EVALUATION OF IMPACT OF CLIMATE CHANGE AND RURAL DEVELOPMENT ON RAINFALL-RUNOFF IN A SOUTHEAST ASIAN WATERSHED BY A DISTRIBUTED MODEL INCORPORATED WITH TANK MODELS FOR SEVERAL LAND USES

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ABSTRACT

It is necessary to incorporate the impact of climate change and economic growth on rainfall-runoff processes in advance. This study aimed to quantitatively analyze changes in runoff due to rainfall variations under climate change scenarios and land use variations under rural development scenarios. The study area was the Dau Tieng watershed in Southern Vietnam, with a total watershed area of 2700 km^2. A distributed rainfall-runoff model was developed, which could overcome issues relating to calculation time and data scarcity in Southeast Asian watersheds. To capture a variety of land uses and spatially non-uniform rainfall characteristics of the tropical region, the distributed rainfall-runoff model was constructed by representing the watershed as a square mesh aggregate. To greatly reduce the calculation time, the original 90 m resolution digital elevation map data was 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 accurately represent land use in the watershed and simulate runoff from the different land uses. A watershed groundwater tank model covering the entire watershed was incorporated to represent a temporally stable base-flow component. Based on scenario analyses, future changes in rainfall-runoff processes with land use and rainfall changes were quantitatively evaluated not only using annual and peak runoff from the entire watershed but also changes in annual runoff and runoff patterns from each land use.

Keywords: Rainfall-runoff analysis, Kinematic wave model, Rainfall change, Land use change, Vietnam

1. INTRODUCTION

Water scarcity is a major issue in developing, tropical Southeast-Asian countries owing 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 has led to increased water consumption and changes in water usage patterns (ADB, 2016). Moreover, flooding occurs almost every year in the wet season and flat low-lying areas are frequently subjected 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 incorporate reservoir inflows over several decades for optimization of rule curves. However, it is difficult to obtain long-term observation data for 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 area of research. The required characteristics of a rainfall-runoff model include the following: (i) shorter calculation times for global optimization of operation rule curves, (ii) easier estimation of the model parameters for application in watersheds with data scarcity problems, such as in

Southeast Asia, (iii) easy and accurate assessments of the impact of future rural development and climate change on runoff. In this study, a distributed rainfall-runoff model was constructed to represent the spatial distribution of land use and rainfall required in (iii). A wide variety of distributed rainfall-runoff models such as TOPMODEL (Beven et al., 1984; Takeuchi et al., 1999; Kazama et al., 2003), Hydro-BEAM (Hydrological river Basin Environment Assessment Model; Kojiri et al. 1998; Park et al., 2003), and GeoHyMos (Geomorphologically-based Hydrological Modeling System; Ichikawa et al., 2001; Sayama and Takara, 2003; Sayama et al., 2005) have been developed. However, in order to satisfy the required characteristics (i), (ii), and (iii) of the rainfall-runoff model, it is necessary to either improve the existing model or develop a new model. Therefore, a new distributed rainfall-runoff model was developed to satisfy these requirements.

As highlighted above, it is necessary to incorporate the impact of climate change and economic growth on rainfall-runoff processes in advance. In addition, in the optimization of the operation rule curves, it is effective to perform the optimization calculation based on the future rainfall-runoff to develop the operation rule curves. This study aimed to quantitatively evaluate the future change of rainfall-runoff by focusing on these two items: rainfall change induced by climate change and land use change accompanying rural development as a result of economic growth.

2. STUDY AREA

The Dau Tieng watershed, located in Southern Vietnam, is approximately 90 km northwest of Ho Chi Minh City (Figure 1). It covers a total watershed area of 2700 km^2, which is predominantly forest and cropland. The average annual rainfall is 1800 mm; 77% of the rainfall occurring between July and November, with significant spatial variation in rainfall. 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 $\times 10^9$ 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), whereas the city suffers from water scarcity during the dry season (January–June). One of the causes is the inadequacy of water resource 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 (Trieu et al., 2014).

3. 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 representing the watershed as a square mesh aggregate, was developed as shown in Figure 2. To greatly reduce the calculation time for the optimization of the operation rule curves, the original 90 m resolution digital elevation map data was scaled to a resolution of 4500 m. In the model currently presented, 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 accurately represented even with the large mesh size of 4500 m, for a more precise reflection of a variety of present land uses and future land use changes.

The 4500 m meshes comprising the watershed were classified into land-meshes and reservoir-meshes. 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.

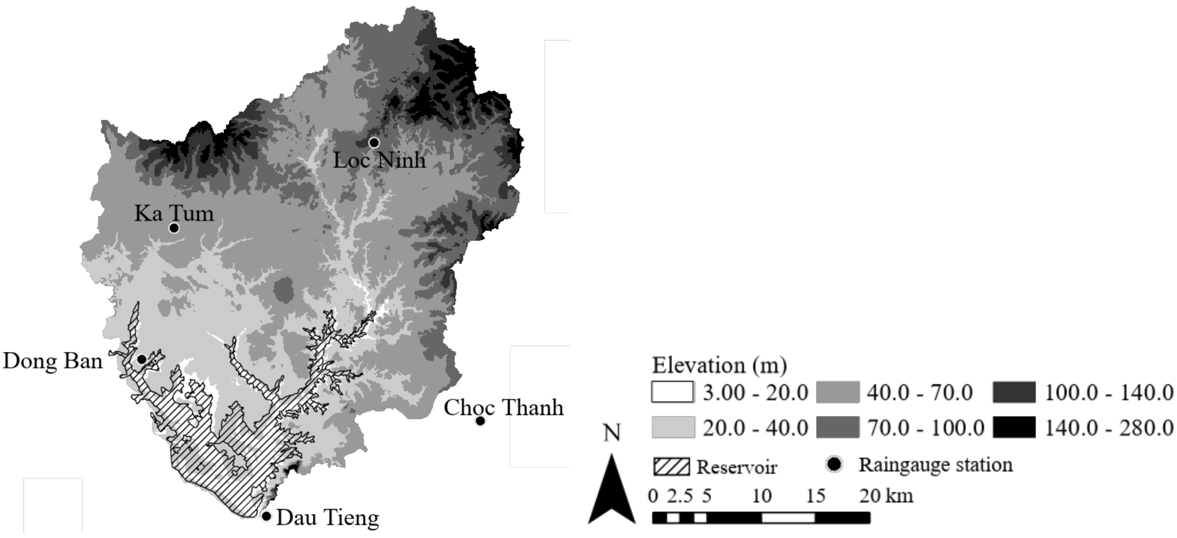

Figure 1. The elevation and rain gauge stations in the Dau Tieng watershed.

As shown in Figure 3, a two-cascade structure for the paddy, upland field, urban tank models, and three-cascade structures for the forest tank models were utilized. 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 such that the water level always maintained the height of the lower-lateral hole assuming that a constant amount of water was stored throughout the year in the 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 into the watershed groundwater tank model was treated as groundwater, and the outflow, which was in proportion to the storage of the watershed groundwater tank model, was equally divided by the number of meshes in the watershed and flowed out to the rivers arranged on each land-mesh element. As rainfall data was only available as daily totals, the runoff from each land use tank model and watershed groundwater tank model were calculated in the form of daily totals. The runoff coefficient of the watershed groundwater tank model was set to 1.0×10^{-3}, the initial storage height was set to the value at the end of the preliminary calculation for the same period. The initial water depth of each land use tank model was also equal to the value at the end of preliminary calculation for the same period.

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 widths. Rainfall on each land-mesh flowed into the 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).

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

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

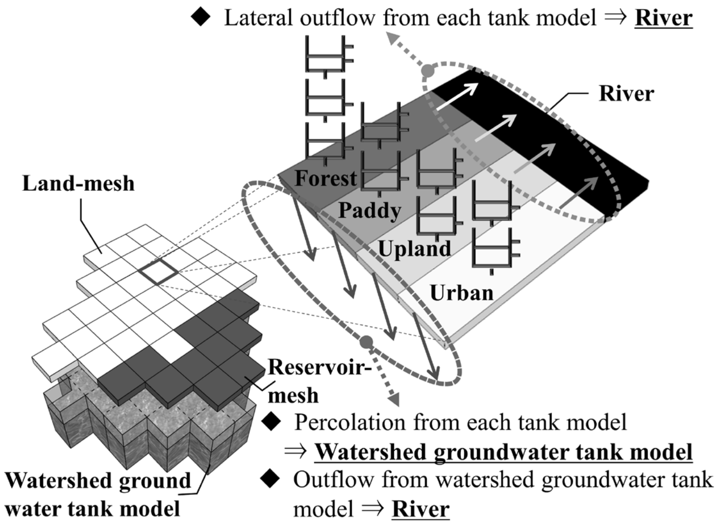

Figure 2. Structure of the distributed rainfall-runoff model.

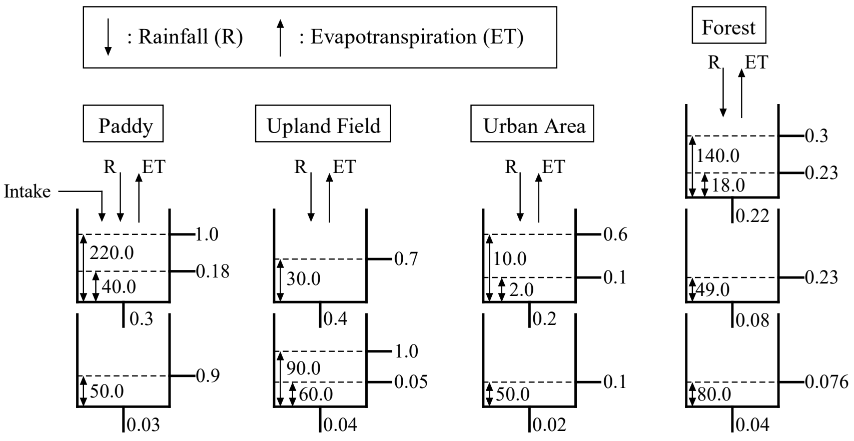

Figure 3. Structure of the tank models for each land use.

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 at 90 s.

4. MODEL APPLICABILITY

Calculations were conducted for each year for 11 consecutive years, 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. Figure 4 shows the result of the calculated watershed runoff and the watershed-averaged areal rainfall in 2007 with the best model fit. We have adopted criteria recommended by Moriasi et al. (2007) to classify the model applicability as very good ($0.75 < \mathrm{NS} \leqq 1.0$), good ($0.65 < \mathrm{NS} \leqq 0.75$), satisfactory ($0.5 < \mathrm{NS} \leqq 0.65$), and unsatisfactory ($\mathrm{NS} \leqq 0.5$). The NS coefficients showed good values in 2000, 2003, and 2007, and satisfactory values were obtained in 2002, 2004, 2005, and 2009. However, the difference in the reproducibility of each year was confirmed as the NS coefficient showed 0.41 in 2001.

The NS coefficient was calculated by dividing the observed values of the watershed runoff in each year into low-water (less than 1 mm/d) and high-water (greater than or equal to 1 mm/d or more). Then, good reproducibility was obtained in 2000, 2003, and 2007, when the NS coefficient in the high-water part was particularly high compared to values from other years. However, the NS coefficient in the low-water part was biased towards low values every year, confirming that reproducibility of the low-water part values was problematic. In addition, as shown in Figure 4, the hydrographs of the observed watershed-averaged rainfall and the discharge in each year indicated that the waveforms were not necessarily similar. Figure 1 indicates that there are few rain gauge stations in the watershed, which has an area of approximately 2700 km^2;

Table 1. Reproduction results of watershed runoff in each year.

Year	Nash-Sutcliffe coefficient
1999	0.50
2000	0.66
2001	0.41
2002	0.56
2003	0.71
2004	0.57
2005	0.54
2006	0.46
2007	0.71
2008	0.48
2009	0.54
1999-2009	0.56

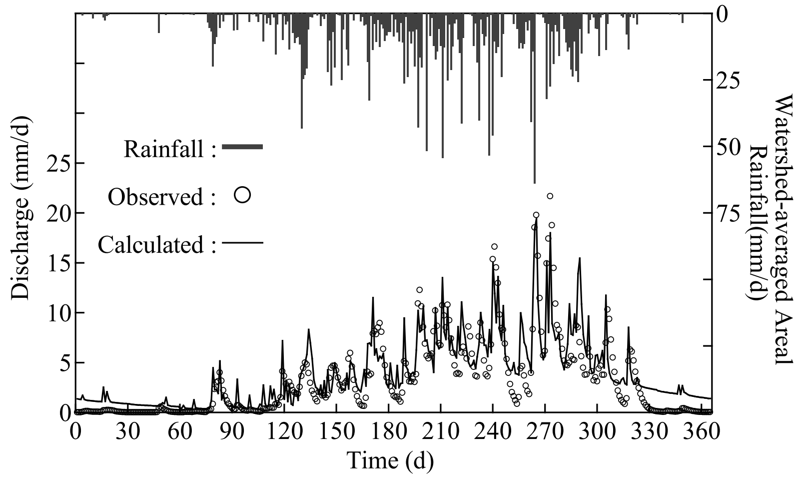

Figure 4. Comparison of the observed and calculated discharge in 2007 (NS=0.71).

consequently, it was not possible to accurately quantify the significantly different rainfall distribution in the watershed.

The difference in runoff characteristics from the watershed examined in Nakagiri et al. (1998; 2000), which were used as references to determine the model parameters, and the watershed examined in this work was a further contributor to the decrease in reproduction accuracy. However, it is difficult to obtain the observed rainfall-runoff data for each land use, which is typically required to determine these parameters. One of the measures is to collectively determine the parameters by an optimization method, but this is difficult because the number of parameters is large, obtaining convergence is difficult, and data for the physical parameters may be missing. On the other hand, the Sugawara's tank model has been previously used for both research and engineering purposes. As a result, input parameters are easy to estimate with reference to previous studies. Given the scarcity of data in Southeast-Asian watersheds, the ability to parameterize Sugawara's tank model was a great advantage.

As highlighted above, this proposed model is highly applicable to watersheds where data scarcity and low data reliability are issues, such as in developing Southeast-Asian countries. To accomplish this applicability, land use tank models are utilized for each mesh element within the distributed rainfall-runoff model. In addition, the mesh size of 4500 m significantly reduced the calculation time and yield reasonable results. Although, the deference in the reproducibility of each calculation year was confirmed, the NS coefficient was 0.56 and satisfactory for 11 consecutive years from 1999 to 2009. Additionally, because reproducibility was particularly good with high-water part, the runoff process after changes in rainfall and land use could be fully evaluated. Therefore, scenario analyses for 11 consecutive years from 1999 to 2009 were conducted.

5. SCENARIO ANALYSES

5.1 Scenarios of land-use change accompanying rural development

In recent years, rapid, rural development has been progressing in Vietnam, and it is expected that the rainfall-runoff processes will also change. Therefore, we conducted scenario analyses assuming land use change accompanying rural development. The following three scenarios were set based on the scenario of land use change in the whole Vietnam from 2007 to 2030 by Van et al. (2013).

- Case 1: Business as Usual (BAU) scenario

The BAU scenario reflects a future in which major socio-economic drivers follow current trends. It assumes that there are no major policy changes (e.g., WTO agreement, REDD, biofuels, etc.). Furthermore, yields will continue to increase at the same pace as in the past. Climate change is assumed to not show any significant impact on agricultural productivity and economic growth, and extreme weather events are not an issue.

- Case 2: High Climate Impact (HCI) scenario

The HCI scenario reflects a global future with rapid temperature change, high sensitivity of crops to global warming, and a CO_2 fertilization effect at the lower end of published estimates. In Vietnam, extreme weather events will be more frequent resulting in flooding in the coastal areas and the Mekong River Delta. Lower yields and flood risks pose a threat to agricultural production and food security and are expected to have a negative impact on GDP growth. No policies are implemented to mitigate or adapt to climate change.

- Case 3: High Economic Growth (HEG) scenario

In the HEG scenario the Vietnamese economy is projected to grow at a higher pace, in line with Vietnamese official growth targets as described by the SEDS (Socio-Economic Development Strategy). A main driver of this growth is assumed to be growth in agricultural yields and official Vietnamese projections for technological change in the manufacturing, and to a lesser extent, the service sector. Climate change is assumed to be absent. The rest of the world is assumed to grow at the same pace.

The land use items shown by Van et al. (2013) were classified into four items: forest, paddy, upland field, and urban area. Here, based on the obtained land use data in 2012, the land use data for 2030 was constructed (Table 2), and the resulting changes in the runoff were predicted.

5.2 Scenarios of rainfall change induced by climate change

In recent years, climate change has become one of the major global scale problems. 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 in the 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 3 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 3. The rain gauge stations used in this study were located in two provinces, the Tay Ninh Province, which included the Ka Tum and Dau

Table 2. The rate of land use change in Dau Tieng Watershed in 2030.

		Area in 2012 (km^2)	Area in 2030 (km^2)	Rate of change (%)
Case 1	Paddy	24.1	19.3	−19.9
	Upland field	180.8	168.7	−6.71
	Urban area	154.8	219.0	+41.5
	Forest	1,733.8	1,686.5	−2.73
	Total	2,093.5	2,093.5	0.0
Case 2	Paddy	24.1	19.9	−17.4
	Upland field	180.8	171.2	−5.34
	Urban area	154.8	221.8	+43.3
	Forest	1,733.8	1,680.6	−3.06
	Total	2,093.5	2,093.5	0.0
Case 3	Paddy	24.1	20.0	−17.1
	Upland field	180.8	161.0	−11.0
	Urban area	154.8	304.0	+96.4
	Forest	1,733.8	1,608.5	−7.23
	Total	2,093.5	2,093.5	0.0

Table 3. 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

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 Figure 1. The rates of rainfall change were different depending on the season. The rainfall amount in each scenario was calculated by using the measured rainfall from 1999 to 2009 and Table 3, while the land use was based on data in 2012.

5.3 Results and Discussion of Scenario Analyses

Table 4 shows the rate of change in the annual runoff and peak discharge in the entire watershed, and Table 5 shows the rate of change in the annual runoff from each land use tank model. In Cases 1 to 3, the increase in the peak discharge in Table 4 was confirmed. Case 3 with the largest urban areas had the greatest increase. However, as shown in Table 2, since the forest area is much larger than the urban area in the study area, it is probable that the increase in the urban area did not have a significant effect on the peak discharge. From Table 5, it may be observed that the annual runoff changes are highly correlated with the rate of change of each land use. Therefore, it is predicted that the peak discharge will increase as paddy, upland field and forest change into urban areas as part of rural development, and that the annual runoff from each land use category will increase or decrease according to the rate of change in each land use category.

In the rainfall change scenarios due to climate change (Cases A to C), both the annual runoff and peak discharge in Table 4 increased. Case C described the largest increase in rainfall-runoff. The peak discharge was confirmed on October 11, 2000, however, the rate of change for the peak discharge in Cases A to C was larger than the rate of change for rainfall in October for each scenario. This was because the rainfall is increasing in all seasons as shown in Table 3, consequently, the watershed was kept moist and the base-flow discharge increased. In addition, in Case B and C, it was confirmed that the number of days of flow into the river from the upland field and forest tank models increased significantly compared to the paddy and urban tank models. Therefore, the annual rates of increase for runoff in the upland field and forest in Table 5 were larger than that in the paddy and urban areas. The rates of change for annual runoff from each tank model in Table 5 demonstrated similar trends as the rate of change for rainfall 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 for 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. In other words, it is expected that the rate of increase and decrease in water level and runoff due to rainfall in paddy fields will be relatively

Table 4. Change of integrating discharge and peak flood in each scenario.

Scenario	Annual runoff change rate (%)	Peak discharge change rate (%)
Case 1	–	+0.32
Case 2	–	+0.48
Case 3	–	+1.19
Case A	+11.9	+14.81
Case B	+20.7	+17.31
Case C	+30.7	+36.36

Table 5. Change of integrating discharge from each land use in each scenario.

Scenario	Change rate of annual runoff from each land use (%)			
	Paddy	Upland field	Urban area	Forest
Case 1	−20.5	−7.4	+40.7	−3.2
Case 2	−18.1	−5.9	+42.5	−3.6
Case 3	−18.4	−12.1	+94.5	−8.2
Case A	+2.4	+16.5	+10.3	+15.7
Case B	+4.1	+26.9	+18.9	+26.6
Case C	+6.0	+39.6	+28.3	+39.9

small compared to that in other land-use types. Based on scenario analyses, future changes in rainfall-runoff processes with land use and rainfall changes were evaluated quantitatively by using not only annual and peak runoff from entire watershed, but also changes in annual runoff and runoff patterns from each land use.

6. CONCLUSIONS

In this study, the distributed rainfall-runoff model, which overcomes the problems of the calculation time and the data scarcity, was developed to quantitatively analyze the future change of rainfall-runoff by focusing on these two items: rainfall change induced by climate change and land use change accompanying rural development as a result of economic growth. To greatly reduce the calculation time, the original 90 m resolution digital elevation map data was 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.

Scenario analysis assuming changes in land use (as a result of rural development) and rainfall change (as a result of climate change) revealed the following: (1) As paddies, upland fields and forests change to urban areas, the annual runoff and peak discharge from each land use increased, (2) As the rainfall increased, the base-flow discharge increased, and the peak discharge might increase more than the rainfall change rate, (3) As the amount of rainfall increased, not only did the amount of runoff from each land use increase, but also the runoff pattern from each land use changed, such as the number of flow days, (4) In paddies where irrigation water was taken, the effect of changes in rainfall on water levels and runoff was smaller than in other land uses. In this way, the future change of rainfall-runoff processes due to rural development and climate change could be quantitatively evaluated based on scenario analysis using this model. 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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