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Sustainable Groundwater Development

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SWAT-MODFLOW INTEGRATION IN ASSESSING GROUNDWATER POTENTIAL IN THE BA RIVER BASIN

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Abstract: *Recharge estimation of surface water to groundwater plays an important role in assessement of groundwater reserve. However, the lack of data such as surface water observation, on-top soil formation, land cover, topography… create the difficulty to quantify this value. In almost cases, hydrogeologistes estimated this value by using a theory number of percentage of the rainfall. This difficulty could be solved with help from surface water balance models such as SWAT, MIKE or WETSPASS… This paper presents some results of intergrate the surface water model using SWAT and groundwater model using Visual MODFLOW to assess groundwater potential in the Ba River Basin (in Central Highlands).*

Keywords: *SWAT, MODFLOW, surface water model, groundwater model, recharge, river-groundwater interaction*

Introduction

Study area

Ba River has its source in Kon Tum Province and flows into the East Sea in Tuy Hoa, Phu Yen Province. It has the largest river valley area in central Vietnam with a total basin area of 13,900 km² and has a total length of 374 km. The total catchment area of Ba River in the Central Highlands region is 10,779 km2. Ba River basin makes up parts of Dak Lak Province, around half of Gia Lai Province and parts of Kon Tum Province. Main tributaries are Hinh River and Ayun River. The source of Ba River starting from Ngoc Linh Mountain in Kon Tum Province. The flood season of Ba River from July to November. The feature of the basin is as follows:

Table 1. Feature of Ba River Basin in the Central Highland Provinces

Items	Value
Basin Area (km^2)	10,779
River Length (km)	322
Elevation Range (m)	86 – 1,745
Average Elevation (m)	778
Average Slope (%)	15
Provinces	Gia Lai, Kon Tum, Dak Lak
Average Precipitation (mm)	1,676
Average Temperature (°C)	23.3

Runoff characteristics

The HMS, MONRE is operating mainly the following four (4) registered hydrological gauging stations in the Ba River basin. The flow duration curves of specific discharge shows that the annual average daily specific discharge was from 0.8 to 1.5 m3/sec/100 km2 and the daily discharges of less than 13.7 m3/s (1.0 m3/sec/100 km2) were recorded for six (6) months at An Khe station.

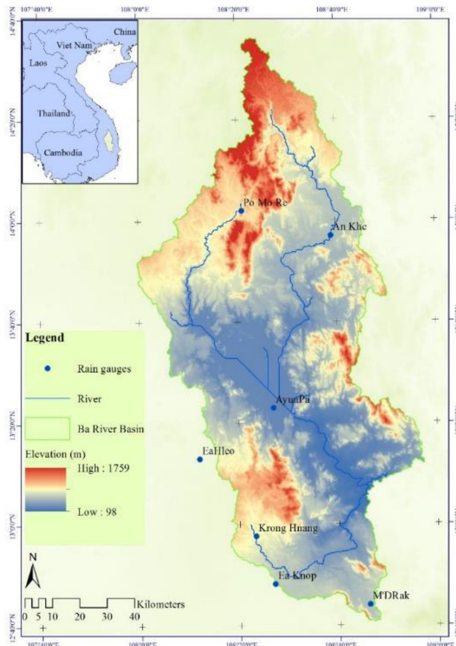


Figure 1. Location of the Ba River Basin and rain gauging stations in the watershed. Elevation change over the watershed is also shown in the figure.

Hydrogeological Condition

In the Central Highland region consists two (2) groups of aquifers, i.e. porous and fissure aquifers. The porous group consists of i) Aquifers in Holocene sediments, ii) Aquifers in Pleistocene sediments and iii) Aquifers in Neogene sediments.

The fissure group consists of iv) Aquifers in Middle Pleistocene basalt, v) Aquifers in Pliocene-Pleistocene basalt, vi) Aquifers in Upper Cretaceous sediments, vii) Aquifers in Lower Middle Jurassic sediments and viii) Aquifers in Neoproterozoic metamorphic formations. Among these aquifers, those in Pleistocene and Pliocene-Pleistocene basalts are the most important and productive due to their large distribution, big thickness, good availability and quality.

Development of the intergrated SWAT-Visual MODFLOW model

SWAT model introduction

Soil and Water Assessment Tool (SWAT) is a physically-based semi-distributed model with its well-known capacity of making use of remote sensing data and simulating water resources system continuously over a long period. By dividing watershed into sub-basins and subsequently Hydrologic Response Units (HRUs), SWAT creates homogeneity of main characteristics in the sub-basin such as land-cover method, soil properties, topology and management. Additionally, watershed can be divided by dominance of one specific feature of land-cover or soil type or management method *(Philip W. Gassman et al., 2007).* In addition to topological data, land-cover and soil data, other climate data is required comprising daily rainfall, maximum/minimum temperature, sun radiation, relative humidity and wind speed. These data can be provided by ground stations or satellite.

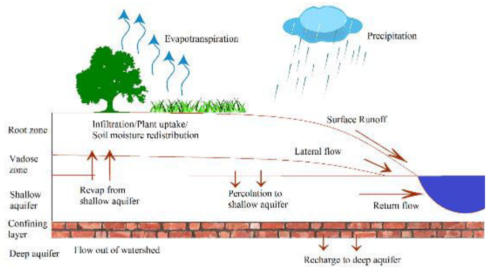


Figure 2. Overview of the SWAT model (edited from Neitsch et al,.2012)

Recharge to the shallow and deep aquifers occurs via percolation and bypass flow of water from the soil surface through the vadose zone. The time taken for water to exit the soil profile and enter the shallow aquifer as recharge depends on the hydraulic properties of the geologic materials in the vadose and the groundwater zones, and the depth to the water table *(Emmanuel Obuobie, 2008).* SWAT uses an exponential decay weighting function used by *Sangrey et al. (1984)* to account for the time delay in aquifer recharge once the water exits the soil profile *(Neitsch et al., 2005).* Recharge to both the shallow and deep aquifers is calculated in SWAT to be:

$$w_{rchrg,i} = (1 - \exp[-1/\delta_{gw}]).w_{seep} + \exp[-1/\delta_{gw}].w_{rchrg,i-1}$$

where: $w_{rchrg,i}$ is the amount of recharge entering the aquifer on day i (mm); δ_{gw} is the delay time or drainage time of the overlying geologic formations (days); w_{seep} is the total amount of water exiting the bottom of the soil profile on day i (mm); and $w_{rchrg,i-1}$ is the amount of recharge entering the aquifer on day i-1 (mm).

The total amount of water exiting the bottom of the soil profile on day i is calculated as:

$$w_{seep} = w_{perc,ly=n} + w_{crk,btm}$$

where: w_{seep} is the total amount of water exiting the bottom of the soil profile on day I (mm); $w_{perc,ly=n}$ is the amount of water percolating out of the lowest layer n in the soil profile on day i (mm); and $w_{crk,btm}$ is the amount of water flow past the lower boundary of the soil profile due to bypass flow on day i (mm).

The delay time, δ_{gw}, cannot be directly measured. It can be estimated by simulating aquifer recharge using different values for δ_{gw} and comparing the simulated variations in water table level with observed values.

Once the total daily recharge is calculated, SWAT partitions this between the shallow and deep aquifer. The amount of water diverted from the shallow aquifer to the deep aquifer via percolation on a given day is:

$$w_{deep} = \beta_{deep} \,.\, w_{rchrg}$$

where: w_{deep} is the amount of water moving into the deep aquifer on day i (mm); β_{deep} is the aquifer percolation coefficient; and w_{rchrg} is the amount of recharge entering both aquifers on day i (mm).

The amount of recharge to the shallow aquifer is:

$$w_{rchrg,sh} = w_{rchrg} - w_{deep}$$

where: $w_{rchrg,sh}$ is the amount of recharge entering the shallow aquifer on day i (mm).

Overview of MODFLOW model

Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions. Groundwater models, however, even as approximations are a useful investigation tool that groundwater hydrologists may use for a number of applications.

Application of existing groundwater models include water balance (in terms of water quantity), gaining knowledge about the quantitative aspects of the unsaturated zone, simulating of water flow and chemical migration in the saturated zone including river-groundwater relations, assessing the impact of changes of the groundwater regime on the environment, setting up/optimizing monitoring networks, and setting up groundwater protection zones.

It is important to understand general aspects of both groundwater flow and transport models so that application or evaluation of these models may be performed correctly.

The protocol to set up a numerical modeling include 4 main steps (Anderson and Woessner, 2002), such as (i) define objectives, (ii) build and revise a conceptual modeling , (iii) develop a numerical modeling and (iv) calibrate and validate model.

The governing equations of variable-density groundwater flow and solute transport are described in detail in many studies by (Voss and Souza, 1987, Diersch, 1988, Holzbecher, 1998a, Guo et al., 2002).

Groundwater modeling begins with a conceptual understanding of the physical problem. The next step in modeling is translating the physical system into mathematical terms. In general, the results are the familiar groundwater flow equation and transport equations. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

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

Where,

K_{xx}, K_{yy}, K_{zz} = hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity;

h = piezometric head;

Q = volumetric flux per unit volume representing source/sink terms;

S_s = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

The Visual Modflow program is one of the common groundwater model software, was developed by U.S. Geology Survey (USGS) to simulate three-dimensional, variable density, transient ground-water flow in porous media. In this study, MODFLOW was used to simulate the groundwater potential of Ba river basin area.

In groundwater modflow model, the recharge from surface water and rainfall is one of the input data. This value could be well estimate by using a surface water model such as SWAT. An intergration SWAT-MODFLOW model could solved the difficulty given by lacking data of recharge from surface water/rainfall to groundwater as well as the discharge from groundwater.

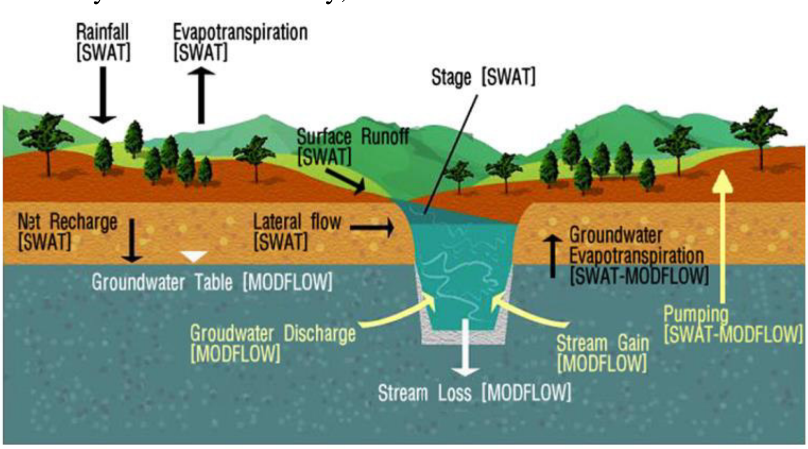


Figure 3. Schematic diagram of combined surface water and groundwater model (Kim et al,.2008)

Recharge simulation by SWAT

Model setup and validation

Topology in the study area is featured by the ASTER Global Digital Elevation Map (ASTER GDEM). Release of the second version of GDEM was jointly announced by The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA) on October 17, 2011. The product can be freely assessable at https://gdex.cr.usgs.gov/gdex/. DEM is used to generate flow direction and most importantly to delineate the sub-basins.

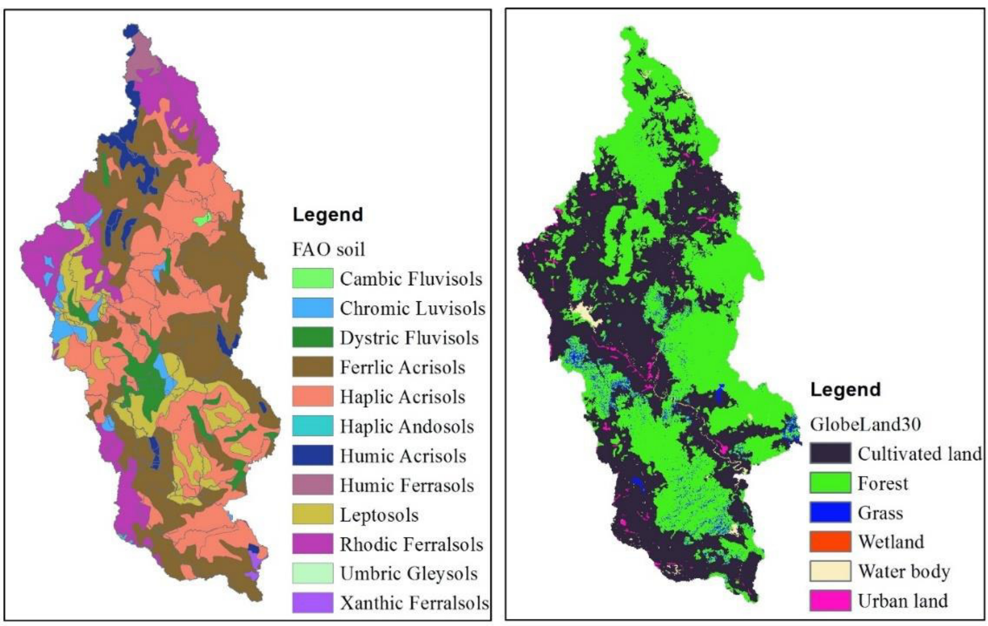


Figure 4. Soil and land-cover data used for the simulation

Land-cover map is necessary to calculate the evapotranspiration rate throughout the watershed. 30m spatial resolution land-cover data is extracted from http://www.globallandcover.com. The product, known as the GlobeLand30 is analysis result of more than 20,000 satellite images from Landsat and HJ-1. GlobeLand30 is very appropriate for SWAT simulation because of its high resolution and less complex classification. Forest and cultivated land are dominant in the study area, taking approximately 49% and 47% respectively.

Soil data is needed to define important soil-water properties which gives significant impact to the interaction between stream water and groundwater. High sensitive parameters include saturated hydraulic conductivity, available water capacity, number of layers in the top profile of soil, thickness of layers and content of sand, silt, clay and rock. Soil data used in this study is a joint product of FAO and many other institutions world-wide named Harmonized World Soil Database (HWSD). This raster-formatted 30 arc-second resolution data comprises over 16,000 soil units.

Table 2. Name and properties of soil in the study area

Soil type	Saturated Hydraulic Conductivity *Ks* (cm/sec)	Available Soil Water Capacity *r* (mm/mm)
Alisols	2.11E-04	0.065
Cambic Fluvisols	3.68E-04	0.160
Carisols	2.11E-04	0.065
Chromic Luvisols	3.04E-04	0.131
Dystric Fluvisols	2.70E-04	0.161
Dystric Gleysols	3.91E-04	0.158
Ferrlic Acrisols	2.88E-04	0.113
Haplic Acrisols	1.71E-04	0.161
Haplic Andosols	1.94E-04	0.107
Humic Acrisols	2.11E-04	0.065
Humic Ferralsols	3.68E-04	0.160
Leptosols	1.91E-04	0.113
Rhodic Ferralsols	4.14E-04	0.155
Umbric Gleysols	4.57E-04	0.160
Xanthic Ferralsols	3.12E-04	0.110

Rainfall data in 12 various rain gauging stations and stream discharge in the Pomore and Ayunpa stations, used for calibration and validation process are provided by the Ministry of Natural Resources and Environment (MONRE), other climate data such as temperature, sun radiation, relative humidity, wind speed are extracted from the National Centers for Environmental Prediction (NCEP), US. The Climate Forecast System Reanalysis (CFSR) was completed over the 36-year period of 1979 through 2014, and will be extended as an operational, real time product into the future.

Table 3. Summary of input data for SWAT simulation

Type of data	Source	Resolution
Digital Elevation Map (DEM)	ASTER/METI and NASA	30 m
Land-cover	GlobeLand30/ China	30 m
Soil	HWSD/FAO	30 arc-second
Climate data	CFSR/NCEP and MONRE	30 km
Discharge	MONRE	Pomore and Ayunpa

The model is manually calibrated thank to understanding of the study area. Observed discharge in the Pomore and Ayunpa stations is used to compare with the discharge value simulated by the model. Coefficient of determination - r and Nash-Sutcliffe efficiency coefficient - E are used to verify the rationality of the output. Values of r and E are calculated as following:

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

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

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.

The results show r = 0.88 and E = 0.83 in the Pomore station and r = 0.66 and E = 0.6 in the Ayunpa station.

Table 4. Some sensitive parameters in the SWAT model

Parameters	Definition	Range
ALPHA_BF	Base-flow alpha factor	0.01-0.2
GW_DELAY	Groundwater delay	31-51
CN2	Initial CSC runoff curve number for moisture condition II	50-60
ESCO	Soil evaporation compensation factor	0.1-0.9
REVAPMIN	Threshold depth of water in the shallow aquifer required for capillary to occur	300-500
GW_REVAP	Groundwater capillary coefficient	0.02-0.2
GWQMIN	Threshold depth of water in the shallow aquifer required for return flow to occur	500-800
SOL_AWC	Available water capacity of the soil	0.1-0.4
R_RCHRG	Deep aquifer percolation fraction	0.05-0.4

SOL_K	Saturated hydraulic conductivity	15-50

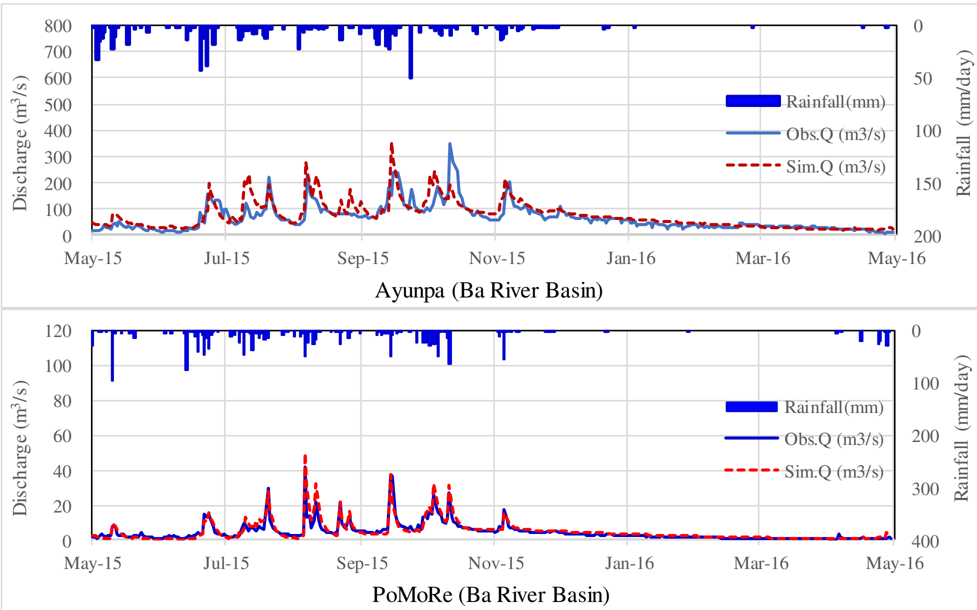


Figure 5. The calibration results in the Pomore and Ayunpa stations

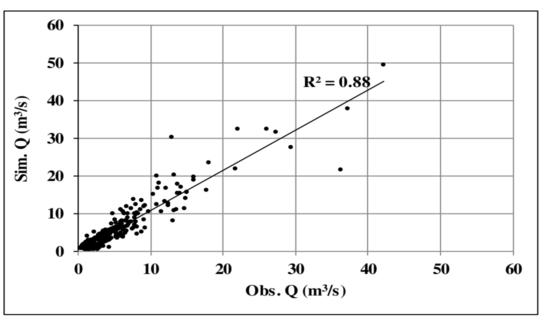


Figure 6. Scatter Plot of Observed vs. Calculated Discharge Groundwater Flow Model Visual MODFLOW

Geometry and structure

The Central Highlands Region has been simulated in 4 seperate models for difference River basin. The simulated area and geographic limitations show in Table 5 below. The area for each simulated model are about 10,000 sq.km and the largest model is 23,550 sq.km for Srepok River basin. With all available of lithological description in wells, observation wells and hydraulic properties such as conductivity, porosity and storage, the models have been assigned with grid cell size of 1.0km x 1.0km.

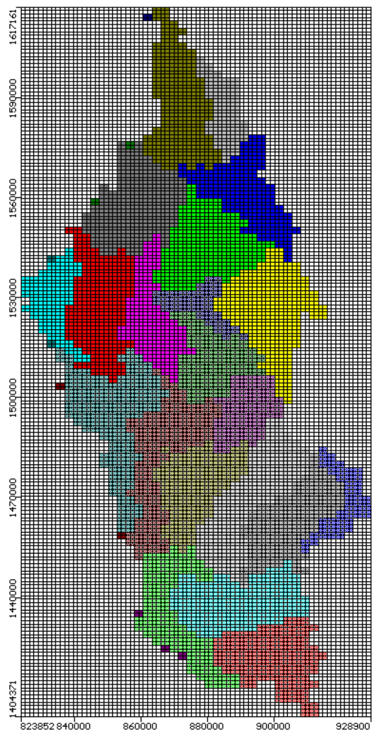


Table 5 Model Structure of groundwater modeling

Item	Condition
Modeling Region	Ba River basin Area: 11,020km^2 (X min =823852; Ymin = 1404371 Xmax =928900; Ymax=1617160) 200 rows and 80 collums
Vertical Limit	Top: Ground surface Bottom: About 180m from the ground surface
Layer	4 layers (Shallow Aquifer: 1, Deep Aquifer: 3)
Unit Grid Cell Size	1.0km x 1.0k

Ground surface of each model has been intopolated by using the Digital Elevation Map (DEM) with scale of 30x30m. The topography shown in 7 - the 3D topography with absolute elevation.

Table 6 Analytical Method of Simulation

Item	Condition
Code	MODFLOW2005 (Visual MODFLOW 2011 4.6.0.164)
Calculation	Transient Simulation
Duration	2006-2016 (10years)
Time Steps	1 day
Calibration Target	Collected groundwater level data

Hydrological setting

The main structural and hydrogeological characteristics of the Central Highlads Region aquifer are known through the geological information and the lithological descriptions from about 400 borehole logs. Four main geological units are considered: 1) the alluvium sand, silty clay with gravel of Quaternary (Q), 2) weathering basalt and porous basalt with tuf in Basalt Pleistocen formation; 3) basalt compact alternate with porous basalt in Basalt Neogen-lower Plestocen formation and 4) sandstone, gravelstone, agrilitxe with peat, diatomit and tholeit basalt in Neogen formation. The digital elevation model (DEM) of each layer surface was interpolated by using kriging method.

Hydraulic parameters such as hydraulic conductivity, porosity and storage of the aquifers are considered heterogeneous taking into account available data show in the Table 7.

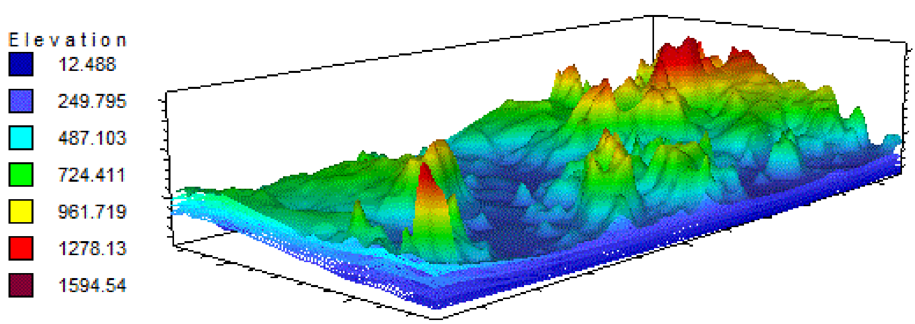
The main geometric-structural and hydrogeological characteristics of the study area in were based on geological and lithological descriptions of 400 boreholes and geological/hydorgeological mapping report for difference areas.

Table 7. Fixed Aquifer Constants

Layer in model/ Geological type	Lithological description	Average Thickness (m)	Hydraulic Conductivity (K, cm/s)		Storage (S)			
			Range of K (cm/s)	Average K (cm/s)	Specific Yield: S_y (-)	Specific Storage Coefficient: Ss (1/m)	Effective porosity (-)	Total porosity (-)
Layer1: Quaternary (Q)	Alluvium sand, silty clay, gravel	5 ÷ 10	2.3E-05 ÷ 1.8E-02	1.90E-03	9.30E-02	1.00E-05	7.50E-02	9.40E-02

Layer 2: Neogen (N)	Sandstone, gravelstone, agrilitxe with peat, diatomit and tholeit basalt	50	3.0E-05 ÷ 1.5E-02	2.10E-03	8.80E-02	1.00E-05	7.10E-02	8.90E-02
Layer 3: Basalt Pleistocen (| $|Q_{II}$)	Weathering basalt and porous basalt with tuf	70	1.2E-07 ÷ 6.9E-01	8.80E-03	8.80E-02	1.00E-05	7.00E-02	8.80E-02
Layer 4: Basalt Neogen-lower Pleistocen (bN_2-Q_I)	Basalt compact alternate with porous basalt	30	4.6E-05 ÷ 9.9E-03	1.70E-03	7.50E-02	1.00E-05	6.00E-02	7.60E-02

Source: based on pumping test data from National Center for Water Resources Planning and Investigation (NAWAPI)



Ba River basin

Figure 7. 3D Visualization of Built Model Grid

Griding

Models of four river basin have been created by using the grid size of 1km x 1km. Depends on the area of each river basin, the number of cells, collumns and rows in numerical models are diffference.

Figure 8. Model Grid for MODFLOW with sub-basin (1km x 1km Grid)

Water table

Until now, more than 200 observation wells have been set in this area by difference organizations and projects. Most of observation wells belong to the Nation Observation Network have been installed since the 1980s and surveyed with daily measurement data. Serveral observation wells belong to local provinces, but all these observation wells are under control by Division of Water Resources Planning and Investigation in Central

Higlands. Some research projects taken by local province, KC08 or DANIDA projects... have also set up several observation wells but normally measured data available only short period (1-2 years depends on the period of each project). For calibration these four models, observed data of groundwater level in 34 wells distributed over the Central Highlands area and observe for difference aquifers and depth. In there, 20 observation well with daily measurements from 1/1/2006 to 31/12/2016, 14 remain observation wells with daily measurements but from 1/1/2014 to 31/6/2016.

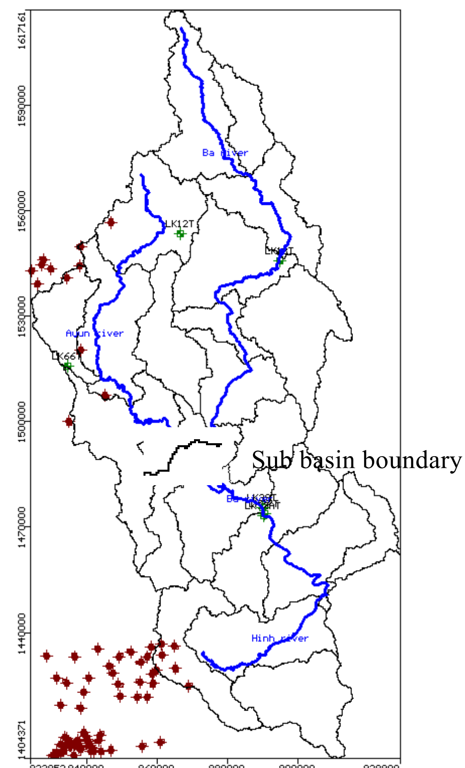
In study area, the first layer with alluvium sand, clay and gravel is unconfined aquifer, but from the second layer to the fourth layer are unconfined to semi-confined and even confined aquifers in some places due to the low permiability material above many areas due to the clay layer with very low permeability (semi-pervious or impervious material). Aquifers in sub-basins are mostly recharged by the direct infiltration of rainfall and baseflow from upstream sub-basins. The natural outflow of the aquifer discharges into the downstream sub-basins and finally into the rivers and springs/reservoirs systems, but also by evapotranspiration and pumping wells.

Role of recharge

Recharge from rainfall is taken into account in the model as inflow applied on the top layer. This recharge was computed with daily time step from 2006 to 2016 for each sub basin by the SWAT model developed by USDA Agriculture Service Research and Texas A&M University. This calculation has been calibrated and simulated with the help of Jica SWAT team. The average recharge used into the model ranges between 0 and 2 mm/day, with an average value of about 0.6 mm/day.

Importance of pumping wells

Pumping wells are included in the

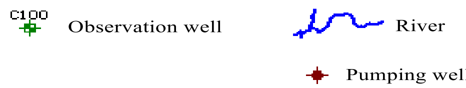


model as boundary conditions. Well screens were set as indicated by the technical description of the wells. Some of them are multi-layer wells. Apemdix 4.1.5 and Figure 4.1.11 below provide information and location of pumping wells area. Nearly 400 pumping wells are owned and operated by municipalities or industries and private wells with total abstraction rate of about 160.000 m3/day (collected data in 2011 and 2013).

Figure 9. Location Map of Pumping Wells and Selected Observation Wells

Boundary conditions

The system model of 4 river basin are constrained by boundary conditions: river boundary condition, recharge and pumping condition. The river boundary condition have been assigned for all main rivers in 4 basins by using observed surface water level in 32 stations (provided by NAWAPI) from 2006 to 2016 period. Along small river and spring, a system of drainage condition (Neumann type) represents draining springs/streams. The river bottom elevation and river width has estimated by using digital elevation map (DEM) with ArcGis helps. The drain conductivity was assumed to be equal to the hydraulic conductivity of the clay and sandy clay layer. The groundwater recharge rate from irrigation and rainfall was specified in the model as a recharge boundary condition, has explained



above. Discharge condition (flux boundary) was assigned for the pumping wells.

Setting Position	Contents
	Groundwater Recharge: Provided data from SWAT Team
River	River Boundary
Ground Surface except for Main River	Drainage Boundary
Pumping Wells	Pumping Rate: Aggregated total groundwater demand by regency/city

Figure 11. Scatter plot of Observed vs. Calculated Average Hydraulic Heads

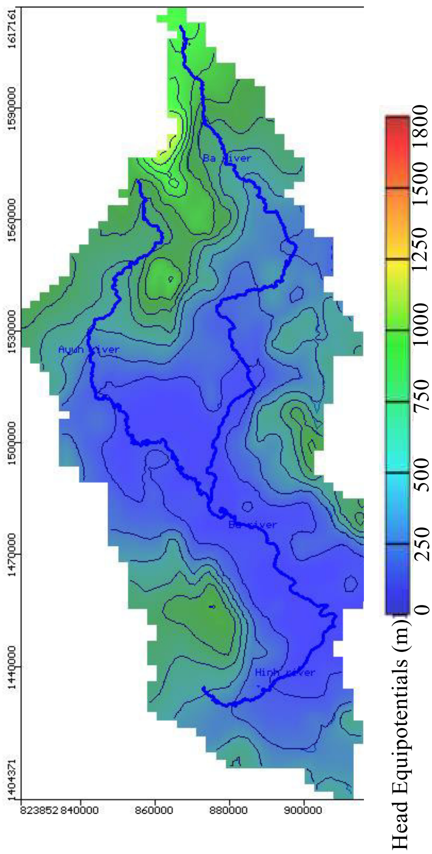


Figure 12 Groundwater contour map

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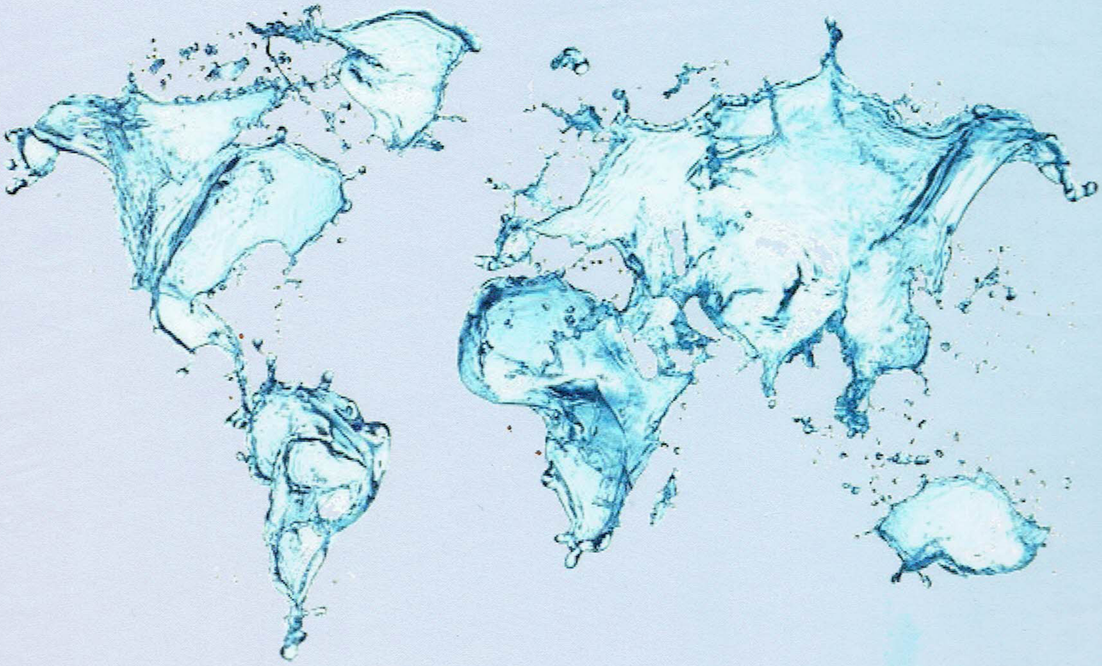

Hanoi University of Mining and Geology (HUMG), National Center for Water Resources Planning and Investigation (NAWAPI) and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) organize the International Conference on Sustainable Groundwater Development (SGD) in Hanoi, Vietnam from 26th to 27th November 2017.

The conference is to mark the 50th anniversary of the Vietnam Hydrogeology education (1967-2017), the special event of Vietnamese Hydrogeologist. The conference theme SGD is an invitation to researchers, academics and professionals to present their research results and exchange their new ideas and application experiences face-to-face.

The major topics announced for SGD 2017 are listed below: Groundwater resources with climate change and sea level rise; Groundwater resources in economic development; Sustainable management and exploitation of groundwater resources; Groundwater resources development and Saltwater intrusion and artificial recharge.

The content of the proceedings book provides a broad overview o recent advances in the fields of Sustainable Groundwater Development for readers.

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