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Numerical Modelling of Seawater Intrusion in Manukan Island's Aquifer

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Abstract: A numerical model SEAWAT-2000 was developed to investigate the current seawater intrusion status in the low lying area of Manukan Island. SEAWAT-2000 output indicated that there is about 1.4% of freshwater and seawater mixing ratio at sea level in low lying area of Manukan Island illustrates the seawater intrusion problem. Upconing process simulated by SEAWAT-2000 showed the current status of seawater intrusion in Manukan Island is about 14.6% of freshwater and seawater mixing ratio at the beneath of pumping well (W6). The improved understanding of current seawater intrusion status is crucial for groundwater management by adjustments pumping schemes to protect groundwater.

Key words: Groundwater · Seawater intrusion · SEAWAT-2000

INTRODUCTION

Small islands have limited sources of freshwater and rely heavily on its groundwater [1,2]. Freshwater in low atolls is balanced between rainfall and continual depletion by evapotranspiration, extraction, discharge and mixing with seawater [3]. In small islands, seawater intrusion is often the consequence of freshwater aquifers overexploitation. Seawater intrusion can be defined as the seawater inflow into freshwater aquifer [4].

Manukan Island has very limited surface water in an exploitable form and relies solely in its groundwater as water supply. Tourism impacts on small islands such as in Manukan made more severe to their limited water resources by an increased in numbers of tourist arrivals to this island about 400% from 1997 to 2004 [5,6]. This has resulted in tremendous increased of groundwater extraction to meet water demand. Additionally, a total of eight dug wells in low lying area have been shut down due to incursion of seawater into the island's aquifer. Currently, only one dug well is operating in groundwater extraction to meet the water demand. With this current situation, overextraction will lead to the depletion of groundwater quantity and quality. The carrying capacity and limits of acceptable change of this island should be considered with an increased in tourism aspect [2].

Overextraction and wells shutdown in Manukan Island's aquifer are indicators that natural equilibrium between fresh and seawater has been disturbed. Therefore considering this fact, present study is to provide useful information to aid in protection of groundwater resources in study area from seawater intrusion using a three-dimensional (3D) finite-difference numerical model, SEAWAT-2000 in Manukan Island. This is a first preliminary attempt is to understand current seawater intrusion using a 3D numerical model. The numerical model output act to improve an understanding of current seawater status in Manukan Island and its groundwater management.

MATERIALS AND METHODS

Manukan Island (5° 57'-5°58'N and 115°59'-116°01'E) covers an area of 206,000 m^2, with a crescent shape, (Fig. 1). The study area is located offshore of Kota Kinabalu, Sabah, East Malaysia on the island of Borneo

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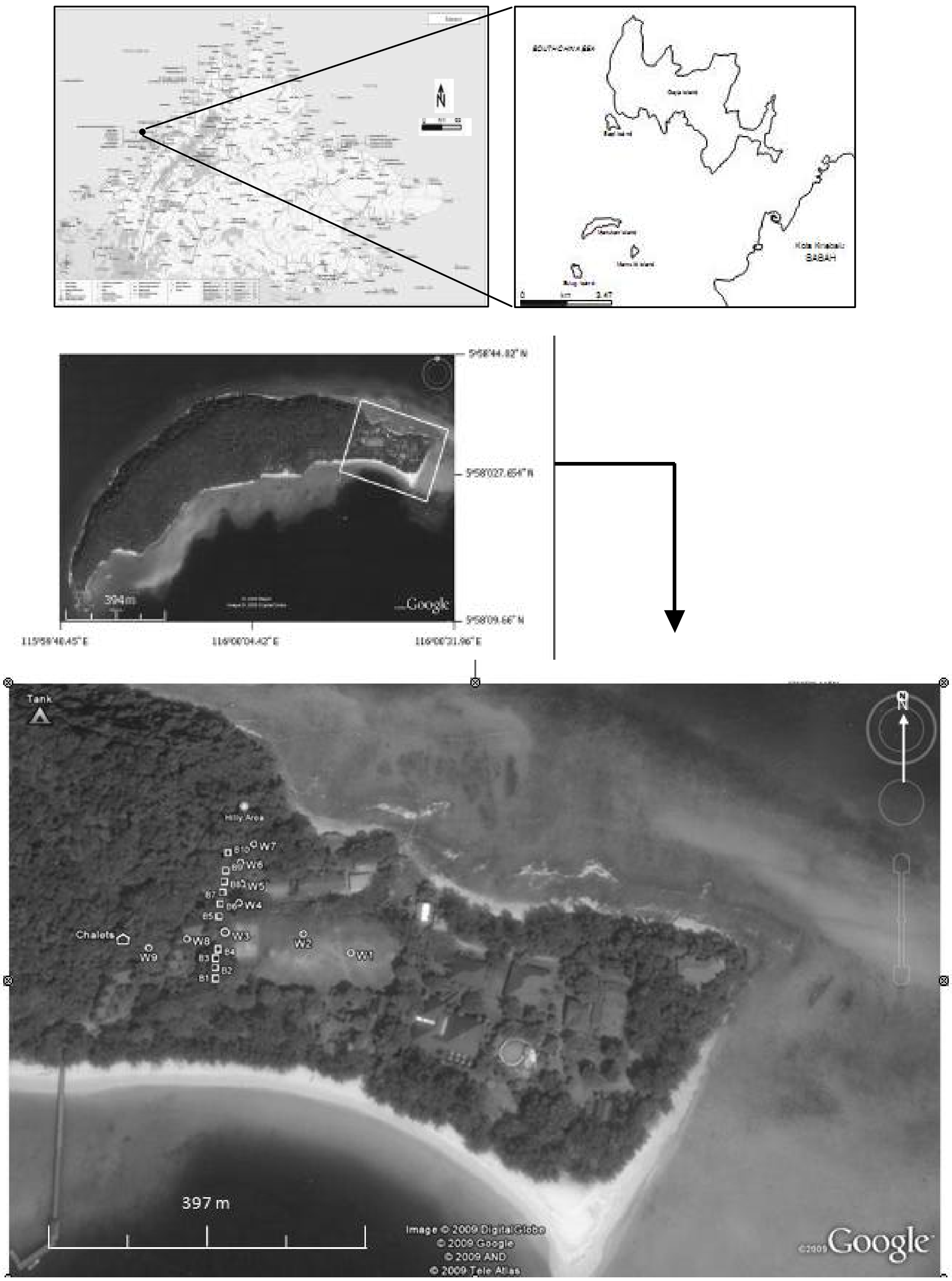

Fig. 1: Location of Manukan Island focusing the low lying part

cover by South China Sea. The island is enacted under Parks Enactment 1978 and managed by The Sabah Parks Trustees and consists of unconfined sandy aquifer and underlain by sedimentary rock [7]. The sedimentary rock of Manukan Island dips (east-northeast) with dipping angles of 15°- 45° and forms a slight symmetrical syncline in the low area [8]. Abdullah *et al.* [9] conducted a study on the morphological of the island found that the thickness of the aquifer from the ground surface to bedrock are approximately, 5.7 m (northern part), 11 m (southern part) and 12 m (at the middle). As this study focused in low lying area, soil profile in the low lying area

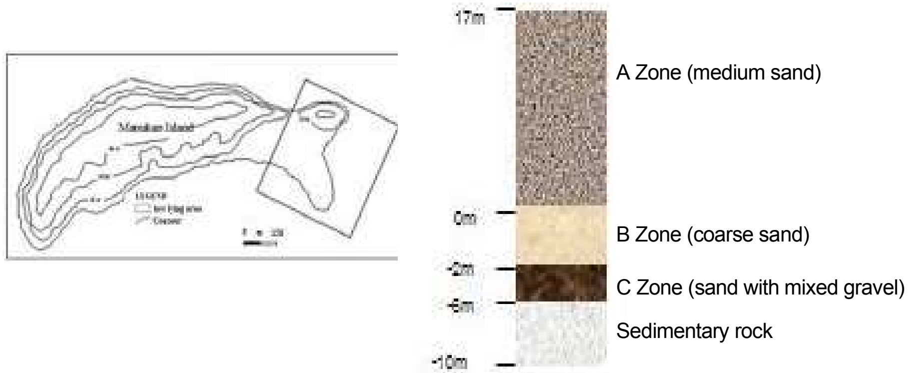

Fig. 2: The soils pro?le of the low lying area of Manukan Island

of Manukan Island was given a focal point. The soil profile at the low lying area (Fig. 2) was developed based on the surface elevation contour map, soil information collected during boreholes construction (Section 3.9.1) and data from Aris *et al.* [5], Abdullah *et al.* [7] and Abdullah [10]. Low lying area in Manukan Island consists of fine to coarse sand mixed with fine gravel [7].

Low lying area was selected in this numerical modeling (Fig. 1) since it has been developed for tourism activities and all the wells for groundwater extraction are located in this area (8 wells have been shut down and only 1 well is currently operating). Eight observation wells and nine boreholes were distributed across the study area to provide a good horizontal and vertical spatial distribution of hydrologic data. Groundwater samplings were done in 2009 (January 2009-December 2009) from the observation wells and boreholes. Hydraulic heads were also measured at observation wells and boreholes using Solinst water level meter. Analysis of chloride was done using Argentometric method [11]. Moreover, the meteorological data from the meteorological station was downloaded to a Twinhead laptop each month during samplings in 2009. SEAWAT-2000 engine in Visual MODFLOW Premium 4.2 was used in this study. SEAWAT-2000 couples the flow and transport equations of two widely accepted codes MODFLOW [12,13] and MT3DS [14] with some modifications to include density effects based on the extended Boussinesq assumptions. The theoretical development numerical solution techniques and computer code of the model are described by Guo and Langevin [15] and Anderson and Woessner [16].

The conceptual model of low lying area was developed based on the surface elevation contour map, information collected during boreholes construction and data from Abdullah [10]. The model grid consists

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	5.42E-4, 1E-5, 1E-5 m/s
Layer 2	4.75E-4, 1E-5, 1E-5 m/s
Layer 3	4.75E-4, 1E-5, 1E-5 m/s
Layer 4 (sedimentary rock)	3.4E-7, 1E-5, 1E-5 m/s
Molecular diffusion	1.0E-9 m^2/s
Freshwater density	1000.0 kg/m^3
Seawater density	1025.0 kg/m^3
Total porosity	0.30%
Specific storage	0.35%
Specific yield	0.25%
Longitudinal dispersivity	1 m
Horizontal transverse dispersivity	0.1 m
Vertical transverse dispersivity	0.01 m
Recharge	mm/year
	Recharge data in 2009 calculated using simple water balance method
Evapotranspiration	mm/year
	Evapotranspiration data in 2009 calculated using Penman method
Constant head	16 m
Recharge concentration	0 mg/l
Constant head concentration	19999 mg/l
Initial Concentration (mg/L)	Based on Jan 2009
Initial head (m)	Based on Jan 2009
Hydraulic heads (m)	
B1-B9	January 2009-December 2009
W1, W2, W3, W4, W5, W7	January 2009-December 2009
Chloride concentration (mg/L)	
B1-B9	January 2009-December 2009
W1, W2, W3, W4, W5, W7	January 2009-December 2009
Pumping rate at W6	72 m^3/day

of 80 columns and 80 rows with grid spacing of 1199 (x-direction) and 778m (y-direction). The unconfined layers were divided into four layers which based on the hydrogeological and soil profile information. Specified head boundary was assigned for the sea (South China Sea). In this present study, it is assumed that the hydraulic conductivities of unconfined aquifer of Manukan Island vary along horizontal and vertical directions. The recharge from the precipitation was assumed to be spatially uniform in the low lying area of Manukan Island. Representative properties of the Manukan Island aquifer (Table 1) were assigned to active model cells. Groundwater recharge and evapotranspiration from the meteorological data were calculated using simple water balance method [17] and Penman method [18] which assigned to top layer.

RESULTS AND DISCUSSION

During calibration using trial and error method, hydraulic heads and chloride concentration values at each borehole and well measured in 2009 were used. Model calibration is stopped at the end of the simulation when reasonable matches between the observed and calculated were achieved (Fig. 3). The computed relative mean square error, RMS, mean error, ME and mean absolute error, MAE were obtained to show the model error and good estimation have been obtained. The model calibrations have indicated a reasonably good match between the observed and calculated hydraulic heads and chloride concentrations. According to Anderson *et al.* [19], maximum acceptable error depends on hydraulic heads and chloride concentration magnitude change over the model.

Numerical model output by means of SEAWAT-2000 showed current status of groundwater quality in the low lying area of Manukan Island. The SEAWAT-2000 output showed that there is about 1.4% of freshwater and seawater mixing ratio at mean sea level in low lying area of Manukan Island (Fig. 4). Seawater-freshwater mixing concentration of 1.4% with chloride concentration 280 mg/L indicates that the mixing concentration exceeds the maximum concentration level (250 mg/L) reported by Malaysian Ministry of Health National Standard [20], World Health Organization [21] and U.S. Environmental Protection Agency [22].

According to a study done by MAO *et al.* [23] in Ardeer (Scotland), seawater intrusion also occurs in pumping wells via the advancement of the seawater at the bottom of the aquifer result from the density difference between seawater and freshwater. Fig. 5 shows the SEAWAT-2000 model output of upconing process at the beneath of the pumping well (W6) which leads to the advancement of the seawater at the bottom of the aquifer result from the density difference between seawater and freshwater. Upconing process is the possible process attributed to the mixing mechanisms of saline water and fresh groundwater in low lying area of Manukan Island.

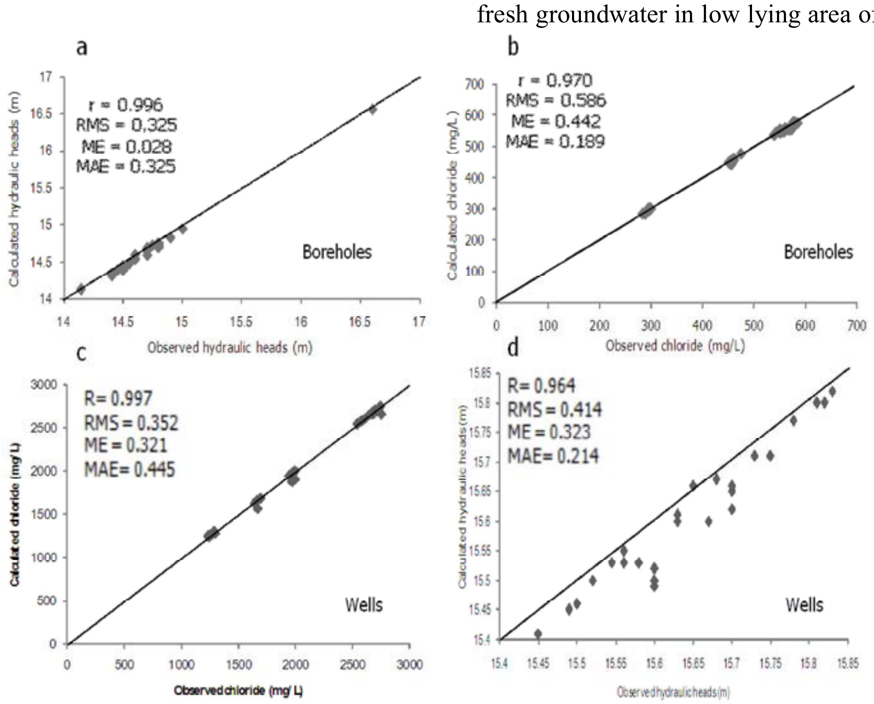

Fig. 3: Comparison between calculated and observed hydraulic heads and chloride concentrations at boreholes and wells (a) calculated and observed hydraulic heads at boreholes (b) calculated and observed chloride concentrations at boreholes (c) calculated and observed hydraulic heads at wells (d)) calculated and observed chloride concentrations at wells

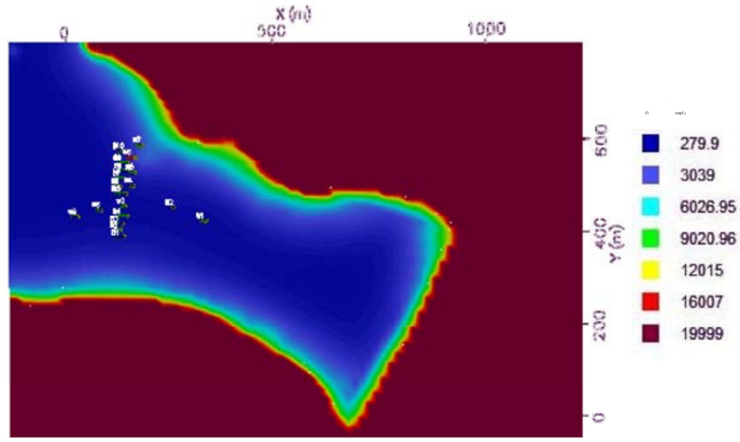

Fig. 4: Freshwater and seawater mixing of 1.4% in low lying area of Manukan Island

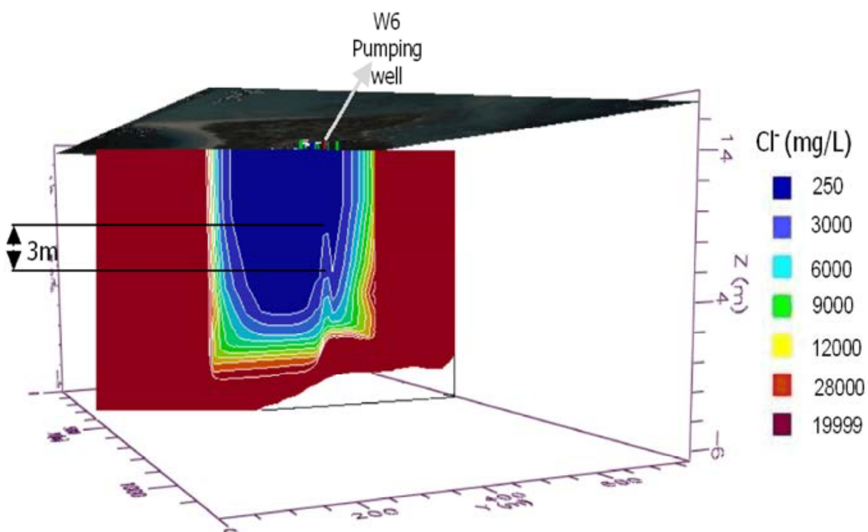

Fig. 5: Upconing process and movement of 14.6% iso-chloride moves about 3m at the beneath of the pumping well (W6)

From the upconing process showed by SEAWAT-2000, it is found the current status of seawater intrusion in Manukan Island is about 14.6% of freshwater and seawater mixing ratio in low lying area of Manukan Island which has moved about 3m at the beneath of the pumping well (W6). Moreover, mean chloride concentration in pumping well (W6) during samplings period is 1899 mg/L, exceeds the maximum drinking water concentration level reported by MOH WHO and USEPA. This explains that the water is no longer potable for drinking water purposes and additional water treatment is needed or well discontinued operation will be required. Thus, groundwater quality of Manukan Island is affected by seawater intrusion attributed to overextraction of freshwater from the aquifer. Paniconi *et al.* [24] showed a strong and direct link between groundwater extraction and seawater intrusion. The chloride concentrations of the groundwater are important when dealing with controlling measurement of seawater intrusion is taken into account. According to Simpson [25], the size and shape of the upconing will grow and shrink as the rate and duration of well pumping change. Adjustment of groundwater pumping scheme for the future is suggested since overexploitation is the most important factor to cause seawater intrusion in the study area. This is crucial in order to protect the freshwater resources in the coastal aquifer of Manukan Island.

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