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Pao-Shan Yu

Yu-Chi Wang

Chun-Chao Kuo

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Pao-Shan Yu[a] , **Yu-Chi Wang**[a] **and Chun-Chao Kuo** [a]

[a]*Department of Hydraulics and Ocean Engineering, National Cheng Kung University, Tainan 701, Taiwan.*

yups@mail.ncku.edu.tw

Abstract: Simulation of flow hydrograph at an ungauged site recently has attracted considerable attention. A distributed rainfall-runoff model not only can describe the spatial heterogeneity of physiographical and hydrological characteristics in the catchment, but also can simulate the hydrological processes inside the studied area. If a distributed rainfall-runoff model can be adequately verified based on measurements both at the outlet and inside the studied area, then confidence that the model can accurately simulate the hydrological processes inside the studied area becomes more justified. The upstream catchment of Yan-Shoei creek was chosen as the study area, and historical flow hydrographs are observed not only at the outlet of the basin, but also at two small reservoirs inside the basin. A grid-based distributed rainfall-runoff model is first calibrated and verified using 12 and five historical storm events respectively, and the model is found to have reasonable rainfall-runoff simulation for the study area. Observed water level hydrographs recorded at these two reservoirs further indicate that the model could accurately simulate the rainfall-runoff process within the studied catchment. Finally, a windows-based program was developed based on the Visual Basic and Geographic information system-Arc View to establish a user-friendly interface. Users can easily input the model data, calibrate the model parameters, run the model and query the simulated flow hydrograph at any ungauged site within the study area.

Keywords: Geographic Information System; Distributed Rainfall-Runoff Model; Window-Based; Ungauged Basin

1. INTRODUCTION

Rainfall-runoff models have been widely applied in water resource projects. Various rainfall-runoff models have been developed. However, the problem of hydrograph simulation in an ungauged basin is still interesting. The structure of rainfall-runoff models has developed from lumped towards distributed types, since the Geographic Information System (GIS) and Remote Sensing (RS) techniques have been developed as useful tools for simulating the spatial heterogeneity of hydrological and physiographical characteristics in the catchment. Therefore, the distributed rainfall-runoff model is known for its ability to simulate the spatial hydrological process inside a basin. Theoretically, such a model can simulate the rainfall-runoff relationship at any site, provided the model has been verified. However, in most works the distributed rainfall-runoff model is only verified using the flow hydrograph at the outlet of the studied basin. This method of verification only demonstrates that the model can simulate the rainfall-runoff relationship from the perspective of the whole basin. This study assumes that a distributed rainfall-runoff model needs to be further verified using historical recorded data inside the study basin. Verifying that a distributed rainfall-runoff model has reasonable ability to simulate hydrological processes both at the outlet and inside the basin suggests that it can also simulate the spatial hydrological processes in the studied basin. This feature of distributed models can be applied to simulate the flow hydrograph at any ungauged site in the basin.

Despite having numerous advantages compared to lumped models [Beven and O’Connell, 1982], the distributed models normally need to pay more attention to input data preparation and model calibration. Accordingly, friendly user interfaces must be developed to enable users to input numerous input parameters. Recently, various public rainfall-runoff models have been developed with friendly user interfaces including HEC-HMS [Hellweger and Maidment, 1999], integration of HSPF [Lohani et al., 2002], windows-based AGNPS [He et al., 2001], HEC-RAS and TR-20 [Buntz, 1998; Kopp, 1998]. This investigation attempts to verify whether the windows-based distributed model proposed in this work has the potential to be applied to ungauged basins. The basin of Yan-Shui Creek, which contains two small reservoirs, is selected here as the study area. The model is verified not only using observed hydrograph at the basin outlet, but also using observed water level at two small reservoirs. The ability to simulate the spatial hydrological process can be extended for ungauged sites within Yan-Shui Creek. This approach is based on interpolation within a gauged basion. The windows-based friendly interface is further devised to enable users to query the simulated flow hydrograph at any ungauged site within the study area.

2. STUDY AREA

The basin of Yan-Shui Creek is located in southern Taiwan and has a drainage area of 343 km^2 and the mainstream length of 41.3 km. A drainage area of 138 km^2 upstream the Feng-Hua Bridge station, the only stream gauging station in the Yan-Shui Creek, was chosen as the study area. Fig. 1 depicts the locations of this stream gauging station and two raingauges. Two small reservoirs, Hu-Tou and Yan-Shoei for irrigation located inside of the basin are shown in Figure 1. Both the Hu-Tou Yan-Suei reservoir reservoir was built for the purpose of agricultural irrigation. Around 90% of the rainfall occurred during the wet period from May to October. Rainfall events caused by typhoons and southwestern convective storms, frequently occurring after typhoons leaving Taiwan, were dominant in annual rainfall and related severe disasters. Both 12 and another five historical flood hydrographs recorded at outlet of the basin are chosen for model calibration and verification. The water levels recorded at two reservoirs were further used to verify the model performance to simulate spatial hydrological processes inside of the basin, which was important feature of a distributed rainfall-runoff model.

3. DISTRIBUTED RAINFALL-RUNOFF MODEL

A detailed description of the model can be referenced by Yu and Jeng [1997]. Only a brief summary is given here. This model is designed for flood event. It is not suit for continuous simulation in this study.

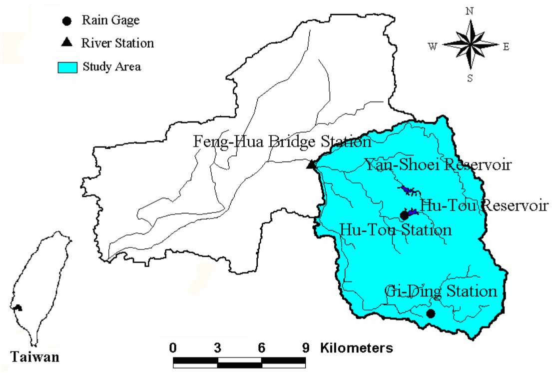

Figure 1. Location of study area

3.1 Catchment Characteristics

The catchment is to be divided into a 0.5×0.5 km grid-based mesh. Based on the soil map, the referenced parameters values of f_o, f_c and k are determined for each grid cell to estimate the infiltration loss. The roughness of the ground surface, which depends on the surface cover, has an influence on the storage coefficient and runoff behaviour is determined by remote sensing image. The topography within each grid cells, including flow direction, surface slope, and flow length, is determined from digital elevation model (DEM).

3.2 Abstraction Loss

Since infiltration dominance in the abstraction losses was unanimously assumed during storm events, only infiltration loss was estimated by Horton equation.

$$f_P(t) = f_C + \left(f_0 - f_C\right)e^{-kt_r} \qquad (1)$$

Where $f_P(t)$ denotes the infiltration capacity, f_0 represents the initial infiltration capacity, f_C is the final infiltration capacity, k denotes the decay constant, and t_r is the time. We set the actual cumulative infiltration equal to the integrated Horton's equation, to adjust the deficiency of the equation (1), which always decreases with time even if the rainfall stops [Waren et al., 1989]. Each storm event has its own antecedent condition and optimal initial infiltration capacity, so a calibrated parameter C_h is used here to obtain the optimal initial infiltration parameters [Yu and Jeng, 1997].

3.3 Flow governing equation

Non-linear conceptual approaches were used here for calculating overland flow and channel flow routing. The continuity and storage equations are written as:

$$I - Q = dS/dt \quad \text{(continuity equation)} \qquad (2)$$

$$S = K \cdot Q^m \quad \text{(storage equation)} \qquad (3)$$

I, Q and S are input, output and storage at a grid. K and m are parameters. To consider the simplest case of overland flow in a grid with length L, width w and water depth y, the volume of water stored in the grid is:

$$S = wyL \tag{4}$$

The discharge, Q, given by Manning's equation is

$$Q = \frac{1.0}{n} wy^{5/3} S_b^{1/2} \tag{5}$$

Substituting (4) into (5) to eliminate the water depth y gives

$$S = \frac{N^{0.6} w^{0.4} L}{S_b^{0.3}} Q^{0.6} \tag{6}$$

Here, S_b is the slope and N is the Manning's roughness coefficient. (6) is the same as (3) with

$$m = 0.6 \tag{7}$$

$$K = N^{0.6} w^{0.4} S_b^{-0.3} L \tag{8}$$

Hence the storage coefficient K in (8) is the function of Manning's roughness coefficient N and the slope. As the actual value of N and S_b may involve some uncertainty, a lumped parameter, C, is introduced in this study to adjust the storage coefficient, and is calibrated from the historical data.

$$(K_i)_{opt} = C(K_i) = C(N^{0.6} w_i^{0.4} L S_b^{-0.3})_i \tag{9}$$

Reservoir routing included in this work based on the Storage-Outflow curves that are developed from Area-Level-Storage and spillway rating curves. The governing equation is the same as (2). The reservoir routing is repeatedly calculated by using inflow, Storage-Outflow curve and continuity equation.

The spatial variability of storage coefficient can be obtained by using the Manning's coefficient N and slope at each grid element as shown in (9), although a lumped parameter C is calibrated for all grid elements. Notably, two separate parameters C_s and C_c were used for overland flow and channel flow. The model calibration parameters may cause the uncertainty of model output. The detailed reference can be traced in our previous findings [Yu *et al.*, 2001].

4. MODEL CALIBRATION AND VERIFICATION

The model parameters in distributed rainfall-runoff models are divided into two kinds: the physical parameters, which can be generated directly from topographic, soil, and vegetation maps, and the calibrated parameters, which are calibrated using historical rainfall and flow data. Three calibration parameters must be calibrated by applying both an optimization technique and an objective function. This study adopts the shuffled complex evolution (SCE) method for model calibration. [Duan *et al.*, 1992].

The distributed rainfall-runoff was calibrated using 12 historical storm events. The calibration results demonstrate that the maximum error of time to peak (ETP) was less than two hours, while the average error of estimated peak flow (EQP) was 6%, the average error of total volume (VER) was approximately 16% and the average coefficient efficiency was 0.89. Figure 2 only shows the worst cases of the calibrated events, and the results indicate that this model achieves a reasonably accurate simulation at Feng-Hua Bridge station.

The average parameters (C_s=0.482, C_c=0.578, C_h=0.053) are used for model verification. Table 1 lists the verification results, which display that the average ETP was around 0.8 hours, the average EQP was below 13%, the average VER was about 30%, and the average coefficient efficiency was 0.75. Figure 3 only illustrates the worst cases of the verification events. The calibration and verification results concluded that the distributed rainfall-runoff model can effectively simulate the rainfall-runoff behaviour from the view of the whole basin. However, the ability of the model to simulate the hydrological process inside the study basin is also interesting.

The automatic monitoring system in the Hu-Tou and Yan-Shoei reservoirs only provided complete hourly records of observed water levels for historical events 15 and 17 to verify the model. Figure 4 compares the observed and simulated water level of event 15 at the Hu-Tou and Yan-Shoei reservoirs. The accurate simulation results show that the distributed model still has good simulation on the rainfall-runoff process in the interior of the study basin. Consequently this distributed model proposed in this work may provide a tool for hydrograph simulation at any ungauged site within the study catchment.

Table 1. The performances for verification storm events

Storm Event	ETP(hr)	EQP(%)	VER(%)	CE
Event 2	1	4.78	-26.81	0.72
Event 14	-1	-20.09	-27.32	0.71
Event 15	0	-22.64	-35.45	0.78
Event 16	-1	-8.15	-29.17	0.80
Event 17	1	-6.21	-29.60	0.72
/Average/	0.8	12.37	29.67	0.75

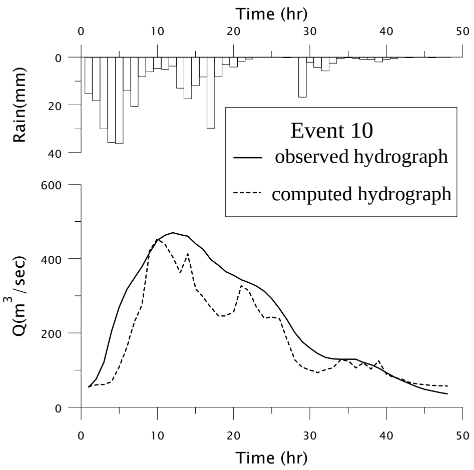

Figure 2. The worst cases of the calibration events

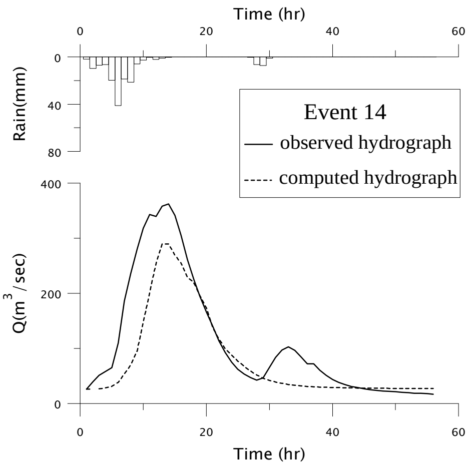

Figure 3. The worst and best cases of the calibration events

5. WINDOWS-BASED INTERFACE

5.1 Interface For Data Generation

A distributed rainfall-runoff model generally requires numerous complicated physical parameters to simulate the heterogeneity of spatial hydrological characteristics. These data may include the catchment boundary, surface slope and elevation, soil and vegetation type, land use and ground cover, reservoir locations and the identification of flow direction and river network. The GIS and RS techniques provide digital geographic information and processing of the satellite image, and not only save a considerable data preparation time, but also enhance data accuracy. However, it depends on users being proficient at using GIS software, which GIS software has powerful functions for calculation and analyses. This study develops a windows-based interface to integrate the distributed rainfall-runoff model with the Arc View Spatial analyst and Hec-GeoHMS [USACE, 2000]. The basic database required for the distributed rainfall-runoff model includes digital elevation; soil type; and land use/cover database. The boundaries of the studied basin and river network are first divided using Hec-GeoHMS software and Digital elevation data, which is also used to estimate the average elevation and slope of each grid. Soil and land use/cover are used to estimate the Manning's n and infiltration rate of each grid. Users can use the pull-down menu to conduct this estimation and can save the estimation results as output files for model input

5.2 Interface For Model Execution, Display And Inquiry

Executing the distributed model involves the steps of model data input; model calibration; model verification; output display and inquiry. A windows-based interface is developed using Microsoft Visual Basic to conduct these procedures. The functions of the various windows are summarized as follows:

5.2.1 Data input window

Users can first go to the window for model data input to fill in the file name and paths for each kind of model data input. This window provides eight buttons for inputting model data, including the files of "hourly rainfall", "hourly runoff", "grid boundary"; "infiltration data"; "channel network"; "topographic data"; "river characteristic", and the file name to be assigned to the model output.

5.2.2 Parameter calibration window

After inputting the model input data file, users can execute model calibration, which requires the input of the ranges of calibration parameters, C_c, C_s, and C_h. and the parameters of the SCE method.

5.2.3 Model verification window

Model verification requires a set of model parameters from model calibration. Users can input the model parameters from the upper-left window of Fig. 5. The observed and simulated hydrographs are automatically displayed in the middle window after pressing the "start to simulate" button. Simulation results, including the error of peak time, peak discharge, runoff volume and efficiency, are displayed in the left window.

5.2.4 Results inquiry window

Since the distributed rainfall-runoff models can simulate the hydrological process inside the catchment, the windows-based interface in this work (Fig.6), enables users to query the hydrographs of each grid or channel section. The hydrographs are shown after users choose the grids of interest from the map and press the button to draw.

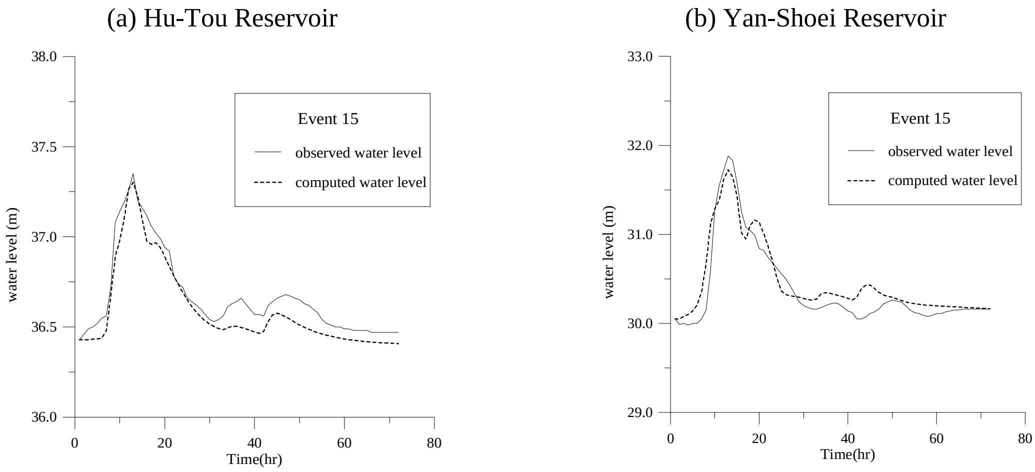

Figure 4. The computed and observed water level of event 15

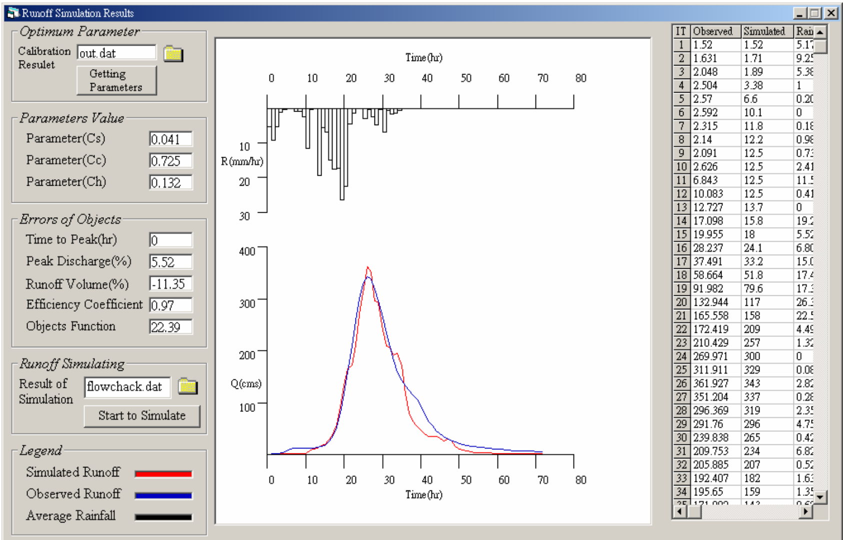

Figure 5. The window of runoff simulating

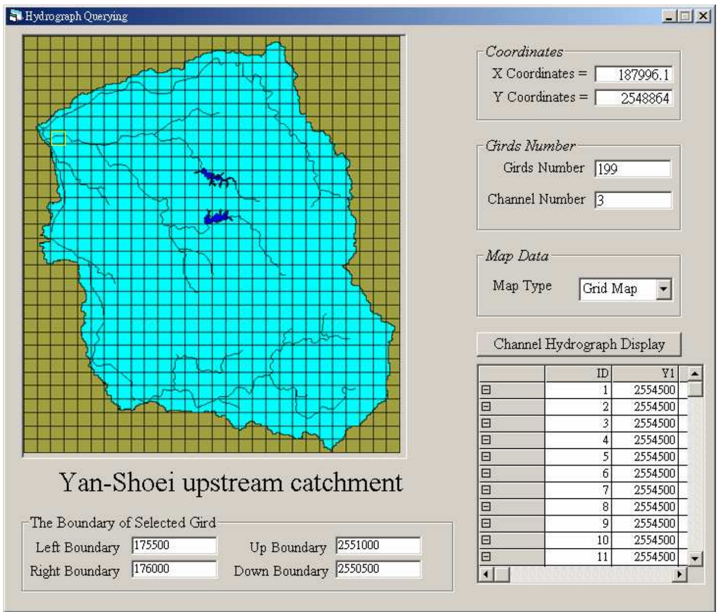

Figure 6. The window of results inquiring

6. CONCLUSION

This investigation established a windows-based distributed rainfall-runoff model for a gauged basin that could interpolate the flow hydrographs at any ungauged site within the catchment. The verification that the distributed rainfall-runoff model has reasonable ability to simulate hydrological processes both at the outlet and inside the basin indicates that the model can accurately simulate the spatial hydrological processes in the subject basin. This feature of distributed models then can be applied to simulate the flow hydrograph at any ungauged site in the basin. The basin of Yan-Shoei Creek, which contains two small reservoirs, was chosen as the study area. Twelve calibration storm events and another five verification storm events provided the data set. However, water level hydrographs were only observed for two storm events at these two small reservoirs to verify the model performance inside the basin. Average model parameters from these 12 calibration storm events were further used for model verification. The calibration and verification results indicate that the proposed model has reasonable ability to simulate the rainfall-runoff relationship.

Because distributed rainfall-runoff models require more complicated topographic and landform data for their input, a friendly interface was developed to enable users to easily generate the model input data, including the catchment boundary, surface slope and aspect, Manning's n and infiltration rate. The distributed rainfall-runoff model was further integrated using Microsoft Visual Basic to develop a windows-based interface. The windows-based interface helps users to easily input the model data, calibrate the model parameters, execute the model and display the simulation results.

7. ACKNOWLEDGMENTS

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