INTEGRATED SWAT-MODFLOW MODEL TO STUDY SALTWATER INTRUSION IN DA NANG COASTAL CITY

Nguyen Bach Thao[1,*], **Thi Van Le Khoa**[2]

[1] *Hanoi University of Mining and Geology*
[2] *Hanoi University of Natural Resources and Environment*

Abstract

This study applied an integrated surface water-groundwater (SW-GW) model, SWAT-MODFLOW to study interaction of surface and groundwater than simulate saltwater intrusion at a regional scale in Da Nang coastal city. Model components were calibrated and validated using monthly river flow data and hydraulic head data for the 2005-2020 period and showed good agreement with observed data. The results demonstrated that GW-SW exchange in the upstream areas had the most pronounced fluctuation between the wet and dry months under historical conditions. The combined potential impact is that intensive groundwater use may have more immediate effects on river flow than those of climate change, which has important implications for water resources management and supply in the future. The results showed that the total average recharge to groundwater from the rivers was varied from 12046 to 23147 m^3/d relative to 50 - 74% of water resources in rain and dry season. Saltwater intrusion intrusion in 2020 is about 100km^2. The area of Son Tra and Ngu Hanh Son districts, groundwater pumping must be reduced to zero, in some other areas, pumping rate do not exceed 250 to 1000 m^3/day with distance to coastline at least 500 to 1400m depends on each area.

Keywords: *surface water, groundwater, SWAT, MODFLOW, Da Nang, saltwater intrusion*

1. Introduction

These days, water scarcity and saltwater intrusion is a widespread problem around the world. Water availability becomes a matter of interest in everywhere, especially in arid or semiarid areas. Traditionally, management of water resources has concentrated on surface water or ground water as if they were separate entities (Winter et al., 1998). However, surface water and ground water are not separate components in the hydrological cycle (Dowlatabadi et al., 2015). In Vietnam, water resources management has mainly focus on the surface water (Chau and Khanh, 2017, Au et al., 2013; Phung et al., 2014), while problems related to groundwater have not been managed in a rigorous manner. In most of the studies have been done, modelling is the most suitable method for simulating surface and groundwater availability.

The Soil and Water Assessment Tool (SWAT) and MODFLOW are 2 well-known and widely used surface and groundwater models, respectively. These two models represent two different environments, and each is limited in its simulation domain with their corresponding strong points and drawbacks. In one side, SWAT is a basin scale, semi-distributed model and is often used to simulate hydrological processes in surface and in shallow aquifer. Its calculation is based on hydrological response units (HRUs), which are conceptual units of homogeneous land use, management, slope,

* *Ngày nhận bài: 01/3/2022; Ngày phản biện: 01/4/2022; Ngày chấp nhận đăng: 10/4/2022*
* *Tác giả liên hệ:Email: nguyenbachthao@humg.edu.vn*

and soil characteristics that extend below the surface to a soil profile depth (Arnold et al., 1998). SWAT model can only simulate shallow ground water flow in a restricted layer, around 6 m below ground surface, in which the seepage below it is assumed to be lost and out of the system (Neitsh et al., 2011). In the other side, MODFLOW presents as a three-dimensional, distributed finite-difference ground water model and it can simulate ground water flow for variably saturated subsurface systems including shallow and deep aquifers. However, the model is limited to investigating ground water-surface interaction, as it cannot simulate surface process. On the other words, the ground water model was not adequately linked to surface water model (Anh et al., 2009; Hiep et al., 2012; Quynh et al., 2014). In those study, ground water recharge, an important input for ground water model, could not be calculated from hydrological components, which are precipitation, evapotranspiration and surface runoff, however it was determined through trial-and-error method during calibration process.

In recent decades, there were some conjunctive simulations of surface water and ground water using SWAT and MODFLOW (Putthividya et al., 2017; Kim et al., 2008; Guzman et al., 2015; Dowlatabadi et al., 2015). In those studies, there were several methods to integrate SWAT and MODFLOW, however the integration through recharge rate between HRUs in SWAT and cells in MODFLOW is the most feasible method. Those studies were successful in evaluation of water availability in various regions of the world and became a useful data to support the water management policy.

Da Nang is a large coastal city in central Vietnam with 74km of coastline, plays an important role in tourism, industrial production and agriculture with a population density of 828 people/km^2 (statistics 4. 2019). Therefore, Da Nang city always faces problems such as insufficient water to meet demand due to overexploitation causing depletion, water pollution and especially saltwater intrusion. Da Nang city has a long coastline, so the aquifers in this area are greatly affected by the saltwater intrusion process, however, there is no work to evaluate saline intrusion using numerical models. Based on the results of survey to establish hydrogeological map of Da Nang city (Central Union for Planning and Investigation of Water Resources, 2012), about 30% of aquifers area is affected by salinity out of total area (Nguyen, 2018). Therefore, it is very urgent to assess the status of saline intrusion into the ground and propose a reasonable exploitation solution. The article uses the method of combining surface water model and underground water model to assess the status of groundwater salinity intrusion in Da Nang area, the model correction is based on the results of water level measurement, total mineralization at the boreholes, thereby providing a reasonable mining solution.

2. SWAT, MODFLOW and their integrated structure

2.1. SWAT model

Soil & Water Assessment Tool (SWAT) is a continuous-time, semi-distributed, process-based rainfall-runoff model (Valentina Krysanova & Jeffrey G. Arnold, 2008). As its name implies, SWAT was developed to simulate the water resource system and assess the impacts of single or multiple changes triggered by natural or human-induced factor to both water quantity and quality.

SWAT is the result of various efforts. In 1980, Knisel developed a model called CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) to simulate the non-point sources. Later, several new models were developed based on CREAMS such as EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984) or GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987). While EPIC was launched to evaluate the efficiency of agricultural practices and non-point source pollutions, GLEAMS demonstrated the ability to assess pesticides and nutrients to groundwater (Valentina Krysanova & Jeffrey G. Arnold, 2008).

Also, in 1987, Arnold & Williams introduced the model SWRRB (Simulator for Water Resources in Rural Basins). Their idea of dividing a large watershed into sub-basins became a highlight of SWAT later on. The SWRRB was upgraded from CREAMS, EPIC and GLEAMS aiming to understand the impacts of management practices on water and sediment transport in poor data river basins.

In the early 1990s, the SWAT model officially came into being after undergoing a merger between ROTO (Routing Outputs to Outlet) (Arnold et al., 1995) and a GRASS (Geographic Resources Analysis Support System) GIS interface (Srinivasan. & Arnold, 1994) and SWRRB. Subsequently, then there is a series of reviews and upgrades. And there were even a number of other versions of SWAT models, tailored for specific goals and different data formats.

SWAT calculates the water balance for each Hydrologic Response Units (HRUs) by basing on the following equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw}\right)_i \tag{1}$$

Where SW_t is the final soil water content at time t (mm), SW_o is the initial soil water content (mm), Rday is precipitation in day i (mm), Q_{surf} is the amount of surface runoff in day i (mm), Ea is the amount of return flow in day i (mm), Q_{seep} is the amount of water entering the vadose zone from soil profile in day i (mm) and Q_{qw} is the amount of return flow in day i (mm)

The inputs required by the SWAT model are topography, land use map, soil map and weather data. The SRTM 1 Arc-Second (30 meter) Global elevation data offered by the United States Geological Survey (USGS), 0.5 km MODIS-based Global Land Cover Climatology, the FAO-UNESCO Soil Map of the World, and the ground-truth meteorological data of the stations located in the study area were used.

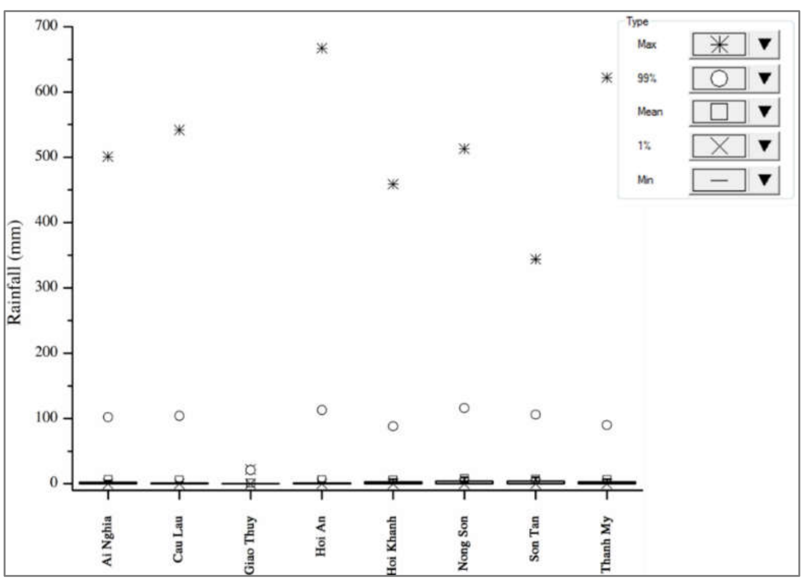

Figure 1. Rainfall variation in the study area (daily data is collected from the records of hydrological and meteorological monitoring stations)

2.2. MODFLOW model

MODFLOW is a three-dimensional finite-difference ground water model developed by Waterloo Hydrogeologic. It can simulate steady and non-steady flows in a saturated system, in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined (Dowlatabadi et al., 2015). The model can consider all common boundary conditions including fixed pressure head, groundwater recharge, variable or constant fluxes etc. In MODFLOW, the aquifer system is meshed by a discretized domain consisting of an array of node and associated finite difference cells (Chiang and Kinzelbach, 1998). Its governing equation is based on Darcy's law which is described by the following partial differential equation

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (2)$$

Where K_{xx}, K_{yy} and K_{zz} are the hydraulic conductivities along the *x*, *y* and *z* axes parallel to the major axes of hydraulic conductivities, *h* is the piezometric head, *W* is a volumetric flux per unit volume representing sources/sink of water, *Ss* is the specific storage of the porous medium, and *t* is time.

2.3. Integrated SWAT and MODFLOW modelling

SWAT-MODFLOW is capable of simulating spatial-temporal groundwater recharge and surface water-groundwater (river-aquifer) interaction (Kim, 2008, Nguyen, 2017). Figure 2a shows the schematic diagram of combined surface water model (SWAT) and groundwater model (MODFLOW). The upper layers including root zone, vadose zone and shallow aquifer are belong to SWAT model, and the lower layer - deep aquifer is belonging to MODFLOW model.

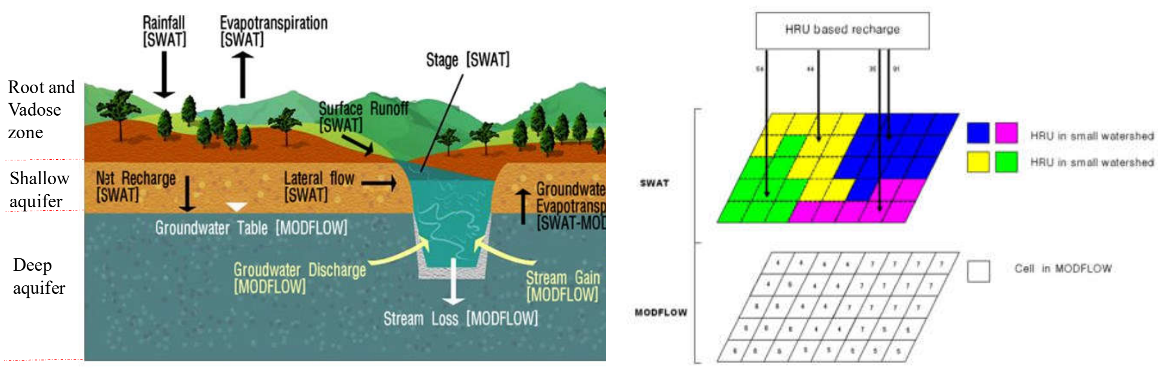

Figure 2. Schematic diagram of a) combining SWAT and MODFLOW ;
b) exchange recharge rate from SWAT to MODFLOW (Kim et al., 2008)

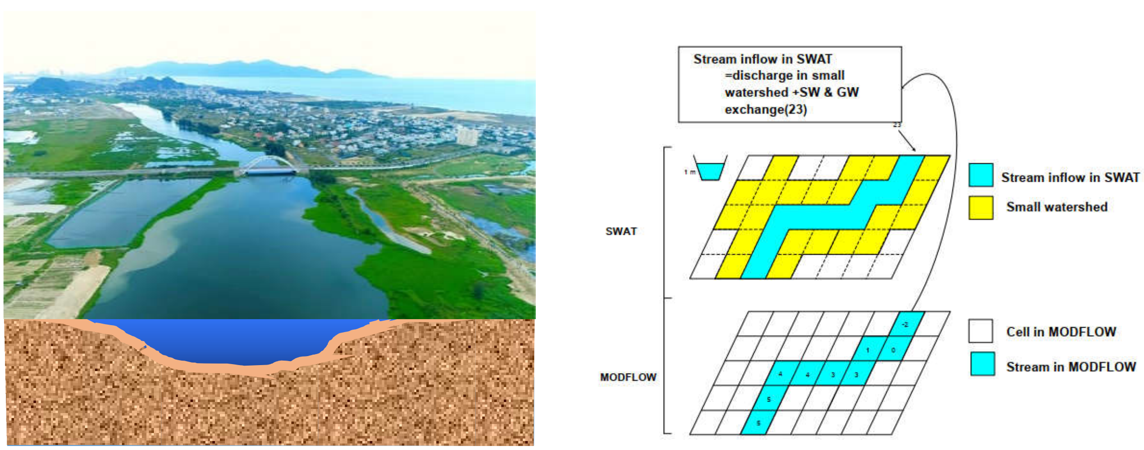

Figure 3. Intergrated surface-groundwater analysis for Da Nang coastal area
(a) and linking river in Modflow with SWAT; (b) (Kim et al., 2008)

In this study, SWAT and MODFLOW were setup to run individually and integrated through the recharge rates. These recharge rates were firstly estimated by SWAT model and presented as groundwater recharge values in HRUs level. In the integration process, the recharge rate of the HRU should be exchanged with cells and used as input data for MODFLOW (Figure 3b). Due to the semi-distributed features of SWAT, spatial location of each HRU in sub basins cannot be determined. Thus, to reflect HRU locations, one HRU is created for each sub basin by dominant land use, soil and slope option (Dowlatabadi et al., 2015).

3. Geological and hydrogeological conditions of Da Nang coastal area

The study area includes three types of terrain including mountains, plains and coastal sand dunes. The North is Bach Ma mountain range with an average height of over 700m, which is the natural border between Da Nang city and Thua Thien Hue. In the northwest, there is Mang mountain 1.712m high, adjacent to the three provinces of Thua Thien Hue, Quang Nam and Da Nang. In the southwest, there is Ba mountain 1.487m high. To the east is the Son Tra mountain range. The coastal plain and the plain south of the city are divided by the Han River. Terrain due to wind reaccumulation of sea sand is found in sand dunes in Ngu Hanh Son and Nam O areas.

The aquifer q is scattered on the surface with a small outcrop of about 3-5km^2. The lithological composition is mixed, including clay, mixed clay, mixed sand, gravel and original rock. According to the results of the experimental water suction pump at the borehole LK710, the aquifer is classified as poor water with flow Q = 0.84 l/s, flow rate q = 0.05 l/s.m. The move changes strongly according to the season, in the dry season many dug wells are exhausted.

The qh aquifer consists of mixed sediments of rivers, seas, swamps, and winds. They are unevenly distributed with a total area of about 160 km^2, hydrogeological characteristics vary by area. The petrographic composition is mainly fine to medium-grained quartz sand, mixed sand, mixed clay, discrete structure with good water capacity. Groundwater dynamics are strongly seasonal with the amplitude varying from 0.45-3.0m in Lien Chieu Hai Chau to 1.8 -11.2m in Son Tra - Ngu Hanh Son area. According to the test results of the water pump in 10 projects, the water storage level of the strata is from medium to rich, the flow rate varies from 0.04 to 3.65l/sm. Although the level of water storage is large, it is a surface aquifer, so it is significantly affected by the process of salinization due to tidal activity; especially in Cau Do and Cam Le rivers, more than 50% of the aquifer area is saline. The chemical type of groundwater in this aquifer is mainly chloride-sodium.

The qp aquifer is distributed over an area of about 360 km^2, the lithological composition includes quartz sand from fine to coarse, sand containing gravel, pebbles. The qp2 water storage layer has a flow rate q = 0.32 l/sm, the average water level. Whereas the qp1 aquifer has a more abundant water content from moderate to rich, the discharge varies from 0.03 to 3.32 l/s.m.

The fissure aquifers in the study area have a distribution area of about 40 km^2, most of which are covered by younger sediments. The petrographic composition is mainly composed of calcareous limestone, cericite schist, shale and quartz schist.

With the hydrogeological characteristics mentioned above, the aquifer that is significant in exploitation is the Holocene and Pleistocene porous aquifer. However, both aquifers have saline intrusion, so a reasonable exploitation plan is required.

4. Results of simulation and discussion

4.1. Surface water availability

Discharge data at the two hydrological stations of Nong Son and Thanh My were used for the calibration and validation process. The calibration period was from 2005 to 2020, and the validation was from 2013 to 2020. The simulation results are evaluated through two coefficients namely Nash - Sutcliffe coefficient (E) and determination coefficient (r). The values of E and r are calculated as following:

$$E = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{sim,i})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2} \quad (3)$$

$$r = \frac{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})\cdot(X_{sim,i} - \overline{X_{sim}})}{\sqrt{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2 \cdot \sum_{i=1}^{n}(X_{sim,i} - \overline{X_{sim}})^2}} \quad (4)$$

Where: $X_{obs,i}$ is observed discharge, $\overline{X_{obs}}$ is average observed discharge, $X_{sim,i}$ is simulated discharge, $\overline{X_{sim}}$ is average simulated discharge, n is number of samples.

According to Moriasi et al. 2007, with the value of r is larger 0.5 and E is greater than 0.75 the simulation results can be judged very well.

Table 1. Results of calibration and validation

Station	r		E	
	Calibration	Validation	Calibration	Validation
Nong Son	0.73	0.75	0.77	0.76
Thanh My	0.74	0.71	0.78	0.80

Table 2. Calibrated SWAT parameters, their description and best range value

No	Parameters	Definition	Range
1	ALPHA_BF	Base flow alpha factor (*days*)	0.1-0.2
2	GW_DELAY	Ground water delay time (*days*)	31-51
3	CN2	SCS runoff curve number of moisture condition II	60-70
4	ESCO	Soil evaporation compensation factor	0.5-0.9
5	REVAPMIN (*mm*)	Threshold water depth in the shallow aquifer for revap to the deep aquifer	300-500
6	GW_REVAP	Ground water revap coefficient	0.02-0.2
7	QWQMIN (*mm*)	Threshold water depth in shallow aquifer required for return flow to occur	600-800
8	SOL_AWC	Soil available water storage capacity (*mm H_2O/mm soil*)	0.2-0.4
9	R_RCHRG	Ground water recharge coefficient for deep aquifer	0.05-0.4
10	SOL_K	Soil conductivity (*mm/hr*)	15-50

4.2. Ground water availability in Da Nang coastal aquifers

The ground surface of basin has been created by using the 30 m resolution Digital Elevation Map (DEM) (Figure 4a). The main geometric-structure and hydrogeological characteristics of the study area were based on the geological and lithological descriptions of 41 boreholes located in Da Nang area. Their characteristics are very complex, however they can be categorized in to three main geological layers (Table 3). The grid size of the model is 1 km x 1 km and the boundary condition are river network, recharge rate and pumping wells (Figure 4b).

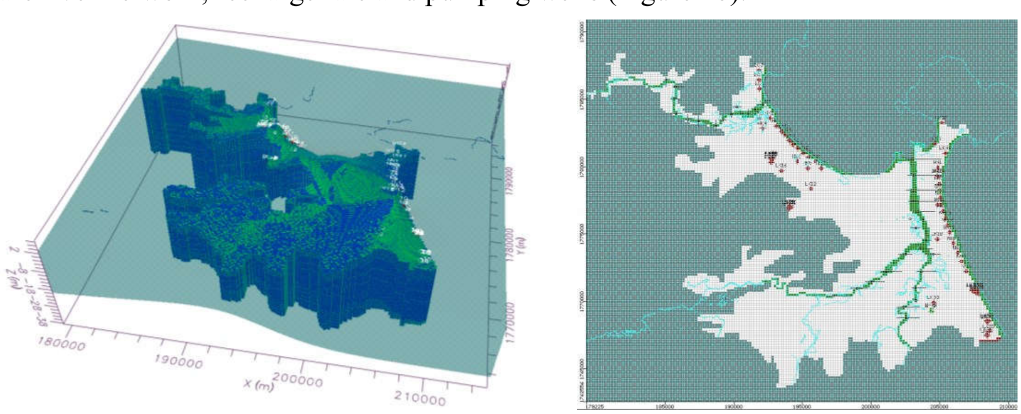

Figure 4. Three-dimensional visualization of model

Table 3. Geometric-structure and hydrogeological characteristics of basin

Layer in model/ Geological type	Lithological description	Average Thickness (m)	Hydraulic Conductivity (K)		Storage (S)			
			Range of *K* (m/day)	Average *K* (m/day)	Specific Yield S_y (-)	Specific Storage *Ss* (1/m)	Effective porosity (-)	Total porosity (-)
Layer1: Holocene aquifer (qh)	Fine to coarse sand with gravel	16.8-20.4	0.14-7.02	4.20	0.006	0.00001	0.075	0.094
Layer 2: Non-continuously Aquitard (maQ_2^1)	Clay with orgarnic	0-13.5	0.0086	0.0086	0.088	0.00001	0.071	0.089
Layer 3: Pleistocene aquifer (qp)	Fine to coarse sand with gravel	15.0-29.0	1.41-20.2	9.27	0.18	0.00001	0.070	0.088

The ground water model was setup to run in turn in 2 conditions of flow a) steady state to get the initial water head for transient state and b) transient state to get ground water availability. The model was first calibrated to fit the observed ground water levels until it reached to an acceptance normalized root mean square (RMS). Figure 8a shows the scatter diagram of calculated and observed head. The RMS was 2,421%, indicated a good simulation result. Figure 8b shows the comparison between simulated and observed ground water level from 2013 to 2020 in borehole QT3. The graph showed a good match between observed and simulation result in term of the the graph's shape and their corresponding peaks.

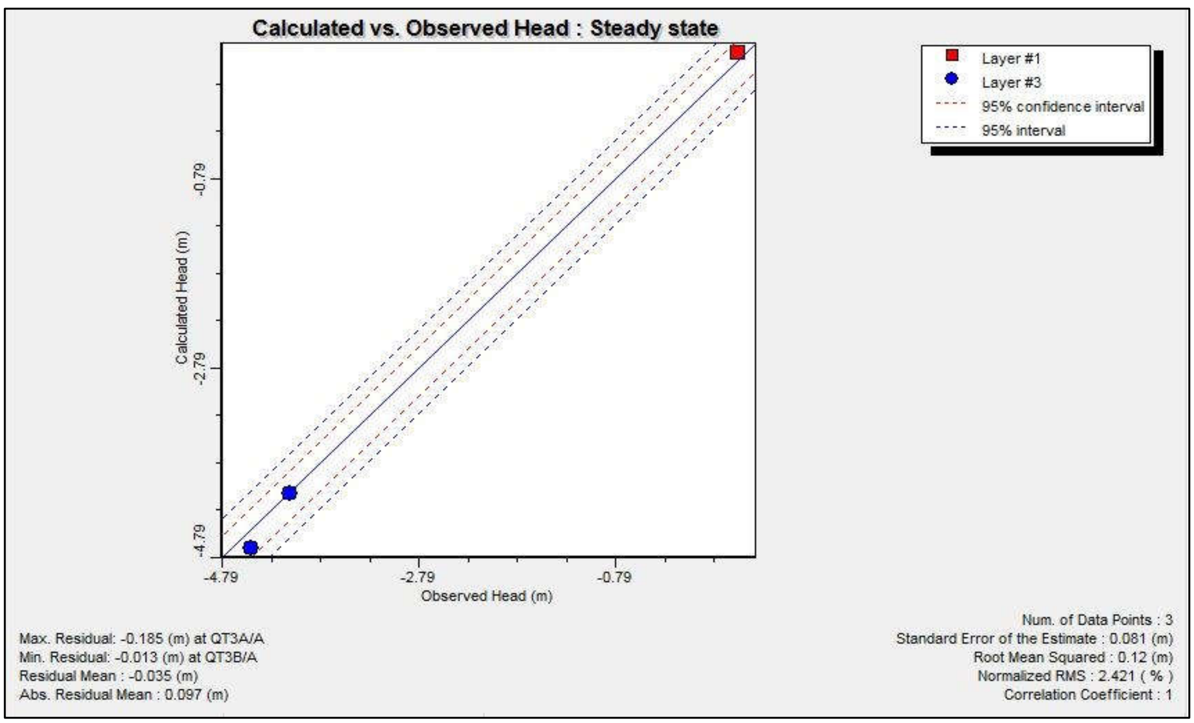

Figure 5. Calibration graph for MODFLOW performance, comparing simulated hydraulic head values to the observed hydraulic head values at 3 observation wells. Similar graphs can be displayed at any time step throughout the simulation period.

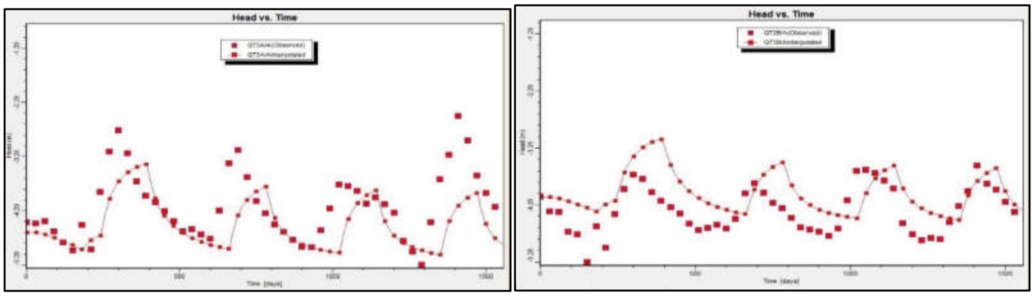

Figure 6. Comparison of the daily simulated vs. observed groundwater head at observation well QT3A and QT3B

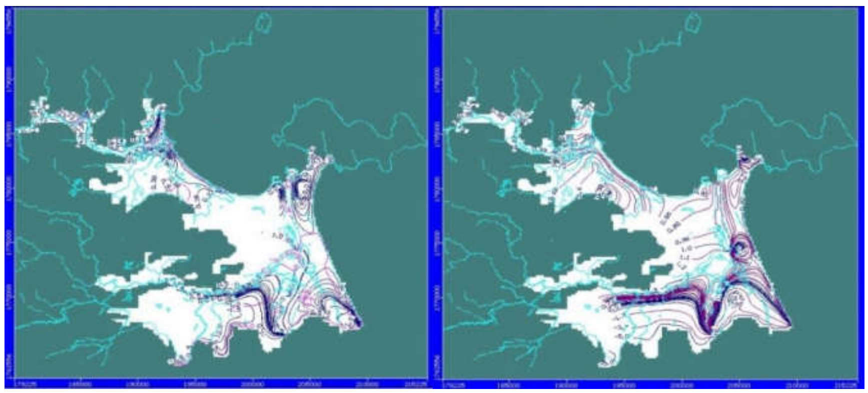

Figure 7. Simulated spartial map of groundwater level (a) in Holocene aquifer and (b) in Pleistocen aquifer in Da Nang coastal area (April 2020)

4.3. Saltwater intrusion in Da Nang coastal area

The results from saltwater intrusion numerical modeling in qh and qp aquifer at 04/2020 show that the initial salinity area of the qh aquifer decreases faster than the qp aquifer because of the precipitation recharge. During the extraction process, flowing to other areas, the surface aquifer is also affected by the replenishment process due to rain, which causes the aquifer to pale. However, the surface aquifer is heavily influenced by rivers and sea, so in the areas along the Han River, Cu De River, Do Toan River and coastal areas, the salinity area increases according to the calculated time series. of the model. Figure 6 shows areas with TDS greater than 1g/l of two aquifers qh and qp at the present time. Accordingly, the total saline aquifer area qh is 41.8km^2 and qp aquifer is 53.4km^2.

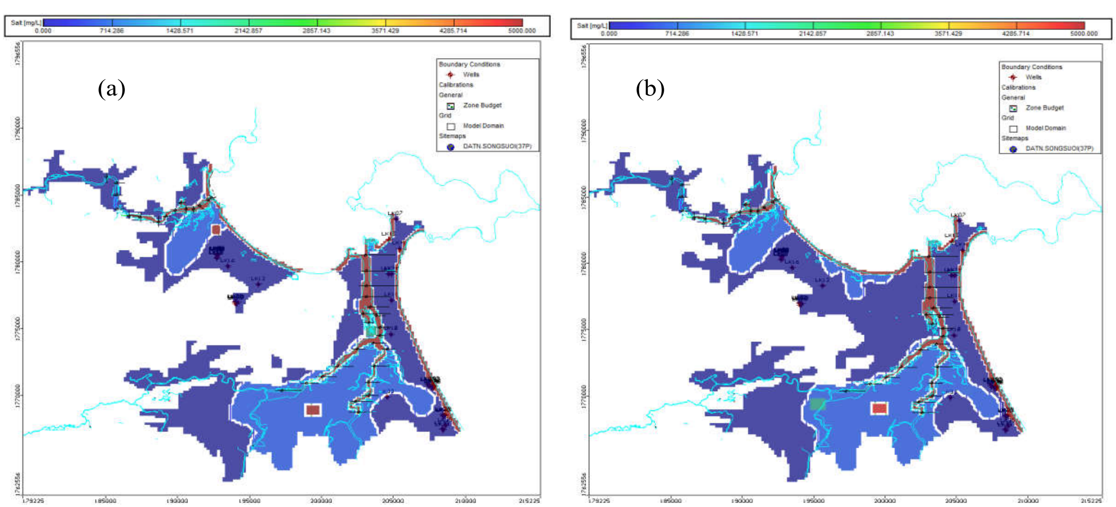

Figure 8. Spatial distribution of saltwater intrusion in groundwater simulated by Visual MODFLOW in April 2020. (a) in Holocene aquifer; (b) in Pleistocen aquifer

5. Conclusion

In this study, an intergrate SWAT and MODFLOW models were conceptualized and developed for simulation of surface and ground water then simulate saltwater intrusion in the Da Nang coastal area. The SWAT model was calibrated and validated at two stream gauging stations Nong Son and Thanh My with Nash - Sutcliffe coefficient (E) values of 0.76 to 0.80. The simulated deep aquifer recharge from SWAT were used as recharge rates for MODFLOW model. The recharge values extracted from the HRU (hydrologic response units) cell conversion interface of SWAT model were used in the cells of MODFLOW. The simulation results including the stream flow and ground water level of two corresponding models were then compared and showed good agreements with observed data. It is demonstrated that the SWAT-MODFLOW is useful tool for simulate of surface-groundwater interaction and saltwater intrusion. This study demonstrated that the recharge from surface to groundwater in Da Nang coastal area is a resource to decrease saltwater area.

Acknowledgments:

The authors express thanks to the research project code B2019-MDA-562-16 from Ministry of Education and Training (Program 562).

References

Arnold, J. G., Srinivasan, R., Muttiah, R. S., William, J. R. (1998). Large area hydrologic modeler and assessment part I: model development. J. Am. Water Resources. As. No. 34, 73-89.

Arnold, J. G. & Williams, J. R. (1987) Validation of SWRRB: simulator for water resources in rural basins. J. Water Resour. Plan. Manage. ASCE 113(2), 243-256.

Arnold, J. G., Williams, J. R. & Maidement, D. R. (1995) Continuous time water and sediment routing model for large basins. J. Hydraul. Engng 121(2), 171-183.

Chau, T. K. and Khanh, D. X. (2017) Study on water balance in Sesan river basin in drought year 2015/2016. Journal of Meteorological. Vol. 678, 44-53.

Chiang, W. H., Kinzelbach, W. (1998). Processing mudflow: a simulation system for modeling ground water flow and pollution. Humburg, Zurich, p. 325.

Do Xuan Khanh, Nguyen Bach Thao (2018) - Integration of SWAT and MODFLOW model to assess the surface and groundwater availability: a case study of Dong Nai basin in 2015 - 2016. Viet Nam Meteorological and Hydrological Administration: Vietnam Journal of Hydrometeorology; Volume ISSN 0866-8744

Dowlatabadi, S., Zomorodian, S. M. A. (2015). Conjunctive simulation of surface water and ground water using SWAT and MODFLOW in Firoozabad watershed. KSCE, 1-12.

Hiep, H. V., Ty, T. V. (2012). Đánh giá tài nguyên nước dưới đất tỉnh Trà Vinh sử dụng mô hình MODFLOW. Tạp chí khoa học DH Cần Thơ. Vol. 23, 42-51.

Kim, N. W., Chung, I. M., Won, Y. S., Arnold, J. G. (2008). Development and application of the integrated SWAT-MODFLOW model. Journal of Hydrology. Vol. 356, 1-16.

Knisel, W. G. (ed.) (1980) CREAMS: a field scale model for chemicals, runoff, and erosion from agricultural management systems. Conservation Research Report 26, US Dept of Agriculture.

Moriasi, D. N., Arnold, J. G., Liew, V., Bingner, R. L., Harmel, R. D., Veith, T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed in simulations. Trans. ASBE, Vol. 50, No.3, 885-99.

Leonard, R. A., Knisel, W. G. & Still, D. A. (1987) GLEAMS: Groundwater Loading Effects on Agricultural Management Systems. Trans. Am. Soc. Agric. Engrs 30(5), 1403-1428.

Nguyen Bach Thao, Cao Viet Anh, Nguyen Dieu Trinh, Hoang Thanh Son and Nguyen Van Duyen (2018) Saltwater intrusion in aquifers of Danang area and solution for sustainable groundwater development. Journal of Mining and Geology Science and Technology. Hanoi University of Mining and Geology. Hanoi.

Nguyen Bach Thao, Thi Van Le Khoa, Hoang Thu, Hang, Vo Thi Cong Chinh - Swat-Modflow intergration in assessing groundwter potential in the Ba River basin. International Conference on Sustainable Groundwater Development, 2017. Vietnam National University Press. ISBN: 978-604-62-9769-7, pp 131-145.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., William, J. R. (2011). Soil and water assessment toll theoretical documentation version 2009. Texas water resources institute technical report No. 406. College station, Texas.

Srinivasan, R. & Arnold, J. G. (1994) Integration of a basin-scale water quality model with GIS. Water Resour. Bull. 30(3), 453-462.

Valentina Krysanova & Jeffrey G. Arnold (2008) Advances in ecohydrological modelling with SWAT—a review, Hydrological Sciences Journal, 53:5, 939-947.

Winter, T. C., Harvey, J. W., Franke, O. L. and Alley, W. M. (1998). Ground water and surface water a single resources. U. S. Geological survey circular 1139, Denver Colorado 79.

Williams, J. R., Renard, K. G. & Dyke, P. T. (1984) EPIC-a new model for assessing erosion's effect on soil productivity. J. Soil Water Conserv. 38(5), 381-383.