiltration of seawater through the beach. The major reason for this phenomenon is the abstraction of groundwater exceeding the limit of natural equilibrium between freshwater and seawater that merged together in a coastal aquifer. Groundwater in these islands exists in the form of thin fragile floating lens, which is often vulnerable to overexploitation and susceptible to seawater intrusion (Singh & Gupta 1999).

The continuous pumping of groundwater to meet various needs on the island may lead to the advancement of seawater at the bottom of the aquifer and deterioration of the groundwater quality. When an aquifer contains an underlying layer of saline water being pumped, a stable cone below the bottom of the well at some depth in the interface will be developed (Hamza 2006). Continuous or overpumping the cone will cause the interface to rise abruptly to the bottom of the well. As a result, the water extracted from the well become salty. Thus, evaluation of seawater intrusion is critical for maintaining a long term supply of groundwater resource of good quality to its management.

Because investigations on groundwater are time-consuming and expensive, mathematical modelling of seawater intrusion has emerged as an important tool for understanding the groundwater flow and movement (Norhan & Kuan 2004). Due to its practical importance, mathematical modellings have dominated the study of complex groundwater problems such as for investigating upconing in the field application due to their ability to tie data and physical principles together into a useful picture of the studied area as well as capable to produce greater and accurate results (Zhou et al. 2005). Mathematical modellings of seawater intrusion have attracted remarkable attention in the water resources literature over the last 20 years (Dierch & Koldditz 2002; Perera et al. 2008). This has been shown in seawater intrusion studies by Galeati et al. (1992); Shoemaker and Edwards (2003); Younes et al. (1999). Saltwater upconing problem generally employed two approaches, viz. sharp interface and density dependent solute transport.

In seawater intrusion studies, density dependent solute transport is needed to simulate the flow in the transition zone between freshwater and seawater (Perera et al. 2008). In a seawater intrusion study, Arlai (2007) and Arlai and Koch (2007) have shown that a constant-density model cannot simulate well the high-contrast-density groundwater regime, as in seawater intrusion. Indeed, this specific groundwater regime needs to be modelled by a density groundwater and solute transport model.

Sipadan island is an oceanic island located between 4° 06′ N and 4° 07′ N and 118° 37′ E and 118° 38′ E off the southeast coast of Sabah, Malaysia. The island is situated at the heart of the Indo-Pacific basin, the centre of one of the richest marine habitats in the world. Acknowledged as one of the best diving and unique spots in Southeast Asia, the name of Sipadan is simply legendary in diving circles, conjuring images of patrolling hammerhead sharks, millions of technicolored reef fish and, above all, dozens of sea turtles swimming peacefully everywhere (WWF 1992). The long term goal is to have Sipadan Island recognised as a UNESCO World Heritage Site. This bid is supported and driven by a number of groups within the Malaysian government and the tourism industry, would guarantee more funding and protection for the island (Wild Asia 2005). Studies reported by Abdullah et al. (1997) and LESTARI, UKM (2005) showed that the island was fast depleting its source of fresh groundwater. This allowed saltwater to seep in, replacing the freshwater in the aquifer, with a potential to damage the island's vegetation and consequently affecting the overall island's ecosystem. The studies revealed that the salinity of the groundwater in the interior part of the island was higher and has a wider range, probably due to the activities of groundwater extraction within the area of the island. A recent hydrochemical study done by Abdullah et al. (2008) on Sipadan island indicated that the salinization of the island's groundwater was due to the increasing ionic concentrations as a result of seawater intrusion into its aquifer system.

This paper describes a three-dimensional density dependent solute transport model which simulates the impact of groundwater pumping with respect to seawater intrusion in an oceanic island's aquifer like Sipadan. Groundwater is the main option and important water resource on the island. This paper reports on the output of seawater intrusion modeling for the island using SEAWAT-2000 software which presents groundwater modeling that couples flow and transport together. It addresses the capability of the program to model the upconing movement in the island's aquifer where the groundwater was extracted through pumping wells. The output of this model can be used by the local water management authorities to understand the seawater intrusion that takes place in many small tropical islands.

MATERIAL AND METHODS

DESCRIPTION OF THE STUDY AREA

Figure 1 shows the location of the study area. Hydrogeology and cross-section of the studied area are shown in Figure 2. The island represents an oceanic island that stands less than 6 m above the ocean floor and composed of several series of Quaternary bioherm facies, which has high porosity and permeability properties (LESTARI UKM, 2005). The length and width of Sipadan island is 620 m and 300 m, respectively. The water table is at an average elevation between 2.66 and 2.99 m above sea level where groundwater flows radially outward to the sea. The island receives an average of 2000 mm/year and solely depends on rainfall to recharge its unconfined aquifer. Dug wells were built on the island to extract freshwater through pumping for daily domestic water supply (Abdullah et al. 2008). It was found that the porosity of the island's aquifer is up to 28% with excellent permeability of more than 250 mD, indicating the susceptibility of the island's groundwater to pollution or seawater intrusion if extraction is done arbitrarily (Abdullah et al. 1997). Most small oceanic islands are relatively permeable, consisting of sand, lava, coral, or limestone, so that seawater is in contact with groundwater on all sides (Todd 1980) which potentially leads to the substantial influence of surrounding seawater on the fresh groundwater in the aquifer (Abdullah et al. 2008).

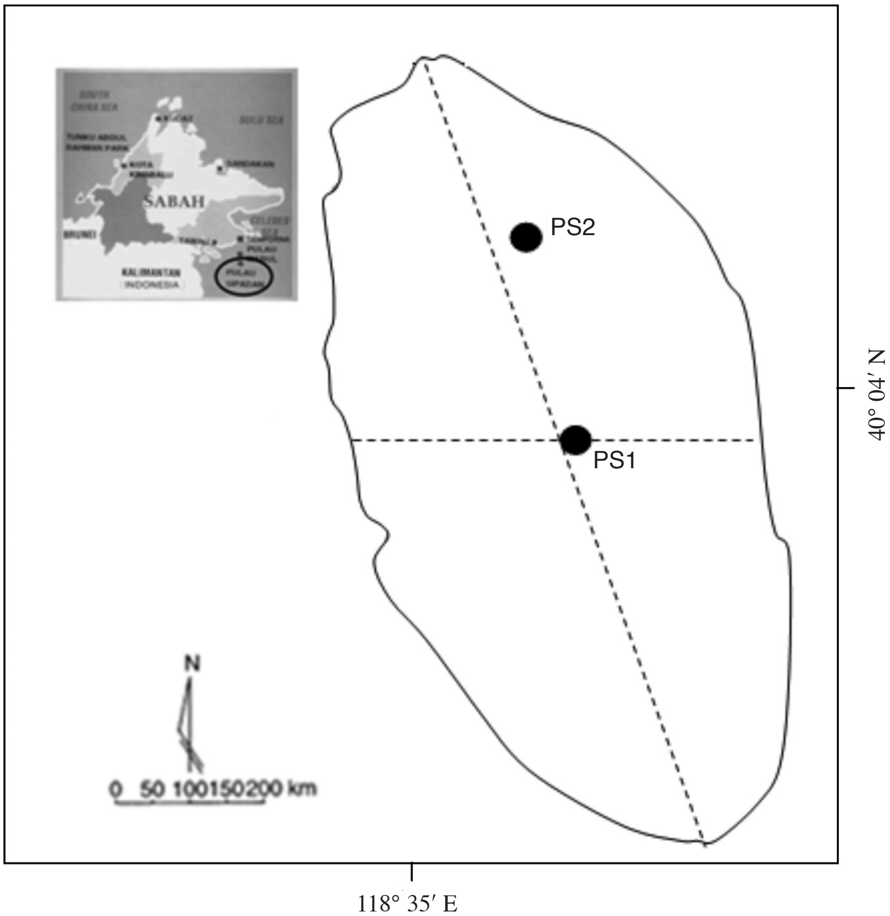

FIGURE 1. Location of study area (Sipadan Island), Sabah, Malaysia

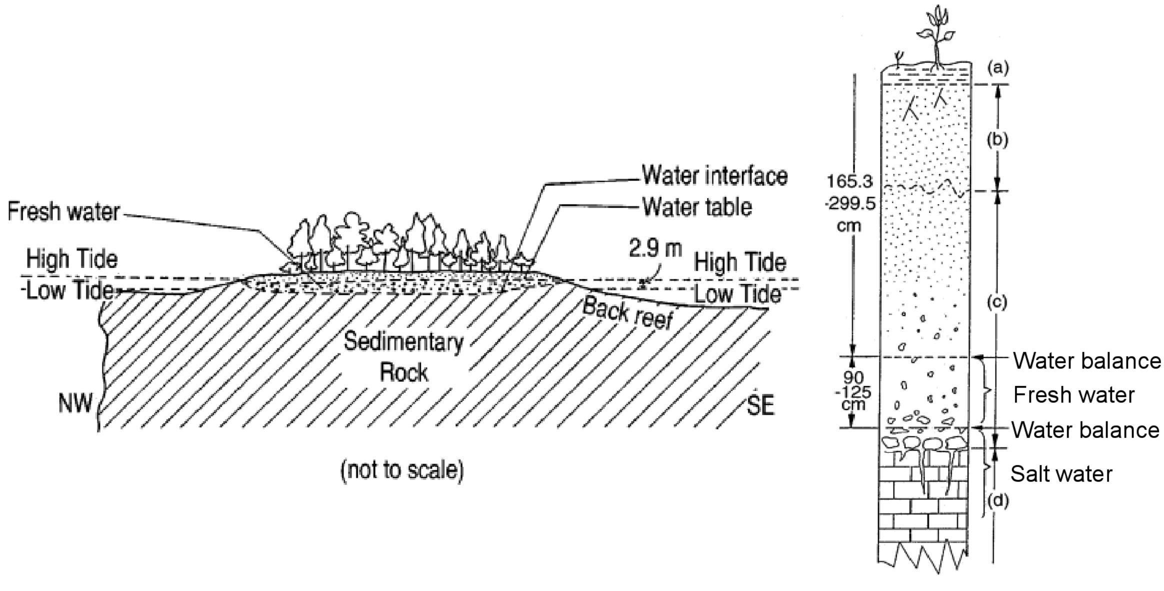

FIGURE 2. Sipadan island's hydrogeological profile

OVERVIEW OF SEAWAT-2000 AND SEAWATER INTRUSION MODEL SETUP

SEAWAT-2000 software presents groundwater modelling that couples flow and transport together (Guo & Langevin 2002). It couples the flow and transport equations of two widely accepted codes MODFLOW (Harbaugh et al. 2000; Mcdonald & Harbaugh 1988) and MT3DS (Zheng & Wang 1999) with some modifications to include density effects based on the extended Boussinesq assumptions. The governing flow and transport equations in SEAWAT-2000 are shown by (1) and (2). Since the program has been useful to simulate variable density flow through complex geological condition, it is applied in the present study to predict the behavior of the groundwater flow in the island's aquifer. The governing flow equation can be written as:

$$\frac{\partial}{\partial X_i}\left[\rho K_f\left(\frac{\partial h_f}{\partial X_i}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial_z}{\partial X_i}\right)\right]=\rho S_f\frac{\partial h_f}{\partial_t}+\theta\frac{\partial h_f}{\partial_t}+\partial\frac{\partial_\rho}{\partial_t}-\rho s q_s, \tag{1}$$

where X_i is the i^{th} orthogonal coordinate, K_f is the equivalent freshwater hydraulic conductivity (L/T), S_f is the equivalent freshwater specific storage ($1/L$), h_f is the equivalent freshwater head, T is the time (T), θ is the effective porosity, (dimensionless), ρs_f is the density of source and sink (M/L_3), q_s is the volumetric flow rate of sources and sinks per unit volume of aquifer ($1/T$), q_s is the volumetric flow rate of sources and sinks per unit volume of aquifer ($1/T$).

The transport equation is given as follows:

$$\frac{\partial\left(\theta C^k\right)}{\theta t}=\frac{\partial}{\partial x}\left(\theta D_{ij}\frac{\partial c^k}{\partial x_j}\right)-\frac{\partial}{\partial x_i}\left(\theta v i c^k\right)+q_s C_s^k+\sum R_n, \tag{2}$$

where C^k dissolved concentration of species, k (M/L^3), D_{ij} is the hydrodynamics dispersion tensor (L^2/T), C^k_s is the concentration of the source or sink flux for species, k (M/L^3), ΣR_n is the chemical reaction term (ML^3/T).

In this study, the basic inputs and conceptual model were developed based on the data collected by Abdullah et al. (1997) and LESTARI UKM (2005). Field data were obtained from two locations, namely PS1 (a well located at the center of the island) and PS2 (a well located nearer to the coast), as shown in Figure 1. Analysis for chloride was done using argentometric method (APHA 1995). The finite difference model grid (Figure 3) consists of 115 columns and 57 rows with grid spacing of 946.0 m (x-direction) and 1052.0 m (y-direction). The height of the model is 30.0 m. Since the pumping well area is considered as more sensitive in comparison to the other places of the model domain, therefore small grids were used for that particular area.

Representative properties of the island's aquifer (Table 1) were assigned to the model cells. Constant head cells were assigned along the bottom of the ocean. A chloride concentration of 19,999 mg/L was assigned for constant concentration, and 0 mg/L for recharge concentration. Initial condition (concentration and heads) for model at active model cells was based on groundwater data of year 1995. There were two pumping wells (PS1 and PS2) in the model domain with boring depths of 5 m, respectively. Based on available groundwater data, one day was chosen as the time step in this study and to be increased by a multiplier factor of 1.2 within which all the hydrological stresses can be assumed constant. Generally, the smaller the time step, the more accurate the predicted results although it will require excessive computation time. Too large time steps will result in instability output (Spitz & Moreno 1996). The assessment of seawater intrusion requires the density dependent solute transport approach. Arlai & Koch (2007), Arlai (2007) and Langevin et al. (2003) highlighted the importance of density effects in a real coastal groundwater system affected by seawater intrusion. Thus, the movement of fresh-saltwater interface in Sipadan Island was modeled using the density dependent solute transport approach. As the focus of this paper is to examine the capability of the developed model to simulate the upconing of saltwater in Sipadan island's aquifer due to groundwater exploitation, the transient simulation model was run for 5 years (1993, 1994, 2004, 2005 & 2008).

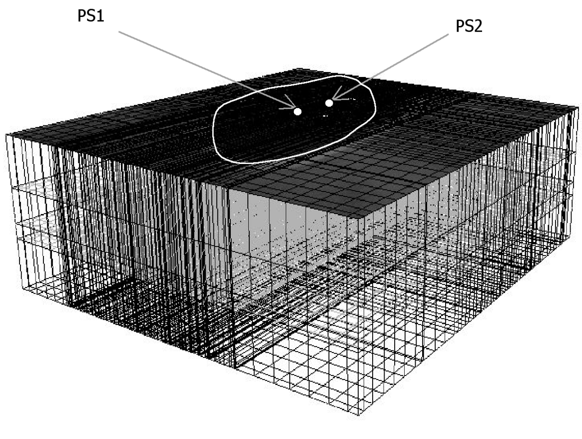

FIGURE 3. The finite difference model grid of Sipadan island

RESULTS AND DISCUSSION

The model in this study was set-up using limited data of specific storage, specific yield, recharge rate and distribution coefficient. Therefore, assumptions were made based on the references available during the time of study. The main purpose of the analysis was to provide an output of seawater intrusion and clarify the position of seawater upconing occurrence in the aquifer of the island. The model calibration is achieved through trial and error approach until the zonation, values of hydraulic conductivities, dispersivity and effective porosity values calculated by SEAWAT-2000 matched with the observed values to a satisfactory degree at the end of simulation with correlation coefficient value more than 0.960. Model calibration is stopped at the end of the simulation when reasonable matches between the observed and calculated

TABLE 1. Input parameters for the model and simulation strategies for this study

Parameter	Value
Hydraulic conductivity (K_x, K_y & K_z)	
Layer 1	6.55×10^{-4}, 1×10^{-5}, 1×10^{-5} m/s
Layer 2	6.55×10^{-4}, 1×10^{-5}, 1×10^{-5} m/s
Layer 3	5.95×10^{-4}, 1×10^{-5}, 1×10^{-5} m/s
Layer 4	5.55×10^{-4}, 1×10^{-5}, 1×10^{-5} m/s
Total porosity	0.30
Effective porosity	0.19
Recharge	2000 mm/year
Specific storage	0.0014
Specific yield	0.35
Longitudinal dispersivity	1 m
Horizontal transverse dispersivity	0.1 m
Vertical transverse dispersivity	0.01 m
Molecular diffusion	1.0×10^{-9} m^2/s
Freshwater density	1000.0 kg/m^3
Seawater density	1025.0 kg/m^3
Constant head	2.4 m
Recharge concentration	0 mg/L
Constant head concentration	19999 mg/L
Initial Concentration	Based on 1993 data

hydraulic head are achieved. After each run, differences between simulated and observed heads were calculated with the goal of every difference being minimal within ± 10%.

The observed and calculated values of chloride concentrations at wells PS1 and PS2 located in the model domain showed good agreement with correlation coefficient more than 0.960 (Figure 4). The scatter plot reveals a well-posed calibration, since all points are closed to the diagonal line, with the correlation coefficient being close to one. The residual between observed and calculated heads was used to calculate the root mean squared error (RMS) and the mean absolute error (MAE). One point of particular importance to the modeler should be to examine how large a model error, i.e. RMS is acceptable for a calibrated model to be considered satisfactory. Usually, the maximally acceptable error depends on the magnitude of chloride concentration change over the model domain and is formulated as the ratio of the RMS. The RMS error values for chloride concentrations of both wells (PS1 and PS2) were found to be within the 10% norm. Therefore, the model can be used as a tool for the prediction of seawater intrusion in the study area. In this study, chloride concentration was used to reflect the water salinity. Since chloride is the major ion in seawater, it plays as an indicator of

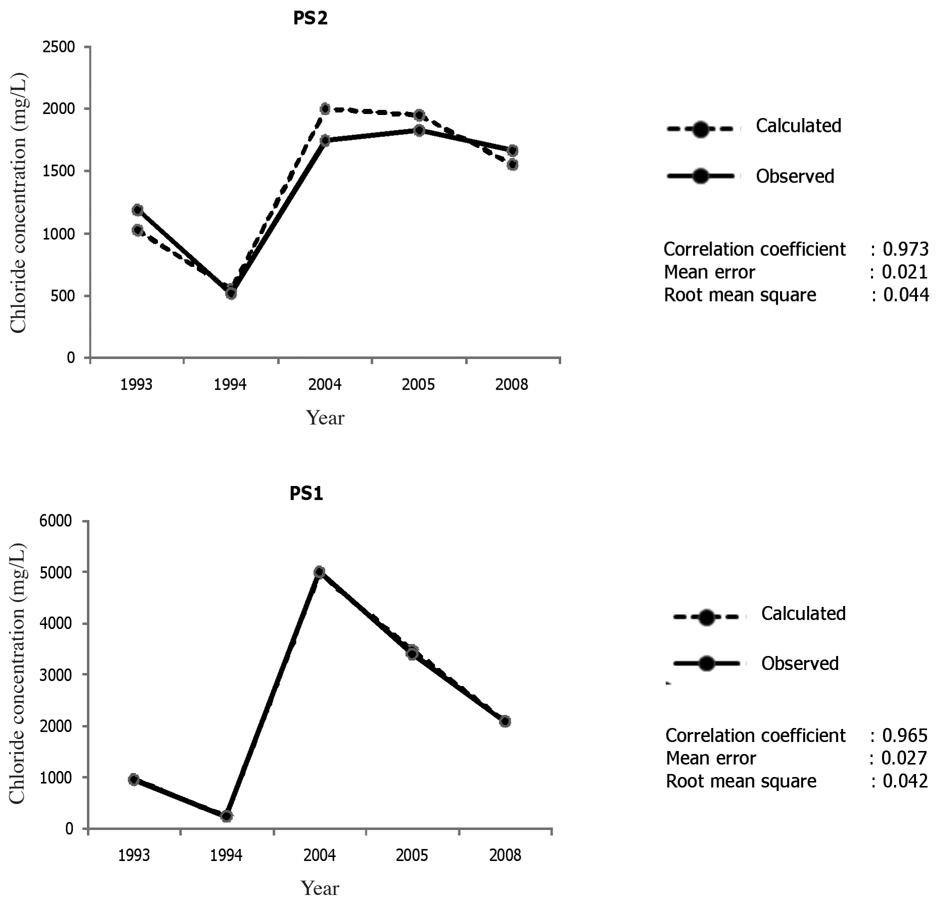

FIGURE 4. The observed and calculated values for pumping wells PS1 and PS2

seawater intrusion. Thus, interest is often focused on the distribution of this ion in the coastal aquifer.

As the island is surrounded by seawater (Figure 3), the contour lines or isochlor in the simulation represent the chloride concentrations in the aquifer. Basically, seawater intrusion may occurs in two ways, viz the advancement of seawater at the bottom of the aquifer, and the infiltration of seawater through the beach. Figure 5 shows the infiltration of seawater through the beach in the island. It demonstrates the infiltration of seawater and freshwater mixing (isochlor of 2.5% and 45%) in layer 1 of model domain. The model output present the freshwater-seawater interface moving towards inland and displacing the extracted fresh groundwater. From the analysis, it is found that the 2.5% isochlor has moved about 63.4 m, while 45% isochlor has moved 12.7 m inland from the coastline of the island.

Intrusion of saltwater into the island's aquifer occurred when pumping of wells lower the groundwater level, enough to cause saltwater moving towards the well due to reversal of hydraulic gradients or decrease in freshwater heads. Figure 6 shows the upconing of saline water as a result of pumping wells on the island. The upconing surface shown in Figure 6 represents the iso-surface 14.5% of seawater freshwater mixing concentration ratio. Seawater freshwater mixing ratio of 14.5% was selected based on the mean concentration of chloride concentration in water samples from pumping wells (PS1 and PS2). It can be seen that the upconing took place at the bottom of each well. Intensive and unregulated exploitation of fresh groundwater from the unconfined aquifer through the wells has contributed to the upconing. When a well is pumped in such an aquifer, it can induce a vertical flow component from the underlying saltwater region, causing the saltwater to migrate upwards and intercepted by the pumping well. The size and shape of the upconing will grow and shrink as the rate and duration of well pumping change (Simpson 2006). Based on the model prediction, keeping all the conditions unchanged, overpumping must be avoided in order to control and limit inward migration of seawater wedge.

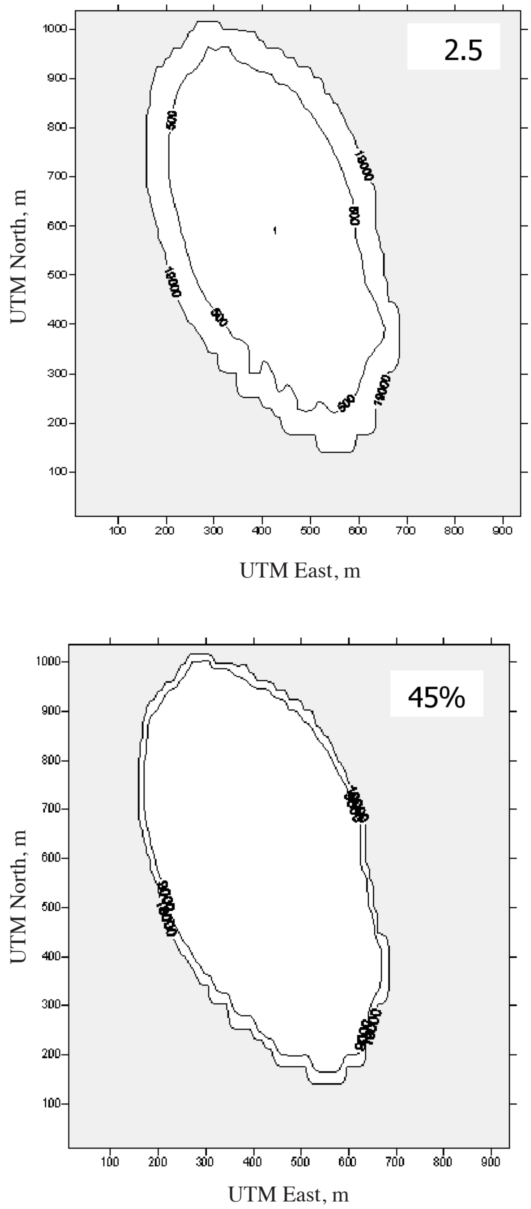

FIGURE 5. The temporal movement of seawater in Sipadan island

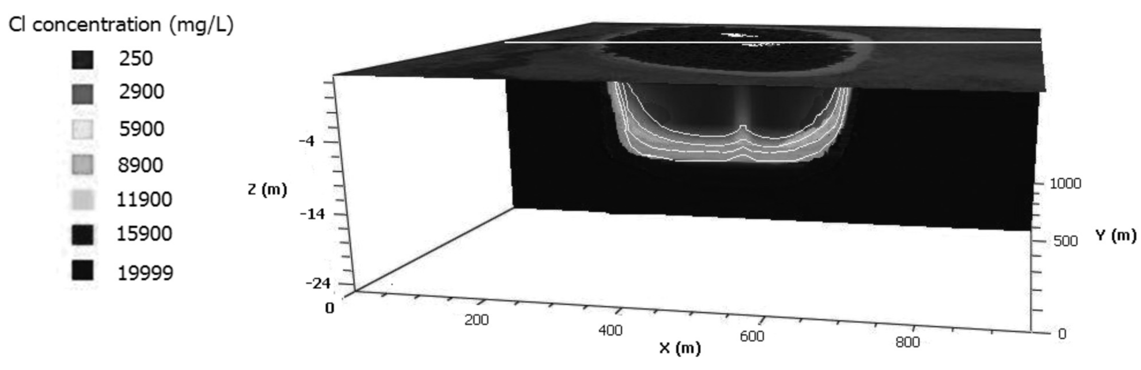

FIGURE 6. Upconing of saline water in Sipadan island's aquifer

The groundwater extraction created a cone of depression in the water table that draws a plume of saltwater toward the pumping well. High values of chloride concentration and other ions associated to saltwater are induced by the upconing. A 5% mixture with seawater causes most freshwaters to become contaminated (Mao et al. 2005). In this study the mixture has exceeded such a value, indicating that the freshwater has been contaminated with seawater. Based on a study done by Abdullah et al. (2008), overpumping of groundwater had occurred at the centre of the island; contributing to the upconing of saline water into the freshwater lens. According to the study, the groundwater at stations PS1 and PS2 showed an increase of salinity and chloride concentration. Both chemical parameters displayed similar trend of salinization pattern. It demonstrates that groundwater pumping activities near to the coastal area are not only reducing the freshwater availability but also contribute to the inward movement of saline water into the aquifer. Basically, if the roots of trees that rely on fresh groundwater are in contact with saline water, eventually the roots will die. Such a condition could cause loss of trees or their capabilities to withstand wind, and finally increase soil erosion. The sustainable management of aquifers is a burning problem in many countries. Thus, the use of scientific tools such as mathematical models in environmental studies plays an important role in this task of problem solving.

Conclusion

This study provides an understanding of seawater intrusion issue in a small oceanic island, using three-dimensional density-dependent model. In Sipadan Island, due to the overextraction of groundwater the infiltration of seawater and freshwater mixing ratio (isochlor of 2.5% and 45%) showed that the interface has moved inland and displaced the freshwater in the aquifer. The 2.5% isochlor has moved 63.4 m, while 45% isochlor has moved 12.7 m inland from the coastline of the island. Upconing occurred at the pumping wells as demonstrated by the output of the model. Intensive and unregulated exploitation of the groundwater from such an unconfined aquifer of the island by pumping wells contributed to the upconing. In order to protect the freshwater resources in the study area from seawater intrusion, adjustment of the groundwater pumping scheme is thus strongly recommended. The application of the model to such an island proved useful in demonstrating the mechanism of seawater intrusion, and specifically the upconing and movement of seawater wedge in the studied area.

Acknowledgements

Financial support from Kurita Water and Engineering Foundation (KWEF), Japan is highly acknowledged. The assistance from Associate Professor Sacchi Takahi of Akita University, Japan is very much appreciated.

References

Abdullah, M.H., Mokhtar, M.B., Sanudin, T. & Awaluddin, A.B. 1997. Do tides affect water quality in the upper phreatic zone of a small oceanic island, Sipadan island, Malaysia?. *Environmental Geology* 29: 112-117.

Abdullah, M.H., Mokhtar, M.B., Musta, B. & Aris, A.Z. 2008. Hydrochemical analyses of a disturbed aquifer of a small island in Malaysia. *Fresenius Environmental Bulletin* 17 (12): 1-9.

APHA. 1995. *Standard Methods for the Examination of Water and Wastewater. 19th Ed. American Water Works Association*. Water Environment Federation, Washington.

Aris, A.Z., Abdullah, M.H., Ahmed, A., Woong, K.K. & Praveena, S.M. 2008. Hydrochemical changes in a small tropical island's aquifer, Manukan island, Sabah, Malaysia. *Environmental Geology* 56: 1721-1732.

Arlai, P. 2007. Integrated groundwater management process (GWM) with 3-D variable density groundwater flow and solute transport to investigate an efficient groundwater management scheme in Bangkok multilayered Aquifer System. *GMSARN International Conference*. 12-14 December, Thailand.

Arlai, P. & Koch, M. 2007. Numerical investigation of the original sources of saline pollution and efficient remediation scenarios in the Bangkok multilayer-aquifer system. *12th National Convention on Civil Engineering, Phitsanulok*. 2-4 May 2007, Thailand.

Dierch, H.J.G. & Koldditz, O. 2002. Variable-density flow and transport in porous media: Approaches and challenges. *Advances in Water Resources* 25: 899-944.

Falkland, A. 1991. Hydrology and water resources of small islands: A practical guide. *Studies and reports on Hydrology* no. 49. UNESCO, Paris, France.

Galeati, G., Gambolati, G. & Neumann, S.P. 1992. Coupled and partially coupled Eularian-Langangrian model of freshwater-seawater mixing. *Water Resource Research* 28: 149-165.

Guo, W. & Langevin, C.D. 2002. User's Guide to SEAWAT-2000: A computer program for simulation of three-dimensional variable-density groundwater flow: technique of water resources investigation. *Technique of Water-Resources Investigations*. Book 6.

Hamza, K.I. 2006. Numerical Analysis of Saltwater Upconing beneath a Pumping Well. *Scientific Bulletin* 41: 453-466.

Harbaugh, A.W., Banta, E.R., Hill, M.C. & Macdonald, M.G. 2000. The US Geological Survey modular ground water models: User guide to modulization concepts and the ground-water flow process. *US Geological Survey.*

Henry, H.R. 1964. Effects of dispersion on salt encroachment in coastal aquifers, in seawater in coastal aquifers. US *Geological Survey Water Supply*: 70-84.

Langevin C.D., Shoemaker, W.B. & Guo, W. 2003. MODFLOW-2000, the U.S. Geological survey modular ground-water model—documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS Transport Process (IMT). *USGS Open-File Report* 03-426.

LESTARI (Institute for Environment and Development) UKM. 2005. *Kajian Status Alam Sekitar dan Keupayaan Tampungan Pulau Sipadan*. Universiti Kebangsaan Malaysia: Bangi.

Macdonald, M.G. & Harbaugh, A.W. 1988. A Modular Three-dimensional Finite Difference Groundwater Flow Model. *US Geological Surveey Technique of Water Resources Investigations,* US Geological Survey.

Mao, X., Enot, P., Barry, D.A., Li, L., Binley, A. & Jeng, D.S. 2005. Tidal influence on behviour of a coastal aquifer adjacent to a low relief estuary. *Journal of Hydrology* 327: 110-127.

Norhan Abdul Rahman & Kuan, W. 2004. Simulation of groundwater flow and pollutant transport for alluvial aquifer in Kampung Tekek, Tioman Island. *Jurnal Teknologi* 41: 21-34.

Perera, E.D.P., Jinno, K., Tsutsumi, A. & Hiroshiro, Y. 2008. Development and verification of a three dimensional density dependent solute transport model for seawater intrusion. *Memoirs of the Faculty of Engineering, Kyushu University* 68: 93-106.

Pinder, G.F. & Copper, H.H. 1970. A numerical technique for calculating the transition position of the seawater front. *Water Resource Research* 6-3: 875-882.

Shoemaker, W.B. & Edwards, K.M. 2003. Potential from saltwater intrusion into the lower Tamiami Aquifer near Bonita Springs, southwestern Florida. *U.S. Geological Survey Water-Resources Investigations Report* 03-4262.

Simpson, H. 2006. Groundwater – An important rural resource: Managing the quantity of groundwater supplies. Management/OMAFRA; Brewster Conant - Department of Earth Sciences/University of Waterloo. http://www.omafra.gov.on.ca/english/environment/06-113.htm. accesced on 3 September 2008.

Singh, V.S. & Gupta, C.P. 1999. Feasibility of groundwater withdrawal in a coral island. *Hydrological Sciences Journal* 44: 173-182.

Spitz, K. & Moreno, J. 1996. *A Practical Guide to Groundwater and Solute Transport Modeling*. John Wiley and Sons: New York.

Todd, D.K. 1980. *Groundwater Hydrology*. 2nd Edition New York: John Wiley & Sons.

WWF (World Wide Fund for Nature) 1992. *Pulau Sipadan: Meeting the challenge of conservation*. WWW Project Number MYS 233/92.

Younes, A., Ackerer, P. & Mose, R. 1999. Modelling variable density flow and transport in porous medium: Re-evaluation of the salt dome flow problem. *Transport of Porous Media* 35: 375-394.

Zhou, Q., Bear, J. & Bensabat, J. 2005. Saltwater upconing and decay beneath a well pumping above an interface zone. *Transport in Porous Media* 61: 337-363.

Mohd Harun Abdullah & Sarva Mangala Praveena*
Water Research Unit, School of Science and Technology
Universiti Malaysia
Sabah Locked Bag 2073 88999 Kota Kinabalu, Sabah
Malaysia

Ahmad Zaharin Aris
Department of Environmental Sciences
Faculty of Environmental Studies
Universiti Putra Malaysia
43400 UPM Serdang, Selangor D.E.
Malaysia

*Corresponding author; email: smpraveena@gmail.com

Received: 8 July 2009
Accepted: 23 March 2010