A Data-driven Method for the Determination of Water-flow Velocity in Watershed Modelling

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Abstract—**Physically-based distributed hydrological models have always played an important role in watershed hydrology. Existing hydrological modeling applications focused more on the estimation of water balance and less on the simulation of water transportation in a catchment. Different from the prediction of flow production, the dynamic simulation of flow concentration depends largely on the field distribution of water-flow velocity. However, it is still difficult to determine the water-flow velocity with terrain analysis techniques, which had always hampered the application of hydrological models in surface water transportation simulation. This study, therefore, proposes a data-driven method for creating a field map of overland flow velocity based on the Manning's equation. Case study on a gauged watershed is undertaken to validate the spatial distribution of flow velocity. The preliminary results indicate that the proposed empirical method can reasonably determine the spatial distribution of water-flow velocity. Further efforts are still required to support the space-time change of flow velocity under the control of micro-topography and instantaneous water depth.**

I. INTRODUCTION

Watershed hydrology is the study of the water cycle at the basin scale. As one of the most important components in hydrological cycle system, the rainfall-runoff process consists of two sub-processes, surface flow generation and concentration. The former refers to the production of surface water from precipitation, which may go through a variety of vertical water transfer between ground, atmosphere, plant canopy, soil surface and underground aquifer. The latter refers to the transportation of excess surface water as the soil moisture gradually becomes saturated [1].

Numerous descriptive or computational hydrological models have been developed to describe or estimate the rainfall-runoff process in a watershed [3]. These watershed models were supposed to answer the following three questions, where to go when it rains, what path to take when it flows, and how long to remain in the basin [4, 6]. Traditional lumped empirical and semi-distributed conceptual models focused mainly on the calculation of water balance between the catchment elements [2]. With the development of remote sensing and geographical information system (GIS) techniques, digital terrain analysis methods have become increasingly applied to support physically-based distributed hydrological models [3]. The GIS-supported models have more potential to provide a clear spatial footprint of hydrological processes [2].

Existing hydrological models have focused more on the calculation of water balance [3], delineation of flow path [7, 9], but less on the dynamic simulation of surface water concentration [8]. That is mainly because of the difficulty in determination of water-flow velocity in space and time. The water-flow velocity is believed to relate to the underlying topography, soil characteristics and water depths. Based on this concept, the Manning's equation has been designed to calculate the flow velocity in open channels [5, 8]. However, it is still difficult to measure the parameters (hydraulic radius and water surface slope) in Manning's equation with terrain analysis techniques. Maidment et al. [5] proposed a modified Manning's equation to roughly estimate the flow velocities by replacing the above two parameters with upstream area and terrain slope. However, research gap still exists in the determination of weighting coefficients. This study, therefore, proposed a more practical data-driven method to determine the field distribution of water-flow velocity.

II. GRID DROP WATERSHED MODELLING

The simulation of surface water concentration is based on the grid drop concept [8], and the modified Manning's equation [5].

A. *Grid Drop Concept*

Rui et al. [8] introduced the concept of grid drop for calculating the process of flow concentration. In this study, as demonstrated in Figure 1, a gridded digital elevation model (DEM) is also used

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to derive cell flow direction and flow paths, then the grid drop concept is involved to simulate the process of surface water transportation by representing the surface runoff with water particles along the flow paths.

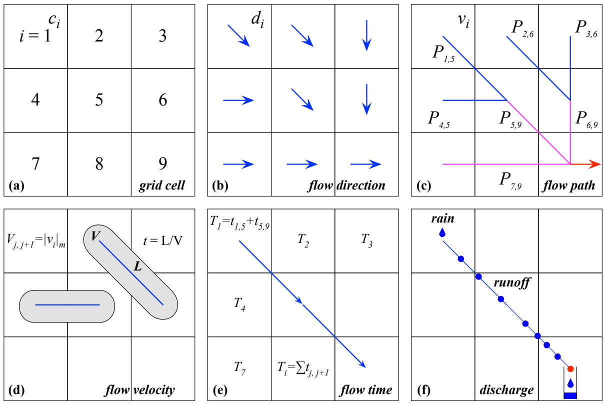

Figure 1. Grid drop framework for flow concentration simulation. (a) an example of gridded elevation model; (b) flow direction derived by D8 algorithm; (c) flow paths extracted by flow accumulation; (d) water-flow velocity on flow path; (e) calculation of flow time; (f) water transportation.

B. Modified Manning's Equation

The Manning's equation (1) has been widely used to calculate water-flow velocity in open channels [2, 5, 8].

$$v = \frac{1}{n} \cdot R_h^{2/3} S_w^{1/2} \tag{1}$$

where v is the estimation of flow velocity, n is the surface roughness coefficient, R_h is the hydraulic radius, and S_w is the water surface slope. Because of the difficulty in measuring hydraulic radius and water surface slope, Maidment et al. [5] suggested that the above equation can be modified to the form (2).

$$v = [v]_m \cdot \frac{A^\alpha S^\beta}{[A^\alpha S^\beta]_m} \tag{2}$$

where $[v]_m$ is the mean value of flow velocities in the basin, A and S are respectively the upstream area and the terrain slope, $[A^\alpha S^\beta]_m$ denotes the mean value of the calculation of $A^\alpha S^\beta$, while α and β are undetermined weight coefficients controlling the impacts on flow velocity.

The modified equation uses the upstream area A and terrain slope S to represent the hydraulic and geomorphic factors, which makes the distributed parameters easy to calculate. Maidment et al. [5] set the values of α and β both to 0.5, and estimated the value of v_m by data calibration. However, there is reason to believe that the weight coefficients should vary between different catchments. This study, therefore, introduces a data-driven method to determine the controlling coefficients and the distributed water-flow velocities.

C. Data-driven Method

The weight coefficients α and β control the impacts of the hydraulic and geomorphic factors on water-flow velocity. The two factors should both have positive correlations with flow velocity. That is, as the water deepens, the hydraulic radius and the water-flow velocity increases. The steeper the terrain slope, the faster the velocity is. This study uses an objective function (3) to determine the values of weight coefficients.

$$\{\alpha, \beta\} = \{\alpha, \beta \,|cor(V, A) = cor(V, S)\} \tag{3}$$

where $cor\,(X, Y)$ means the correlation coefficient between variable X and variable Y. This study assumes that the hydraulic factor A and the geomorphic factor S have the same impact on flow velocity.

As the calculation of $A^\alpha S^\beta$ determines the spatial distribution of water-flow velocity, the mean velocity $[v]_m$ controls how fast or slow the process of watershed concentration will be. That is, the faster the $[v]_m$, the sooner the peak discharge is. This study uses the recorded outlet discharge data for calibrating the value of $[v]_m$.

III. CASE STUDY ON WATERSHED CONCENTRATION

A case study on watershed concentration is undertaken to validate the proposed data-driven method.

A. Testing Basins

As illustrated in Figure 2, the testing basins are located at the border areas of the four states of Oklahoma, Arkansas, Missouri and Kansas. As a sub-basin of the Baron Fork at Eldon (with a basin area of 795 km^2), the Peacheater Creek at Christie has a catchment area of 69.80 km^2.

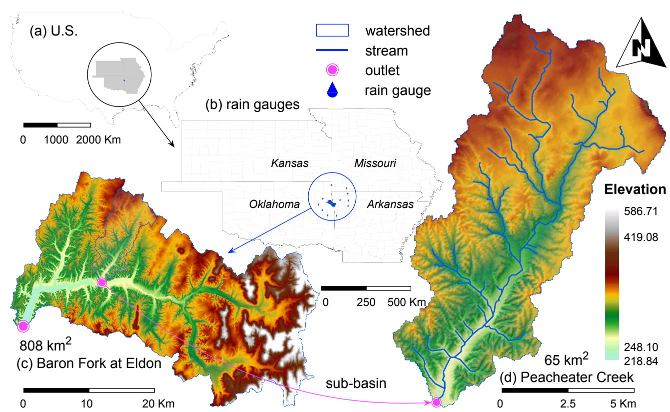

Figure 2. Testing basins in Central United States. (a) the continental United States; (b) the rain gauges surrounding the testing basins; (c) the basin of Baron Fork at Eldon; (d) the sub-basin of Peacheater Creek at Christie.

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The Global Digital Elevation Model (GDEM) data, acquired by the advanced spaceborne thermal emission and reflection radiometer (ASTER), is used for terrain analysis in this study. The ASTER GDEM data set (Version 2, spatial resolution 30 meters) is collected from the International Scientific & Technical Data Mirror Site provided by Computer Network Information Center of Chinese Academy of Sciences (http://www.gscloud.cn). In addition, gauged precipitation (grid format, cell size: 4 km) and outlet discharge data (hourly records) are also collected for watershed modelling.

B. Data Calibration

In the Baron basin, Figure 3 shows the correlation coefficients between (A, S) and v by changing the values of α and β from 0 to 1 (a). From the direction of Z axis (b), the crossing line denotes the pairs of value for (α, β) that the correlation coefficient of A and v is equal to that of S and v. If set the values of α and β to 0.5 (c), there will be a negative correlation between S and v.

This study, therefore, intends to determine the values of weight coefficients with the maximum common correlation coefficients. As shown in Figure 3(d), the solid purple line denotes the common correlation line in XOZ plane, while the dash purple line means the common correlation line in XOY plane. That is, when the value of α is 0.26, and β equals to 0.58, the two basin factors (A, S) have the maximum correlation with water-flow velocity v.

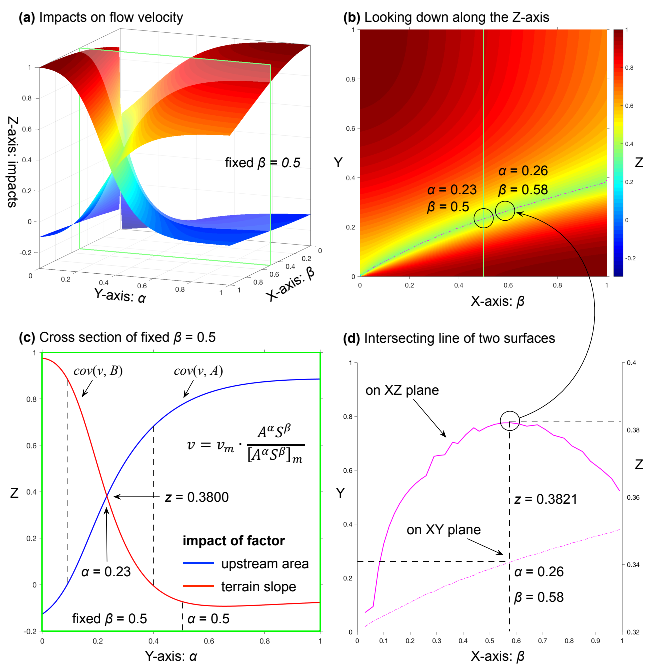

Figure 3. Calibration of weight coefficients in modified Manning's equation. (a) correlation coefficients between (A, S) and v; (b) the crossing line (purple dash) denotes the equal impacts; (c) the changing impacts by fixing the weight coefficient β to 0.5; (d) the crossing line from Z-axis and Y-axis.

By changing the value of $[v]_m$ and calculating the correlation coefficients between predicted and observed discharges, Figure 4 illustrates the calibration process of mean flow velocity. That is, when the mean flow velocity of Peacheater basin is 0.07 m/s, there is the highest accuracy, and the Baron basin can obtain the highest accuracy with a mean flow velocity of 0.70 m/s.

IV. RESULTS ANALYSIS AND DISCUSSIONS

A field map of water-flow velocity is created to support the watershed concentration modeling with above calibrated weight coefficients and parameters. The outlet discharges are predicted and compared to gauged records to validate the calibration results.

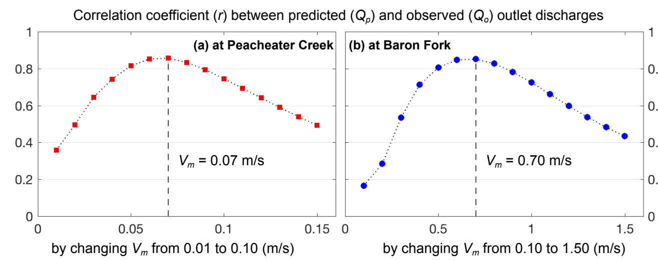

Figure 4. Calibration of mean flow velocity in modified Manning's equation. (a) prediction accuracy by changing the value of $[v]_m$ from 0 to 0.15 m/s at Peacheater Creek basin; (b) prediction accuracy by changing the value of $[v]_m$ from 0 to 1.5 m/s at Baron Fork basin.

A. Time-area Map

For each cell in the Baron Fork basin, a constant value will be calculated by the modified Manning's equation to represent the water-flow velocity. Based on the D8 algorithm proposed by O'Callaghan and Mark [7], the flow time from each cell to the basin outlet can then be accumulated by setting the weights with flow length and velocity. As illustrated in Figure 5, a time-area map is created for the Baron Fork basin, and the grid drop concept is applied to conduct the simulation of watershed concentration.

B. Unit Hydrograph

The distributed hourly rainfall intensities are converted into drops and assigned to the grid cells, then these drops will concentrate along the flow paths under the control of water-flow velocities. By comparing the predicted discharges at the basin outlets with observed records, we can then evaluate the reasonableness of calibrated values.

Figure 6 shows the unit hydrographs of the testing basins from November 1 to December 31 in 1996. Indicators including Nash and Sutcliffe efficiency (NSE), correlation coefficient (R), and balance coefficient (B) are calculated to describe the simulation accuracy of watershed concentration.

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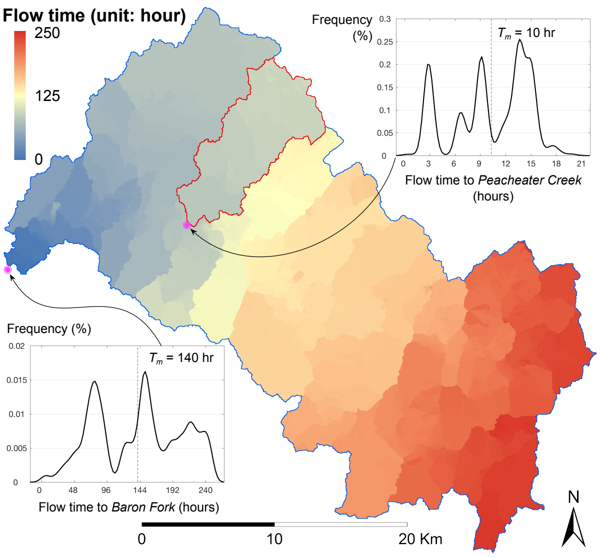

Figure 5. Time-area map for the testing basins.

As shown in Figure 6, the NSE, R and B of Baron basin are respectively 0.6178, 0.8511 and 1.3079, while those values of Peacheater are 0.2707, 0.7560 and 1.6652. These preliminary results of unit hydrographs indicate that the proposed method of determining field distribution of water-flow velocity can achieve quite acceptable performance.

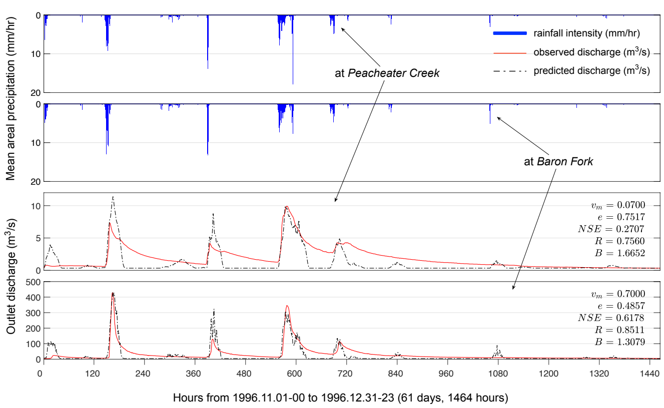

Figure 6. Unit hydrographs of the two testing basins.

V. Conclusions

This study proposed an empirical method for the determination of field distribution of water-flow velocity. The parameters and weight coefficients in the modified Manning's equation are calibrated with field data. A case study on watershed concentration has been conducted to assess the proposed method. The predicted outlet discharges indicate that the proposed method can achieve quite reasonable field distribution for water-flow velocity. Further efforts are still required to validate the calibration outcomes in different basins, and to support time-changing water-flow velocity as the water depth changes during the watershed process.

Acknowledgment

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