APPLICATION OF VIC HYDROLOGICAL MODEL FOR SIMULATING RIVER FLOW OF RED RIVER SYSTEM TO SUPPORT WATER RESOURCE MANAGEMENT

Nguyen Duc Luong[1]*

Abstract: *This study aimed to apply the Variable Infiltration Capacity (VIC) hydrological model for simulating the daily river flow during the period of 2005-2014 for the Red River System, Vietnam. For this purpose, the VIC-3L hydrological model forced with satellite meteorological datasets was set up for the Red River Basin at the spatial scale of 0.1^o × 0.1^o (~11km × 11km). The daily monitored river flow data at four hydrological monitoring stations (Lao Cai, Yen Bai, Son Tay, and Ha Noi) along the Red River System for the period of 2005-2014 were used to evaluate the VIC-3L model performance. The study results showed that with the selection of appropriate soil parameters, it is possible to utilize the VIC-3L model to generate the daily river flow data for the Red River System. The VIC-3L model could capture the river flow dynamics of the Red River System. However, for the better model performance, future studies with respect to model calibration and validation should be carried out for more down-stream stations of the Red River System.*

Keywords: *VIC hydrological model; Satellite meteorological data; Model calibration; Red River System.*

Received: October 2nd, 2017; revised: October 31st, 2017; accepted: November 2nd, 2017

1. Introduction

The Red River Basin (Fig. 1) is among the largest river basins in the world which stretches across three countries including China, Laos, and Vietnam. Its total area is approximately 169,020 km^2, of which 81,240 km^2 (48%) in China, 1,100km^2 (0.65%) in Laos, and 86,660 km^2 (51.35%) in Vietnam. Administratively, the Red River Basin covers 26 provinces and cities in the North of Vietnam, including Ha Noi - the capital city of Vietnam. In terms of socio-economic development of the Red River Basin, water resources play an important role in contributing to the development of key economic sectors, especially agriculture. In the recent years, anthropogenic activities have put huge pressure on the water resources (surface water pollution, over-exploitation of groundwater, etc...). This pressure is further increasing under the impact of climate change. Sustainable management of water resources in the Red River Basin which required related scientific knowledge is indeed one of the most critical issues for the regional development.

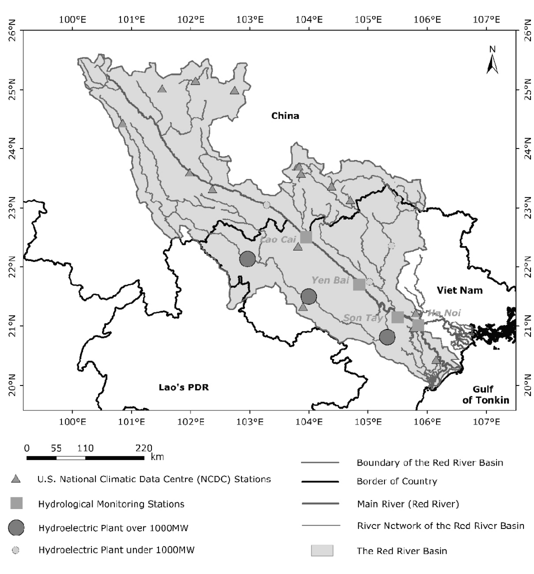

Figure 1. *Study map of Red River Basin*

Traditionally, hydrological monitoring network plays an important role in providing necessary hydrological data to support water resources management decision-making activities. In addition, hydrological modeling of the basin has also been used as an alternative approach to generate hydrological data needed for water management. Through such modeling, hydrological variables, such as runoff, infiltration rate, evapotranspiration, and river flow, which are important for water resource management, can be routinely generated in a spatially distributed manner at the expense of equally routine but easier to measure meteoro-

[1] *Dr, Faculty of Environmental Engineering, National University of Civil Engineering.*
* *Corresponding author. E-mail: luongnd1@nuce.edu.vn.*

logical forcing data (e.g., precipitation, wind speed, temperature). A hydrological model can yield information on water availability at closer space–time resolutions, where it is very hard to place gauges. Thus, a hydrological model can bridge gaps in in situ measurement as well as keep track of the terrestrial component of the dynamic water cycle [1].

As there is a general lack of in situ meteorological data availability for forcing a hydrological model, there is often a need to use the more widely available satellite-based forcing products [2]. Satellite-based geodetic and remote sensing platforms are increasingly common in collecting hydrological measurements [3]. The ability to collect data and monitor rivers by using satellite-based techniques is likely to become increasingly necessary. There are also satellite-based precipitation products like the Climate Prediction Center morphing technique [4], Precipitation Estimation from Remotely Sensed Imagery Using Artificial Neural Networks [5], and Tropical Rainfall Measuring Mission-based 3B42RT [6]. There are also new satellite missions proposed for enhancing the availability of such hydrological data, such as precipitation (Global Precipitation Measurement (GPM) mission [7]), streamflow (Surface Water and Ocean Topography (SWOT) mission [8]), and soil moisture (Soil Moisture Active and Passive (SMAP) mission [9]). Fairly high spatial (0.25^o) and temporal resolution (3 hourly) satellite precipitation data are already routinely available [1].

Although a hydrological model can be a potential tool for simulation of water management variables (runoff and river flow), there have been very few studies on the application of hydrological model for estimating the daily flow of the Red River System in the Red River Basin. There has been only one previous study using MIKE 11 hydrological model for the simulation of the flow during the period of 1996-2006 in the Red River Basin [10]. However, that study divided the Red River Basin into five sub-basins and just used the observed rainfall data provided by only five hydrological monitoring stations as the input data for MIKE 11 model. This could limit the evaluation of the flow dynamics of the Red River System and affect the accuracy of simulated results. Thus, in this study, we apply a macroscale and spatially distributed hydrological model forced with satellite meteorological datasets for estimating the daily river flow of Red River System in the Red River Basin which can be used to complement the monitored river flow data towards supporting the water resource management.

2. Material and methods

2.1 Hydrological model input data

In this study, the following types of data were collected, processed, and analyzed for setting up the hydrological model: 1) topographic data, 2) meteorological forcing data, 3) vegetation data, and 4) soil data.

For topographic data, a digital elevation model (DEM) was created for the Red River Basin (Fig. 2) by collecting elevation data from the Shuttle Radar Topographic Model (SRTM). The resolution of this DEM was 0.1^o.

The meteorological data including daily rainfall (mm), max and min air temperature (^oC), and wind speed (m/s) during the period of 2005-2014 for the entire Red River Basin were collected from 19 U.S. NCDC weather stations (Fig. 1). The land cover properties for the Red River Basin were taken from the U.S. Geological Survey (USGS), which shown in Fig. 3.

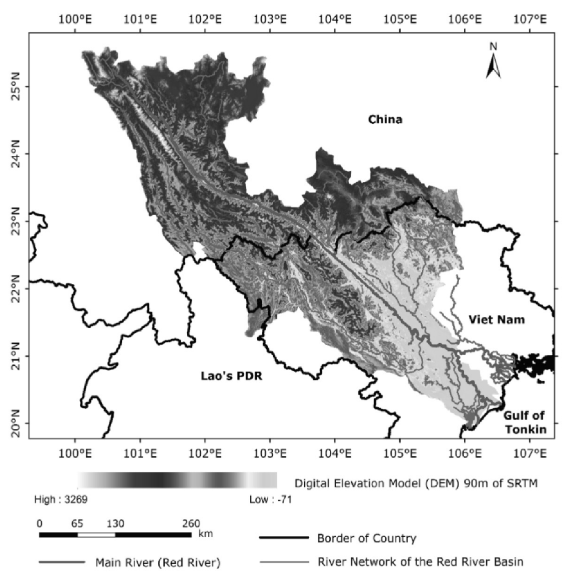

Figure 2. *Map of elevation and river network of Red River Basin*

Vegetation data such as the leaf area index (LAI) was obtained from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and regridded to 0.1o grid cells for integration in the hydrological model. Soil type data (Fig. 4) was collected from Food and Agriculture Organization including soil parameters such as porosity and saturated hydraulic conductivity.

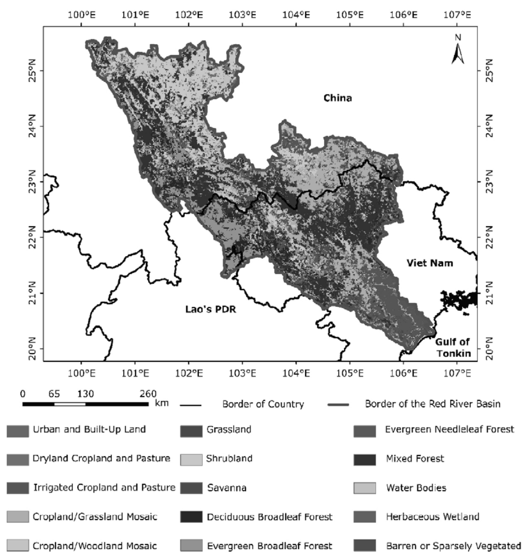

Figure 3. *Land cover properties for Red River Basin*

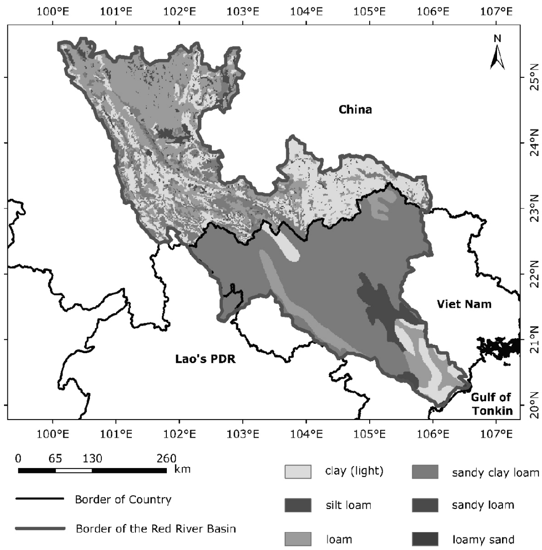

Figure 4. *Soil type for Red River Basin*

Table 1. *Summary of hydrological model input data*

No	Data	Unit/ Resolution	Frequency	Period Calibration	Validation	Source
1	Topography	90 m	-	2005-2009	2009-2014	SRTM
2	Rainfall	mm	Daily	2005-2009	2009-2014	GSOD (NCDC)
3	Maximum Temperature		Daily	2005-2009	2009-2014	GSOD (NCDC)
4	Minimum Temperature		Daily	2005-2009	2009-2014	GSOD (NCDC)
5	Wind speed	m/s	Daily	2005-2009	2009-2014	GSOD (NCDC)
6	Vegetation	-	-	2005-2009	2009-2014	MODIS
7	Soil Type	-	-	2005-2009	2009-2014	FAO

The input data for VIC hydrological model used in this study is summarized in Table 1.

2.2 VIC hydrological model

The Variable Infiltration Capacity (VIC) model, first developed [11], was used as the macroscale distributed hydrological model. VIC is a large-scale, semi-distributed macroscale hydrological model. It is capable of solving full water and energy balances. The basic structure of the VIC model was described in detail [11]. In this study, the version of VIC-3L model was used for the simulation of river flow of the Red River System. The schematic of the VIC-3L model with mosaic representation of vegetation coverage is shown in Fig. 5. The more details on the VIC-3L model's features can be found in [11].

The spatial resolution of model is 0.1°×0.1° (~11km×11km). We apply the VIC-3L model to simulate the daily river flow for the Red River System for the period 2005-2014. For evaluating the simulated results, we use the daily monitored river flow data obtained from four hydrological monitoring stations (Lao Cai, Yen Bai, Son Tay, and Ha Noi with their locations

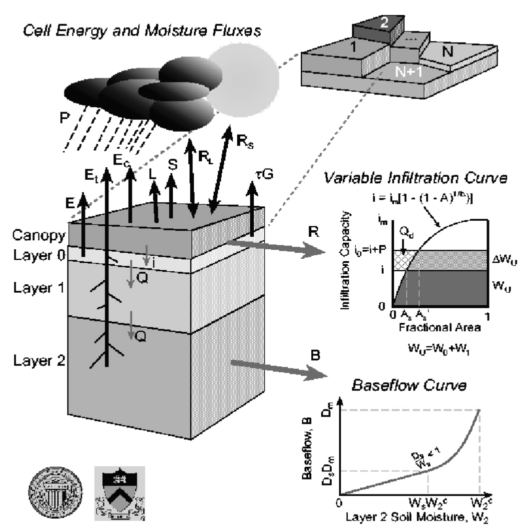

Figure 5. *Schematic of the VIC-3L model with mosaic representation of vegetation coverage*

shown in Fig. 1) along the Red River System for the same period of 2005-2014.

In order to evaluate the VIC-3L hydrological model performance, this study used the metrics of Pearson's correlation coefficient (R) and Nash-Sutcliffe efficiency (NSE). The R values which range from -1 to 1, is an index of the degree of linear relationship between the observed and simulated data. The NSE which calculated by the equation (1) is used to assess the predictive power of the VIC-3L model, and the values can range from - ∞ to 1.0, with NSE = 1 being the optimal value. With the NSE values between 0.0 and 1.0, the model performance can be acceptable; whereas the NSE values < 0.0 means that the model performance is unacceptable [12,13].

$$NSE = 1 - \left[\sum_{i=1}^{n} \left(obs_i - sim_i \right)^2 \right] / \left[\sum_{i=1}^{n} \left(obs_i - \overline{obs} \right)^2 \right] \quad (1)$$

where $\overline{obs}$ represents the mean observed flows; obs_i and sim_i represent the observed and simulated flows being evaluated, respectively; and subscript *i* refers to the time (day).

3. Results and discussions

The VIC-3L hydrological model simulation period was divided into two parts: 2005-2009 and 2010-1014. The daily simulation period 2005-2009 was used for calibration, while the period 2010-2014 was used for validation (at daily time step). The daily river flows simulated by the VIC-3L model for the period 2005-2009 at four hydrological monitoring stations of the Red River System are shown in Fig. 6.

It can be seen that the trend of daily simulated river flows relatively agree well with the daily monitored river flows at all hydrological monitoring stations. The overall trend indicates that the river flows increase rapidly during the rainy season (May to Oct) and decrease during the dry season of every year. In the year of 2008, the simulated river flows were overestimated during the peak flows during the rainy season at the stations of Lao Cai, Son Tay, and Ha Noi. At Son Tay station, the simulated river flows were underestimated in comparing to the monitored river flows during the early months of the years.

Fig. 7 provides a summary of the correlation of the simulated river flows with the monitored ones for four hydrological monitoring stations. The relative correlations were found between the simulated and monitored river flow data for three stations of Yen Bai, Son Tay, and Ha Noi (*R*=0.61, 0.77, and 0.68, respectively). The lowest correlation (*R*=0.55) was seen for the Lao Cai station. This suggests that further studies with respect to model calibration might be needed for improving the model performance.

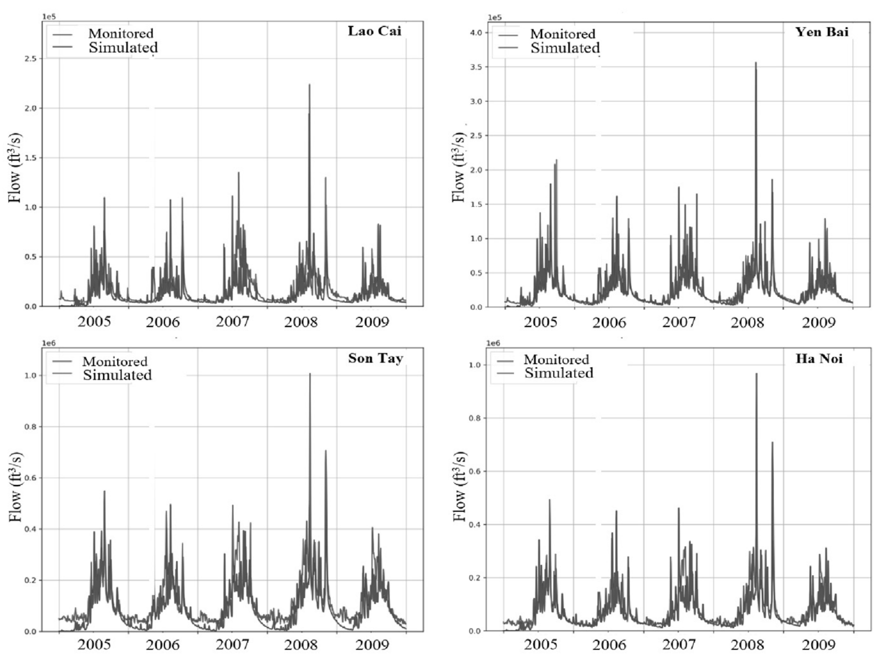

Figure 6. *Comparison between simulated and monitored river flows for the period 2005-2009 at four stations of the Red River System*

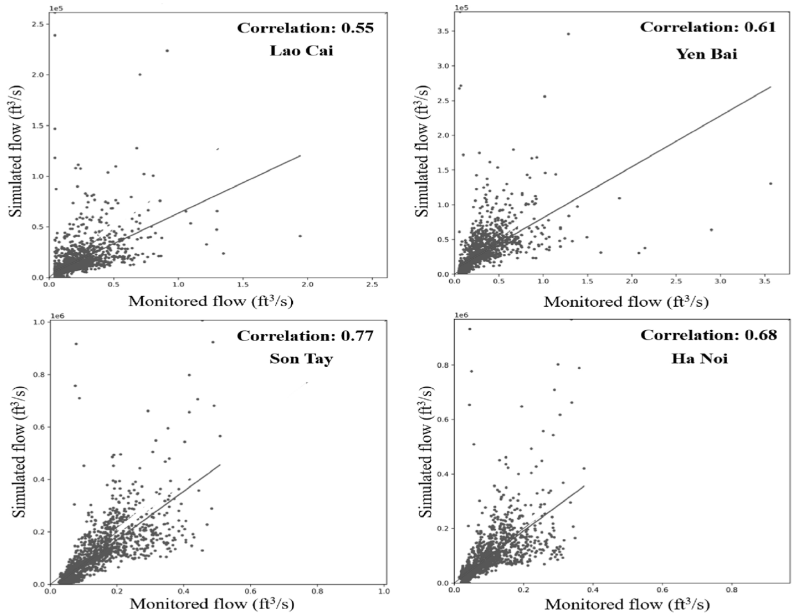

Figure 7. *Correlation between simulated and monitored river flows for the period 2005-2009 at four stations of the Red River System*

Among the model parameters to be calibrated, the ones recommnded are soil parameters such as variable infiltration curve parameter (b_infil), fraction of the DS-max parameter (Ds), fraction of maximum soil moisture (Ws), and thickness of each soil moisture layer (depth). Previous studies have shown that these parameters are the most sensitive set requiring calibration [1,11]. A set of parameters with different combinations were used for model simulation for sensitivity analysis. The calibrated soil parameters for the VIC-3L model are shown in Table 2.

Table 2. *Calibrated soil parameters for VIC-3L model*

Soil parameter		Range used for sensitivity studies
b_infil		0.00001 - 0.4
Ws		> 0.5
Ds		< 1.0
Depth	first_layer	0.40
	second_layer	0.60

The NSE values obtained for the calibration case were 0.355, 0.320, 0.458, and 0.372 for the Lao Cai, Yen Bai, Son Tay, and Hanoi station, respectively. These results implied that the model performance can be acceptable.

The VIC-3L model's validation was made for the period of 2010-2014 with the use of calibrated parameters in the previous step to see how well the VIC-3L model can indeed simulate the hydrological trends in the Red River Basin. The daily river flows simulated by the calibrated VIC-3L model for the period 2010-2014 at four stations of the Red River System are shown in Fig. 8. It is shown that the trend of the river flows simulated by the VIC-3L model stills following the trend expressed by the monitored river flows at all hydrological monitoring stations. This suggests that the VIC-3L hydrological model with the satellite products used as the inputs has sufficient skill to simulate the expected interseasonal hydrological trends in the Red River Basin.

The correlation between the simulated and monitored river flows for the period 2010-2014 at four stations of the Red River System is shown in Fig. 9. It is found that the correlation between the simulated and monitored streamflow data was significantly improved for the stations of Lao Cai, Yen Bai, and Ha Noi. The NSE values obtained for the validation case were 0.272, 0.350, 0.487, and 0.113 for the Lao Cai, Yen Bai, Son Tay, and Hanoi station, respectively. These results implied that the VIC-3L model performance was still good enough.

It can be seen that this study with the application of VIC-3L model using both ground- and satellite-based datasets could satisfactorily simulate the river flow dynamics over the basin-wide scale for the Red River Basin which could overcome the limitation of previous study [10] where the Red River Basin was divided into five sub-basins for simulation. On the other hand, the simulation skill of the VIC-3L model in this study is similar to those reported by the other studies in the world [14,15].

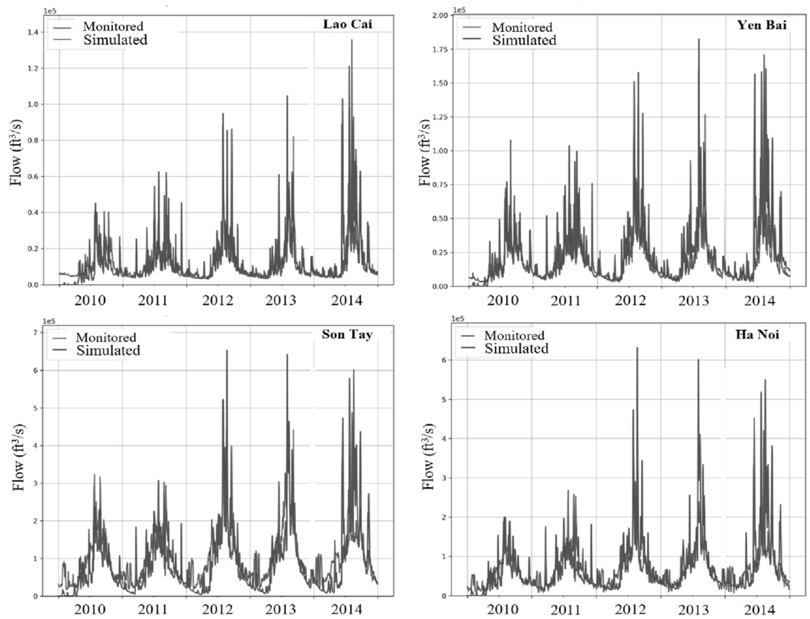

Figure 8. *Comparison between simulated and monitored river flows for the period 2010-2014 at four stations of the Red River System*

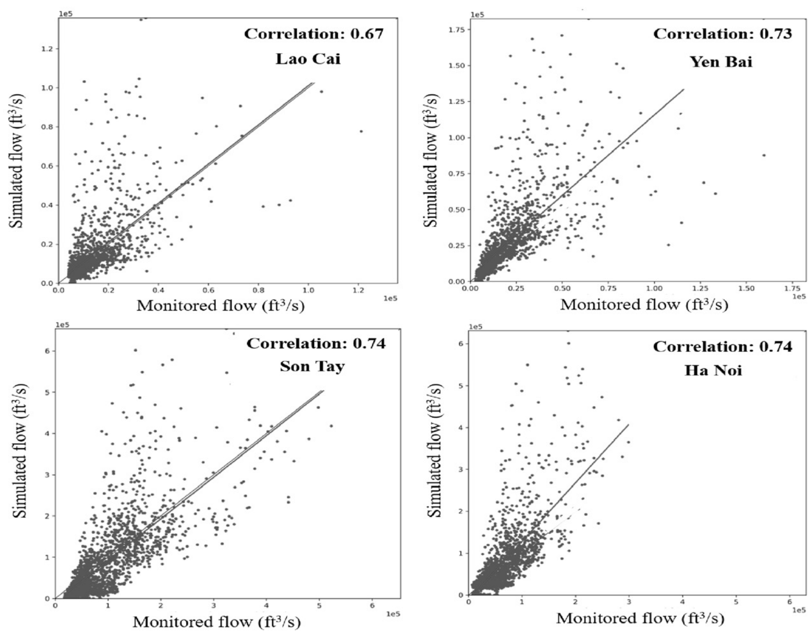

Figure 9. *Correlation between simulated and monitored river flows for the period 2010-2014 at four stations of the Red River System*

4. Conclusions

In this study, the VIC-3L hydrological model forced with the satellite meteorological datasets was applied for simulating the daily river flow of Red River System. It is generally shown that the VIC-3L model could be used to generate the daily river flow of the Red River System which agreed relatively well with the monitored data and the model could capture the river flow dynamics of the Red River System. The simulated river flow data could be used to complement the monitored data for supporting water resources management decision-making activities. The model provided a platform for conducting various future studies, such as satellite precipitation error propagation, developing tools to improve precipitation estimation and to assess the skill of climate model forecast precipitation data.

However, for the better model performance, future studies with respect to model calibration and validation are recommended. The VIC-3L hydrological model was calibrated only at one up-stream station (Lao Cai station) and three mid-stream stations (Yen Bai, Son Tay, and Ha Noi stations) of the Red River System. Probably, the calibration for more down-stream stations of the Red River System should be carried out to improve the model's predictability and achieve a better representation of the physical parameters.

Acknowledgement

This study is part of PEER project "Application of Geodetic, Satellite Remote Sensing and Physical Modeling Tools for Management of Operational Groundwater Resource in the Red River Delta, Vietnam" (2015-2018). The author would like to thank USAID for providing financial support for this project.

References

1. Siddique E-Akbor A.H.M., Hossain F., Shum C.K., Tseng S., Yi Y., Turk F.J. (2014), "Satellite Precipitation Data–Driven Hydrological Modeling for Water Resources Management in the Ganges, Brahmaputra, and Meghna Basins", *Earth Interactions*, 18(17):1-25.

2. Gebregiorgis A.S., Hossain F. (2013), "Performance evaluation of merged satellite rainfall products based on spatial and seasonal signatures of hydrologic predictability", *Atmospheric Research*, 132-133:223-238.

3. Al-Khudhairy D.H.A., Leemhuis C., Hoffmann V., Calaon R., Shepherd I.M., Thompson J.R., Gavin H., Gasca-Tucker D. (2001), "Monitoring wetland ditch water levels in the North Kent Marshes, UK, using Landsat TM imagery and ground-based measurements", *Hydrological Sciences Journal*, 46(4):585–597.

4. Joyce R.J., Xie P. (2011), "Kalman filter-based CMORPH", *Journal of Hydrometeorology*, 12(6):1547-1563.

5. Hsu K.L., Gao X., Sorooshian S., Gupta H.V. (1997), "Precipitation estimation from remotely sensed information using artificial neural networks", *Journal of Applied Meteorology and Climatology*, 36:1176-1190.

6. Huffman G.J., Adler R.F., Bolvin D.T., Nelkin E.J. (2010), "The TRMM Multisatellite Precipitation Analysis (TMPA)", *Satellite Rainfall Applications for Surface Hydrology*, Gebremichael M. and Hossain F., Eds., Springer, 3-22.

7. Smith E.A., Asrar G., Furuhama Y., Ginati A., Mugnai A., Nakamura K., Adler R.F., Chou M.D., Desbois M., Durning J.F., Einaudi F., Entin J.K., Ferraro R.R., Guzzi R., Houser P.R., Hwang P.H., Iguchi T., Joe P., Kakar R., Kaye J.A., Kojima M., Kummerow C.D., Kuo K.S., Lettenmaier D.P., Levizzani V., Lu N., Mehta A.V., Morales C., Morel P., Nakazawa T., Neeck S.P., Okamoto K., Oki R., Raju G., Shepherd J.M., Simpson J., Sohn B.J., Stocker E.F., Tao W.K., Testud J., Tripoli G.J., Wood E.F., Yang S., Zhang W. (2007), "International Global Precipitation Measurement (GPM) Program and Mission: An overview. Measuring Precipitation from Space: EURAINSAT and the Future" (V. Levizzani, P. Bauer, F.J. Turk, eds.), *Advances in Global Change Research*, Vol. 28, Springer, Dordrecht, NETHERLANDS, 611-653.

8. Alsdorf D.E., Rodriguez E., Lettenmaier D.P. (2007), "Measuring surface water from space", *Review of Geophysics*, 45(2):RG2002.

9. Entekhabi D., Coauthors (2010), "The Soil Moisture Active Passive (SMAP) mission", *Proceedings of the IEEE*, 98(5):704-716.

10. Luu T.N.M., Garnier J., Billen G., Orange D., Le T.P.Q., Tran H.T., Le L.A. (2010), "Hydrological regime and water budget of the Red River Delta (Northern Vietnam)", *Journal of Asian Earth Sciences*, 37:219-228.

11. Liang X., Lettenmaier D.P., Wood E.F., Burges S.J. (1994), "A simple hydrologically based model of land surface water and energy fluxes for GSMs", *Journal of Geophysical Research*, 99(D7):14415-14428.

12. Nash J., Sutcliffe J.V. (1970), "River flow forecasting through conceptual models partI:a discussion of principles", *Journal of Hydrology*, 10(3):282-290.

13. Moriasi D.N., Arnold J.G., Van Liew M.W., Bingner R.L., Harmel R.D., Veith T.L. (2007), "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations", *Transactions of the ASABE*, 50(3):885-900.

14. Iqbal N., Hossain F., Lee H., Akhter D. (2016), "Satellite Gravimetric Estimation of Groundwater Storage Variations Over Indus Basin in Pakistan", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* 9(8):3524-3534.

15. Iqbal N., Hossain F., Lee H., Akhter D. (2017), "Integrated groundwater resource management in Indus Basin using satellite gravimetry and physical modeling tools", *Environmental Monitoring and Assessment,* 189(3):128.