Development of a Grid-based Distributed Runoff Model and Flood Scenario Analyses in Dau Tieng River Watershed, Vietnam

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Abstract: In this study, we propose a grid-based distributed runoff model based on the spatial distribution of rainfall and land use in Dau Tieng River watershed, Southern Vietnam. In the model, the inflow/outflow matrix was integrated to effectively represent water flow between meshes, simplify programming, and shorten calculation time. Model accuracy was almost satisfactory even though rainfall and discharge observations were limited. The model was then applied to predict future changes in runoff resulting from a number of rural development and global warming scenarios. Results of the scenario analyses showed that land use changes due to rural development led to increased runoff and a more peaked hydrograph, and that variations in runoff were proportional to the rainfall variability rate associated with changes in rainfall due to global warming.

Keywords: Distributed model; GIS; Flood analysis; Scenario analysis; Global warming; Rural development

1 Introduction
Southern Vietnam has a typical tropical climate, with 80% of annual rainfall occurring in the wet season, and daily rainfall concentrated between the hours of 14:00 and 18:00. In the wet season, flooding occurs almost every year and flat low-lying areas are frequently subject to damage from inundation (Claudia et al., 2013; Prime Minister of Vietnam, 2007; Xue et al., 2011). It may be said the people living there live with the floods; however, others consider that it is preventing the independent development of Vietnamese society and economy (Otsubo, 2004; Tanji et al., 2004). Furthermore, flood frequency has increased since the mid 1990s due to an increased number, intensity, and discharge of rainfall events associated with global warming and rural/urban development. Therefore, flooding is becoming a significant social problem in Vietnam, as well as in watersheds of many developing countries in Southeast Asia (Huong and Pathirana, 2013). As such, a prompt response is essential.

In order to design policies for infrastructure improvement aimed at flood prevention, it is necessary to predict future flooding using a flood analysis model. To date, several flood analysis models have been proposed; however, the limited availability of hydrologic and watershed data in developing countries makes model application difficult. Lumped-parameter runoff models use observed rainfall and discharge data to determine model structure and parameters, and thus, they are difficult to apply in watersheds lacking observational data. In distributed-parameter runoff models, however, it is possible to set approximate values for model parameters by integrating the momentum equation, based on formulas such as Manning’s, into the model. Hence, they may be applied in watersheds lacking observed rainfall and discharge data (Kadoya, 1979; Shiba et al., 2013).

In this study, we developed and applied a distributed-parameter runoff model in a watershed lacking observed rainfall and discharge data in Southern Vietnam. We also simulated the effects of land use changes associated with rural development, and rainfall changes induced by global warming, and used the model to predicted changes in flood discharge.

2 Study area
2.1 Dau Tieng watershed
The Dau Tieng watershed, located in Southern Vietnam (Figure 1), is an upstream tributary of the Saigon River, which flows from Cambodia into the Eastern Vietnam Sea through the Ho Chi Minh City area. The Dau Tieng watershed is approximately 90 km northwest of Ho Chi Minh City. It has a total watershed of 2,700 km², of which the water surface area accounts for approximately 10%, and ranges in elevation from 24–100 m above mean sea level. Most of the area is covered by forest and cropland. Over the last 30 years, annual average rainfall was 1800 mm, although there is a high degree of variability through the year, and 77% of rainfall occurs between July and November.

Dau Tieng reservoir, located in the downstream of Dau Tieng watershed, is the largest multipurpose reservoir in Vietnam with an effective storage capacity of $1.58 \times 10^9$ m³. The reservoir water is used not only for industrial, domestic, and agricultural demands but also for preserving the river ecosystem, preventing saltwater intrusion, and maintaining freshwater discharge into the river (Ngoc et al., 2011, 2013, 2014).
2.2 Database construction

The databases required for model development were constructed using the Geographic Information System (GIS) ArcGIS 10.3.1 (Esri Company).

2.2.1 Watershed boundary

The watershed boundary was based on a 90 m mesh Digital Elevation Model (DEM), which designated the basin inside the boundary as 1 and the area outside the boundary as 0. The study area was represented by a total of 567,000 meshes when using the 90 m DEM; however, this resulted in an enormous model calculation time. Therefore, to shorten the calculation time, we reduced the resolution of the mesh data from 90 to 900 m, which resulted in a total of 5,670 basin meshes (2,869 land and 354 reservoir). To identify the watershed boundary in the coarse-grained data, the boundary meshes were subdivided into $10 \times 10$, and where there were more 1 s than 0 s, the mesh was classified as basin.

2.2.2 Elevation

The elevation data was also subject to coarse graining; the 90 m mesh data shown in Figure 1 were aggregated into $10 \times 10$ meshes and averaged to give the 900 m mesh elevation. In our model, the calculation used for tracking water flow from a mesh assumed that the water flowed down into the lowest of eight neighboring meshes. However, owing to the DEM coarse graining, there were some examples where the center of nine meshes was the lowest point (i.e. a depression), so we smoothed and revised the elevation data in these cases.

2.2.3 Land use

We obtained 90 m mesh land use data in which every mesh was assigned a number based on its land use type (Figure 2), and carried out coarse graining to convert the 900 m mesh data. The most frequently occurring land use type in each $10 \times 10$ mesh was adopted as the land use type after coarse graining. Additionally, we combined land classes with similar rainfall-runoff characteristics, as shown in Table 1.

There were obvious anomalies in the constructed land use mesh data due to errors in the original data, which were manually corrected using Google Earth satellite images of the area. In addition, owing to the coarse graining, land use types with smaller areas, such as bare field and urban areas, disappeared from the constructed data. The final 900 m land use data are shown in Figure 3.

2.2.4 Rainfall

We used daily rainfall data for five recent flood events (Table 2), recorded at the five stations shown in Figure 4. The Thiessen Polygon Method was used to determine the rainfall station of each mesh.
Hourly rainfall data are necessary for basin scale flood analyses; however, no hourly observations were available for the Dau Tieng watershed. Therefore, daily rainfall data were converted to hourly data using a chart for distributing daily rainfall over a 24 h period, as shown in Figure 5.

The chart is based on rainfall patterns in past flood events in South Vietnam, and expresses the proportion of daily rainfall distributed within each hour. This type of chart is often used in Vietnam, as there are few locations where hourly rainfall data observations are available.

2.2.5 Discharge
To evaluate the accuracy of the completed rainfall-runoff model, we obtained hourly discharge data for the study area (from Dau Tieng Irrigation Exploitation and Management Company, Vietnam).

3 Grid-based distributed runoff model

3.1 Basic equations
The kinematic wave method using Manning’s formula as the momentum equation was adopted as the basic equation for water flow (Kadoya, 1980). Within the Manning’s formula, the equivalent roughness corresponding to each land use can be set, allowing us to reflect current or changed land use in the scenario analyses. In the modeling, we numbered each mesh sequentially from the top left (northwest edge) to the bottom right (southeastern edge), and assigned serial numbers \( k = 1 \)–2869. The reservoir meshes were assigned a uniform number, \( N_i = 2870 \).

Assuming that water flows from the highest mesh \( i \) into the lowest \( j \) of the eight neighboring meshes, the momentum equation was constructed as in Eq. (1).

\[
Q_{ij} = \frac{1}{N_{ij}} B_{ij} h_i R^{\frac{2}{3}} I_j^{1/2}
\]  

(1)

where \( Q_{ij} \) is the outflow from mesh \( i \) to \( j \) (m³/s), \( N_{ij} \) is the average of the equivalent roughness at mesh \( i \) and \( j \) (m⁴⁴³), \( B_{ij} \) is the transverse distance of flow between mesh \( i \) and \( j \) (≈ 900 m), \( h_i \) is water depth in mesh \( i \) (m), \( R_i \) is the hydraulic radius of mesh \( i \) (m), and \( I_j \) is the water surface slope between mesh \( i \) and \( j \). \( N_{ij} \) was set corresponding to the land use of each mesh based on standard values in Kadoya (1980). Values of \( h \) and \( R \) were derived only from mesh \( i \), not the average of mesh \( i \) and \( j \), in order to ensure calculation stability. \( I_j \) was calculated by Eq. (2) and Eq. (3) using elevation data outlined in section 2.2.2.
\[ H_i = EL_i + h_i \quad (2) \]
\[ I_{ij} = \frac{H_i - H_j}{L_{ij}} \quad (3) \]

where \( H_i \) and \( H_j \) are the water level of mesh \( i \) and \( j \) (m), respectively, \( EL_i \) is the elevation of mesh \( i \) (m), \( h_i \) is the water depth of mesh \( i \) (m), and \( L_{ij} \) is the longitudinal distance of flow between mesh \( i \) and \( j \) (900 m).

The continuity equation was designed as Eq. (4).

\[ \frac{d h_{ki}}{dt} = \frac{1}{A} \left( Q_{i,\text{in}} - Q_{i,\text{out}} \right) + r_{ki} \quad (4) \]

where \( k \) is the mesh number of the land area (1 to \( N_l - 1 \), \( N_l = 2870 \)), \( h_{ki} \) is the water depth of mesh \( k \) (m), \( t \) is time (s), \( Q_{i,\text{in}} \) is the inflow to mesh \( k \) (m³/s), \( Q_{i,\text{out}} \) is the outflow from mesh \( k \) (m³/s), \( r_{ki} \) is the effective rainfall of mesh \( k \) (m³/s), and \( A \) is the area of each mesh (= 900 m × 900 m = 810,000 m²). As wet season flood runoff was being modeled, the observed rainfall data were used unmodified as the effective rainfall. In addition, we did not consider evapotranspiration and percolation because of the short-term nature of the flood analysis.

Eq. (4) is a simultaneous ordinary \((N_l - 1)\)-differential equation, and Runge-Kutta-Gill’s Method was adopted as the numerical solution. The time step was set to 120 s. Total discharge from the study area, derived from the outflow of each mesh as in Eq. (1) and Eq. (4), was calculated using Eq. (5).

\[ Q_j = \sum_{i=1}^{N_l} Q_{n_{ij}} + A \cdot n_r \cdot r_{(N_l)} \quad (5) \]

where \( Q_j \) is the total discharge from the study area (m³/s), \( n_i \) is the total number of meshes in which rainfall flows to the reservoir, \( m \) is the mesh number in which rainfall flows to the reservoir, \( Q_{m,N_l} \) is the outflow from mesh \( m \) to \( N_l \) (m³/s), \( A \) is the area of each mesh (= 900 m × 900 m = 810,000 m²), \( n_r \) is the number of reservoir meshes (= 354), and \( r_{(N_l)} \) is the effective rainfall in the mesh \( N_l \) (m³/s).

### 3.2 Inflow/outflow matrix

In model construction, information on the direction of water inflow/outflow to each mesh is required. An inflow/outflow matrix using the elevation of each mesh was designed to extract this information effectively, assist programming, and shorten calculation time. First, we created a square matrix of 2780 rows and columns corresponding to the serial number assigned to each mesh. The initial values of each mesh were set to zero and, based on elevation differences between pairs of meshes, new values were assigned. A value of -1 was assigned to \((i, j)\), when water flowed out from mesh \( i \) to mesh \( j \). Conversely, a value of +1 was assigned to \((j, i)\) as water from mesh \( j \) flowed into mesh \( i \). The inflow/outflow matrix was made for all meshes and used for flow calculations.

### 3.3 Verification data and reproducibility index

Our preliminary calculations showed that the accuracy of observed hourly discharge data, derived from daily rainfall data using the chart in Figure 5, was low. Hence, we judged that verification of model results using hourly discharge data would be difficult. Instead, we used daily discharge data that added up the hourly discharge every 24 h. To evaluate the reproducibility, the absolute error (AE), relative error (RE), \( \chi^2 \) error, and the Nash-Sutcliffe coefficient (NS) were used (Kadoya and Nagai, 1980; Nash et al., 1970).

### 3.4 Determination of model parameters and model applicability

Values for equivalent roughness \( N \) of land cover parameters in the model were first determined using the literature (Kadoya, 1980). Then, we set the value of \( N \) for five stages as shown in Table 3; the value with the highest reproducibility in five flood events was taken as the most suitable model parameter. In addition, we chose a weight for AE that emphasized the role of high water, and one for NS that measured hydrograph compatibility in four indexes because it was a precise evaluation of the flood analysis. Finally, equivalent roughness \( N \) values of 1.5 and 0.4 were adopted for forest and upland field meshes, respectively. The value of \( N \) for urban and commercial areas was set to 0.025. Although these categories disappeared in the coarse-grained land use data, they were still used in the scenario analyses.

### 3.5 Model applicability and discussion

Results of model reproducibility and application of the model to the five flood periods are shown in Table 4 and Figures 6–10. In Table 4, it can be seen that the reproduction result varies with each flood period.

This is also reflected in the calculated and observed discharge hydrographs (Figures 6–10). Flood period 2 was reproduced best (Figure 7), and reproduction of flood period 1 was good. However, flood periods 3–5 (Figures 8–10)

### Table 3: Setting of equivalent roughness

| No. | Forest | Upland field |
|-----|--------|--------------|
| 1   | 1.0    | 0.3          |
| 2   | 1.3    | 0.38         |
| 3   | 1.5    | 0.4          |
| 4   | 1.7    | 0.42         |
| 5   | 2.0    | 0.5          |

### Table 4: Model applicability

| Flood period | AE   | RE   | \( \chi^2 \) error | NS   |
|--------------|------|------|--------------------|------|
| No. 1        | 1.08×10⁶ | 0.384 | 5.43×10⁶          | 0.493 |
| No. 2        | 4.87×10⁶ | 0.265 | 1.88×10⁶          | 0.718 |
| No. 3        | 2.48×10⁶ | 0.702 | 2.69×10⁴          | -0.757 |
| No. 4        | 1.05×10⁷ | 0.502 | 9.69×10⁴          | -7.20×10⁻⁴ |
| No. 5        | 1.71×10⁷ | 0.671 | 1.40×10⁷          | -8.69  |
were not reproduced well by this model. Possible explanations for the poor reproduction results in flood periods 3–5 include the following: (1) the actual hourly rainfall pattern was different from that estimated using the chart for distributing daily rainfall over 24 h; (2) there were large errors in the observed discharge data because observed outflows at Dau Tieng reservoir outlets were collected at 07:00 each day and considered to be daily mean flow, but water level and flows of the reservoir changed significantly during flood events. Moreover, model reproducibility might have been affected by mesh land use choice. The most frequently occurring land use of every 10 × 10 mesh was adopted during coarse graining from the 90 m to the 900 m mesh, and other land use types occurring in the mesh did not contribute to the equivalent roughness of the mesh. However, almost satisfactory reproduction results were
provided for flood periods 1 and 2, even though data were difficult to obtain and calculations were based on limited data. The model is easily transferred to other watersheds by editing the elevation and land use data in a GIS, and changes in flood discharge resulting from changes in the spatial distribution of land use and the spatial/temporal distribution of rainfall can therefore be predicted. In addition, by including the inflow/outflow matrix in the model, calculation time is reduced, making it straightforward to apply to other watersheds. The proposed distributed runoff model is highly appropriate for watersheds with insufficient hydro-meteorological data.

4 Scenario analyses
We applied our distributed runoff model to simulate two scenarios: 1) land use changes due to rural development; 2) changes in rainfall quantity due to global warming.

4.1 Land use change due to rural development scenario
In recent years, rapid urbanization and community development have progressed in all areas of Vietnam, and subsequent land use changes are affecting river discharge. Therefore, we carried out a scenario analysis to consider the impacts of land use changes due to rural development.

4.1.1 Scenario setting
The baseline for land use data was taken as 2006. Land use change in the past 10 years and results of local interviews carried out in May, 2014, were used to set up four scenarios (Table 5).
- Scenario No. 1: current land use (2016). Urban and commercial areas were added to the 2006 data using current satellite images (Google Earth).
- Scenario No. 2: assumes extension of urban and commercial areas from scenario No. 1.
- Scenario No. 3: urban and commercial areas are the same as scenario No. 1, but areas of forest have been developed into upland fields. Forest meshes with relatively low elevations (50 m or less) have been converted into upland field.
- Scenario No. 4: Assumes extension of urban and commercial areas from scenario No. 3 with an expansion rate equal to that in scenario No. 2.

Land use changes were represented by changing the equivalent roughness value $N$. Total discharge from the study area was calculated for the four rural development scenarios and the changes were compared. We used flood periods 1 and 2 for flood event simulation as they were well reproduced by the model.

4.1.2 Results
Table 6 shows the simulation results for the five rural development scenarios. First, land use scenarios No. 1 and No. 2 produced minimal changes to discharge in both flood periods 1 and 2. In these scenarios, upland fields and forest were replaced by urban and commercial areas, which have much lower $N$ values, 1/10–1/100, and associated reduced flow resistance. However, we considered that scenarios Nos. 1 and 2 did not have a significant influence on discharge.
because of their small proportion of urban and commercial areas. Scenario Nos. 3 and 4 (Table 6) produced larger increases in peak flood discharge in both flood periods 1 (Figures 11, 13) and 2 (Figures 12, 14). In these scenarios, we consider that there was a large decrease in flow resistance due to changes in the equivalent roughness value associated with drastic replacement of forest and upland fields with urban and commercial areas. These results demonstrate that an increased discharge and a more peaked hydrograph are associated with land use changes due to rural development.

4.2 Change in rainfall amount due to global warming scenario

Today, global warming is considered as one of the most serious global issues that will inevitably lead to sea level rise and climate change (Luke et al., 2014). Vietnam is said to be one of the countries most at risk from global warming (ISPONRE and UNEP, 2009); thus many research areas and administrative policies concerning global warming have been promoted. In the following scenario analysis, we examine the impact of global warming in terms of changes in the amount of rainfall.

4.2.1 Scenario setting

Two rainfall change scenarios were used in the analysis, for 2050 and 2100. These were produced by the Ministry of Natural Resources and Environment, Vietnam, in 2012, based on rainfall totals from 1980 to 2010 (Tables 7 and 8). The scenarios were applied in two provinces, Tay Ninh, which includes the Ka Tum and Dau Tieng rainfall stations shown in Figure 4, and Binh Phuoc, which includes Loc Ninh, Dong Ban, and Chon Thanh rainfall stations. As in the rural development scenario, data from flood periods 1 and 2 were used in the analysis. Rainfall in each flood period was changed for each scenario, based on data in Tables 7 and 8; then total discharge from the study area was calculated, and differences in the flood hydrograph were examined. Model land use was based on the 2006 data.

4.2.2 Results

Peak flood discharge and percentage increases in flood discharge for each global warming scenario are shown in Table 9, and flood hydrographs are compared in Figures 15–18. First, in the global warming scenario of 2050, the percentage change in the flood peak was +4.98% and −4.57% for flood periods 1 and 2, respectively (Table 9).

| Table 7: Global warming scenario, 2050 |
| --- |
| Province | Month 12–2 | Month 3–5 | Month 6–8 | Month 9–11 |
| Tay Ninh | −8.9 | −4.7 | +3.2 | +5.0 |
| Binh Phuoc | −7.1 | −4.8 | +1.7 | +4.9 |

| Table 8: Global warming scenario, 2100 |
| --- |
| Province | Month 12–2 | Month 3–5 | Month 6–8 | Month 9–11 |
| Tay Ninh | −17.0 | −9.0 | +6.0 | +9.6 |
| Binh Phuoc | −13.6 | −9.2 | +3.3 | +9.4 |

| Table 9: Peak flood and percentage change in each scenario |
| --- |
| Flood period | Peak flood (m³/d) | (%) | Peak flood (m³/d) | (%) |
| Original | 6.22×10⁷ | — | 4.82×10⁷ | — |
| 2050 | 6.53×10⁷ | +4.98 | 4.60×10⁷ | −4.57 |
| 2100 | 6.82×10⁷ | +9.61 | 4.40×10⁷ | −8.75 |
This corresponds with the changes in rainfall shown in Table 7. Both provinces showed increased rainfall in September, during flood period 1, and decreased rainfall in April, during flood period 2. The close correspondence between changes in rainfall and discharge is reflected in the hydrographs shown in Figures 15 and 16. In the global warming scenario for 2100, as for 2050, the percentage change in flood discharge in each period corresponds to the percentage rainfall change, as shown in Table 9 and Figures 17 and 18.

The above result demonstrates that rainfall changes associated with global warming are matched by corresponding changes in flood discharge in the study area.

5 Conclusions
In this study, we constructed a grid-based distributed runoff model for the Dau Tieng watershed in Southern Vietnam, and used it for flood discharge scenario analyses. The distributed runoff model was based on DEM and land use data of the study area, and a kinematic wave method, using Manning’s formula as the momentum equation, was adopted as the basic equation. An inflow/outflow matrix was integrated to effectively express water flow between meshes, simplify the programming, and shorten calculation time. We tested the model using the five most recent flood events, with equivalent roughness values of 1.5 for forest meshes, 0.4 for upland field meshes, and 0.025 for urban and commercial area meshes. However, some of the flood periods were difficult to reproduce because hourly rainfall observations were not available, and the observed hourly discharge data was less accurate. In addition, the coarse graining of the original study area data is regarded as one of the reason for low reproducibility.

We carried out scenario analyses using the proposed model, assuming land use changes due to rural development and rainfall changes as a result of global warming. The results revealed that an increased flood discharge and a more peaked runoff hydrograph were associated with land use changes due to rural development. Moreover, in response to rainfall changes associated with global warming, changes in flood discharge approximately correspond to the percentage change in rainfall.

In the distributed runoff model constructed in this study, in principle, rainfall and discharge observations are required in order to determine model structure, including model parameters. However, we found that we could construct the model for a basin lacking rainfall and discharge observations by adopting the Manning’s formula as the momentum equation, as it was therefore possible to estimate the model parameter of equivalent roughness. In addition, owing to defining the inflow/outflow matrix that describes the relationship between meshes in the processing of water flow, namely, the inflow/outflow relationship, we were able to construct a model that could be easily applied to other basins. By improving the applicability of flood analysis models, this research aims to contribute towards developing more effective flood prevention policies in Vietnam and elsewhere.

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