Development of a Distributed Rainfall-Runoff Model Incorporated with Tank Models of Several Land Uses and Evaluation of Impact of Climate Change on Rainfall-Runoff in a Vietnamese Watershed

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Abstract

In this study, a distributed rainfall-runoff model, which could overcome the problems of calculation time and data scarcity in Southeast Asian watersheds was developed to quantitatively analyze the changes in runoff due to rainfall variations under future climate change scenarios. To capture a variety of land uses and the spatial non-uniform rainfall characteristics of the tropical region, a distributed rainfall-runoff model, which represents the watershed as a square mesh aggregate, was constructed. To greatly reduce the calculation time, the original digital elevation map data with a 90 m mesh were scaled to a resolution of 4500 m. Four Sugawara's tank models representing the rainfall-runoff characteristics of paddy, upland field, urban, and forest areas were incorporated into each mesh element to simulate the runoff from different land uses. A watershed groundwater tank model covering the entire watershed was incorporated to represent the temporally stable base-flow component. The scenario analyses related to future rainfall change indicated that the annual runoff and peak discharge from the watershed increased with the change rates of the future rainfall. The annual runoff discharge had almost the same trend as the rainfall change rates, and the peak discharge was higher than the increase rates of rainfall during the period.

Keywords: *Runoff analysis, Kinematic wave model, Rainfall change, Southeast Asia*

Introduction

Water scarcity is a major issue in developing Southeast Asian countries located in tropical regions due to increasing populations caused by economic growth, and saltwater intrusion into the lower reaches of large rivers during the dry season (Kummu *et al*., 2016; Adepelumi *et al*., 2009). In addition, changes in lifestyle and socio-economic activities in recent years is leading to increased water consumption and changes in water usage patterns (ADB, 2016). However, flooding occurs almost every year in the wet season and flat low-lying areas are frequently subject to damage from inundation (WMO/GWP, 2008). There are concerns that the water scarcity and flooding damage situation will worsen due to future climate change and rapid economic growth. Accordingly, an efficient water resource management framework, which considers both water supply and flood control from a long-term perspective, is urgently required. Multipurpose reservoirs are widely used for efficient management of water resources. The authors have been developing a global optimization method for operation rule curves of multiple multipurpose reservoirs located in a Southeast Asian watershed (Takada *et al*., 2019). It is necessary to grasp reservoir inflows over several decades to optimize the rule curves. However, it is difficult to obtain long-term observation data of reservoir inflows in Southeast Asian watersheds where problems such as scarcity of necessary hydrological, climatic, and watershed data or low reliability data exist. Therefore, long-term runoff simulation by a rainfall-runoff model is crucial for this kind of research. The required characteristics of a rainfall-runoff model include the following: (i) shorter calculation time for global optimization of operation rule curves, (ii) easier estimation of the model parameters for application to Southeast Asian watershed where data scarcity is often a problem, (iii) easy and accurate assessment of the impact of future rural development and climate change on runoff. In this study, a new rainfall-runoff model was developed to overcome those requirements. As highlighted above, it is necessary to grasp the impact of climate change and economic growth on rainfall-runoff processes in advance. This study focused on the rainfall change under the climate change, and aimed to evaluate the future change in the runoff process quantitatively.

Study Area

The Dau Tieng watershed is located in Southern Vietnam, approximately 90 km northwest of Ho Chi Minh City (**Fig. 1**). It has a total watershed area of 2700 km^2, which is predominantly forest and cropland. The average annual rainfall is 1800 mm, although 77% of rainfall occurs between July and November, and the spatial variation in rainfall is significant. The Dau Tieng reservoir, located in the lower part of the Dau Tieng watershed, is one of the largest multipurpose reservoirs in Vietnam with an effective storage capacity of 1.58×10^9 m^3. The reservoir contributes significantly to water resources in Ho Chi Minh City, located downstream. In Ho Chi Minh City, flooding often occurs during the rainy season (July – December), while there is water scarcity during the dry season (January – June). One of the causes is the inadequacy of water resources management in the Dau Tieng watershed. Therefore, an accurate estimate of the runoff from the Dau Tieng watershed is required for appropriate management of water resources (Ngoc *et al*., 2014).

Development of Distributed Rainfall-Runoff Model

To capture a variety of land uses and the non-uniform rainfall characteristics of a tropical region, a distributed rainfall-runoff model, which represents the watershed as a square mesh aggregate, was newly developed as shown in **Fig. 2**. To greatly reduce the calculation time, the original digital elevation map data with a 90 m mesh were scaled to a

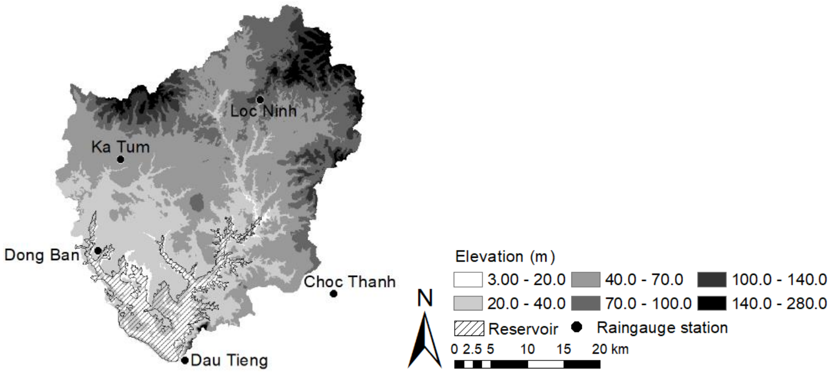

Fig. 1 Topography and rain gauge stations in the Dau Tieng watershed.

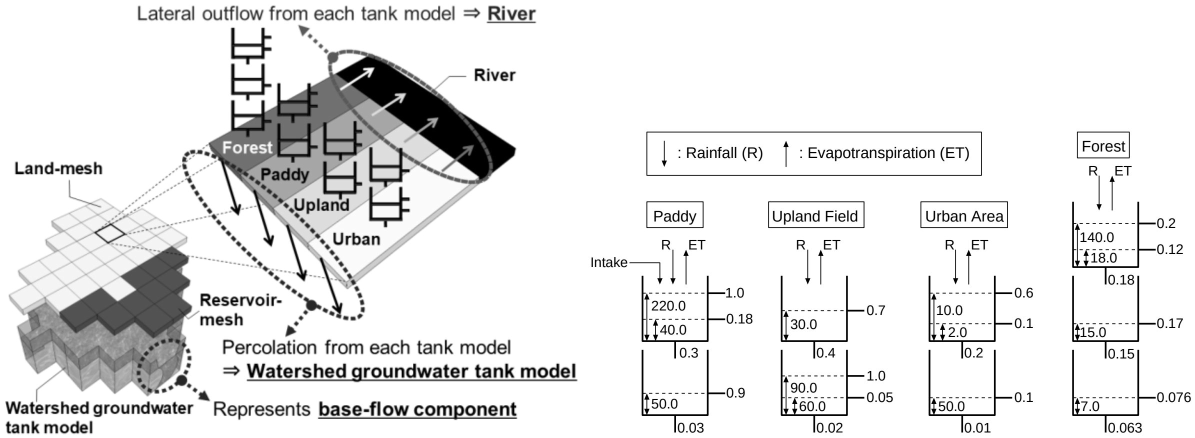

Fig. 2 Structure of the distributed rainfall-runoff model

resolution of 4500 m. In the new model, Sugawara's tank models (Sugawara *et al.*, 1974) for each land use were incorporated into each mesh element of the distributed rainfall-runoff model to capture land use in the watershed accurately and improve model performance. By introducing the tank models for each land use, the rainfall-runoff from several land uses in each mesh element could be represented accurately even with the large mesh size of 4500 m, and a variety of the present land uses and the future land use changes could be reflected more precisely. The 4500 m meshes comprising the watershed were classified into land-mesh and reservoir-mesh. All land-mesh elements contained paddy, upland field, urban, and forest areas depending on the proportional area inside the element. Rivers were also incorporated as one of the elements in each land-mesh depending on the catchment area of each mesh. Tank models for the paddy, upland field, urban, and forest areas were set into each land-mesh element. In addition, a watershed groundwater tank model covering the entire watershed was incorporated to represent the temporally stable base flow component. As shown in **Fig. 2**, a two-cascade structure for the paddy, upland field, urban tank models, and three-cascade structure for the forest tank models were set. The height of the upper lateral hole in the first tank of the paddy tank model represents the height of the ridge, and the height of the lower lateral hole represents the inundation depth of paddy fields. The water depth of the first tank of the paddy tank model was set so that water level always kept the height of the lower lateral hole assuming that a constant amount of water was stored throughout a year in paddy fields. The coefficients of each tank model were determined by trial and error based on the values of Nakagiri *et al*. (1998; 2000). The lateral outflow from each tank model flowed into the river in each mesh element, and the percolation from each tank model flowed into the watershed groundwater tank model. The inflow water to the watershed groundwater tank model was discharged from the end of the watershed as groundwater in proportion to the storage height of the watershed groundwater tank model. Takada *et al*. (2018) demonstrated the detailed construction of various data required for the model such as watershed boundary, elevation, land use, rainfall, evapotranspiration, and river width. Rainwater that fell on each land-mesh flowed into river of each mesh element, either directly or through the tank models, and flowed down from the highest mesh i to the lowest mesh j. The river flow between meshes was calculated by the kinematic wave model of Eqs. (1) and (2).

$$Q_{i,j} = \frac{1}{N} B_{i,j} h_i R_i^{2/3} I_{i,j}^{1/2} \tag{1}$$

$$\frac{dh_k}{dt} = \frac{1}{A_k}\left(Q_k^{\mathrm{In}} + Q_k^{\mathrm{Tank}} - Q_k^{\mathrm{Out}} - Q_k^{\mathrm{Irrigation}}\right) + P_k - E_k \tag{2}$$

where i and j are the mesh element numbers, $Q_{i,j}$ is the outflow from element i to j (m^3/s), N is the roughness coefficient ($s \cdot m^{-1/3}$), $B_{i,j}$ is the average river width between element i and j (m), h_i is the water depth in element i (m), R_i is the hydraulic radius of element i (m), $I_{i,j}$ is the topographical gradient between element i and j, k is the land-mesh element number, h_k is the water depth of element k (m), t is the time (s), A_k is the river area of element k (m^2), Q_k^{In} is the inflow to element k (m^3/s), Q_k^{Tank} is the sum of the inflow from the tank models of element k (m^3/s), Q_k^{Out} is the outflow from element k (m^3/s), $Q_k^{\mathrm{Irrigation}}$ is the intake irrigation water from the river to the first tank of paddy tank model of element k (m^3/s), P_k is the rainfall into element k (m/s), and E_k is the evapotranspiration from element k (m/s). The roughness coefficient N was set to 0.15 with reference to Chow (1973). The Runge-Kutta-Gill method was adopted for obtaining the numerical solution of Eqs. (1) and (2), and the time discretization step was set to be 90 s.

Model Applicability

Calculations were conducted for each year from 1999 to 2009 when observed data were available, and the values for observed and calculated watershed runoffs were compared to evaluate the model applicability. **Table 1** shows Nash-Sutcliffe (NS) coefficients (Nash and Sutcliffe, 1970) for each calculation year. **Fig. 3** shows the result of the watershed runoff calculations and the watershed-averaged areal rainfall in 2000, 2003, and 2007, respectively. The results of simulation showed a good fit in 2000, 2003, and 2007 with NS coefficients of 0.7 or higher. However, there were differences in the reproduction accuracy of each year. It was implied that the differences were caused by large errors in the observed rainfall or watershed runoff discharge data. It was additionally implied that the reproducibility was lowered since there were relatively few rain gauge stations for the watershed area of approximately 2700 km^2 as shown in **Fig. 1**. The difference in runoff characteristics from

Table 1 Reproduction result of runoff in each year.

Year	Nash-Sutcliffe coefficient
1999	0.50
2000	0.70
2001	0.43
2002	0.57
2003	0.70
2004	0.55
2005	0.58
2006	0.49
2007	0.73
2008	0.46
2009	0.53

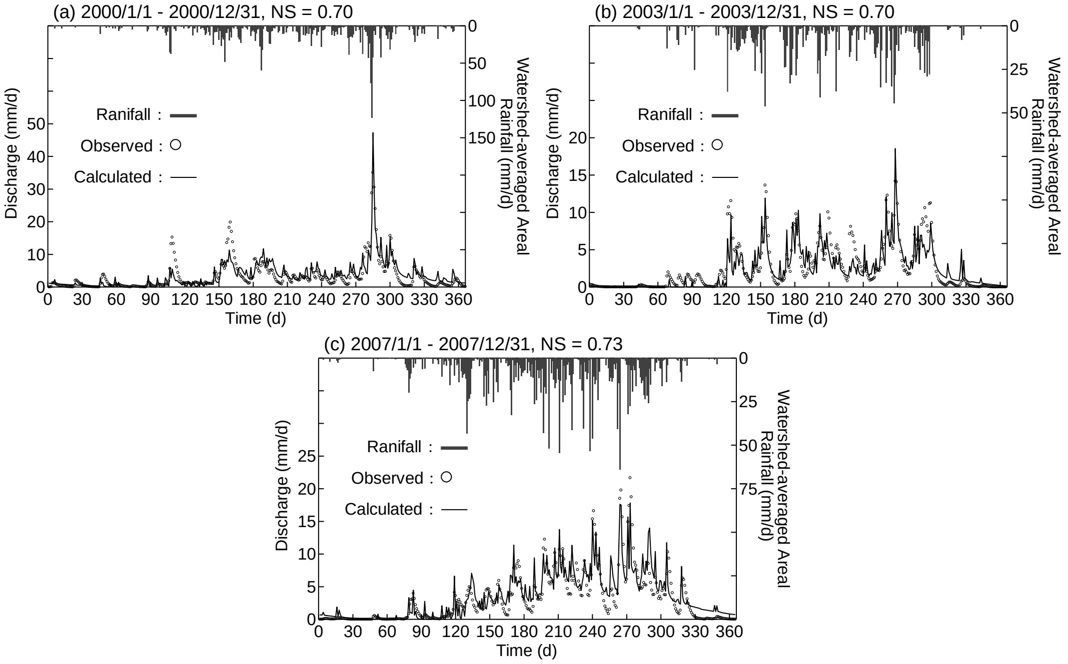

Fig. 3 Comparison of the observed and calculated discharge.

the study area of Nakagiri *et al*. (1998; 2000), which were used as a reference to determine the model parameters, was a further reason causing the decrease in reproduction accuracy. However, it was difficult to determine those parameters by introducing an optimization method, judging from the accuracy of the observed rainfall and runoff data. On the other hand, the Sugawara's tank model has been known to be highly applicable, with several actual achievements in research and engineering fields. Therefore, it was easy to estimate model parameters with reference to previous applications.

Scenario Analyses

In recent years, climate change is one of the major problems on global scale. Vietnam is regarded as one of the most vulnerable countries to the impact of climate change (Dasgupta *et al*., 2007). In this study, scenario analyses were conducted by focusing on the rainfall change under future climate change scenarios. The climate change scenarios based on the IPCC assessment report (IPCC, 2013), which were developed and published as the

Table 2 Rainfall change rate of each scenario in Dau Tieng Watershed.

Scenario	Province	Rainfall change rate (%)			
		Dec - Feb	Mar - May	Jun - Aug	Sep - Nov
Case A (2016 – 2035)	Tay Ninh	+12.4	+0.5	+13.3	+9.8
	Binh Phuoc	+19.8	−9.3	+13.4	+11.5
Case B (2046 – 2065)	Tay Ninh	+18.2	+10.8	+16.7	+12.2
	Binh Phuoc	+43.4	+14.0	+16.9	+11.2
Case C (2080 – 2099)	Tay Ninh	+24.9	+10.2	+20.9	+23.5
	Binh Phuoc	+48.7	+15.5	+19.5	+30.6

Table 3 Change of runoff and peak discharge in each scenario.

Scenario	Annual runoff change rate (%)	Peak discharge change rate (%)	Change rate of annual runoff from each land use (%)			
			Paddy	Upland field	Urban	Forest
2000_A	+13.21	+14.07	+2.8	+14.8	+11.6	+12.6
2000_B	+20.52	+16.32	+4.4	+22.4	+18.3	+19.6
2000_C	+32.50	+34.29	+6.8	+35.7	+29.4	+31.6
2003_A	+13.63	+14.40	+2.1	+15.6	+10.8	+12.3
2003_B	+23.15	+17.03	+3.4	+26.1	+19.1	+21.0
2003_C	+35.83	+35.59	+5.3	+40.1	+30.0	+32.9
2007_A	+12.64	+14.35	+2.6	+14.7	+10.4	+11.9
2007_B	+20.80	+18.05	+4.3	+23.1	+18.4	+20.0
2007_C	+30.00	+36.98	+6.5	+33.4	+26.2	+28.7

newest version by the Ministry of Natural Resources and Environment, Vietnam in 2016 (MONRE, 2016), were used for setting rainfall change scenarios in this study. **Table 2** shows the rate of rainfall change in three scenarios. In the rainfall change scenarios, the rate of rainfall change was different among the provinces where each rain gauge station was located as shown in **Table 2**. The rain gauge stations used in this study were located in two provinces, the Tay Ninh Province, which included the Ka Tum and Dau Tieng rain gauge stations, and the Binh Phuoc Province, which included the Loc Ninh, Dong Ban, and Choc Thanh rain gauge stations as shown in **Fig. 1**. The rates of rainfall change were different depending on the season. The proposed model obtained good reproducibility of rainfall-runoff in 2000, 2003, and 2007, which were used as control years for the analysis. The rainfall amount in each scenario was calculated by using the actual rainfall amount in a control year and **Table 2**. The land use was based on data in 2012.

Results and Discussion of Scenario Analyses

Table 3 shows the change rates of annual runoff and peak discharge from the watershed, as well as the change rates of annual runoff from each tank models resulting from the scenario analyses. Both the annual runoff and peak discharge from the watershed increased in the order of the Case A, B, C. The annual runoff discharge from the watershed had the almost same trend as the rainfall change rates. The peak discharge from the watershed was larger than the increase rates of rainfall during the periods. The change rates in annual runoff from each tank model in **Table 3** had similar trends as the rainfall change rate for each scenario in the tank models for the upland field, urban, and forest areas.

However, the increase rate of annual runoff was small only in the paddy tank model. This was caused by the intake irrigation water from the river in each land-mesh used to maintain a constant storage depth in the first tank of the paddy tank model.

Conclusions

In this study, the distributed rainfall-runoff model, which could overcome the problems of the calculation time and the data scarcity in Southeast Asian watersheds, was developed to quantitatively analyze the runoff change due to the future rainfall change. To greatly reduce the calculation time, the original digital elevation map data with a 90 m mesh were scaled to a resolution of 4500 m. The model was constructed by incorporating the Sugawara's tank models for four land uses of paddy, upland field, urban and forest areas into each mesh element of the distributed rainfall-runoff model to capture the rainfall-runoff from land use accurately and improve model performance. A watershed groundwater tank model covering the entire watershed was incorporated to represent the temporally stable base flow component. The model was highly applicable to watersheds where data scarcity and low accuracy are problems in Southeast Asian developing countries. It was also an effective model for cases in which calculation time reduction was essential, such as global optimization. In addition, it was possible to calculate runoff that should consider land use change and spatial distribution of rainfall for each mesh. As results of scenario analyses, it was implied that the annual runoff and peak discharge from the watershed increased with the future rainfall change rates. The annual runoff discharge had the almost same trend as the rainfall change rates, and the peak discharge was larger than the increase rates of rainfall during the period. Based on the results of this study, the authors will develop a global optimization method for operation rule curves of multiple multipurpose reservoirs located in the Southeast Asian watershed.

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