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Research Paper

Modeling for analyzing effects of groundwater pumping in Can Tho city, Vietnam

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ABSTRACT

In this study, the steady-state groundwater model in the study area, Can Tho city, a capital of Mekong Delta, was developed. To construct the numerical groundwater model for the Can Tho city, the concept and model boundary were set by hydrological data (model layers), digital elevation map (drainage and surface) and Mekong Delta region groundwater model results (groundwater head boundary). Investigation and compilation of data for the model input such as aquifer properties, hydraulic parameters and meteorological data were conducted and initially assigned to the model for a grid cell. The calibrated model successfully simulated groundwater heads comparing with observation heads at 14 monitoring wells. Simulation of spatial groundwater heads distribution of the aquifer includes groundwater pumping stations for domestic and industry was conducted as expected from the conceptual model. Its results clarified groundwater drawdown areas in the city. Impact zones of groundwater pumping are also addressed and known as vulnerable zones to land subsidence. Finally, to understand the effects of projected increased demands on groundwater for water supply, the model was used to predict the groundwater decline based on the trend of increased pumping until 2035. The formation process of cones of depression under current and increased pumping operation was also modelled in 3D to evaluate the impacts of dense distribution of pumping wells on groundwater resources in the Can Tho city.

Introduction

The Mekong Delta (MD) of Vietnam is one of the most vulnerable regions in the worlds especially under impacts of the climate change (Tuan et al., 2007). From the past networks in the MD. Unexceptionally, the study is in center of MD having accessed to water from Bassac river - one main branch of the Mekong River basin located (Fig. 1). The population rapidly growing in the study area cause of high water demand in recent years. In addition, wastewater until now, surface water has been used as the main water source of the living and production activities in the MD. For that reason, people can get access easily to the water at all canal and changing of hydrological regime have impacted on quality and quantity of surface water. Therefore, it could not meet for domestic use, the effective

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using of domestic and industrial supply which has been limited due to surface water quality degradation (Tuan et al., 2007). Since the last ten years, groundwater (GW) has considered as an option of fresh water use in the study area. The trend of GW use has strongly increased in the study area because its quantity and quality are more stable than surface water (Thomas, 2008). Because of its availability, GW is convenient resources to access for purposes of water usage. It has led to large-scale GW developments in the study area (IUCN, 2011). However, the GW drawdown phenomenon is clearly observed in the study area. It shows the drop-down at the observation wells in Can Tho city from 2000 to 2009 (DONRE, 2012), especially at the aquifer where the most of the depths of pumping wells are located. GW pumping can cause the cone of depression that may form the zones, where will be vulnerable to impacts of pumpage (USGS, 1997). These zones relate to the land subsidence issues, and they have been widely reported in some studies (Syvitski et al., 2009). Moreover, the land subsidence has also been recognized through primary studies in the urban areas of MD (Fujihara et al., 2015). It is necessary to find a proper modeling tool for GW assessment under pumping impacts in the study area, and it is very essential as a first step of. Moreover, since the GW potential of the aquifer underlying Mekong Delta has greatly unknown due to the lack of GW technical assessment (Boehmer et al., 2000; Phuc, 2008), there are some constraints for the effectiveness of sustainable GW planning (Vien, 2009). Development or application appropriate GW models in the study area will help analyze effects of GW abstraction and understand GW situation (Anderson et al., 1992) in scientific approaches for sustainable GW management in the future.

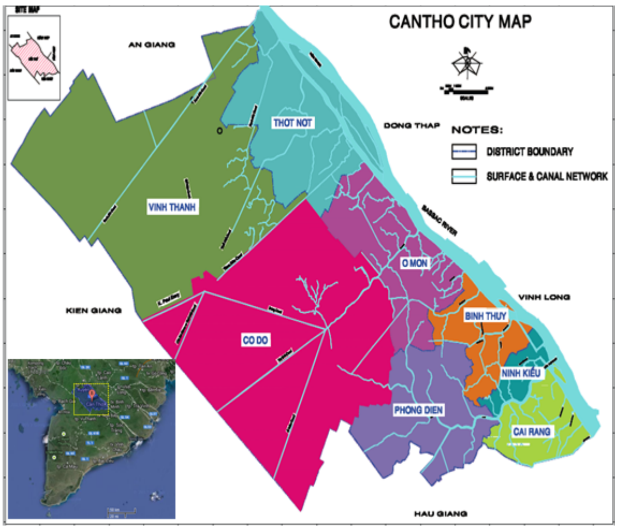

Fig. 1. Map of canals network in Can Tho city *(DOC, 2011)*

2. Model building

2.1 GW flow model

GW flow was simulated by using iMOD, a 3D finite difference GW modeling program. This software is developed by Deltares institution, Netherland. It has been used for dynamic GW flow simulation in the transient/ steady state. The iMOD is commonly constructed with available input parameters for regional scale GW flow modeling. The small-scale model with a smaller grid size should be integrated with a large-scale model by GIS processing (Vermeulen et al., 2013). The iMOD approach allows gathering the available input data to be stored at its finest available resolution. These data do not have to be clipped to any pre-defined area of interest or pre-processed to any model grid resolution. Resolutions of parameters can differ, and the distribution of the resolution of one parameter can also be heterogeneous. This approach also allows the modeler to interactively generate models of any sub-domain within the area covered by the data set. Moreover, it can be used for full three-dimensional modeling in a complicated hydro-geological property with various natural hydrological processes and artificial activities. In addition, to calculate the GW head distribution in space and time, iMOD can simulate the response of aquifer systems to different scenarios on GW resources. There are a wide range of useful packages such as rivers, abstraction wells and drainage. The user can also control the solution methods and procedures through a wide range of options. The software accepts various input formats of raster images, ARGIS geo-database, and shape files. There are several import options for borehole data and text formatted files.

2.2 Model equation

To develop a numerical model of an aquifer, the concepts and laws that control the physical process of the system should be translated into mathematical equations with partial differential equations. Model equation is derived by mathematically combining the water balance equation with Darcy's Law in three dimensions as following:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} - W \quad [1]$$

where x is the Cartesian spatial coordinate x, y, z; h = h(x,t) is hydraulic conductivity as a function of x, y, z; S_s is specific storage; W is source (negative for sink).

The model domain is discretized in space by sub-dividing the area into blocks/cells. The size of cells in x and y-direction are uniform over a row and over column, and are defined a varying spatial resolution for the model area. If the fluid density is constant, the water balance of a block/cell, expressed by sum of all flows into or out of a block and its changes in storage, represents the equation (Essink, 2000):

$$\sum Q_i = S_s \frac{\Delta\varphi}{\Delta t} \Delta V \qquad [2]$$

where S_s is specific storage of the porous material; Q_i is total flow rate in the block/cell; ΔV is volume of the block/cell; $\Delta\phi$ is change in head over a time interval of length Δt.

$$Q_{i,j-1/2,k} + Q_{i,j+1/2,k} + Q_{i-1/2,j,k} + Q_{i+1/2,j,k} + Q_{i,j,k-1/2} + Q_{i,j,k+1/2} + Q_{ext_{i,j,k}} = SS_{i,j,k} \frac{\phi^t_{i,j,k} - \phi^{t-\Delta t}_{i,j,k}}{\Delta t} \Delta V \qquad [3]$$

where $\phi^t_{i,j,k}$ - $\phi^{t-\Delta t}_{i,j,k}$ is backward difference approach which mean that $\Delta\phi/\Delta t$ is approximated over a time interval which extends backward in time from t.

2.3 Model structure

The construction of the GW flow model of the iMOD requires the definition of the conceptual model, the model domain with flow boundary conditions and the aquifer properties.

Conceptual model: the conceptual model approach involves the usage of the GIS tools to create the model of the site being modeled. The data are then assigned to the grid. To enable studying of GW potentiality in the study area, the conceptual model of iMOD has been constructed. It is based on the geology formation which was defined by borehole data provided by Vietnam South Division for Water Resources Planning and Investigation (DWRPIS, 2009) to create hydrogeological profiles.

MD region is characterized by the presence of alluvial aquifer and aquifer sediments (Anderson, 1978) which are represented by borehole wells test data. Therefore, total of 5 hydrogeological cross-section profiles was set by connecting corresponding interfaces between the boreholes. Based on those constructed profiles, aquifer layers were interpolated by Kriging method.

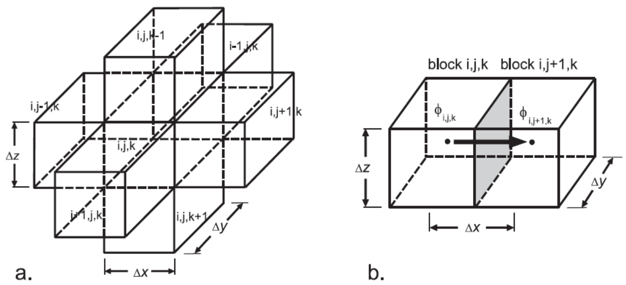

Fig. 2 Block [i,j,k] with the surrounding blocks (a); flow between block [i,j,k] and [i,j+1,k] (b) (Essink, 2000)

Applying equation above to block [i,j,k] taking into account the flows from the six adjacent blocks, see Fig. 2, as well as an external flow rate Q_{ext} (pumpage) yields:

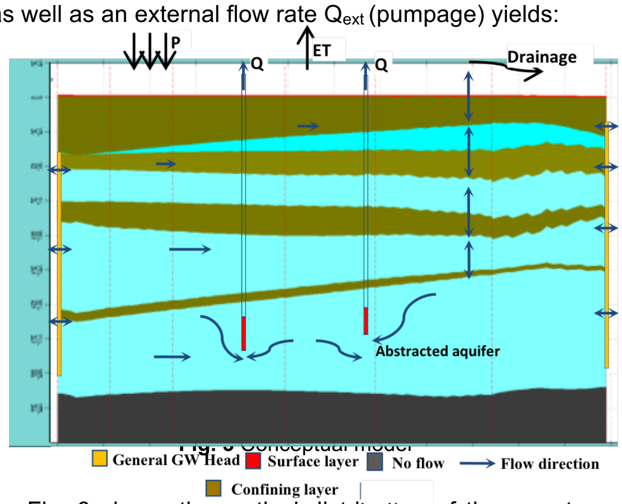

Fig. 3 Conceptual model

Fig. 3 shows the vertical distribution of these water-bearing layers in relation to surface level. The confining layers represent largely low hydraulic conductivity units, such as clay and split that impede the flow of water between aquifers whereas the aquifer layers are termed aquifers because they have physical properties that allow for the storage and flow of water between the grains of sediment.

Model domain: the simulation procedure was started by dividing the iMOD domain into a suitable grid pattern on which all the input items are performed via input menus. The total surface area of the model domain reaches 5760 km^2. The computational grid for the aquifer domain in the study area is divided into 576054 cells. The dimension of the cell nodes reaches 100 m for the cultivated and reclaimed areas (Fig. 4).

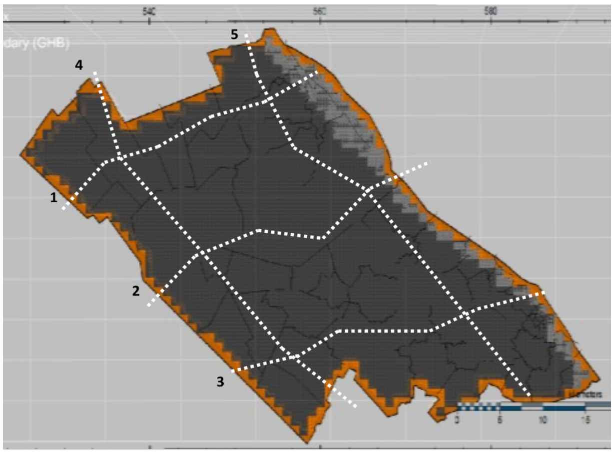

Fig. 4 The model domain grid and the boundary conditions

Boundary conditions: for calculating GW flow in the aquifers of a region, conditions at the study area's boundaries must be given. In this model, the boundary conditions are defined: (i) specified head represents the area that can be impacted by pumping; (ii) head dependent flux represents the surface water area for the Bassac River and (iii) general GW head boundary (GHB) represents the boundary along the edges of the model domain. Because the entire MD has been simulated on a coarse scale of 1000 m x 1000 m, by a simulation network of 308 columns and 410 rows in iMOD, and the layout of the 33 sub-models primarily developed to create a final model result for the entire MD at a scale of 100 m x 100 m (Fig. 5). Those values were initially set for the GHB cells. This value was adjusted during calibration.

Initial GW head distribution: GW level measurements through 14 observation wells in model domain during January, 2009 were used to construct a contour map for the initial GW head distribution. Therefore, all subsequent simulations were started from January 2009 heads as the initial condition. Compilation of comprehensive GW head data in the study area began at that time.

Drainage and surface level were analyzed based on digital elevation map (DEM) optimization with resolution of 90 m x 90 m which was applied to extract the existing drainage features and to evaluate the head of surface water bodies provided by College of Environment and Natural Resources (CENRes), Can Tho University. Furthermore, this resulted flow direction operations which follow the existing drainage pattern with corrected DEM in which existing drainage feature are more pronounced. Because the DEM scales in 90 m x 90 m resolution whereas the model has 100 m x 100 m resolution, the adjusted irregularly spaced point data were interpolated with 100 m x 100 m and converted into ASCII file for iMOD's input. It has been used to update the top of the hydrological system as well as the drainage levels throughout the study area.

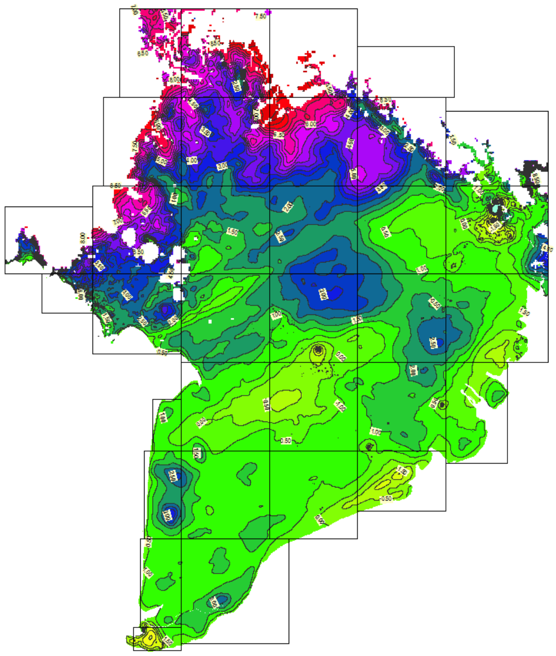

Fig. 5 Simulated phreatic heads for sub-models at grid size of 100 m x 100 m (Vermeulen et al., 2013)

2.4 Model input

Hydraulic parameters were determined by aquifer pumping test conducted by DWRPIS and Haskoning Company in 2000 for all layers. Evaluation of aquifer properties is based on the pumping test analysis which is given on Table 1. These determine how easily water moves through the aquifer, how much water is stored, and how efficiently the well produces water. Aquifer properties were addressed by the results of pumping test data at ten locations in the study area. The analyses were obtained as mathematical solution of Theis, Cooper Jacob straight line and recovery methods. For the model input, the parameter to be estimated and distributed across the model grid is either transmissivity or hydraulic conductivity which are constant within a given grid cell. The corresponded hydraulic parameters are interpolated and preliminarily categorized into zones by mapping. These zones will be optimized during calibration process.

Table 1. Hydraulic parameters from pumping test for aquifers in the study area

ID	Coordinates			Aquifer (m)			KD (m^2/d)	C (day)	S	C*S (day)
	x (m)	y (m)	z (m)	From (m)	To (m)	D (m)				
860-CT	1106561.00	589306.00	2.000	66.0	91.0	25.0	529.0	22.9	0.00843	0.1930
861-CT	1104608.90	578867.90	1.400	81.0	105.0	24.0	755.0	179.0	0.00148	0.2649
862-CT	1108200.00	575970.00	0.900	79.0	99.0	20.0	896.0	464.0	0.00104	0.4826
863-CT	1111136.00	571326.73	1.210	113.0	140.0	27.0	369.0	471.0	0.00143	0.6735
864-CT	1117683.56	568581.52	1.740	82.0	100.0	18.0	4949.0	231.0	0.00200	0.4620
866-CT	1106368.32	584397.47	1.450	88.0	112.0	24.0	911.0	38.4	0.00183	0.0703
867-CT	1107619.85	585211.16	3.300	69.0	112.3	43.3	844.0	35.0	0.00194	0.0679
868-CT	1109116.25	585597.66	3.900	97.0	122.0	25.0	844.0	18.3	0.00211	0.0386
869-CT	1111525.00	584335.00	2.200	128.0	148.0	20.0	120.0	2.9	0.00199	0.0057
871-CT	1116109.10	578733.10	0.950	127.0	146.0	19.0	1800.0	confined		

Rainfall is the main recharge of shallow or unconfined aquifer. The rainfall data of rain gauge stations have been collected and analyzed. The mean annual precipitation has a bimodal distribution with most of rainfall occurring during rainy season from May to November. Generally the entire city receives an annual average rainfall depth which has decreased in recent five years (2008 - 2012), from 1230 mm to 1530 mm (DONRE, 2012). Interpolation techniques, ordinary Kriging method and the empirical relationship between the elevation (i.e. DEM) and the rainfall were applied to study the spatial distribution of the rainfall within the model area.

Evaporation describes the water loss of shallow GW that will occur under a given climatic condition. Recent research has demonstrated that evaporation of GW can play a significant role in the local water cycle, especially in dry season (Korkmaz, 1988). Evaporation data were collected from meteorological station located in the city. The trend of evaporation has been increasing in recent 10 years, which is in particular that the highest evaporation is reported during the months of February and March, and the lowest one is in Septembers and Octobers (DONRE, 2012). This value is calculated by input data of the evaporation coverage and the depth to the GW level estimated by iMOD during the period of running the model. The input data include: (i) the potential ET value per cell, for which the average open pan evaporation (ETO) was assumed; (ii) The extinction depth of evaporation of GW, which was assumed at 3-meter depth below the surface; and (iii) The surface elevation, which is the same as top elevation of the first layer in the GW model and is therefore imported in the evaporation package of the iMOD module per grid cell.

2.5 Model calibration and sensitivity analysis

Proper model calibration is important in hydrologic modeling studies to reduce uncertainty in model simulation (Engel et al., 2007). Measured GW levels collected on January, 2009; May, 2010 and December, 2011 were used to calibrate for the current condition. In this study, steady-state calibration for the current condition was conducted through a trial and error process, in which the initial estimates of the aquifer system were iteratively adjusted over reasonable ranges to improve the match between simulated and observed GW levels. Measured and calculated GW heads of 14 observation wells in the study area served as calibration targets for the model. There are basically two methods of model calibration: trial and error adjustment and automated parameter optimization (Anderson et al., 1992). Generally in GW modeling, root mean square error (RMSE) value reflects accuracy of model through the difference between measured and calculated GW heads. Ideally, RMSE of model-calculated GW heads at calibration points should be less than 10%, and Nash-Sutcliffe's coefficient of efficiency should be around 0.75:1 for a good model (Lutz et al., 2007). In order to obtain the acceptance model, calibration was carried out based on adjusting: (i) GHB value and (ii) hydraulic conductivity and storage coefficient.

The primary changes made to hydraulic parameters (K, S) during calibration were adjustments to values assigned to individual K and S zones, rather than adjustments to the spatial sizes and shapes of the zones. Through the calibration process, as these initial values were found not to give appropriate results, the hydraulic parameter values were optimized to obtain good agreement on GW head distribution; Fig. 6 shows the results of the optimized K and S zones for abstracted aquifer.

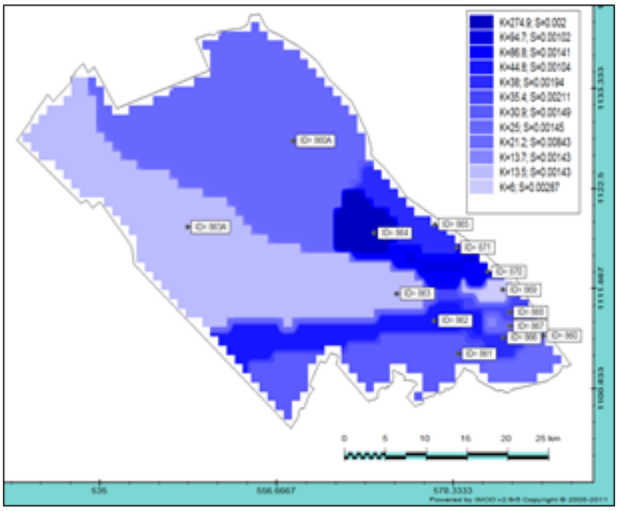

Fig. 6 Results of the optimized hydraulic parameter zones

Model calibration results were qualitatively evaluated by comparing contoured maps of calibration target GW levels to the GW head observations. The errors in the simulation heads were also quantified by determining the RMSE, MAE for the model residuals (target head - model head). During model evaluation steps, simulated heads are slightly greater than observed heads on average. However, the calibration for GW levels falls within acceptance ranges, that is, RMSE is about 0.21 m and less than 10 percent (average for 14 observation wells). The simulated steady-state heads had a mean residual of 0.17 m. The high value of Nash-Sutcliffe's coefficient of efficiency (0.92-0.94) between simulated and observed heads indicates that the calibrated model can be accepted as a good GW model of the study area (Table 2 and Fig. 7).

Table 2 Model calibration and evaluation results

Wells	Jan,2009			May, 2010			Dec, 2011		
	Observed Head (maSL)	Calculated Head (maSL)	Residual (m)	Observed Head (maSL)	Calculated Head (maSL)	Residual (m)	Observed Head (maSL)	Calculated Head (maSL)	Residual (m)
QT11A	-4.28	-4.38	-0.1	-5.03	-5.07	-0.04	-4.94	-5.14	-0.2
BS01A	-5.46	-5.32	0.14	-6.03	-6.21	-0.18	-5.69	-6.02	-0.33
QT12A	-5.31	-5.31	0	-5.97	-6.06	-0.09	-5.41	-5.79	-0.38
BS02A	-5.53	-5.73	-0.2	-6.36	-6.52	-0.16	-6.29	-6.23	0.06
QT09A	-5.41	-5.67	-0.26	-6.38	-6.40	-0.02	-5.94	-6.15	-0.21
QT16A	-6.84	-6.61	0.23	-7.57	-7.45	0.12	-7.81	-7.96	-0.15
BS04A	-6.60	-6.95	-0.35	-7.29	-7.39	-0.10	-6.89	-6.54	0.35
QT06A	-5.08	-5.28	-0.2	-5.64	-5.78	-0.14	-5.49	-5.42	0.07
BS03A	-6.21	-6.07	0.14	-6.98	-6.96	0.02	-6.34	-6.46	-0.12
BS06A	-6.46	-6.87	-0.41	-6.48	-6.94	-0.46	-4.63	-4.49	0.14
BS05A	-6.46	-6.57	-0.11	-6.97	-6.52	0.45	-4.87	-4.97	-0.1
QT10A	-5.24	-5.12	0.12	-5.92	-5.96	-0.04	-4.62	-4.81	-0.19
QT18A	-4.90	-5.06	-0.16	-5.64	-5.88	-0.24	-5.86	-6.09	-0.23
QT17A	-5.24	-5.08	0.16	-5.64	-5.78	-0.14	-5.42	-5.49	-0.07
	RMSE = 3.72 %; MAE= 0.18 m; NSE = 0.92			RMSE = 3.32 %; MAE= 0.16 m; NSE = 0.94			RMSE = 3.7 %; MAE= 0.18 m; NSE = 0.94		

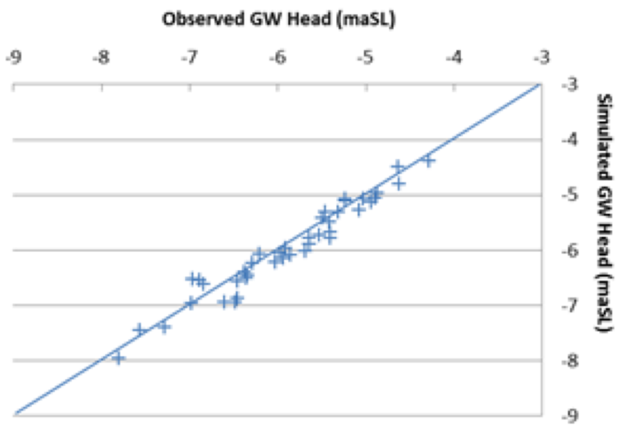

Fig. 7 Comparison of simulated vs. observed head: steady state

The purpose of sensitivity analysis is to observe the model response to the variation in GHB and hydraulic conductivity. Sensitivity of the model was evaluated by RMSE after multiplying each parameter a time by 0.4 to 1.6 of the initial value and model's run-file. The RMSE related to each run were plotted gains the multiplying factor. As the results, in case of the changes in factor of hydraulic conductivity, RMSE responses were less than the changes in factor applied to GHB cell values. The GHB was shown to be higher sensitive parameter than hydraulic conductivity (Fig. 8).

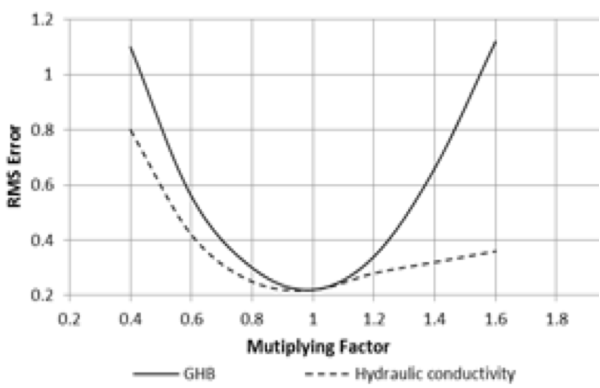

Fig. 8 Sensitivity analysis

3. Model simulation

3.1 Simulation of current pumping

GW pumping

The investigation on wells distribution was conducted in 2011, and it revealed that high capacity extraction wells are centralized domestic water supply stations and industrial water supply stations, whereas the low capacity extraction ones belong to households. The observed data in the past ten years indicated a significant trend of lowering of GW levels, especially in Pleistocene aquifers (abstracted aquifers). According to the result of hydrological profiles, the Pleistocene aquifer is distributed at the depth of 100m to 250m where pumping wells are located. Centralized domestic water supply stations are mainly located at following districts: Binh Thuy, Cai Rang, Co Do, O Mon, Phong Dien, Thot Not, Thoi Lai and Vinh Thanh. Based on collected data from Center for Water Supply and Environmental Sanitation of Can Tho city (CWSES), the result of demand of GW was analyzed and synthesized. The chart in Fig. 9 shows GW exploitation for domestic use which has been increased year by year. It shows the highest GW demand in Thot Not district.

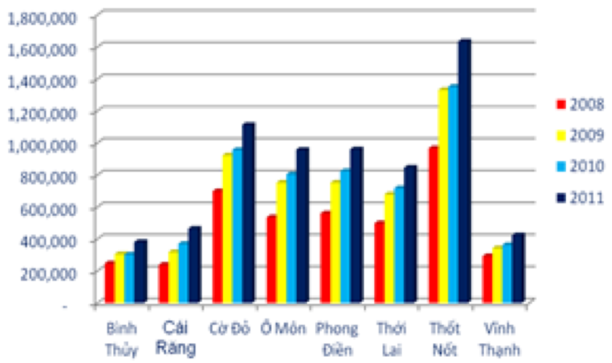

Fig. 9 GW demand for centralized domestic water supply

In recent years, industry has been promoted and expanded in Can Tho city. There are three industrial zones in Can Tho: Tra Noc 1, Tra Noc 2 and Thot Not. Tra Noc industrial zone has officially operated since 1990 and is fully covered by factories at the present. Water supply sources for industrial production are rivers and GW. However, in order to meet high quality requirement of production, most factories use GW for production processes. The capacity of exploitation wells is very high; 50 - 100 m^3/h; and trend of GW demand has increased year by year (Fig. 10).

The well package of model input is designed for outflow through pumping wells. Most of them are equipped with electric pumps, and their coordination was examined by DWRPIS.

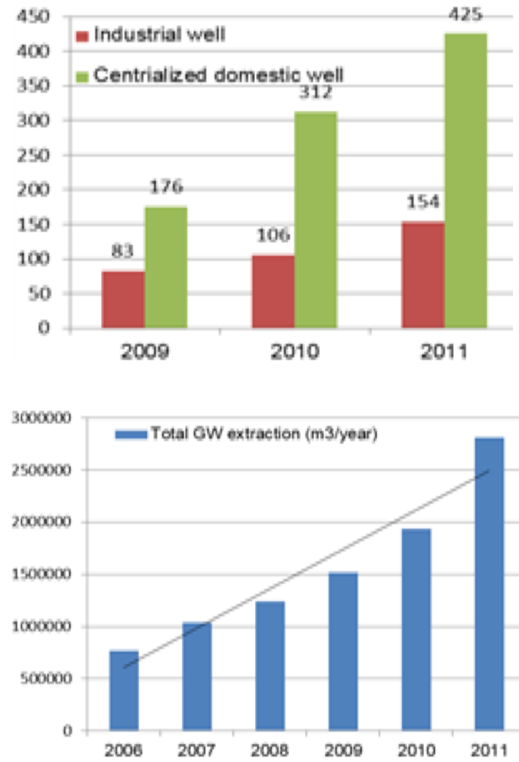

Fig. 10 GW demand for industry and GW abstraction well development

Pumping parameters such as depth, capacity and pumped schedule were provided by CWSES and Industrial Zone Agency (IZA). In order to estimate the amount of pumping in reality, 30 typical wells were investigated and measured in 2011. Such data of each abstraction well such as ID, coordination, depth and pumping capacity obtained by the above investigation was handled by the well package for model input. Each well was designated with its properties on cell basis in the model grid. All abstraction wells were assigned into model domain by programing (Fig. 11).

Simulation results

Fig. 12 shows the simulation of the spatial distribution of the simulated heads (100 m x 100 m) at the abstracted aquifer (100 m to 250 m). The comparison between the simulated and observed heads is presented with GW drawdown areas of decline coincident with the wells serving in the 14 observation points (Fig. 13). The results show visualized movement of GW heads and aquifer responses under current pumping in Can Tho city. Generally, 1/2 area of the abstracted aquifer in the city is affected by pumping. If the growing pumping is maintained in the future, this area will be larger than it is in current situation.

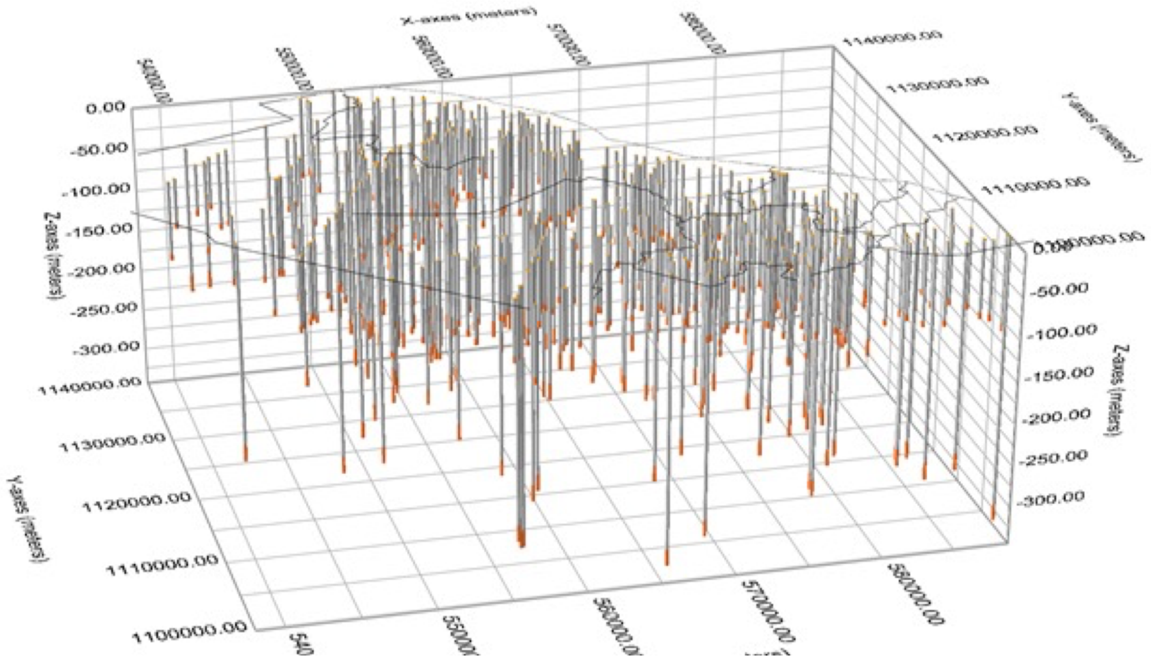

Fig. 11 Current distribution of pumping wells in Can Tho city

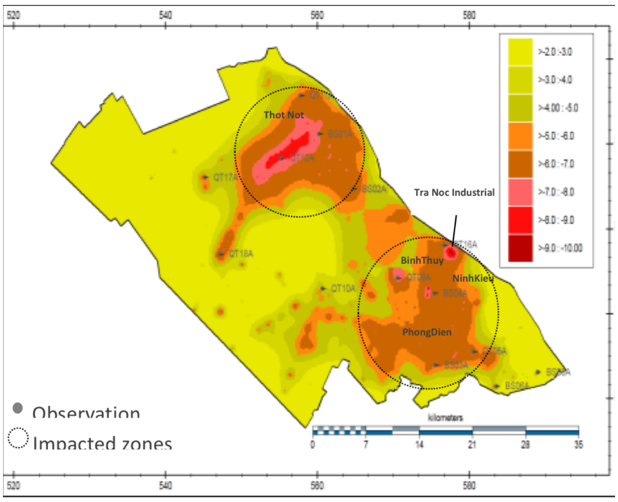

Fig. 12 Simulated map of spatial GW heads (maSL)

The land subsidence occurs when porous formations that once held water collapse, which results in the surface layer settling. This may occurs where the city was built on unconsolidated land such as Mekong Delta. The excessive GW pumping may cause a significant increase in land subsidence rates in the city that exceed the rate of sea level rise (Fujihara et al., 2015). Based on simulation results, two zones of GW drawdown are developed in a part of: Thot Not, Binh Thuy, Ninh Kieu and Phong Dien by GW pumping. These zones may be known as vulnerable zones to the land subsidence. The land subsidence rates are also highly relevant to GW drawdown rates, and it is one of factors that contribute to water level rise and flood magnitude, resulting in inundations that have been severe in the city, especially in Tra Noc industrial zone (Binh Thuy) and the urban zone (Ninh Kieu). Fig 12 shows the extended trend of the area of GW drawdown for these zones that may occur in South and West side of the city.

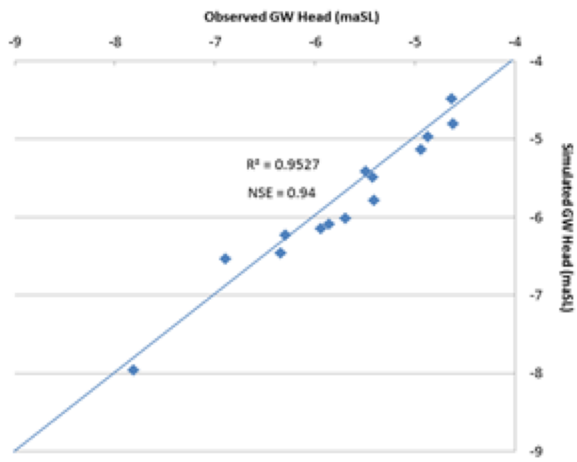

Fig. 13 Comparison of simulated vs. observed GW drawdown by current pumping

3.2 Predicted effects of increased pumping

Because assessment tools such as a decision support system are still limited, there are some constraints for local government to project GW resources planning. Therefore, GW management frameworks are carried out just on experience basis (IUCN 2011). However, to meet the increased water demand in the future, CWSES projected that the distribution net of GW supply stations will be extended, which means the amount of pumping will increase.

Based on the current trend of GW use provided by CWSES, this simulation assumed that the increasing pumping by approximately 100 percent in 2035. Moreover, because the city government recommends to limit GW use of industrial water supply in the future, the projected increased demands on GW for the industry will be 50 percent in 2035.

Therefore, to understand how this increased pumping may affect GW flow, we assumed that this increased demand will be supplied by existing wells (Fig. 11), and we also simulated the increased water demand by increasing concurrently the pumping rate for all centralized domestic water supply station by 100 percent and industrial supply by 50 percent. Because it is certain that new wells will be installed to meet the increased demand, and because the locations of these new wells cannot be predicted, the results are highly speculative. The simulation of spatial GW heads under current pumping (Fig. 12) will be assigned to initial conditions for the predicted effects of increased pumping. GHB conditions for the city boundary did not change for this simulation.

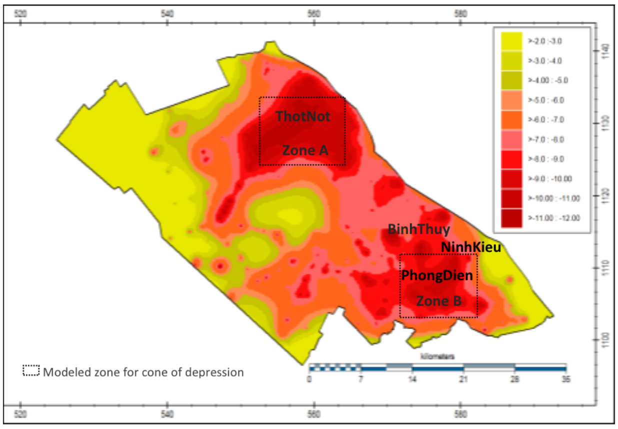

Fig. 14 Model computed heads for the aquifer under increased pumping in 2035

The effects of increased pumping make additional areas of GW decline in the city, resulting in 2/3 area of city aquifer which was impacted by pumping (Fig. 14). Comparing predicted water levels during increased pumping with those levels at current pumping results, we find that the average head decline in the city aquifer will be approximately 2.0 meters (Fig. 12 & Fig. 14). The maximum head decline which occurs at Thot Not and Phong Dien is around 4 to 5 meters and around 3 to 4 meters respectively (Fig. 15). The effects of increased pumping in the Can Tho city aquifers indicate maximum additional drawdown to be in the range of a few meters.

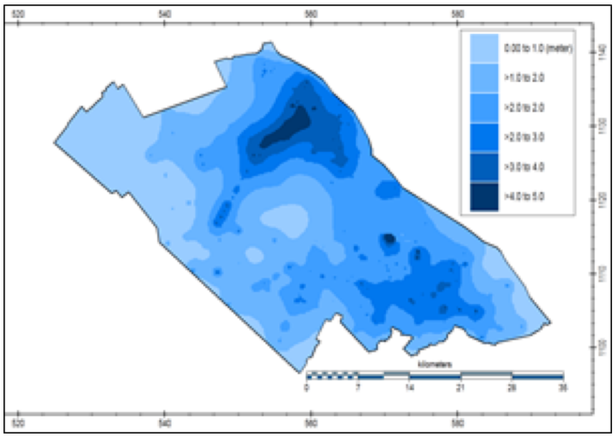

Fig. 15 Predicted differences in GW heads between current and increased pumping

To figure out why the strong GW drawdown and the highest decline occurs in Thot Not and Phong Dien, the 3D-simulation of zone A and zone B (Fig. 14) were conducted under current and increased pumping. The visualized simulation of 3D in Fig. 16 points out the cones of depression which have been developed by the impact of densest abstracted wells in these zones. There are the correlation between drawdown magnitude and pumping wells distribution. The results imply that wells distribution has been inappropriately planned, which means that distance of pumping wells is quite close. Therefore, the cones of depression are overlapped, which makes the highest decline of GW and changing of the direction GW flow into South-West side of the city (Fig. 16). The interference will reduce the water available to each well and well interference can be a problem when many wells are competing for the water of the same aquifer, particularly at the same depth.

The new wells will likely to be installed by water utilities at additional locations. Therefore, their locations should be planned. In order to evaluate how reasonable distances of these wells are, the model can be used for illustrative and discussion purposes to reach wells planning purposes.

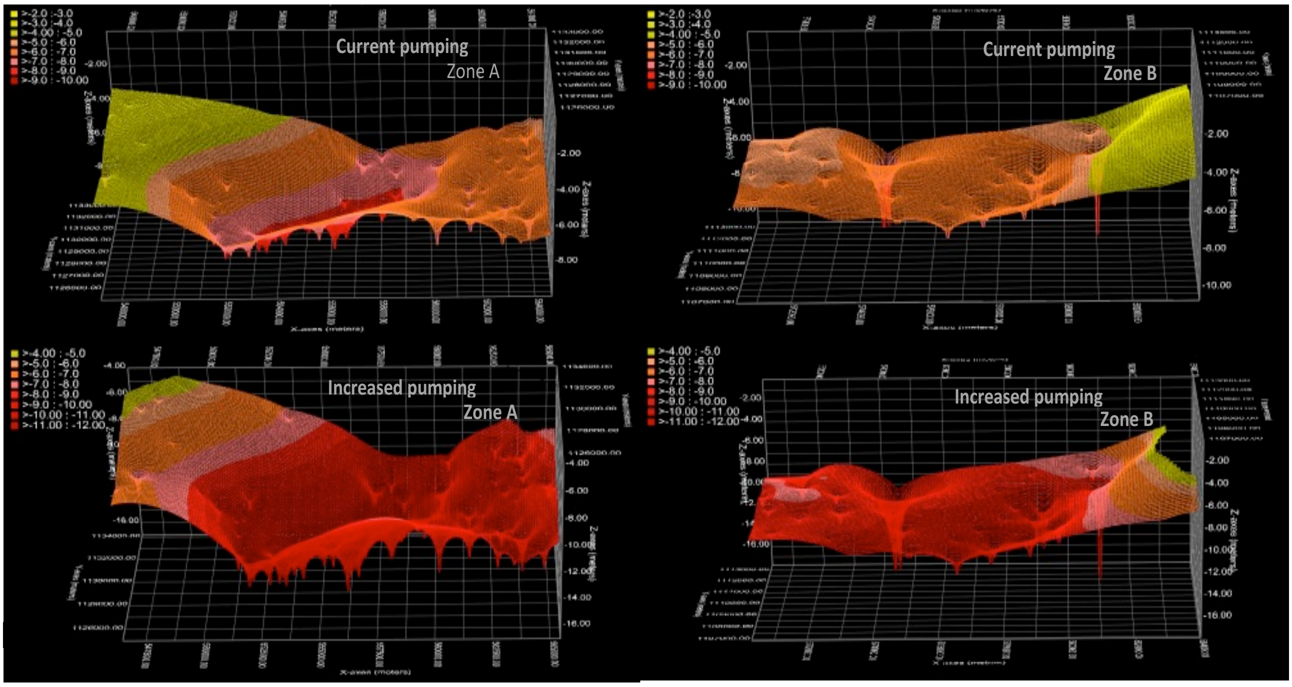

Fig. 16 Formed cones of depression 3D-simulation between current and increased pumping

4. Conclusions

GW is a critical source of water in Can Tho city. It supports human economic activities such as domestic and industrial water supplies as well as sustains aquatic ecological systems. GW simulations performed by numerical models are now the state of the practice for professional and research assessments of GW availability and determination of sustainable water use for the city. To construct the numerical model, the grid setting of hydrogeology profiles, DEM and GW head boundary were conducted by compilation and data analysis. The calibrated GW model flow for the Can Tho city successfully simulated GW heads comparing with observation heads. It was confirmed that the established model can work properly to evaluate the human or natural impacts.

As expected from conceptual model, the simulation of spatial GW heads distribution of the aquifer including current GW pumping stations for domestic and industry clarified the areas GW decline in the city. These areas are also addressed and known as vulnerable zones to the land subsidence. Moreover, because GW has been under increasing pressure of population growth, high water demand for productions will threaten to undermine its sustainable use. Therefore, to understand the effects of projected increased demands on GW for water supply in 2035, the model was used to predict the GW decline. The areas of GW decline are significantly increased by projected pumping. These areas may be relevant to potential issues in the future.

The formation for the cones of depression under current and increased pumping operation was also modeled in 3D to point out the impacts of dense distribution of pumping wells. The tool can be used for illustrative and discussion purposes to optimize new wells distance and distribution in the future.

Generally, the model is conducted as the first assessment tool for GW resources in the Can Tho city. Its results allow the stakeholders to evaluate how well their interests would fare in terms of the available GW resources. People are able to see which areas may be more vulnerable to GW exhaustion and its process under the pumping impact. The Water Authority and the conservation groups are more interested in how modeling outputs represent a potential aquifer recovery.

However, model predictions are only as good as the information used to construct and calibrate models. In this regard, there are several improvements to numerical models that could make results more useful for water management. There are very few pumping tests and borehole structure data which have been made. The analyses on these data indicate that the up-middle aquifer may not be a fully confined system, and it may be connected between the upper and lower aquifers. To clarify the details of the geo-structures to know the connectivity, detailed reliable drilling records and pumping test data should be required to enhance the information of the aquifer system including the connectivity and its behavior. Another possible source of inaccuracies is related to such input data such as estimates of pumping. GW pumping rates used in this model are averages computed from incomplete water-use records. These data are inadequate for future work that simulates transient responses of aquifers to seasonal and annual changes in climate and pumping. Accurate and complete water pumping records for large capacity water wells are needed to allow any model to simulate field conditions of head and flow.

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References

Anderson, H.R. (1978): Hydrogeologic reconnaissance of the Mekong Delta in South Vietnam and Cambodia. USGS Water Supply Paper: 1608-R

Anderson, M.P., and Woessner, W.W. (1992): Applied groundwater modelling, CA, Academic Press, 20-256.

Boehmer, W. (2000): Groundwater study Mekong Delta - Modelling report, HAS KONING B. V. Consulting Engineers and Architects, in association with Division of Hydro-Geology and Engineering Geology for the South of Vietnam and ARCADIS Euroconsult: 136.

DONRE (2011): Annual report of natural resource and environment, Department of Natural Resources and Environment for Can Tho city, 23-80 (in Vietnamese).

DWRPIS (2009): Research of geological structure and classification of N-Q sediments in Mekong Delta, Division for Water Resources Planning and Investigation for the South of Vietnam, 24-86 (in Vietnamese)

Engel, B., Storm, D., White, M., and Arnold, J.G. (2007): A hydrologic/water quality model application protocol, Journal of American Water Resources Association, 72-80.

Essink, O. (2000): Groundwater modeling. Utrecht University Press, The Netherland, 134–138.

Fujihara, Y., Hoshikawa, K., Fujii, H., Kotera, A., Nagano, T., and Yokoyama, S. (2015): Analysis and attribution of trends in water levels in the Vietnamese Mekong Delta, Hydrological processes, **30(6)** 835–845.

IUCN (2012): Groundwater in the Mekong Delta, Discussion paper. International Union for Conservation of Nature.

Korkmaz, N. (1988): The estimation of groundwater recharge from water level and precipitation data, Journal of Islamic Academy of Sciences, **1(2)** 67–93.

Phuc, D.D. (2008): General on groundwater resources in Vietnam, ADB-TA-4903 VIE, 51–65.

Syvitski J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G. R. Brakenridge, John Day, Charles Vörösmarty, Y. Saito, L. Giosan, and R. J. Nicholls (2009): Sinking deltas due to human activities, Nature Geoscience, **2:** 681–686.

Thomas, N., and Harro, S. (2008): Challenges of the groundwater management in the Can Tho city Viet nam, BGR-Symposium: Sanitation and Groundwater Protection, Conference proceeding, 110–172.

Tuan, L.A., Hoanh, C.T., Miller, F., and Sinh, B.T. (2007): Chapter 1: Flood and salinity management in the Mekong Delta, Challenges to sustainable development in the Mekong Delta: Regional and national policy issues and research needs, 6–25.

USGS - United State Geological Survey (1997): Model-ling groundwater flow with MODFLOW and related programs, USGS Fact Sheet FS-121-97.

Vermeulen, P.T.M., Quan, N.H., Nam, N.D.G., Hung, P.V., Tung, N.T., Thanh, T.V., and Rien, D. (2013): Groundwater modelling for the Mekong Delta using iMOD, 20th International congress on modelling and simulation, Australia, 2499–2505.

Vien, D.V. (2009): Strongly degradation of groundwater in Mekong Delta, VOV online report (in Vietnamese).

Symbols and abbreviations

CENRes	College of Environment & Natural Resources
CWSES	Center for Water Supply and Environmental Sanitation of Can Tho city
DEM	digital elevation map
DONRE	Can Tho's Department of Natural Resources and Environment
DWRPIS	Division for Water Resources Planning and Investigation for the South of Vietnam
ET	evapotranspiration
ET_O	open pan evapotranspiration
GHB	groundwater head boundary
GW	groundwater
IUCN	International Union for Conservation of Nature
IZA	Industrial Zone Agency
MAE	Process Simulation Analyst
MD	Mekong delta
RMSE	Root Mean Squared Error
USGS	United State Geological Survey