

A NEW HYDROLOGIC RESPONSE FUNCTION PHYSICALLY DERIVED FROM DEM AND REMOTE SENSING IMAGE

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This study proposes a physically-based distributed instantaneous unit hydrograph by adopting the concept of IUH, which is derived based on physical runoff mechanism by combining DEMs, remote sensing and kinematic wave approximation. The heterogeneity of the watershed can be well represented by DEMs, remotely sensed data and kinematic wave approximation in the proposed physically-based distributed instantaneous unit hydrograph. As for ungauged area or the area with poor hydrologic record, the geomorphologic IUH proposed in the study is expected to be a reference for water resources designing and evaluation.

INTRODUCTION

Physically-based spatially distributed models provide a thorough description of watershed hydrologic scheme through rainfall to runoff simulation. However, massive computation task and CPU time diminish the advantage of this kind of models. An IUH based on a time-area method concept derived by viewing a watershed as a distributed nonlinear system is proposed in this study, which well describes a watershed hydrologic behavior within lighter computational burden.

The central idea of the time-area method is a time contour or an isochrone. If one uses orthogonal grid-based data to describe watershed relief, an isochrone is a contour joining those grid cells in the watershed which are separated from the outlet by the same travel time. Hence, the time-area diagram indicates the distribution of travel time of different parts of the watershed drains to the outlet [1]. Through describing the water movement mechanism by kinematic wave approximation, the travel time to the outlet is calculated; and exploring the relationship between the travel time and the number of grid cells, a histogram (i.e. time-area diagram) is extracted.

The hydrologic response function is viewed as a time-varient characteristic function in the study and is developed to include the effect of water movement mechanism in the output watershed hydrograph. Since the IUH is derived by using kinematic wave approximation, the time base of the IUH is related to the given rainfall intensity. Superpositioning of different IUHs is adopted when a hydrograph is composed by different rainfall duration.

In this study, a distributed instantaneous unit hydrograph is established and applied to the Yasu River basin (377km²), which is located in Shiga Prefecture, midwest side of

Honshu, Japan. The distributed instantaneous unit hydrograph proposed herein reflects topographic feature(e.g.: land cover, slope, etc.) of the basin in the hydrologic response function, including the water movement scheme in rainfall-runoff processes.

DERIVATION OF DISTRIBUTED INSTANTANEOUS UNIT HYDROGRAPH

A concept of the instantaneous unit hydrograph has been revealed by Clark [2] in 1945. His time-area curve is the earliest geomorphologic rainfall-runoff model in the world. This kind of model needs no hydrologic record. Only geomorphologic data to establish the relationship between rainfall and runoff is requested. In this study, kinematic approximation is used to calculate the time of water movement between DEM grid cells. Then by dividing the basin into several isochrones, the time-area histogram which denotes the relationship between travel time and area is derived.

Process of DEM

The DEMs data used in the study is 50m grid digital map, published by Geographical Survey Institute, Japan, in 1997. The DEM process algorithm used in this study is based on the algorithm proposed by Jenson and Domingue [3] and Jenson and Trautwein [4]. Comparing the elevation of the central grid to its eight adjacent cells, the flow direction of the central grid is determined. According to the flow direction, the flow path from the specific grid to the outlet of the basin and the drainage area of the grid is retrieved; and the distance of each grid inside the basin to the outlet is calculated according to the length of the flow path as shown in Figure 1.



Figure 1. Distance to the outlet of the basin. (unit: m)

Use of kinematic wave approximation

The distance-area curve obtained above is simply space related, and no temporal relationship is included. To obtain the temporal relationship kinematic wave approximation is used for transferring the spatial relationship into a temporal one. For this purpose, land use data for determining roughness coefficients and rainfall data for outflow calculation is necessary.

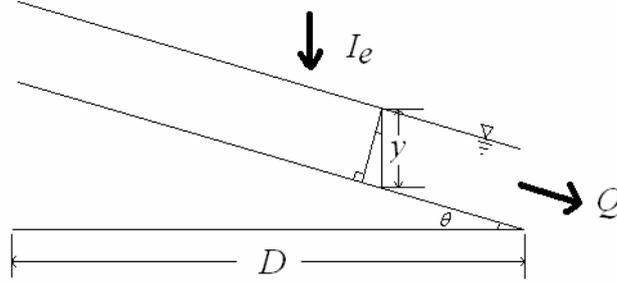


Figure 2. Using kinematic wave approximation to calculate the travel time between grids.

Consider a profile of a single grid cell as shown in Figure 2. For a given rainfall excess intensity i_e , the equilibrium flow discharge for a given drainage area (contribution area) A is equal to $i_e A$. By calculating the discharge of each grid inside the basin, the distributed instantaneous unit hydrograph of the basin is retrieved through describing the mechanism of the water movement.

To consider the direct runoff velocity change due to rainfall excess intensity, kinematic wave approximation is included into the extraction of the IUH. With the velocity of water movement between grids, the travel time of water movement is obtained.

The momentum equation of kinematic wave can be expressed in the form as Eq.(1):

$$q = a(y \cdot \cos \theta)^m \quad (1)$$

where q denotes discharge per unit width, a and m are constants, y denotes water depth vertical to the datum and θ denotes the angle between flow direction and the horizon. This reveals the relationship between the velocity and water depth.

By comparing the equation with Manning's equation, a is expressed in the form as Eq.(2):

$$a = \frac{\sqrt{\sin \theta}}{n} \quad (2)$$

where n denotes Manning roughness coefficient. Substituting Eq.(2) into Eq.(1), and transferring the unit width discharge q into water discharge by multiplying rainfall intensity and drainage area A , water depth y is represented as Eq.(3) as below:

$$y = \sec \theta \cdot \left(\frac{n}{\sqrt{\sin \theta}} q \right)^{\frac{1}{m}} = \sec \theta \cdot \left(\frac{n}{\sqrt{\sin \theta}} \frac{I_e \cdot A}{B} \right)^{\frac{1}{m}} \quad (3)$$

where B denotes the width of the cell orthogonal to the flow direction. By retrieving the water depth of the grid, travel time t of the grid is solved by dividing distance by water movement velocity as shown in Eq. (4)

$$t = \frac{D \cdot \sec \theta}{V} \quad (4)$$

where V denotes water movement velocity.

Roughness coefficient determination

The roughness coefficient was determined from ASTER remote sensing image classification (Figure 3). ASTER is a high efficiency optical sensor equipped on satellite TERRA which covers a wide spectral region from the visible to the thermal infrared by 14 spectral bands. A 2nd level processed image is used. Data acquisition date is 8th, Dec. 2003. The ERDAS IMAGINE is used as a tool to proceed the atmosphere correction, geometric correction and land cover classification.

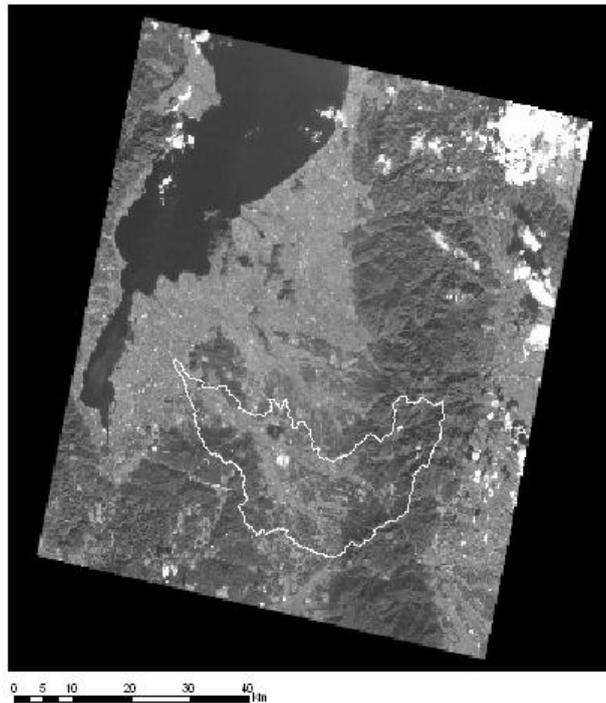


Figure 3. ASTER image, the white line delineate watershed boundary.

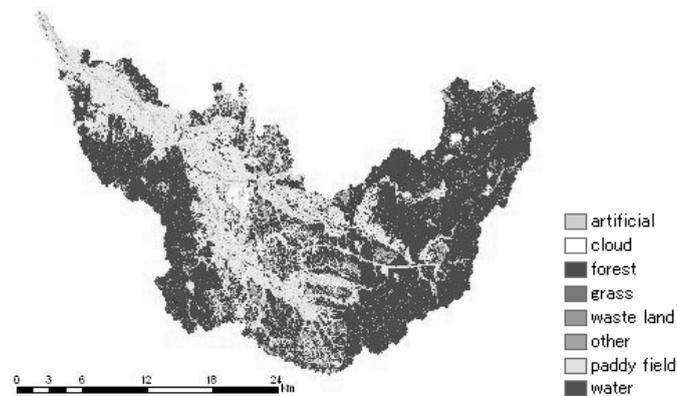


Figure 4. Land cover classification by using the ASTER image.

Table 1. The category of the land cover and its percentage inside the basin.

Categories	Artificial	Paddy field	Other usage	Water	Forest	Wasteland	Grass
Percentage	12.65%	12.40%	0.02%	0.04%	52.62%	6.60%	2.72%

The land cover is divided into 8 categories: paddy field, forest, artificial object, wasteland, cloud, other usage, water and grass land. Figure 4 shows the result of classification. After the procedure of classification, the area classified as cloud is replaced by using an existing land use data. The land use data is acquired through the web page of Ministry of Land, infrastructure and transport, Japan. Time of land use data acquisition is 1997. Table 1 shows the percentage of each category inside the watershed. The value of the Manning roughness coefficient was calibrated by several rainfall events with the land use classification.

Rainfall data

The rainfall data was collected from four rainfall gauging stations inside the Yasu River basin; Yasu, Minakuchi, Kouka and Oogawara. The average precipitation was calculated according to the weight of each rainfall station obtained by using Thiessen polygon method.

Utilization of IUH

Rainfall event with different rainfall intensity will cause different outflow hydrograph. That is because the overland flow velocity increases with rainfall intensity. The IUH proposed in this study can well reflect such hydraulic phenomenon. As shown in Figure 5, the peak magnitude of the proposed IUH is rising while rainfall excess intensity is increasing. Also the time of the peak of the proposed IUH declines with rainfall excess intensity is raised. This implies that the proposed model can well reflect the nonlinearity caused by different rainfall excess intensity.

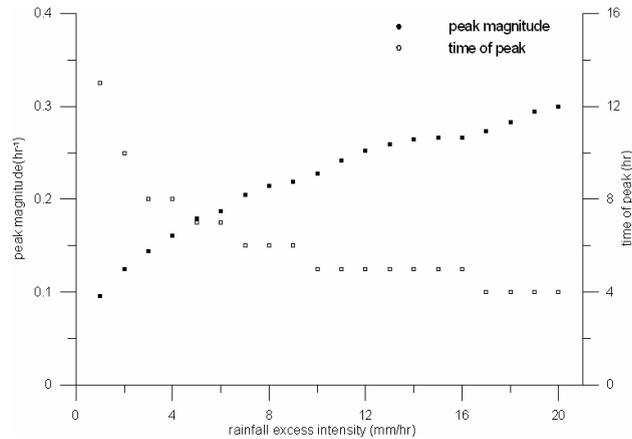


Figure 5. Relationship between rainfall excess intensity to peak magnitude of IUH and time of IUH peak.

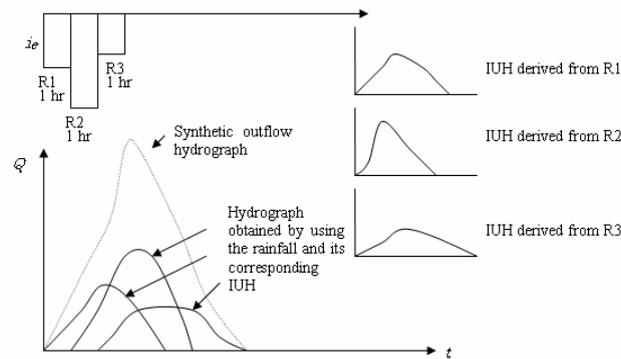


Figure 6. Use of rainfall excess intensity and its related IUH to retrieve outflow hydrograph.

Minshall [5] found that one UH could not adequately define the shape of a hydrograph derived from a storm of unit duration. Consequently, different UHs are required to represent the watershed runoff response if the rainfall intensity varied. As shown in Figure 6, different IUHs and its related rainfall excess intensity is used to compose the outflow hydrograph. By applying the tools and data mentioned above, a physically based watershed instantaneous hydrograph is extracted.

SIMULATION RESULTS

Two storm events at Yasu River basin were simulated as shown in Figure 7 and 8 as below. As in Figure 7, the error of peak discharge is 1.27%, and the error of time to peak is 2 hour. As in Figure 8, the error of peak discharge is 6%, and the error of time to peak is 1 hour.

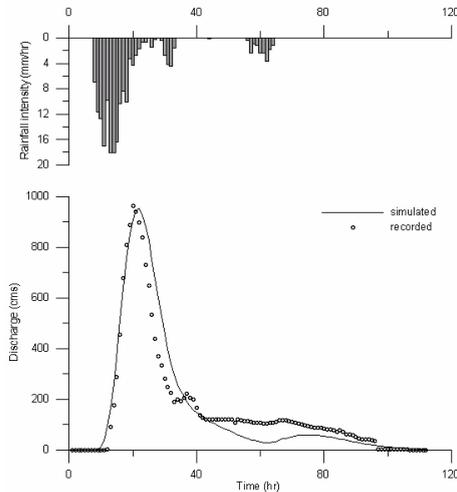


Figure 7. simulation result of 1997/07/26

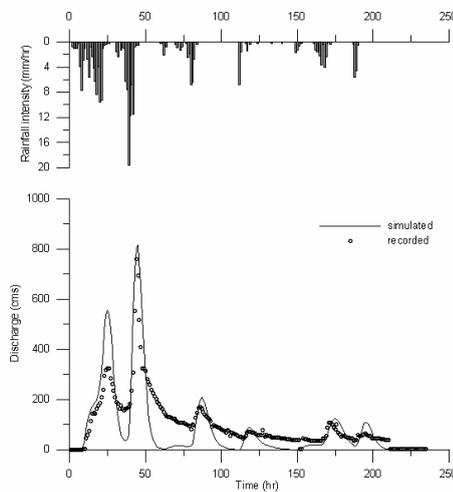


Figure 8. Simulation results of 1998/09/21

Table 2. Simulation results.

Rainfall Event	1997/07/26.03-1997/07/30.03	1998/09/21.00-1998/09/30.00
EQ_p	1.27%	6%
ET_p	2hr	1 hr
R^2	0.9349	0.77
IOA	0.9791	0.90
$EQ_p (\%) = \frac{(Q_p)_{simulated} - (Q_p)_{recorded}}{(Q_p)_{recorded}}$		Q_p : peak discharge
$ET_p (hr) = (T_p)_{simulated} - (T_p)_{recorded}$		T_p : time to peak
$R^2 = 1 - \frac{(\sum (Q_{recorded} - Q_{simulated})^2)}{(\sum (Q_{recorded} - \bar{Q}_{recorded})^2)}$		Q : discharge
$IOA = 1.0 - \frac{\sum [(Q_{recorded})_i - (Q_{simulated})_i]^2}{\sum [(Q_{recorded})_i - \bar{Q}_{recorded}]^2 + [(Q_{simulated})_i - \bar{Q}_{simulated}]^2}$		

The results show that the instantaneous unit hydrograph simulated the rainfall-runoff relationship of the basin well. The detail of the rainfall events and simulation results is shown in Table 2.

CONCLUSIONS

Manipulating UH to estimate the stream flow hydrograph of the specific point needs lots of hydrologic record (e.g. rainfall data, discharge data). For ungauged areas and those

basins where the hydrologic environment is changed by human activity or urbanization, it is inadequate to adopt the method.

To solve the problem, a geomorphologic instantaneous unit hydrograph is proposed. The heterogeneity of the watershed, orographical feature and land cover can be well represented by using DEMs, remote sensing images and kinematic wave approximation.

The time base of the proposed IUH is determined by rainfall excess intensity. Time of peak and peak magnitude of the IUH also change with different rainfall excess intensity. This means the proposed IUH can reflect the impact of varied rainfall intensity. Use of remote sensing images to determine roughness coefficient makes the model enable to reflect the impact of land cover changing. This implies the method is capable to adapt to a watershed with poor hydrologic records. The method can be recognized as a good reference for water resources planning and design for ungauged areas and those basins where the hydrologic environment has been changed by human activity or urbanization.

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