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Recharge and Aquifer Response: Manukan Island's Aquifer, Sabah, Malaysia

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Abstract

Manukan Island is a small island located in North-West of Sabah, Malaysia was used as a case study area for numerical modeling of an aquifer response to recharge and pumping rates. The results in this study present the variations of recharge into the aquifer under the prediction simulations. The recharge rate increases the water level as indicated by hydraulic heads. This shows that it can alter groundwater of Manukan Island which has been suffering from an overexploration in its unconfined the aquifer. The increase in recharge rate (from 600 mm/year to 750 mm/year) increases the water level indicated by hydraulic heads. A reduction in pumping rate (from 0.072 m^3/day to 0.058 m^3/day) not only increases the amount of water levels in aquifer but also reduces the supply hence a deficit in supply. The increase in hydraulic heads depends on the percentage reduction of pumping and recharges rates. The well water has 1978.3 mg/L chloride with current pumping (0.072 m^3/day) and recharge rates (600 mm/year). However, with an increased of recharge rate and current pumping rate it has decreased about 1.13%. In addition, reduction in pumping rate made the chloride concentration decreased about 2.8%. In general, a reduction in pumping with an increase in recharge rate leads to a decreased in chloride concentrations within the vicinity of cone of depression. Next, to further develop the numerical model, the model should focus on climate change variables such as consequences of climate change are increase in air temperature, increase in sea surface temperature, and more extreme weather conditions. These parameters are considered critical parameters for climate change impact modeling in aquifers. The behavior of the aquifer and its sustainable pumping rate can be done by applying a computer modeling component.

Keywords: small island; recharge rate; pumping rate; groundwater sustainability

1. Introduction

Most of tropical small islands have limited sources of freshwater, no surface water or streams and fully reliant on rainfall and groundwater recharge. The inhabitants of these islands mostly depend on groundwater to meet their needs, particularly for drinking and tourism purposes. The demand for fresh water has been rising in response to the increase of activities and development in tourism sector (Singh and Gupta, 1999; Aris *et al.*, 2007). Many small islands are experiencing water stress at the current levels of groundwater extraction at an outstripping supply. The freshwater lens on small islands may easily be overexploited or polluted and vulnerable to climate change, pressure of island resources and the associated impacts to freshwater resources (Griggs and Peterson, 1993; Singh and Gupta, 1999; Climate Change, 2007).

The most significant and immediate consequences of climate change are increase in air temperature, increase in sea surface temperature, changes in rainfall (precipitation) patterns and more extreme weather conditions (Tompkins *et al.*, 2005). Vulnerable to climate change has become more frequent in many countries in the recent decade and Malaysia is not excluded from this phenomena. Effects of climate change will alter the global hydrological cycle in terms of distribution and availability of regional water resources. A warmer climate with its increased climate variability will increase the risk of floods and droughts (Climate Change, 2007; Intergovernmental Panel on Climate Change, 1997). One of the significant consequences is climate variability which causes changes in rainfall patterns and groundwater recharge in coastal environment especially to small islands (Intergovernmental Panel on Climate Change, 1997). Changes in rainfall during rainy season reflect the groundwater recharge, as a sensitive function of the climatic factors, local geology, topography and land use (Dragoni and Sukhija, 2008). The islands complex and dynamic system will response vigorously in variable and complex ways to climate change (Watson *et al.*, 1998). Most research on the potential impacts of climate change to the hydrologic cycle has been directed at forecasting the potential impacts to surface water, river discharge and quality. Study done by Sophocleous and Devlin (2004) as well as Devlin and Sophocleous (2005) showed that sustainability is a function of recharge. Recharge rates cannot be ignored despite to the fact that sustainable pumping rates can be estimated without them. Climate Change (2007) indicated that in warmer climate there is a risk of flood impacts by climate changes. Relatively little research has been undertaken to determine the sensitivity of aquifers to changes in critical input parameters such as increase in precipitation and recharge (Vaccaro, 1992; Loaiciga *et al*., 2000). Globally, studies have been reported in the literature on the decrease in recharge which gives problems to groundwater resources (Zhou *et al*., 2003; Moustadraf *et al*., 2008; Puraji and Soni, 2008). Moreover, pressure of island resources deals with overdrafts of fresh water by pumping well distort the natural recharge-discharge equilibrium causes drawdown of the watertable a rise or upconing of the saltwater interface. Greater withdrawals create localized upconing and also result in a regional reduction in thickness of the freshwater lens (Rejani *et al*., 2008). According to Hamza (2006), when an aquifer contains an underlying layer of saline water being pumped, only the upper portion of the aquifer is penetrates. A stable cone below the bottom will develop of the well at some depth in the interface, and the well will still discharge freshwater. Continuous or overpumping the cone will be unstable and the interface will rise abruptly to the bottom of the well. This will cause the water extracted from the well become salty. Evaluation of seawater intrusion is critical for maintaining a long term supply of groundwater resource of good quality to its management.

Present study is concerned with using a three-dimensional finite-difference numerical model to develop an understanding of groundwater sustainability under current aquifer conditions. Secondary objectives include evaluating the groundwater resource affected by vulnerable to climate change (recharge rate) and pressure of island resources (increased in pumping rates) using variable density SEAWAT-2000 code (Guo and Langevin, 2002), a combined version of MODFLOW and MT3D. This output is to gain insights about the future changes in groundwater due to vulnerable to climate change (recharge rate) and pressure of island resources (pumping rates) in hydraulic levels and chloride concentrations. The results of this study are foundation for more evaluations of the groundwater system in this tropical island. It is vital to study the impact of groundwater withdrawal and work out a comprehensive scheme of groundwater exploitation consistent with the natural constraints existing on the island.

2. Materials and Methods

2.1. Study area

Manukan Island (5° 57’-5 °58’N and 115 °59’-116 01’E) in Fig. 1 covers an area of 206,000 m^2, about one and half kilometers long and three kilometer wide in the middle. The area has a warm and humid climate and receives annual rainfall between 2,000 and 2,500 mm. The island consists of unconfined sandy aquifer and underlain by sedimentary rock (Abdullah *et al*., 2002). Abdullah *et al*. (2002) 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). Generally, the profiles at low lying area are flatter and thinner than hilly area. On the low lying area of Manukan Island, the small area and low elevations lead to very limited water storage (Abdullah *et al*., 2002). Almost 80% of the area is covered by dense vegetation on high relief area (eastern part), while the rest of the area is located on the low lying area of the island (western coastline). 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 currently operating in groundwater extraction to meet the domestic supply. With this current situation, large pumping of groundwater to meet the domestic supply will lead to the depletion of groundwater level and deterioration in its quality. The carrying capacity and limits of acceptable change of these islands should be considered with an increased in tourism aspect (Aris *et al*., 2009).

Low lying area (Fig. 1) selected for this study as the area has been developed for tourism activities. All the pumping wells for groundwater extraction are located in this area. Total of 10 boreholes were constructed and installed by hand auger manually to a depth of between 1 and 3.5 m from the ground surface level. The core soil samples obtained during the boreholes construction were taken into lab for soil physical parameters (hydraulic conductivity and porosity). A pumping well and 10 boreholes were distributed across the study area (Fig. 1) to provide a good horizontal and vertical spatial distribution of hydrologic data. Hydraulic heads and chloride concentration data were collected from October 2008-February 2009 from the well and boreholes. Water samples were pumped through silicon tubing to polyethylene sampling bottles via a peristaltic pump. Analysis for chloride was done using argentometric method (APHA, 1995).

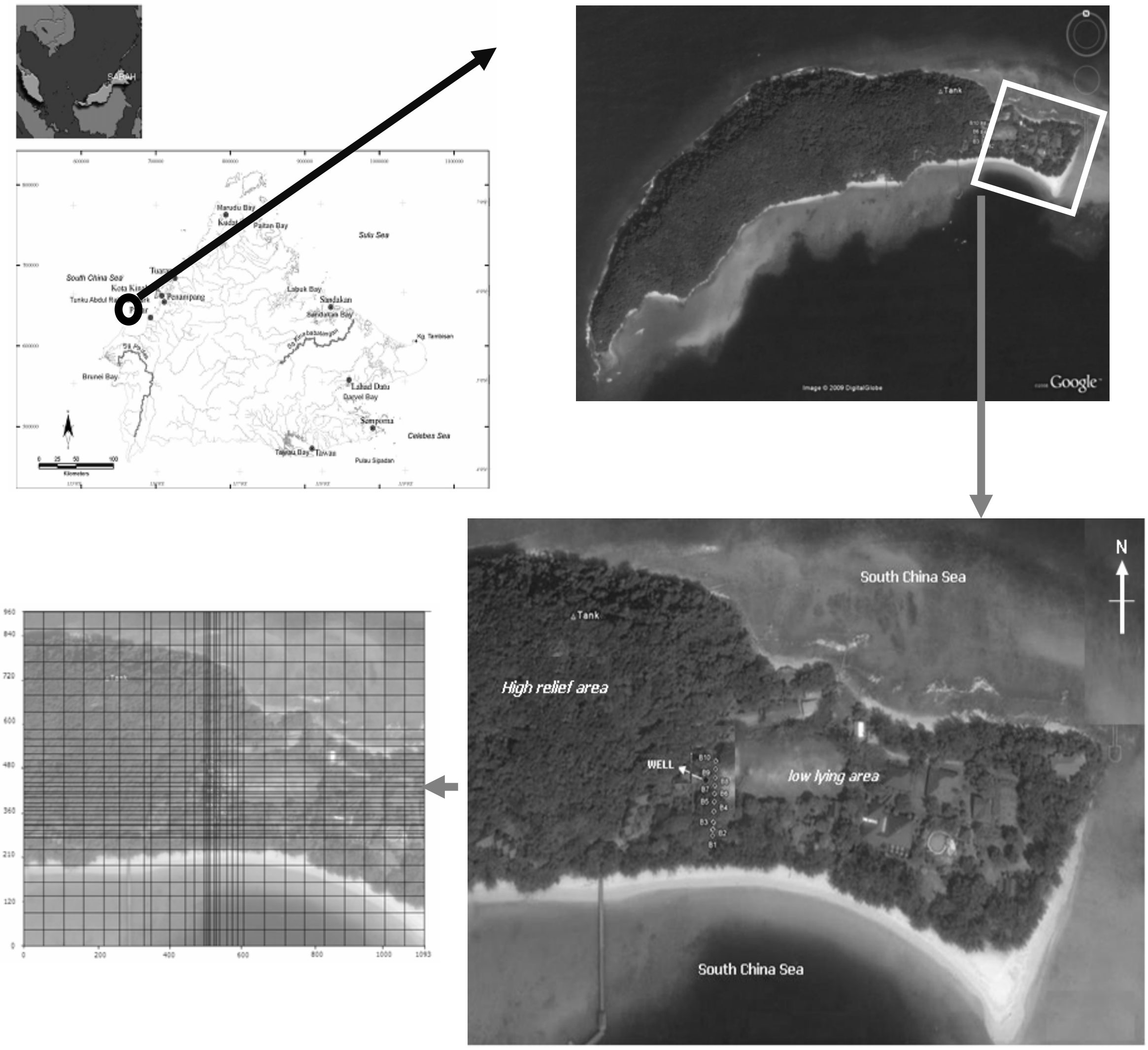

Figure 1. Location of Manukan Island focusing at low lying area and the spatial discretization for three dimensional numerical model

SEAWAT-2000 is the latest modeling software available in groundwater modeling that couples flow and transport together (Guo and Langevin, 2002). SEAWAT-2000 couples the flow and transport equations of two widely accepted codes MODFLOW (Mcdonald and Harbaugh, 1988; Harbaugh *et al*., 2000) and MT3DS (Zheng and 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 as in Eqs 2.1 and 2.2. This package has been very useful to simulate variable density flow through complex geological. One advantage of SEAWAT-2000 is that it uses MT3DMS to represent solute-transport, the program contains several methods for solving the transport equation. Hence, SEAWAT-2000 software package was selected in the present study to simulate the groundwater flow and solute transport to predict the behavior of groundwater of Manukan Island aquifer.

$$\frac{\partial}{\partial x_i}\left[\rho K_f\left(\frac{\partial h_f}{\partial x_i}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial_x}{\partial x_i}\right)\right]=\rho S_f\frac{\partial h_f}{\partial_t}+\theta\frac{\partial h_f}{\partial_t}+\partial\frac{\partial\rho}{\partial_t}-\rho s q_s$$

(Eq. 2.1)

Where;

X_i = i^{th} orthogonal coordinate

K_f = equivalent freshwater hydraulic conductivity (L/T)

S_f = equivalent freshwater specific storage (1/L)

h_f = equivalent freshwater head

t = time (T)

θ = effective porosity (dimensionless)

ρs = density of source and sink (M/L_3)

q_s = volumetric flow rate of sources and sinks per unit volume of aquifer (1/T)

The transport equation is as followed:

$$\frac{\partial(\theta c^k)}{\partial_t}=\frac{\partial}{\partial_x}\left(\theta D_{if}\frac{\partial c^k}{\partial_{xj}}\right)-\frac{\partial}{\partial x_j}\quad(\theta v i c^k)+\rho_s C^k_s+\sum R_x$$

(Eq. 2.2)

Where:
C^k = dissolved concentration of species, k (M/L^3)
D_{if} = hydrodynamics dispersion tensor (L^2/T)
C^k_s = concentration of the source or sink flux for species, k (M/L^3)
$\sum R_x$ = the chemical reaction term (ML^3/T)

The conceptual model for this study was developed based on the surface elevation contour map, information collected during boreholes construction and data from Abdullah *et al*. (2002). The low lying area of Manukan Island unconfined aquifer is consist of fine to coarse sand mixed with gravel. The model grid consists of 28 columns and 30 rows with grid spacing of 1093 (x-direction) and 906 m (y-direction) and divided into 2 layers based on the hydrogeological information. The top elevation of layer one corresponds with island land elevation. The bottom of layer two is set at an elevation of 7.0 m below the mean sea level. Model input parameters are given in Table 1. Based on groundwater data availability, one day was chosen as the time step in this study and to be increased by a multiplier factor by 1.2 within which all the hydrological stresses can be assumed constant. According to Spitz and Moreno (1996), time step is required for transient state. Generally, the smaller the time step, the more accurate the predicted results although it will require excessive computation time. Temporally, the simulation numerical model is transient with a total simulation time of five months from October 2008-February 2009 was used in the model, with each stress period representing one month of simulation month. In this study, model calibration is achieved through trial and error approach by adjusting the value of hydraulic conductivity as done in various groundwater modeling studies (Rejani *et al*., 2008).

Predictive simulations were performed after the model has been calibrated and validated. In predictive simulation, the parameters optimized during calibration are used to predict the system response to future events. Recharge rate was selected as precipitation patterns are significantly influenced by changes in the global-circulation patterns induced by climate change. Changes in precipitation have important implications for all aspects of the hydrologic cycle including groundwater resources (Allen *et al*., 2004). Due to this fact, reduced pumping has been selected with an aim of assessing the groundwater resources. The reduced pumping rate by 25% was selected as the number of tourists plunged year by year, it is crucial to meet the demand of groundwater in the island. Ong'or *et al*. (2007) showed that reduced pumping rate by 25% was acceptable range compared to other pumping rates in terms of groundwater management. Predictive simulations were performed to minimize the overexploration in the unconfined aquifer of Manukan Island. Scenarios selected for this study are presented in Table 2:

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
Layer 2 (Sedimentary rock)	3.4E-7, 1E-5, 1E-5
Total porosity	0.30
Effective porosity	0.15
Specific storage	0.0014
Specific yield	0.35
Longitudinal dispersivity	1 m
Horizontal transverse dispersivity	0.1 m
Vertical transverse dispersivity	0.01 m
Constant head	0 m
Recharge concentration	0 mg/L
Constant head concentration	19999 mg/L
Initial Concentration	Based October 2008
Evapotranspiration	0.3-0.35 mm/year

Table 2. Selected Scenarios for this study

Scenario	Explanation
Scenario 1	Current pumping rate (0.072 m^3/day) and recharge rates (600 mm/yr)
Scenario 2	Current pumping rate (0.072 m^3/day) with an increased in recharge rate (vulnerable to climate change) impacted by an increased of precipitation by 25% (750 mm/year)
Scenario 3	Reduced pumping rate (0.054 m^3/day) influence by pressure of island resources with an increased in recharge rate by 25% (750 mm/year)

3. Results and Discussion

During calibration, a total of 55 observed hydraulic head and chloride values (ten boreholes and a pumping well) measured from October 2008 to February 2009. Model calibration is stopped at the end of the simulation when reasonable matches between the observed and calculated hydraulic head are achieved. As illustrated in Figs 2-3, the overall correlation coefficients (r) are 0.97 and 0.95 for the hydraulic heads and chloride concentrations, respectively. The model calibrations concentrations, respectively. The model calibrations indicate a reasonably good match between the observed and calculated hydraulic heads and chloride concentrations. It is noteworthy that the model calibration performed for this study is the preliminary nature due to the limited number and duration of the observation data. Therefore, additional model calibration should be attempted when more field data become available in the future with the continuous monitoring in study area.

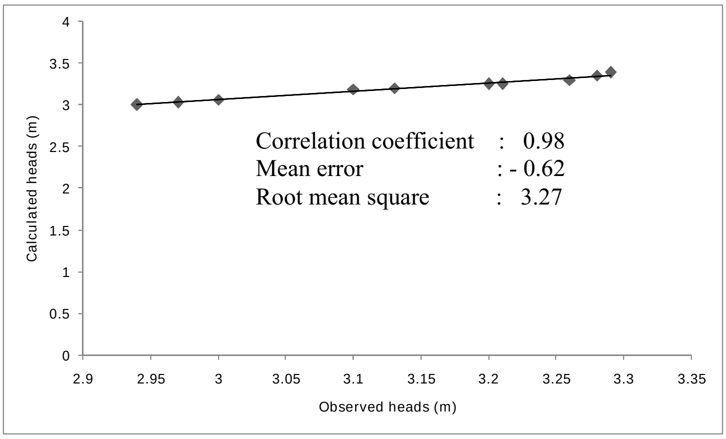

Figure 2. Scatter diagram showing the goodness of fit between the observed and calcuated heads for February 2009

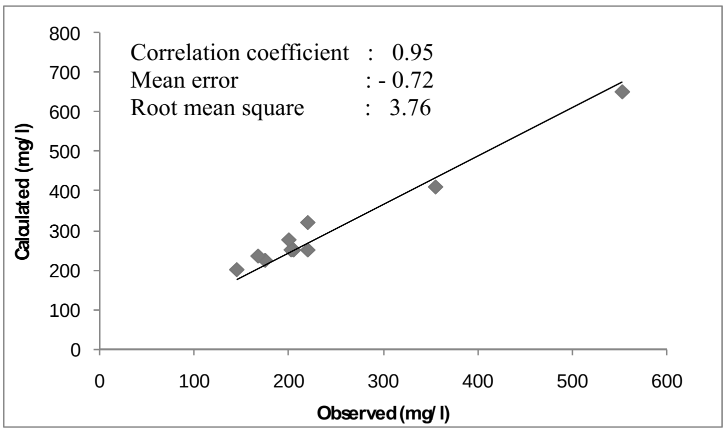

Figure 3. Scatter diagram showing the goodness of fit between the observed and calculated chloride concentration for February 2009

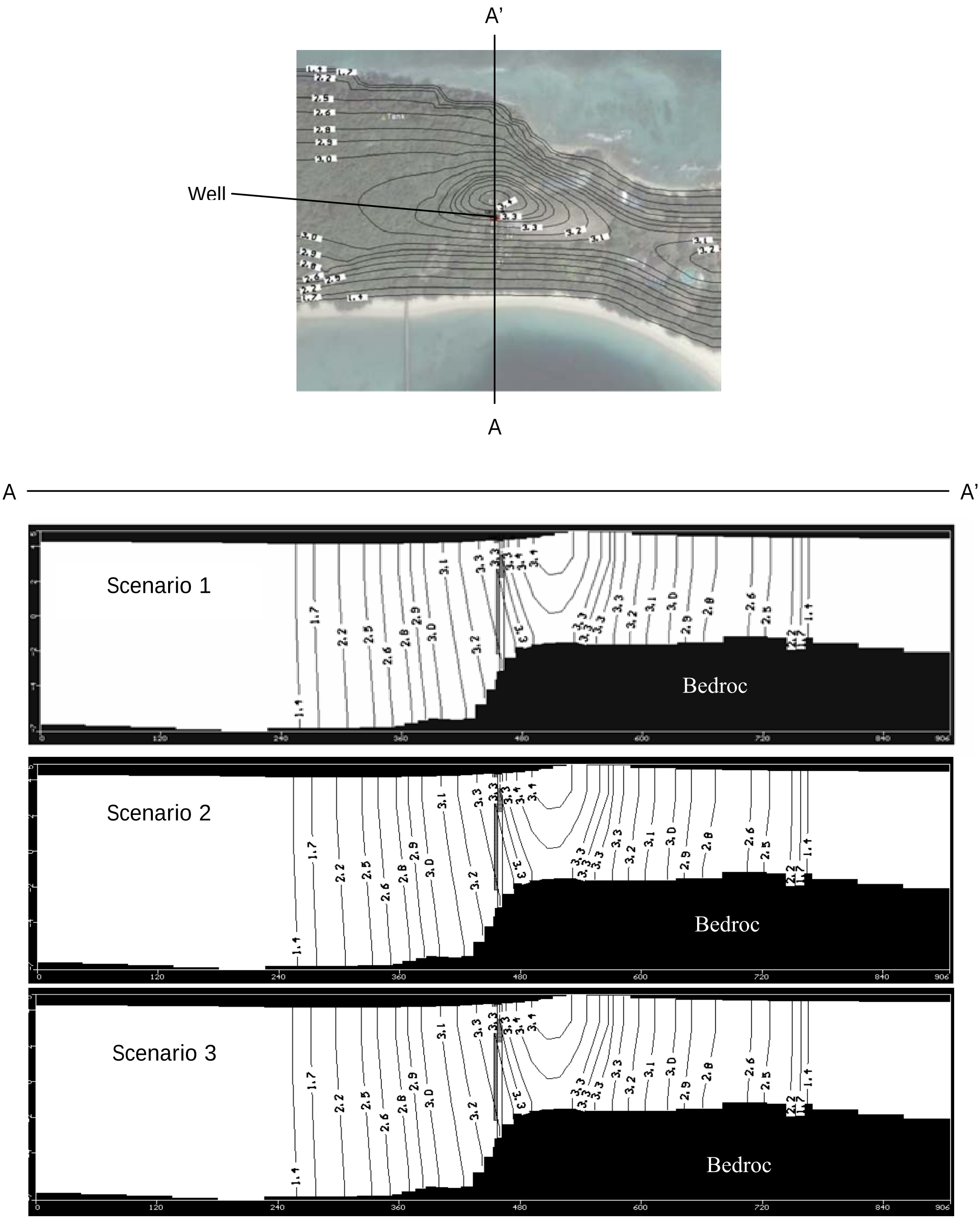

Figure 4. Hydraulic heads simulations in three different scenarios

3.1. Impact of increased recharge rate and reduced pumping rate on water quantity

Recharge, pumping of groundwater and tidal influences the fluctuation of hydraulic heads in the island (Hahn *et al*., 1997). According to Intergovernmental Panel on Climate Change (1997), coral islands and atolls are particularly sensitive to changes in groundwater recharge because all their water supply comes from the groundwater. Fig. 4 shows the hydraulic heads at three different scenarios (Scenarios 1, 2, and 3) simulated in this study. The recharge rate increases the water level as indicated by hydraulic heads in Scenario 2 compared to Scenario 1. This shows that it can alter the bad effects of overdrafts in Manukan Island which has been suffering from an overexploration in its unconfined aquifer. The increase in hydraulic heads depends on the percentage reduction in pumping and recharges rates. A reduction in pumping rate (Scenario 2) not only increases the amount of water levels in aquifer but also reduces the supply hence a deficit in groundwater levels. This simulation showed that with 25% reduction of pumping rate allows groundwater level increase hence addressing the environmental restoration issues with significant water volume stored within the given time limit. Even though 50% reduction of pumping rate with an increase in recharge rate leads to increase of hydraulic heads but it is unacceptable. This is because the water is needed to cater tourism and domestic uses in this touristic island. A combination of reduction in pumping rate and increase in recharge rate (due to climate change) in Scenario 3, which embraces not only the quantity but also quality for both environmental restoration and island aquifer, is desired. Recent studies conducted by Chen *et al*. (2004) and Moustadraf *et al*. (2008) showed that groundwater level fluctuations have a strong correlation with climatic trends. According to Climate Change (2007), groundwater recharge may increase in areas where heavy precipitations are major sources of groundwater recharge. Similarly in this study, the output showed the recharge rate increases water level as indicated by the hydraulic heads. However, according to Moustadraf *et al*. (2008), groundwater recharge is less efficient when the rainfall pattern is short and intense. Moreover, inconsistency in climate change in terms of precipitation influences the groundwater recharge.

3.2. Impact of increased recharge rate and reduced pumping rate on water quality

The prognosis of chloride in groundwater due to pumping and recharge rates was carried out using the calibrated model. The chloride concentration in groundwater was investigated at local scale within the vicinity of cone of depression. The well water has about 1978.3 mg/L chloride with current pumping and recharge rates in Scenario 1. However, with an increase of recharge rate and current pumping rate (Scenario 2) has decreased about 1.13% or 22.2 mg/L. In addition, reduction in pumping rate made the chloride concentration decreased about 2.8% or 2.8 mg/L. In general, a reduction in pumping with an increase in recharge rate (Scenario 3) leads to a decreased in chloride concentrations within the vicinity of cone of depression (Figs 5-6). Similarly, a study done by Ong' or *et al*. (2007) in Jining, China showed a reduction in pumping rates by 15-25% and increased artificial recharge has decreased the chloride concentration in water quality. In general, the modeling output showed that chloride concentrations in pumping well are far higher than the limit of (WHO, 2004) of 250 mg/L in pumping well. The decrease in chloride concentrations due to reduction in pumping rate (25%) with an increase in recharge rate can be attributed to the dilution of precipitated minerals, modifying its permeability by widening the pores/fractures allowing more water of lower chloride concentrations and diluting it (Ong' or *et al*., 2007). According to Samsudin *et al*. (2008), heavy rainfall that directly recharges the aquifer had flushed out most of the salts from the aquifer. Moreover at 25% reduced pumping with an increase in recharge rate and with an increased of recharge rate seems to be the better risk option as it offers an optimum in terms of both water quality and quantity combined for the most visited tourist island, such as in this study. It is worth noting that even though reduction about 50% in pumping rate with an increased in recharge rate will lead to reduction in chloride concentrations, but it is unacceptable in this tourist island. Devlin and Sophocleous (2005) stated that recharge could affect the quality of the water in the aquifer thus also impacting associated ecological communities.

3.3. Groundwater sustainability

According to Allen *et al*. (2004), as a part of the hydrologic cycle, it can be anticipated that groundwater systems will be affected by changes in recharge (encompasses changes in precipitation). It is highly probable that the effect of climate change such as in recharge rate will lead to adjustments in the global hydrological cycle which will affect the distribution and availability of regional water resources. According to Sen (2008), the direct groundwater recharge mode is more sensitive to direct natural recharge than indirect natural recharge. Direct natural recharge is such as an increase of precipitation due to climate change whereas indirect natural recharge is water fulfills the soil moisture and evapotranspiration process before reaching groundwater reservoir. Many researchers believe that climate change mainly governs the groundwater recharge compare to vegetation and evapotranspiration. On the other hand, high recharge rate areas (areas with highly pervious soils) may be at risk for contamination. Rainwater can percolate through coarse-grained deposits so rapidly that surface contaminants are not "filtered out" before water enters the aquifer. Shallow aquifers or areas with shallow soils may also be at risk for contamination. In shallow groundwater, rainwater may not move through enough sub-surface material to "filter out" contaminants before the water enters the aquifer (Alley, 1993). Briefly, the Water Budget Myth is the idea that sustainable pumping must not exceed the recharge rate in a given aquifer (Bredehoeft, 2002). As a result, efforts should be made to measure recharge rates as accurately as possible when an evaluation of sustainability is the objective. Any modern assessment of groundwater sustainability can be done by applying a computer modeling component to assess the behavior of the aquifer and its sustainable pumping rate.

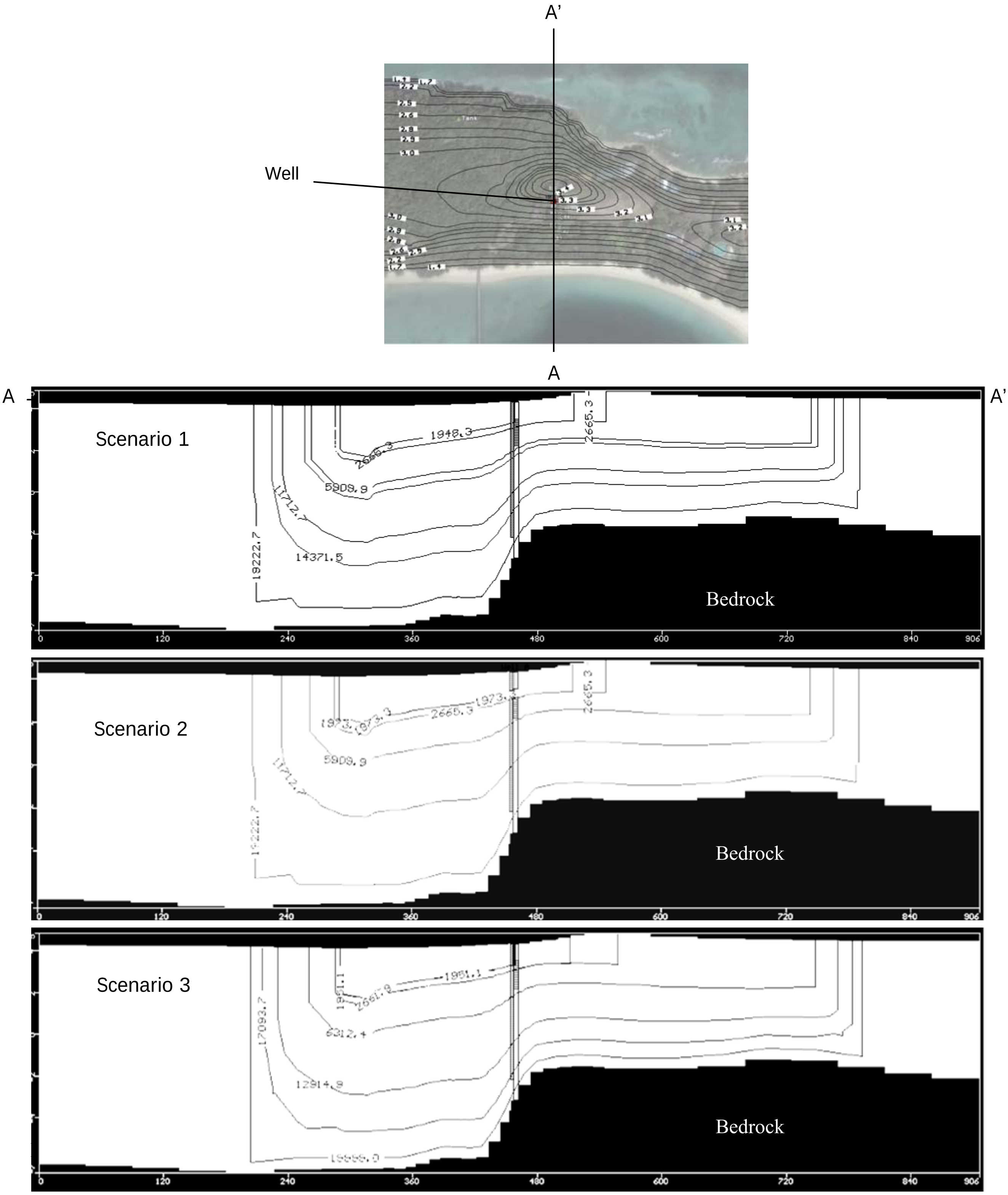

Figure 5. Chloride concentrations simulations in three different scenarios

3.4. Limitation of the model

A three dimensional numerical model of unconfined aquifer of Manukan Island strictly based on the increase of precipitation which leads to an increase in recharge rate and reduced in pumping rate. Next, the model should focus on climate change variables such as consequences of climate change are increase in air temperature, increase in sea surface temperature, and more extreme weather conditions. These parameters are considered critical parameters for climate change impact modeling in aquifers. High temperature and low precipitation and low temperature with high precipitation will be the extreme cases to be

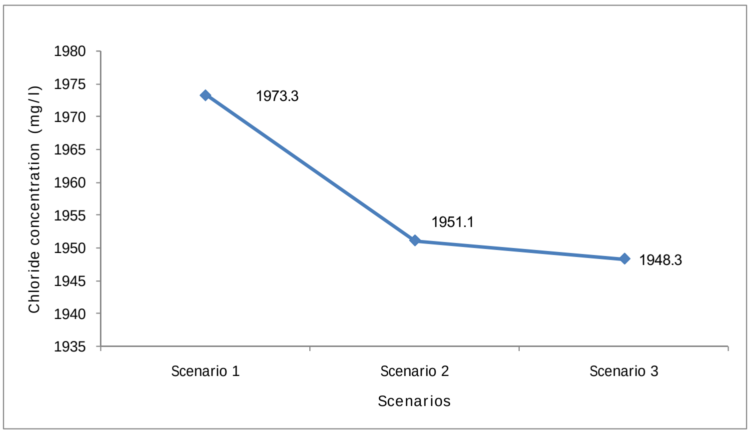

Figure 6. Reduction in chloride concentration in three different scenarios

evaluated using large set of data. Since the Manukan aquifer is the single most important source of water, appropriate investments should be made to ensure that each of major components of hydrological water budget are adequately quantified, understood and incorporated in the future model.

4. Conclusion

The present study constructed a three-dimensional finite-difference numerical model for an understanding of groundwater sustainability under current pumping and recharges rate aquifer conditions in Scenario 1. The results of simulations showed that there are impacts on changes of increased recharge to hydraulic heads in Scenarios 2 and 3. The increase in recharge rate (from 600mm/year to 750 mm/year) increases the water level indicated by hydraulic heads. The increase in hydraulic heads also depends on the percentage reduction in pumping and recharges rates. Besides, a reduction in pumping rate (from 0.072 m^3/day to 0.058 m^3/day) not only increases the amount of water levels in aquifer but also reduces the supply hence a deficit in supply. In general, a reduction in pumping with an increase in recharge rate leads to a decrease in chloride concentrations within the vicinity of cone of depression. The well water has about 1978.3 mg/L chloride concentration with current pumping and recharge rates. However, with an increase of recharge rate and current pumping rate, it has decreased about 1.13%. In addition, a reduction in pumping rate leads to the decrease of chloride concentration of 2.8%. It is highly probable that the effect of climate change such as in recharge rate will lead to adjustments in the global hydrological cycle which will affect the distribution and availability of regional water resources. Next, to further develop the numerical model, the model should focus on climate change variables such as temperature and evapotranspiration. Groundwater sustainability can be done by applying a computer modeling component to assess the behavior of the aquifer and its sustainable pumping rate. The results of this study are foundation in order to work out a comprehensive scheme of groundwater exploitation consistent with the natural constraints existing on the island.

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