

## **SIMULATION OF GROUNDWATER FLOW AND POLLUTANT TRANSPORT FOR ALLUVIAL AQUIFER IN KAMPUNG TEKEK, TIOMAN ISLAND**

NORHAN ABD RAHMAN<sup>1</sup> & WOEL-KEONG KUAN<sup>2</sup>

**Abstract.** Tioman Island is situated in the east coast of Peninsular Malaysia. With rapid growth in tourism industry, the demand for water supply is expected to increase in this island. From previous studies, groundwater was found to be a potential source of water. A 3-dimensional numerical modelling software (Visual MODFLOW) is used to simulate the groundwater flow and pollutant transport of the aquifer in Kampung Tekek, for the prediction of available yield of groundwater, and also for studying the migration of potential contaminant source, i.e. nitrate, due to the withdrawal. The groundwater flow simulation results showed that the aquifer is capable of pumping 4000 m<sup>3</sup>/day. Results of pollutant transport modelling showed that the estimated concentration of nitrate in the pump well is generally low and complies with World Health Organisation (WHO) standard for drinking water.

*Keywords:* Groundwater flow, pollutant transport, numerical model, Visual MODFLOW, island

**Abstrak.** Pulau Tioman terletak di pantai timur Semenanjung Malaysia. Akibat pembangunan yang pesat dalam industri pelancongan, permintaan terhadap bekalan air dijangka akan meningkat di pulau ini. Daripada kajian yang telah dijalankan sebelumnya, didapati airbumi merupakan sumber air yang berpotensi. Satu perisian model 3-dimensi (Visual MODFLOW) telah digunakan untuk menghasilkan model aliran airbumi dan pengangkutan bahan pencemar di Kampung Tekek dengan tujuan meramal simpanan airbumi dan penyebaran bahan pencemar, iaitu nitrat, semasa pengepaman. Daripada keputusan simulasi aliran airbumi yang diperolehi, pengepaman akuifer di Kampung Tekek dapat mencapai pada kadar 4000 m<sup>3</sup>/hari. Kajian model bahan pencemar menunjukkan kepekatan bahan pencemar nitrat yang tercatat di telaga pam didapati agak rendah dan memenuhi piawaian air minuman *World Health Organisation* (WHO).

*Kata kunci:* Aliran airbumi, bahan pencemar, model numerik, Visual MODFLOW, pulau

### **1.0 INTRODUCTION**

Tioman Island is one of the main tourist attractions, situated offshore in the south-east of Pahang, Peninsular Malaysia, and surrounded by South China Sea. Fresh water can be obtained naturally on this island, as surface water and groundwater. According to the analytical data in 1999, provided by Hasan *et al.* [1], the supply of the surface runoff is limited and fluctuated seasonally. Therefore, the alternative supplement to the

<sup>1</sup> Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM, Skudai, Johor Darul Takzim, Malaysia. E-mail: norhan0123@yahoo.co.uk

<sup>2</sup> Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia. E-mail: wkkuan@yahoo.com

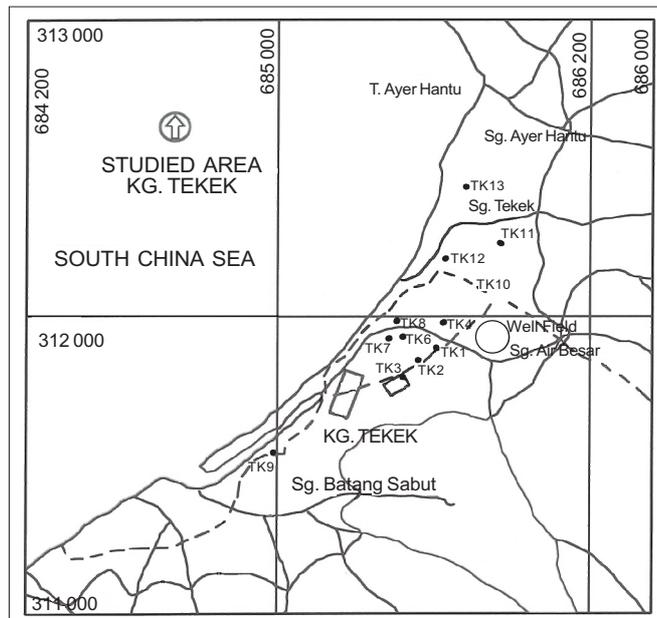
surface water would be the groundwater. One of the early researches by the Geological Survey Department in early 1990s has found that there are sufficient groundwater resources in Kampung Tekek and Kampung Juara, where the former is capable of producing water at 1368 m<sup>3</sup>/day [2,3].

Investigation on groundwater is very costly and time-consuming, especially in conducting pumping test and construction of observation wells [4,5]. Therefore, simulation through a modelling tool is a better choice, provided that adequate and sufficient data are available. In this paper, a numerical modelling software, Visual MODFLOW, is used to simulate the groundwater flow and pollutant transport of the alluvial aquifer in Kampung Tekek, based on the available data.

The study focuses on the groundwater flow system for the prediction of the available yield of the alluvial aquifer, by studying the drawdown of water table at different modes of pumping rate and also the pumped wells distribution. This model is also used to study the migration path and concentration of potential point source of contaminant, at a given pumping rate, for different recharge concentration and distribution coefficient for sorption ( $k_d$ ) value. Nitrate is assumed as the potential contaminant since leakage may occur from the existing septic tank on this island.

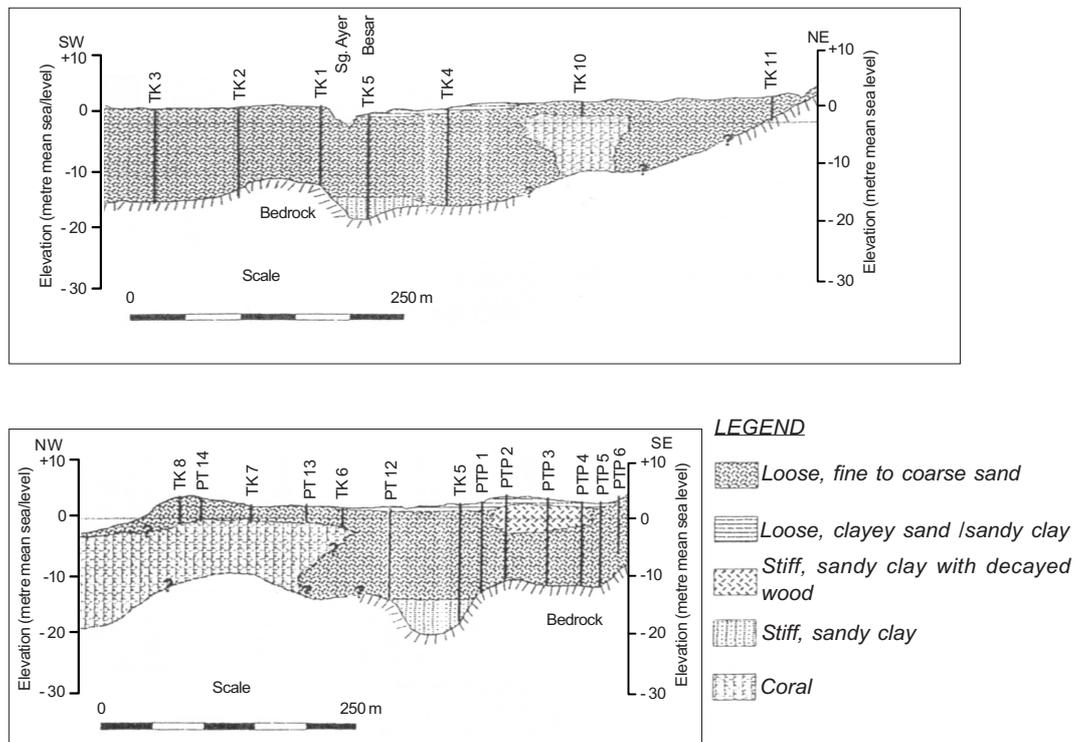
## 2.0 DESCRIPTION OF THE STUDY AREA

Tioman Island is located in the vicinity of 2°43'00" to 2°54'00" N latitude and 104°06'00" to 104°12'30" E longitude. The area of study in Kampung Tekek encompasses area between X: 684200 to X: 686200 and Y: 311000 to Y: 313000 (Figure 1).



**Figure 1** Studied area of Kampung Tekek, Tioman Island

Kampung Tekek is one of the main villages providing accommodation for the tourists in the west coast of Tioman Island. According to the hydrogeological data, the aquifer in Kampung Tekek is classified as an unconfined aquifer. This aquifer consists of a layer of permeable medium at an average thickness of 12 m before reaching the impermeable granitic bedrock (Figure 2). In general, the aquifer in Kampung Tekek is formed by alluvium, a permeable medium that can be found as patches along the coastline in low-lying areas. South China Sea borders this area in the west and steep terrain of impermeable medium igneous rock is in the east. There are four main streams running through the village which are Sungai Batang, Sungai Air Besar, Sungai Tekek, and Sungai Air Hantu. Recharge for the sand aquifer is mainly through the direct infiltration from rainfall and adjacent river. Natural discharge of the groundwater will contribute to the river base flow, subsurface outflow, evaporation, and transpiration [6,3].



**Figure 2** Geological cross-section of aquifer system [6]

## 2.1 Groundwater Quality

The groundwater quality data used in this study was collected by the Minerals and Geoscience Department of Malaysia from March – September 1999. The samples were collected from selected observation wells, twice during the monitoring period. The overall quality of the groundwater in Kampung Tekek is good and suitable for

domestic consumption, with minor water treatment. However, samples from observation wells which were closer to the coastal area were found to have higher contents of chloride, sodium, and sulphate, that might be due to the saline water intrusion. Iron, manganese, aluminium, copper, and lead contents have also been detected to be higher than the permissible WHO drinking water limit, in some of the groundwater samples. In Kampung Tekek, groundwater from the alluvial aquifer varied from the calcium carbonate at the northern part, to the sodium chloride type at the southern part, near Sungai Air Besar [6].

In Tioman Island, septic tanks are the potential source of nitrate ( $NO_3^-$ ) and phosphorus contamination to the groundwater, due to effluent discharge through the seepage pits [7]. Typically, phosphorus contamination is considered together with nitrogen. However, this is less important because many soils are able to reduce possible phosphorus contamination by their phosphorus fixing capabilities, but the extent of nitrogen flow in groundwater can be activated through the adsorption-ion exchange phenomena, exhibited by soils [8,9].

### 3.0 METHODOLOGY

The process of achieving the objectives in this study involves a series of procedures. They can be categorised into four basic approaches namely, data collecting, simulation using computer model, calibration, and analysis of study cases. Simulation processes include creation of conceptual model through data evaluation, development of groundwater flow model using Visual MODFLOW, calibration of the model in steady state, and simulation of groundwater flow and pollutant transport in transient state.

Finite difference method has been adopted by Visual MODFLOW in simulating the flow [10]. In this method, the governing equation is replaced by a difference equation that embodies conservation principles of the original differential equation. The three dimensional flow equation is described as follows:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad (1)$$

where,

- $K_{xx}, K_{yy}, K_{zz}$  – values of hydraulic conductivity along  $x$ ,  $y$ , and  $z$  coordinate axes
- $H$  – hydraulic head
- $W$  – flux term that accounts for pumping, recharge or other sources, and sinks
- $S_s$  – specific storage
- $x, y, z$  – coordinate directions
- $T$  – time

The partial differential equation describing the rate and transport of contaminants of species  $k$  in three-dimensional, transient groundwater flow systems can be written as follows:

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i} \left( \theta D_{ij} \frac{\partial C^k}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (\theta v_i C^k) + q_s C_s^k + \sum R_n \quad (2)$$

where,

- $C^k$  is the dissolved concentration of species  $k$
- $\theta$  is the porosity of the subsurface medium
- $x_i$  is the distance along the respective Cartesian coordinate axis
- $D_{ij}$  is the hydrodynamic dispersion coefficient tensor
- $v_i$  is the seepage or linear pore water velocity
- $q_s$  is the volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative)
- $C_s^k$  is the concentration of the source or sink flux for species  $k$
- $\sum R_n$  is the chemical reaction term.

The information used in this model was based on the data collected from September, 1998 until December, 1999 by Minerals and Geoscience Department Malaysia [6]. Some of the assumed parameters are according to Hasan *et al.* [1].

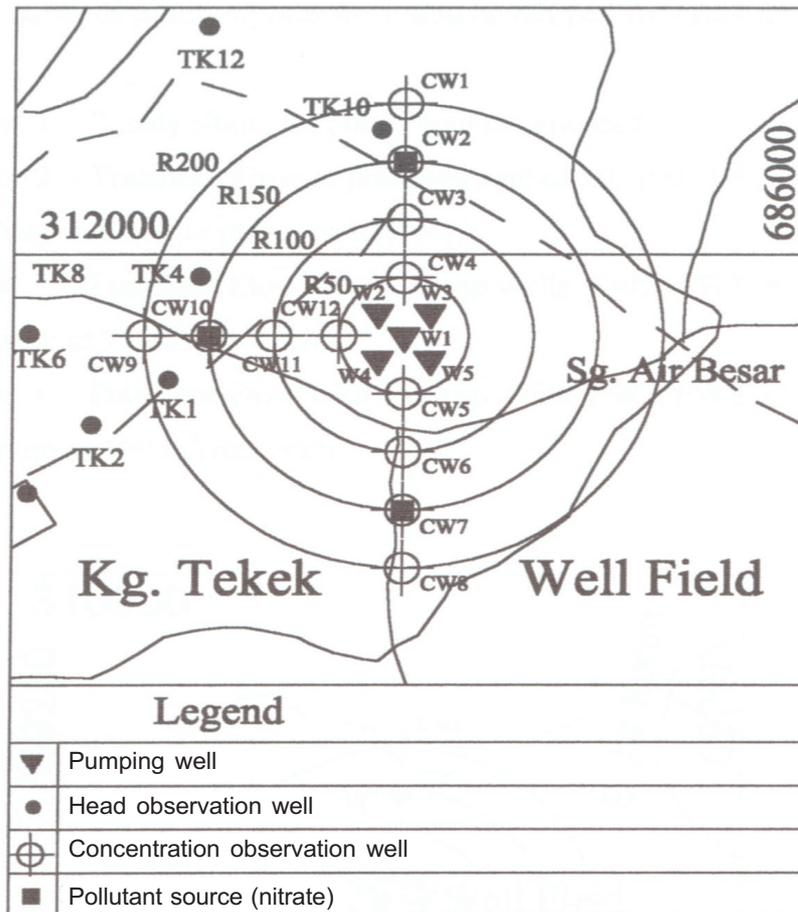
### 3.1 Study Cases for Flow Simulation

A series of pump wells namely, W1, W2, W3, W4, and W5 are located (Figure 3) at a distance of 40 m vertically, and horizontally from each other. In this study, 3 cases with different pumping rate were applied for groundwater simulation:

- (1) Case 1 – Steady state. Pump well W1 was not activated.
- (2) Case 2 – Pump well W1 operated at different pumping rate of 1000, 2000, 3000, 4000, and 6000 m<sup>3</sup>/day.
- (3) Case 3 – Four pump wells W2, W3, W4, and W5 operated at 1000 m<sup>3</sup>/day, and 1500 m<sup>3</sup>/day respectively.

### 3.2 Study Cases for Pollutant Transport Simulation

For pollutant transport simulation, different contaminant modes were applied to the model at a constant pumping rate of 4000 m<sup>3</sup>/day in W1. The contaminant sources were assumed to release constantly from wells, CW2, CW7, and CW10 at different rate and value of distribution coefficient for sorption. The contaminant wells, CW2, CW7, and CW10 are located 150 m from the centre of well field, W1 (Figure 3). It was



**Figure 3** Pump wells and concentration observation wells layout plan

arranged in such a way to examine the contaminant migration from different direction, when withdrawing groundwater in W1. The study cases for pollutant transport simulation are given as follows:

- (1) Case 1 – Distribution coefficient,  $k_d = 0$ . The contaminant released constantly from wells CW2, 7, and 10 at 50 mg/L, 500 mg/L, and 1000 mg/L respectively.
- (2) Case 2 – Distribution coefficient,  $k_d = 0.01$ . The contaminant released constantly from wells CW2, 7, and 10 at 50 mg/L, 500 mg/L, and 1000 mg/L respectively.
- (3) Case 3 – Distribution coefficient,  $k_d = 0.0001$ . The contaminant released constantly from wells CW2, 7, and 10 at 50 mg/L, 500 mg/L, and 1000 mg/L respectively.

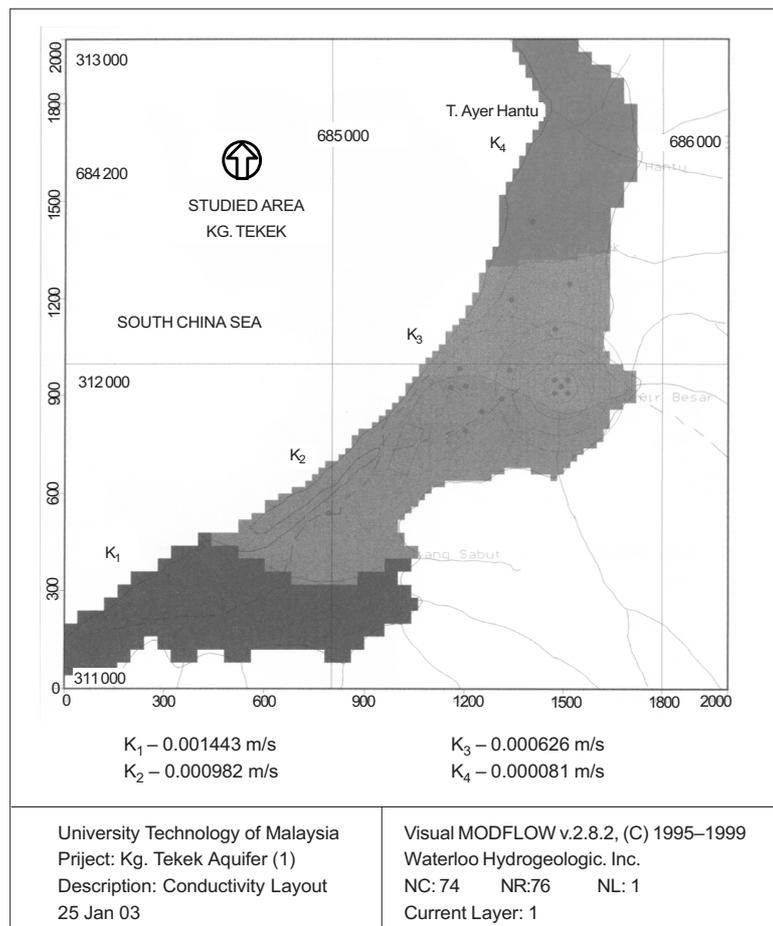
In this study, recharge concentration at 50 mg/L was constantly released for a period of 50 years while the duration of recharge concentration at 500 mg/L and 1000 mg/L was for one year.

## 4.0 ANALYSIS AND RESULTS

### 4.1 Calibration Results for Groundwater Flow Simulation

From the calibration analysis, simulation of aquifer as isotropic and heterogeneous (Figure 4) compared with isotropic and homogeneous (a constant hydraulic conductivity,  $K$  value throughout the entire study area) has resulted in a better performance. The result of normalised Root Mean Square (RMS) of the observed head in August, 1999, and simulated head in 12 observation wells for the isotropic and heterogeneous model was given by 9.263%, which is less than 11.517% for the isotropic and homogeneous model (Table 1). Therefore, the simulation of Kampung Tekek aquifer as isotropic and heterogeneous was adopted in this study.

The depression cone caused by pumping for each case was represented by equipotential contour lines, which indicate the hydraulic head or water level from mean sea level. The term 'hydraulic head' used in this study refers to the water table of



**Figure 4** Hydraulic conductivity zoning plan (Isotropic and heterogeneous)

**Table 1** Calibration analysis of 12 observation wells

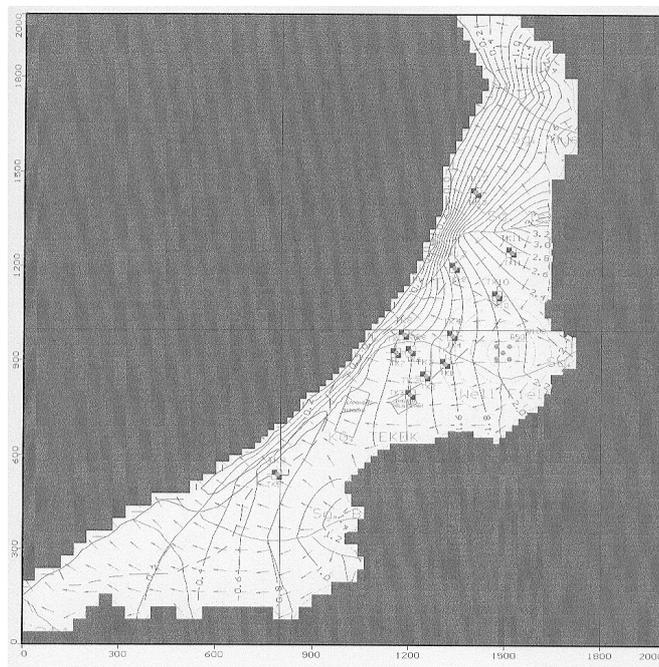
	<b>Isotropic and heterogeneous</b>	<b>Isotropic and homogeneous</b>
Mean error	-0.027 m	0.038 m
Mean absolute	0.153 m	0.191 m
Standard error of the estimate	0.059 m	0.073 m
Root mean squared (RMS)	0.198 m	0.246 m
Normalized RMS	9.263%	11.517%

groundwater from the mean sea level, where the positive value is above the mean sea level, and the negative value is below the mean sea level.

The results of each case are discussed as follows:

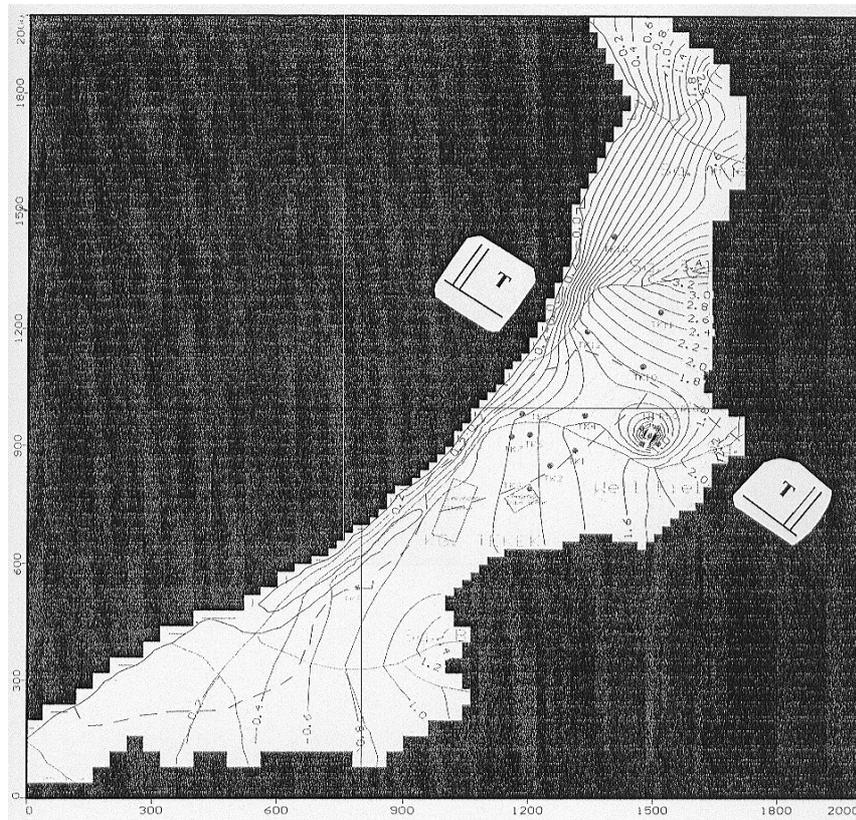
(1) Case 1: No pumping (Steady state)

From the hydraulic head contour plot, it was obvious that the direction of groundwater flow was moving towards South China Sea. It was proved by the contour line that indicated the hydraulic head which was reducing, approaching the coastal line (Figure 5). The initial water table recorded in the pump well W1 from the simulated model equals to 2.02 m (MSL).

**Figure 5** Hydraulic head contour in steady state

- (2) Case 2: Pump working at the rate of 1000, 2000, 3000, 4000 & 6000 m<sup>3</sup>/day in well W1, respectively

When the pumping was activated at the rate of 1000 m<sup>3</sup>/day in well W1, the flow equipotential contour and cross sectional view showed a depression cone located at the pump well location. By increasing the pump rate value in well W1 in the input module of Visual MODFLOW, the drawdown in the pump well was found to be increased. The depression cone due to the drawdown has become more significant when the pumping rate has increased to 4000 m<sup>3</sup>/day (Figure 6).



**Figure 6** Hydraulic head contour (4000 m<sup>3</sup>/day)

- (3) Case 3: Pumps working at the rate of 1000 m<sup>3</sup>/day (W2 & W3) & 1500 m<sup>3</sup>/day (W4 & W5)

From the output results, the simulated hydraulic head for 4000 m<sup>3</sup>/day in Case 2 was similar to the simulated hydraulic head for 4 × 1000 m<sup>3</sup>/day in Case 3, in the observation wells TK 1-13, located beyond the pump well field. However, the simulated hydraulic head in the 5 pump wells, W1-5 varied significantly. The lowest simulated hydraulic head recorded was -1.448 m in pump well W1 at 4000 m<sup>3</sup>/day but the hydraulic head

increased to the range of 0.271 – 0.544 m in pump wells W2-5 at  $4 \times 1000 \text{ m}^3/\text{day}$ . Similar result was also obtained for pumping rate of  $6000 \text{ m}^3/\text{day}$  and  $4 \times 1500 \text{ m}^3/\text{day}$ . The simulated hydraulic head for 2 different cases were tabulated in Table 2.

**Table 2** Simulated hydraulic heads at different pumping rates in Kampung Tekek

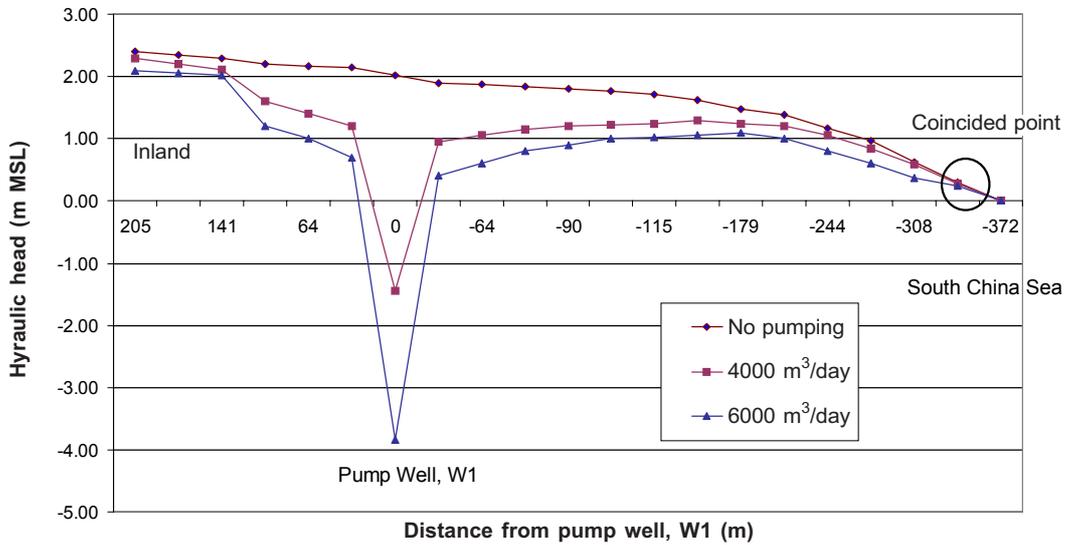
Well name	*Observed head (m)	Pumping rate ( $\text{m}^3/\text{day}$ )			
		4000	$4 \times 1000$	6000	$4 \times 1500$
		Simulated head (m)			
OW1/W1	–	–1.448	0.593	–3.838	–0.228
OW2/W2	–	0.454	0.271	–0.418	–0.712
OW3/W3	–	0.522	0.340	–0.362	–0.656
OW4/W4	–	0.670	0.489	–0.093	–0.382
OW5/W5	–	0.725	0.544	–0.050	–0.339
TK1	1.340	1.423	1.423	1.358	1.358
TK2	1.150	1.257	1.257	1.206	1.205
TK3	1.190	1.158	1.158	1.111	1.111
TK4	1.530	1.365	1.364	1.263	1.263
TK6	0.980	1.158	1.158	1.134	1.134
TK7	1.210	0.982	0.982	0.969	0.969
TK8	0.910	0.930	0.930	0.916	0.916
TK9	0.780	0.708	0.708	0.707	0.707
TK10	2.100	1.684	1.684	1.471	1.472
TK11	2.920	2.524	2.524	2.448	2.448
TK12	1.650	1.459	1.459	1.415	1.415
TK13	1.940	1.406	1.406	1.400	1.400

\*Observation head data in August 1999 [6]

From the analytical result, a section T-T cutting through the aquifer was applied to the aquifer, as shown in Figure 6 for Case 1 and 2. The drawdown of water table was interpolated from the figure and plotted against its distance from the pump well location. From the graph plotted, the effect of pumping to the drawdown of hydraulic head was reducing relatively to their distance from pump well W1 (Figure 7). However, this effect has terminated since the simulated hydraulic head for pumping rates of  $4000 \text{ m}^3/\text{day}$  and  $6000 \text{ m}^3/\text{day}$  coincided with the observed hydraulic head in steady state, before reaching the shoreline (South China Sea).

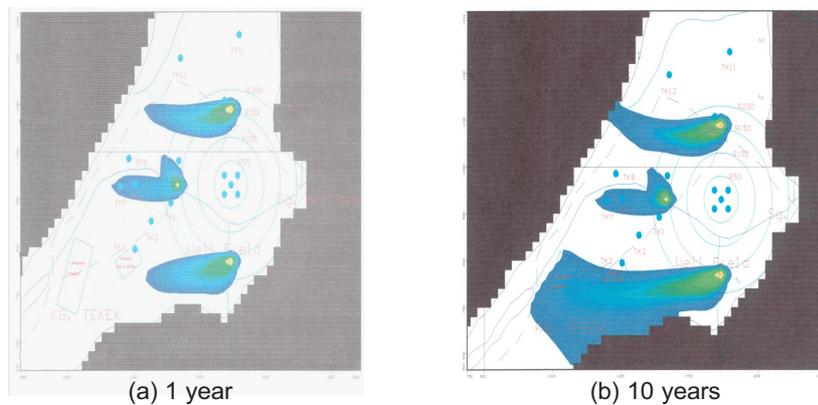
#### 4.2 Analysis and Results for Contaminant Migration Simulation

In Case 1, the distribution coefficient for sorption,  $k_d$ , was set at 0. The maximum concentration of nitrate estimated at  $50 \text{ mg/L}$  of recharge in source recharge wells



**Figure 7** Cut section T-T – Hydraulic head at different pumping rates

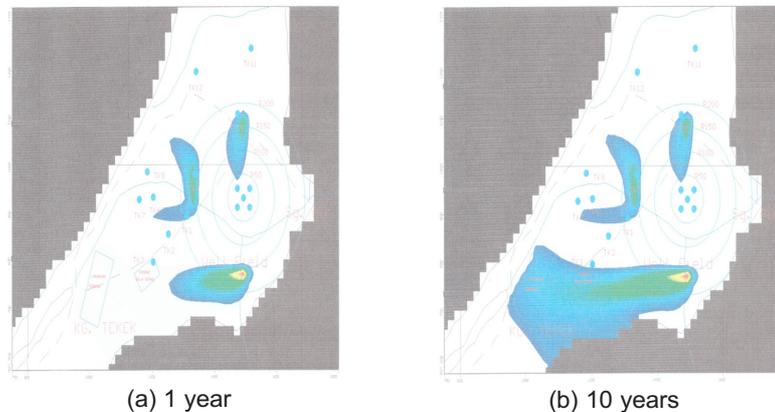
CW2, CW7, and CW10 were 0.1079, 0.1885, and 0.1051 mg/L respectively. For other observation wells, the estimated concentration of nitrate was insignificant or nearly undetectable. When the source recharge rate increased to 500 mg/L, the concentration of nitrate in source recharge wells CW2, CW7, and CW10 were estimated at the maximum concentration of 1.0791, 1.8240, and 1.0283 mg/L respectively. The estimated nitrate concentrations in other observation wells at the same recharge were below 0.3720 mg/L. By increasing the recharge rate of nitrate to 1000 mg/L, the estimated concentration at the said source recharge wells were recorded as 2.16, 3.65, and 2.10 mg/L respectively. In pump well W1, the estimated concentration of nitrate was recorded at the maximum values of 0.004, 0.034, and 0.07 mg/L at recharge rates of 50, 500, and 1000mg/L respectively. The migration paths of contaminant ( $k_d = 0$ ) for 1 and 10 years are shown in Figure 8.



**Figure 8** Migration path of contaminant ( $k_d = 0$ )

In Case 2, the distribution coefficient for sorption,  $k_d$ , was set at 0.01. Estimated maximum concentrations of nitrate at 50, 500, and 1000 mg/L of recharge in the source recharge wells CW2, CW7, and CW10 were below 0.0027 mg/L. While for other observations wells and pump well W1, estimated concentration of nitrate was almost undetectable.

In Case 3, the distribution coefficient for sorption,  $k_d$ , was set at 0.0001. The result was similar to Case 2 where most of the observation wells were not contaminated by nitrate, including pump well W1. Maximum concentrations at source recharge wells CW2, CW7, and CW10 were estimated at 0.09, 0.12, and 0.09 at 50 mg/L recharge; 0.05 mg/L at 500 mg/L recharge; 0.10 mg/L at 1000 mg/L recharge. The migration paths of contaminant ( $k_d = 0.0001$ ) for 1 and 10 years are shown in Figure 9.



**Figure 9** Migration path of contaminant ( $k_d = 0.0001$ )

Generally, the contaminant migration path directions were moving towards South China Sea, following hydraulic gradient in steady state. When the pump was activated at the rate of 4000 m<sup>3</sup>/day, the contaminant moved towards the pump wells, especially at recharge point CW2. At CW10, the migration path was also affected but not as significant as at CW2. The migration pattern of contaminant in CW7 was similar to the pattern in steady state. This was due to the distance of concentration wells from Sungai Air Besar. CW2 is located furthest from Sungai Air Besar while CW7 is located just beside Sungai Air Besar. For CW10, the river separated it from the pump well W1. In this study, Sungai Air Besar was assumed to have a constant head value throughout the simulation period. This constant head value reduced the pumping effect to the migration of contaminant in each concentration well.

Since the withdrawal of groundwater affected the migration path or transport direction of contaminant, this might lead to the contamination of groundwater in the pump well, if leakage of contaminant happened in the studied domain in the future. One should examine the concentration of contaminant in the pump well regularly if withdrawal of groundwater is going to be implemented in the studied areas. However,

the estimated concentration of nitrate contaminant in the pump well was generally low at given recharge concentration.

In all the 3 cases mentioned above, the distribution coefficient for sorption,  $k_d$ , was set at 3 different values of 0, 0.01, and 0.0001 to evaluate the effects of sorption on the rate and transport of contaminant in the groundwater. From the analysis, the estimated concentration in Case 1 ( $k_d=0$ ) was the highest, followed by Case 3 ( $k_d=0.0001$ ), and Case 2 ( $k_d=0.01$ ). Hence, higher sorption value would reduce the concentration of contaminant. Due to the lack of information on distribution coefficient,  $k_d$ , sorption was not included in Case 1 in which its value was set at 0. The estimated concentration was found to be the highest and considered as the worst situation if contaminations occur in the future.

### 4.3 Limitation of the Model

This model was developed using limited data which was not totally derived from the measurement parameters such as specific storage, specific yield, effective porosity, recharge rate, distribution coefficient, and others. Due to lack of such critical data, assumptions were made based on the limited data and references available at the time or determined through the calibration processes.

## 5.0 CONCLUSION

From the flow simulation result, significant drawdown in the pump well between each different pumping rates can be observed. It was found that, due to the pumping effect, the water drawdown reduced relatively to their distance from the pump well. The influence from the withdrawal had stopped before reaching the shoreline, in which the hydraulic head of the groundwater along the shoreline was still above mean sea level. Hence, the storage of ground water at pumping rate of 4000 m<sup>3</sup>/day in Kampung Tekek was sufficient for withdrawal.

After distributing the pumping rate into 4 wells, results showed that no further decrement of hydraulic head accrued beyond the well field. Therefore, if the groundwater is going to be proposed as an alternative use of the surface water, the number of pump well should not be limited to one since there is no decrement to the drawdown. With additional pump wells, maintenance of wells can be carried out in shift without affecting the continuity of water supply or disturbing the water supply due to malfunctioning of mechanical or electrical components in any pump well.

From the pollutant transport modelling, the highest value of estimated concentration was obtained from Case 1, in which there was no sorption ( $k_d=0$ ) at the given recharge concentration with pumping rate of 4000 m<sup>3</sup>/day. The estimated concentration of contaminant in the pump well W1 was found to be in compliance with WHO Standard [11] of nitrate concentration for drinking water.

For future study, the model should incorporate more field data, especially the pumping test data and water quality data, to better estimate the model parameters such as hydraulic conductivity and distribution coefficient of sorption for both flow, and pollutant transport modelling through the process of verification.

### ACKNOWLEDGEMENT

The authors would like to thank to the Research Management Centre (RMC), Universiti Teknologi Malaysia, for the financial support under Vote No. 71573.

### REFERENCES

- [1] Daulay, H. B., N. A. Rahman, A. H. Mohd. Kasim, and K. Nasir. 2001. Study on Water Resources in Tioman Island. *Journal Teknologi*. 34 (F): 51-62.
- [2] Awang, M. N., and P. Loganathan. 1991. *Prospek Sumber Air Tanah Pulau Tioman, Pahang*. Jabatan Penyiasatan Kajibumi Malaysia.
- [3] Awang, M. N. 1988. Kajian Keseimbangan Air di Kampung Tekek dan Kampung Juara, Pulau Tioman. *Laporan Persidangan Geologi Tahunan Ke-19, Jilid 2*. Malaysia: Jabatan Penyiasatan Kajibumi.
- [4] Delleur, J. W. 1999. *The Handbook of Groundwater Engineering*. USA: CRC Press LLC.
- [5] Chunmiao, Z., and G. Bennelt. 1995. *Applied Contaminant Transport Modeling: Theory and Practice*. New York: Van Nostrand Reinhold.
- [6] Mohamad, I. C., and M. R. Ramli. 2000. Groundwater Potential in Kampung Tekek and Kampung Juara, Pulau Tioman, Pahang. *The Regional Conference on Hydrology and Environment of Small Island*. Tioman Island. Malaysia.
- [7] Department of Environment. 1997. *Final Report, Groundwater Quality Monitoring Project*. Kuala Lumpur: Department of Environment.
- [8] Todd, D. K., and D. E. McNulty. 1976. *Polluted Groundwater*. New York: Water Information Center Inc.
- [9] Domenico, P. A., and F. W. Schwartz. 1998. *Physical and Chemical Hydrogeology (2<sup>nd</sup> ed)*. New York: John Wiley & Son Inc.
- [10] Waterloo Hydrogeologic Inc. 2000. *Visual MODFLOW User's Manual*. Canada: Waterloo Hydrogeologic Inc.
- [11] World Health Organization. 1985. *Guidelines For Drinking Water Quality Vol. 1-3*. Geneva: World Health Organization.