RAINFALL-RUNOFF SIMULATION BY USING DISTRIBUTED INSTANTANEOUS UNIT HYDROGRAPH DERIVED FROM APPLYING FLOW ACCUMULATION VALUE OF DEM

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Flow Accumulation Value (FAV) denotes water accumulates along the flow paths dictated by the topography. For any specific location in a basin, by adjusting FAV to proper units, the flow accumulation is synonymous with drainage area. In this study, by combining DEM and Kinematic Wave routing method, discharge of the surface runoff of specific location inside the basin within given rainfall intensity has been calculated, and water depth and velocity also has been derived. By adopting the concept of IUH and through describing the runoff mechanism, the traveling time of water movement from any specific location of the basin to the outlet is examined; consequently, a distributed instantaneous unit hydrograph of the basin is derived.

Key Words: *IUH, Flow Accumulation Value, DEM, GIUH*

1. INTRODUCTION

Use of unit hydrograph(UH) for predicting storm runoff is a criticized, but widely used and accepted, tool in hydrologic analysis and synthesis[1]. Unit hydrograph theory has been applied in estimating the relationship between rainfall and runoff for many years. However, manipulating the unit hydrograph to estimate the outflow hydrograph of the specific basin needs lots of hydrologic record (e.g.: rain fall data, discharge record) to calibrate the model. Thus, for ungauged area and those basin where the hydrologic environment has been changed by human activity or urbanization, it is inadequate to adopt the model.

In a basin delineated by watershed divide, surface runoff inside the area drains to the unique outlet of the area. To view the basin as a linear system and use a hydrologic response function to simulate the relationship between rainfall and runoff was started by Sherman[2]. Clark[3] proposed the time-area method. He used the time-area curve of the basin as an input to linear reservoir and obtained the outcome hydrograph as the basin hydrologic response function. This could be seen as the prototype of the instantaneous hydrograph. Johnston and Cross[4] modified the time-area curve by including the impact of landscape slope to the water movement, which made the hydrologic response function could reflect the effect of the landscape to the watershed. Edson[5] assumed the shape of the basin hydrologic response function was a parabola, and simplified the impulse response function to a two parameters characteristic function which related to the watershed geomorphic factors. The Soil Conservation Service[6] assumed the watershed unit hydrograph as a simple triangle, which simplified the analysis of small scale watershed. Gupta et al.[7] approached the watershed hydrologic response function in statistic way, that is directly related the peak discharge of the watershed as a function of four geomorphic factors.

Thus, the unit hydrograph theory plays a very important role in the developing of deterministic hydrology. The geomorphologic instantaneous unit hydrograph combined the watershed river network to the estimation process of the hydrologic response function (Rodriguez-Iturbe and Valdes[8]; Gupta et al.[9]; Lee and Yen[10]). Lee and Yen[10] derived the watershed hydrologic response function which could reflect the impact of rainfall intensity to the outflow hydrograph by combining the kinematic wave and GIUH. **Table 1** shows the brief

Table 1 The development of hydrologic response function.

Unit Hydrograph	Sherman(1932)
Instantaneous Unit Hydrograph	Clark (1945) Johnston and Cross(1949) Edson(1951) Gupta et al. (1969)
Geomorphologic Instantaneous Unit Hydrograph	Rodriguez-Iturbe and Valdes(1979) Gupta et al. (1969), Gupta et al. (1980) Lee and Yen(1997)

development of the watershed hydrologic response function.

Most researches view the hydrologic response function as a time-invarient characteristic function, and ignore the impact of hydraulics scheme to the watershed hydrograph. The time base of the unit hydrograph is related to rainfall duration and nothing to do with rainfall intensity in the UH theory. Superpostioning will be adopted when a hydrograph is composed by different rainfall duration. However, according to former researches, rainfall event with different rainfall intensity will cause different outflow hydrograph. Also the overland flow velocity will increase with rainfall intensity. Consequently, in order to simulate the rainfall-runoff relationship precisely, adopting hydraulics to analysis the overland flow movement scheme is a must. The GIUH includes the geomorphic factors and rainfall intensity into the watershed hydrologic response function. However, the acqusition of geomorphic factors is a heavy burden, also the traveling time computaion is heavy. If the watershed hydrologic response function could be derived directly from the DEM data without any further computation, it could simplify the derivation of such hydrologic response function.

In this study, a distributed instantaneous unit hydrograph is established by combing hydrology and hydraulics, and applied in the Yasu River basin(377km^2). The distributed instantaneous unit hydrograph proposed herein reflects topographic feature(e.g.: land space use, land cover, slope, etc.) of the basin in hydrologic response function, and also consider the water movement scheme which caused by the rainfall processes.

2. DERIVATION OF THE DISTRIBUTED INSTANTANEOUS UNIT HYDROGRAPH

The derivation of the distributed instantaneous unit hydrograph could be divided into several steps as below:

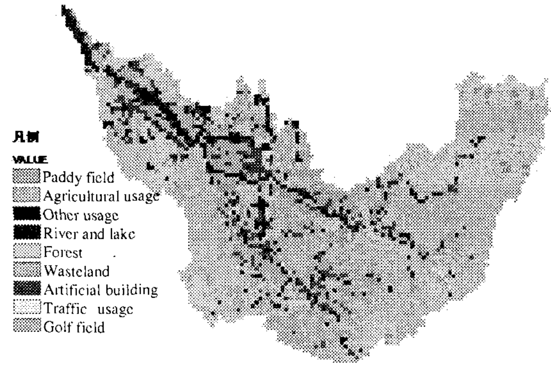

Fig.1 Land use of Yasu River basin.

(1) Usage of DEM

Concept of the instantaneous unit hydrograph has been revealed by Clark[3] in 1945. His time-area curve is the earliest geomorphologic rainfall runoff model in the world. Model like this needs no hydrologic record but only geomorphologic data to establish the relationship between rainfall and runoff. By dividing the basin into several isochrones, the time-area histogram which denotes the relationship between travel time and area could be derived. Here, DEM is used efficiently to extract the geomorphic factor. The DEM algorithm using in this study is based on the algorithm proposed by Jenson and Domingue[11]. The main idea is by comparing the elevation of the central grid to its eight adjacent cells, the flow direction of the central grid could be 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 could be retrieved; the distance of each grid inside the basin to the outlet is be calculated according to the length of the flow path.

(2) Extraction of instantaneous unit hydrograph

The distance-area curve obtained from the previous procedure is simply space related; no temporal relationship is included. In order to obtain the temporal relationship of any point inside the basin to the outlet, kinematic wave was used, in this study, to transfer the distance into time.

a) The determination of the overland flow roughness

In this study, the roughness coefficient was determined from the land use data in 1977 acquired through the web page of Ministry of Land, infrastructure and transport, as shown in **Fig.1**. The original land use data was divided into 12 categories: paddy field, agricultural usage, forest, artificial building, traffic usage, wasteland, other usage, river and lake, coast, ocean and golf field. **Table 2** shows the category of the landuse and its

Table 2 Category of land use and its percentage.

Categories	Percentage
Paddy field	19.39%
Agricultural usage	2.41%
Other usage	3.36%
River and lake	4.47%
Forest	59.70%
Wasteland	2.01%
Artificial building	6.38%
Traffic usage	0.36%
Golf field	1.92%

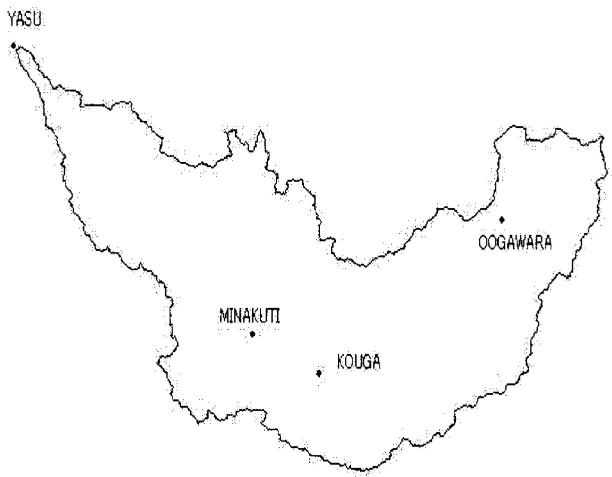

Fig.2 Locations of the rainfall stations.

percentage inside the basin. The value of the Manning roughness coefficient was calibrated by several rainfall events.

b) Rainfall data

The rainfall data was collected from four rainfall gauging stations inside the Yasu River basin, they are Yasu, Minakuti, Kouga and Oogawara, as shown in **Fig.2**. The average precipitation was calculated according to the weight of each rainfall station which obtained by using Thiessen polygon method.

c) Extraction of the IUH

As in **Fig.3**, the watershed is divided into several time zones. In each time zone, the time which water drains to the outlet of the watershed is assumed to be the same. Suppose one unit rainfall excess happens on the basin at time step t = 0, then the travel time that runoff drains from zone A_1 to the outlet is one unit time step, and the volume of the water is A_1. Consequently, a time-area histogram could be derived as shown in **Fig.4**. This is the time-area method proposed by Clark[3]. By utilizing the DEM, the distance of each cell to the outlet of the basin according to the flow path could be easily obtained as shown in **Fig.5**.

By comparing the elevation of adjacent grid cells

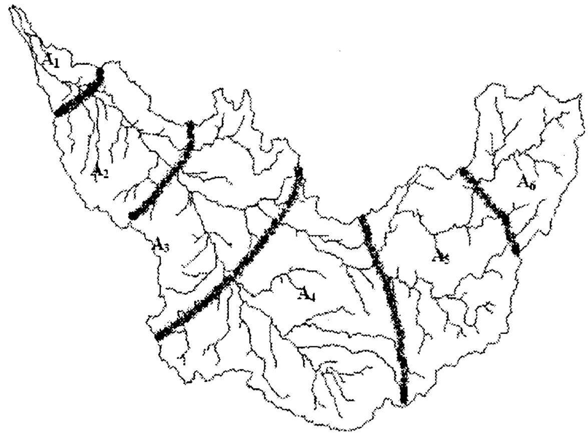

Fig.3 Time-area graph.

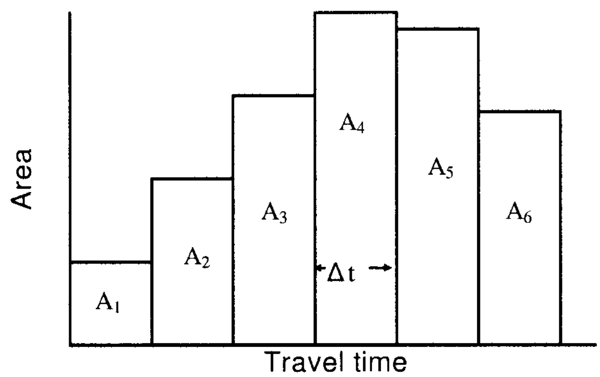

Fig.4 Time-area histogram.

around the specific one, flow direction could be determined. By counting the number of cells which drains into the specific cell according to the flow direction, the Flow Accumulation Value (FAV) could be counted. **Fig.6** shows the result. By adjusting FAV to proper unit, FAV is synonymous with drainage area. The discharge over the grid cell could be calculated by given rainfall intensity, duration and drainage area through kinematic wave equation. The direct runoff produces by rainfall excess was divided into overland flow and channel flow in this study, as to reveal the different mechanism of water movement.

For a given rainfall intensity i_e, the equilibrium flow discharge Q_0 is equal to i_eA, where A is drainage area. By acquiring the discharge of each grid inside the basin, the distributed instantaneous unit hydrograph of the basin could be retrieved through describing the mechanism of the water movement. **Fig.7** and **Fig.8** show the relationship between FAV and the discharge, and the dimensionless IUH which is derived from previous steps.

Here, to consider the direct runoff velocity change due to rainfall intensity, kinematic wave theory is included into IUH. With the velocity of water movement from grid to grid and the distance between grids, the traveling time of water

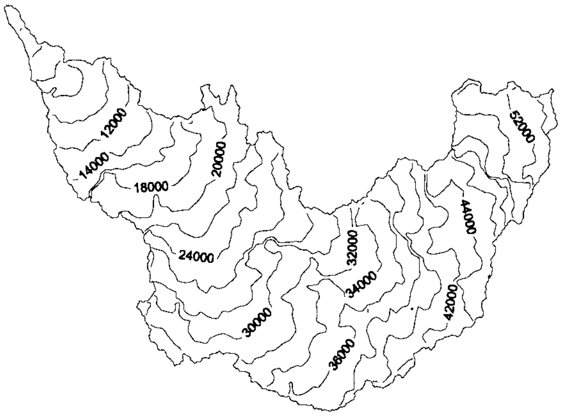

Fig.5 Distance to the outlet of the basin.

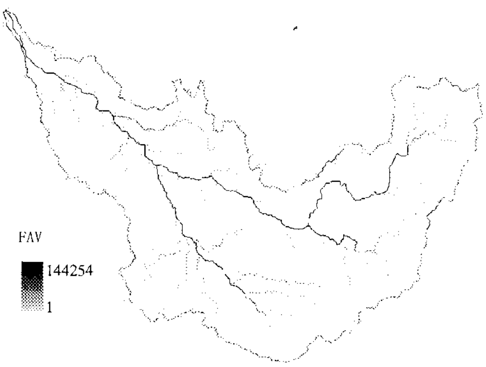

Fig.6 FAV of Yasu River basin.

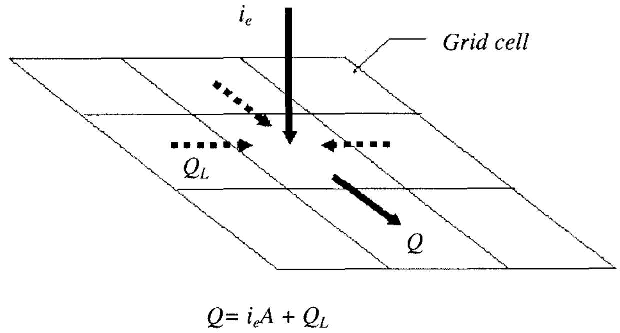

Fig.7 The relationship between the FAV and the water depth on each cell. Q_L denotes lateral inflow of the central cell.

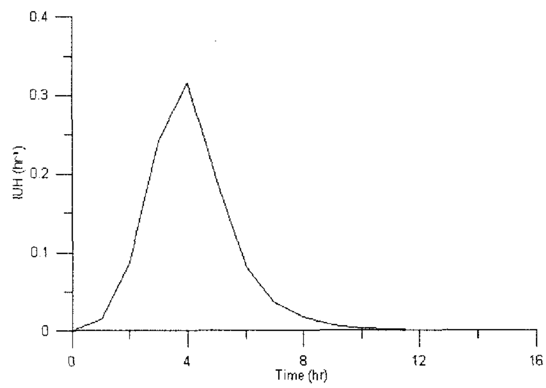

Fig.8 Instantaneous Unit hydrograph of Yasu River Basin.

movement is obtained. The momentum equation of kinematic wave could expressed in the form as Eq.(1):

$$V = \alpha y^{m-1} \tag{1}$$

where V denote velocity, α and m are constants, y denotes water depth. This reveals the relationship between the velocity and water depth.

By comparison the equation to Manning's equation, α is expressed in the form as Eq.(2):

$$\alpha = \frac{\sqrt{s}}{n} \tag{2}$$

where s denotes slope and n denotes Manning roughness coefficient. Substitute Eq.(2) into Eq.(1), FAV is converted into water discharge by multiplying rainfall intensity and grid area, which can solved for water depth y as Eq.(3) as below:

$$y = \left(\frac{n}{\sqrt{s}} q\right)^{\frac{1}{m}} = \left(\frac{n}{\sqrt{s}} \frac{Q_0 \cdot FAV}{B}\right)^{\frac{1}{m}} \tag{3}$$

where q denotes discharge per unit width, Q_0 denotes discharge of single grid under given rainfall Intensity and B denotes the width of the cell.

By retrieving the water depth of the grid, traveling time of the grid is solved by dividing distance by water movement velocity, and IUH capturing the effect of rainfall intensity is established.

3. SIMULATION RESULTS

As mentioned above, different rainfall intensity and different Manning roughness lead to different IUH. **Fig.9** shows the simulation results by using different IUH which extracted under different given rainfall intensity. In this study, two storm events of Yasu River basin were simulated as shown in **Fig.10** and **Fig.11** by using single IUH in specific rainfall intensity.

For the event of 19th to 22nd June, in 1997, single IUH with the rainfall intensity of 10 mm/hr fits best to the observed hydrograph. During the period, average rainfall intensity is 11.71 mm/hr. As in **Fig.10** the error of peak discharge is -2.45%, and the error of time to peak is 1 hour. As for the event of 18th September to 2nd October, 1998, in the case the average rainfall intensity is 2.09 mm/hr, the rainfall intensity at 5 mm/hr fits the best. As in **Fig.11** the error of peak discharge is -4.56%, and the error of time to peak is 3 hour.

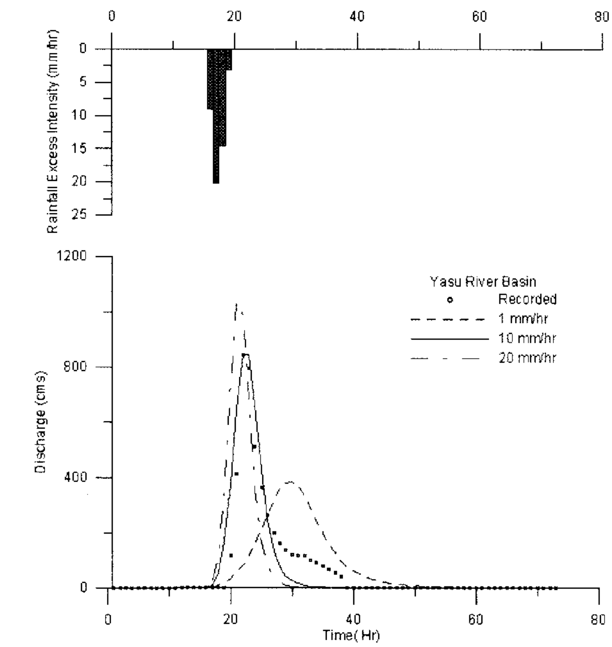

Fig.9 Simulation result by using IUH derived from different rainfall intensity. (1997/06/19.17-1997/06/22.02)

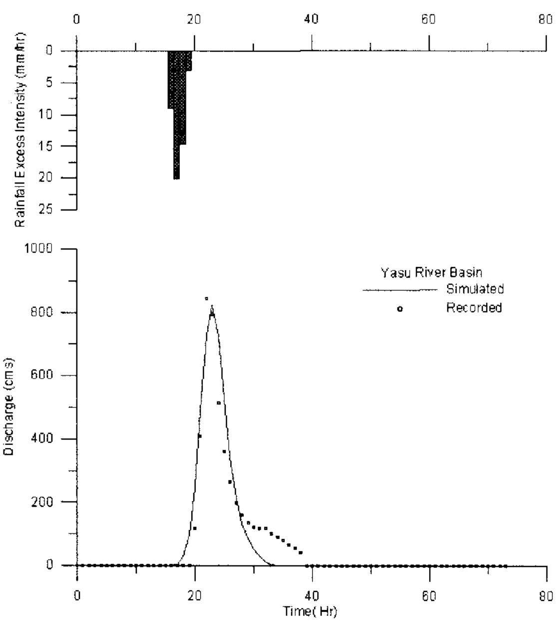

Fig.10 Simulation result by using single IUH. (1997/06/19.17-1997/06/22.02, *Ie*=10mm/hr)

The basic assumption of IUH is that the system is linear, which implies that the principle of proportionality and superposition is adequate in the processing. Synthetic outflow hydrograph by using multiple IUH derived from different rainfall intensity is examined in this study. **Fig.12** shows the concept of composing of different hydrograph which derived from different rainfall intensity. The result of adding the outflow hydrograph produced from IUH of specific rainfall intensity at

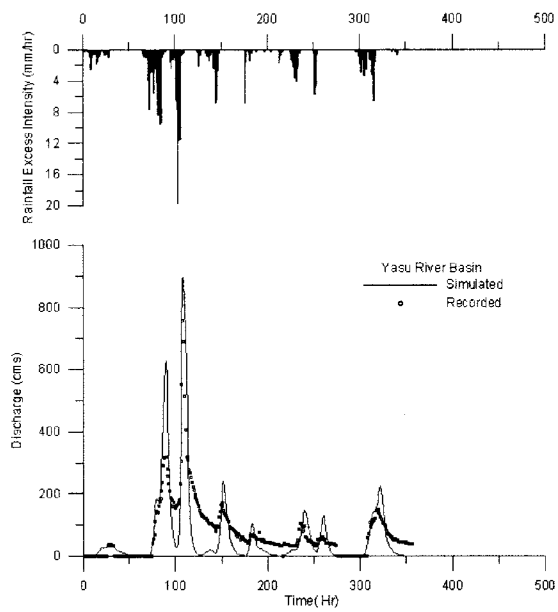

Fig.11 Simulation result by using single IUH. (1998/09/18.08-1998/10/02.12, *Ie*=5mm/hr)

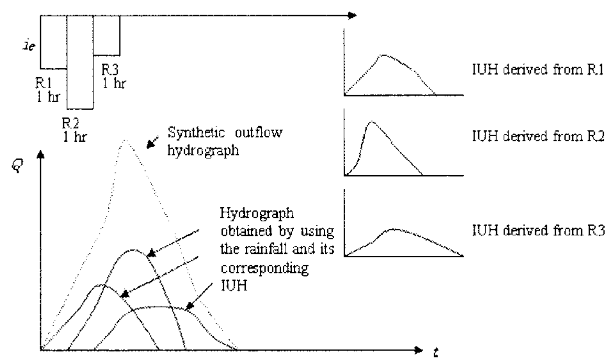

Fig.12 Composing the hydrograph from different rainfall intensity and its corresponding IUH.

each time step is shown in **Fig.13** and **Fig.14**. As in **Fig.13**, the error of peak discharge is 0.49%, and the error of time to peak is 0 hour. As in **Fig.14**, the error of peak discharge is 18.10%, and the error of time to peak is 1 hour.

The data of the rainfall events and simulation result is as shown in **Table 3**. The result shows that for short term rainfall event, the simulation result fits better, which implies that the IUH derived from FAV shows better fit for short period or single event of rainfall-runoff simulation.

4. CONCLUSIONS

The land use, land cover and rainfall intensity are the most important features which control the rainfall-runoff mechanism. A physically-based distributed instantaneous unit hydrograph extracted by using FAV was proposed in this study. The method could reflect the topographic feature and

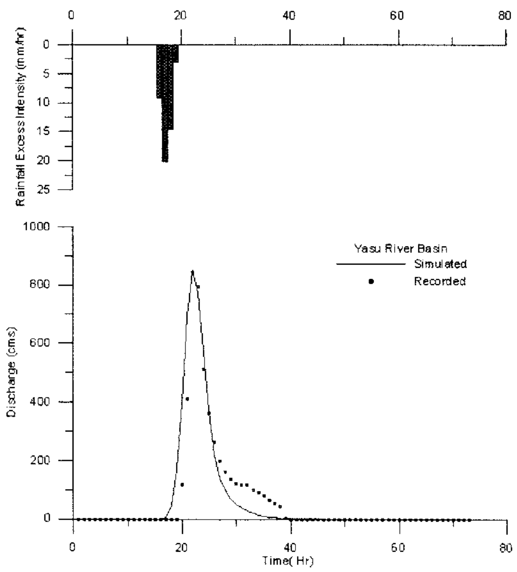

Fig.13 Simulation result by using multiple IUH. (1997/06/19.17-1997/06/22.02)

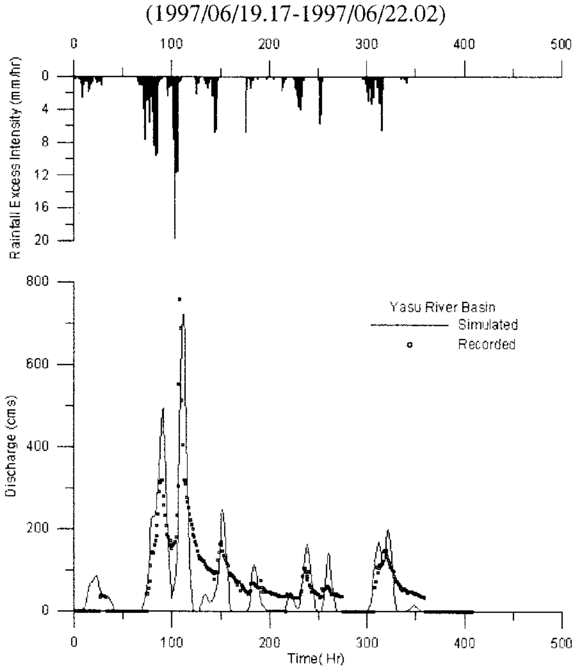

Fig.14 Simulation result by using multiple IUH. (1998/09/18.08-1998/10/02.12)

rainfall intensity by combining hydrology and hydraulics. Two kinds of usage of distributed IUH-single distributed IUH method and multiple distributed IUH method were examined in the study. The results show that by setting the average rainfall intensity which is similar to observed one, the single IUH well reproduce the hydrograph. As for multiple distributed IUH method, short term rainfall event performs better than the longer one.

Comparing to traditional geomorphic hydrologic model, distributed IUH was acquired by the DEM; there is no need to acquire the geomorphic factors. Topographic feature and rainfall characteristic also reflect well in the model, which implies that the

Table 3 Comparison of simulation result.

Rainfall Event	1997/06/19.17-1997/06/22		1998/09/18.08-1998/10/02.12	
Average rainfall intensity	11.713 *mm/hr*		2.09 *mm/hr*	
Method	Single 10 *mm/hr*	Multiple	Single 5 *mm/hr*	Multiple
EQ_p	-2.45%	0.49%	-4.56%	18.10%
ET_p	1 hr	0 hr	3 hr	1 hr
R^2	0.7614	0.8875	0.6566	0.7249

$$EQ_P\ (\%) = \frac{(Q_P)_{simulated} - (Q_P)_{recorded}}{(Q_P)_{recorded}}$$

$$ET_P\ (hr) = (T_P)_{simulated} - (T_P)_{recorded}$$

$$R^2 = \Sigma(Q_{recorded} - Q_{simulated})^2 / \Sigma(Q_{recorded} - \overline{Q_{recorded}})^2$$

model is suitable for real time flood forecasting purpose or rainfall-runoff simulation over ungauged area.

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