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A Time-Varying Distributed Unit Hydrograph method considering soil moisture content

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Abstract: The distributed unit hydrograph (DUH) method has been widely used for flow routing in a watershed, because it adequately characterizes the underlying surface characteristics and varying rainfall intensity. Fundamental to the calculation of DUH is flow velocity. However, the currently used velocity formula assumes a global equilibrium of the watershed and ignores the impact of time-varying soil moisture content on flow velocity, which thus leads to a larger flow velocity. The objective of this study is to identify a soil moisture content factor, which, based on the tension water storage capacity curve, was derived to investigate the response of DUH to soil moisture content in unsaturated areas. Thus, an improved distributed unit hydrograph, based on time-varying soil moisture content, was developed. The proposed DUH considered the impact of both the time-varying rainfall intensity and soil moisture content on flow velocity, assuming the watershed to be not in equilibrium but varying with soil moisture. The Qin River basin and Longhu River basin were selected as two case studies, and the synthetic unit hydrograph (SUH), time-varying distributed unit hydrograph (TDUH) and the current DUH methods were compared with the proposed method. The influence of time-varying soil moisture content on the flow velocity and flow routing was evaluated. Results showed that the proposed method performed the best among the four methods. The shape and duration of the unit hydrograph can be mainly related to the soil moisture content at the initial stage of a rainstorm. When the watershed is approximately saturated, the grid flow velocity is mainly dominated by excess rainfall.

Keywords: Time-varying distributed unit hydrograph, Runoff routing, Flow velocity, Soil moisture content, Excess rainfall

1. Introduction

Flood is a natural disaster with occurring suddenly and causing serious harm (Jongman et al., 2014; Alfieri et al., 2015; Munich, 2017). Global flood losses account for about 40% of the total losses of all kinds of natural disasters. Accurate flood forecasts can provide a decision-making basis for reservoir operation, flood control,

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and optimal allocation of water resources, which, in turn, plays a significant role in water resources management, development and utilization, and economic growth and reconstruction.

Flow routing is an important component in a hydrological model, whose accuracy directly affects flow forecasting. The Unit Hydrograph (UH), proposed by Sherman (1932), is one of the methods most widely used in the development of flood prediction and warning systems for gauged basins with observed rainfall–runoff data (Singh et al., 2014). The UH, which is a surface runoff hydrograph resulting from one unit of rainfall excess uniformly distributed spatially and temporally over the watershed for the specified rainfall excess duration (Chow 1964), can be categorized into 4 major types (Singh, 1988), including traditional, probability, conceptual, and geomorphologic methods (Bhuyan et.al. 2015).

The traditional methods establish the relationships between parameters used to describe the UH (e.g. peak flow, time to peak and time base) and parameters used to describe the basin. Snyder (1938), Mockus (1957) and U.S. Soil Conservation Service (SCS) (2002) proposed some traditional methods, which are still used. The disadvantages of these methods are that they do not yield adequately satisfactory results, and their application to practical engineering problems is tedious and cumbersome (Nigussie et al., 2016).

Since most UHs have steeper rising limbs than their receding sides, which can be characterized by probability distribution functions (PDFs). Due to their similarity in the

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shape of statistical distributions, many PDFs were used for the derivation of UHs. The difficulties of these methods are that the distribution functions are diverse, and the parameters depend on numerous hydrological data (Bhuyan et al., 2015).

Conceptual methods are another technique for deriving UHs. Nash (1957) proposed a conceptual model characterized as a succession of n linear reservoirs connected in series with the same storage coefficient K for the derivation of the instantaneous unit hydrograph (IUH). Dooge (1959) proposed a generalized IUH based on linear reservoirs, linear channels, and time-area concentration diagram. Bhunya et al. (2005) and Singh et al. (2007) represented a hybrid and extended hybrid model based on the linear reservoir model. Singh (2015) proposed a new simple two-parameter IUH with conceptual and physical justification. Khaleghi et al. (2018) suggested a new conceptual model, namely, the inter-connected linear reservoir model (ICLRM). However, the conceptual model neglects the impact of uneven spatial distribution of the basin's underlying surface on the UHs.

Using the time-area method developed by Clark (1945), Rodriguez-Iturbe (1979) proposed a geomorphologic instantaneous unit hydrograph (GIUH) method, which couples the hydrologic characteristics of a catchment with geomorphologic parameters (Kumar et al., 2007). In this method, the IUH corresponds to the probability density function of travel times from the locations of runoff production to the watershed outlet (Gupta et al., 1980; Singh, 1988). With the development of digital elevation models (DEMs) and geographic information system (GIS) technology, the formulation of width function-based geomorphological IUH methods are available, the rigidity of which is reflected in its incapacity to account properly (i.e. to respect the geometry) for the distribution of rainfall (Rigon et al., 2016).

The UH method assumes some hypotheses (i.e. linear, time invariant, spatially homogeneous rainfall) in the application. Contrary to the linear assumption, basins have been shown to exhibit nonlinearity in the transformation of excess rainfall to stormflow (Bunster et al., 2019). Of course, this is an accepted compromise in challenging hydrological studies over the past few decades, especially for ungauged basins. Minshall (1960) showed that different rainfall intensities significantly corresponded to different UHs for a small watershed. Rodríguez-Iturbe et al. (1982) extended the GIUH to the geomorphoclimatic IUH (GcIUH) to cope with this nonlinearity by incorporating excess rainfall intensity in the determination of the IUH. Lee et al. (2008) proposed a variable Kinematic wave GIUH corresponding to time-varying rainfall intensity for the calculation of runoff concentration, which warrants consideration for rainfall-runoff modelling in ungauged catchments that are influenced by high intensity rainfall. Du et al. (2009) proposed a GIS based routing approach to simulate storm runoff with the consideration of spatial and temporal variability of runoff generation and flow routing through hillslope and river network. IA similar work was done by Muzik (1996), Gironás et al. (2009), and Bunster et al. (2019).

It is difficult for the traditional, probability, conceptual, and geomorphologic methods to fully consider the geomorphic characteristics of the watershed while

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incorporating the nonlinearity of rainfall-runoff process (e.g. time-varying rainfall intensities). Thus, the spatially distributed unit hydrograph (DUH) method attracted much attention. The of DUH conceptualizes that the unit hydrograph can be derived from the time-area curve of a watershed by the S-curve method (Muzik, 1996). The DUH can be essentially classified as a type of geomorphoclimatic unit hydrograph, since its derivation depends on watershed geomorphology, rainfall, and flow hydraulics (Du et al., 2009). The spatially distributed flow celerity and temporally varying excess rainfall intensities can be considered in DUH (Bunster et al., 2019).

In the DUH method, the travel time of each grid cell can be calculated by dividing the travel distance of a cell to the next cell by the velocity of flow generated in that cell (Paul et al., 2018). The travel time is then summed along the flow path to obtain the total travel time from each cell to the outlet. The DUH is thus derived using the distribution of travel time from all grid cells in a watershed (Bunster et al., 2019). Some DUH methods assumed a time-invariant travel time field and ignored the dependence of travel time on excess rainfall intensity (Melesse & Graham, 2004; Noto and La Loggia, 2007; Gibbs et al., 2010), while others suggested various UHs corresponding to different storm events, namely time-varying distributed unit hydrograph (TDUH) (Martinez et al.,2002; Sarangi et al., 2007; Du et al., 2009). Compared to the fully distributed methods based on the momentum equation, the DUH method is a more efficient method that allows for the use of distributed terrain information in an ungauged region. The DUH methods better account for the spatial information of

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watershed and time-varying rainfall-runoff process than do the traditional methods. The DUH also has been developed as an alternative method to semi-distributed and fully distributed methods for rainfall-runoff modelling (Bunster et al., 2019).

Besides excess rainfall intensity, researchers have also focused on the upstream contributions to the travel time estimation in the time-varying DUH method. For instance, Maidment et al. (1996) defined the velocity in the cell as a function of the contributing area to take into account the velocity increase observed downstream in river systems (Gironás et al., 2009). Gad (2014) applied a grid-based technique implementing the stream power formulation to relate flow velocity to the hydrologic parameters of the upstream watershed area through a simple parametric approach. Similar work has been done by Saghafian and Julien (1995), Bhattacharya et al. (2012) and Chinh et al. (2013). An important drawback of this method is the assumption that the watershed is near global equilibrium. Bunster et al. (2019) developed a spatially time-varying DUH model that accounts for dynamic upstream contributions and characterized the temporal behavior of upstream contributions and its impact on travel times in the basin. However, this time-varying DUH also assumed that equilibrium in each individual grid cell was reached before the end of the rainfall excess pulse. When there accrues continuous excess-rainfall in a watershed, the soil moisture content and surface runoff increase, and the infiltration rate decreases, leading to an acceleration of flow routing velocity, until the entire basin is saturated and the routing velocity reach its maximum. This assumption of equilibrium globally or in grid cells yields slower

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travel times, shorter times to peak, and higher peak discharges. However, these approximations neglect the impact of dynamic changes of soil moisture exchange and water storage in unsaturated regions.

The objective of this study is therefore to propose a time varying distributed unit hydrograph method for runoff routing that accounts for dynamic rainfall intensity and soil moisture content based on the existing Xinanjiang (XAJ) model. The main contributions of the present study are as follows. First, a soil moisture content proportional factor in the unsaturated area was identified and expressed based on the Pareto distribution function. Second, the travel time expression function based on the kinematic wave theory was modified by considering the soil moisture content proportional factor. Besides rainfall intensity, the influence of time-varying soil moisture storage on flow velocity in the watershed was considered, where runoff generation is dominated by saturation-excess mode. Finally, the Qin River basin and Longhu River basin in the Guangdong Province, China, were selected as two case studies. The flow forecast method mainly consisted of the calculation of excess rainfall and the derivation of DUH. A new routing method was developed to incorporate the behavior of dynamic changes of soil moisture content and rainfall intensity, and the XAJ model was adopted to calculate the excess rainfall. The SUH, DUH and TDUH methods were compared with the proposed method, and sensitivity analysis of parameters was conducted.

2. Improvement of flow routing method

2.1 Calculation of flow velocity considering time-varying soil moisture content

The DUH relies on the computation of travel time over a basin. Grimaldi et al. (2010) found that the Soil Conservation Service (SCS) formula, given by Eq. (1), can be used to adequately define the basin flow time. This formula was also used by NRCS (1997) and Grimaldi et al. (2012), but this formula is time invariant and the time-varying rainfall intensity should be considered, which is given by Eq. (2). Wong (1995), Muzik (1996), Bedient and Huber (2002), Gironas et al. (2009), Du et al. (2009) and Kong et al. (2019) used this formula.

$$V = k \cdot S^{\frac{1}{2}} \tag{1}$$

$$V = k \cdot S^{\frac{1}{2}} \cdot \left(\frac{I_t}{I_c} \right)^{\frac{2}{5}} \tag{2}$$

where V (m/s) is the flow velocity; k (m/s) is land use or flow type coefficient; S (m/m) is the slope of the grid cell; I_t (mm/h) represents the excess rainfall intensity at time t; and I_c (mm/h) represents the reference excess rainfall intensity of the basin.

These formulas assume that equilibrium in individual grid cell can be reached before the end of the rainfall excess (Bunster et al., 2019), which leads to larger flow velocity, shorter travel time, and higher peak discharge. Actually, the hillslope flow velocity in each grid is related to soil moisture content. Fast subsurface velocities and quick runoff responses to precipitation have been observed on many hillslopes (Hutchinson & Moore, 2000; Peters et al., 1995; Tani, 1997). The exact mechanisms

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that cause water to move through the preferential flow path network are not well quantified, but it is often assumed that saturated soil provides the connection between preferential features (Sidleet al., 2001; Steenhuis et al., 1988). Many studies have also shown that antecedent moisture condition, precipitation intensity, precipitation amount, topography and so on play a significant role in this phenomenon (Sidle et al., 2000; Tsuboyama et al., 1994; Anderson et al., 2009).

To that end, a soil moisture factor θ_t was introduced to characterize the soil moisture content in unsaturated areas. Because the flow velocity will reach its maximum value when the entire basin is saturated, this new factor (θ_t) was added to the current time-varying flow velocity formula as

$$V = k \cdot S^{\frac{1}{2}} \cdot \left(\frac{I_t}{I_c}\right)^{\frac{2}{5}} \cdot (\theta_t)^{\gamma} \tag{3}$$

where θ_t (unitless) represents the state of the soil moisture content of unsaturated areas at time t; and γ (unitless) is an exponent smaller than unity, which represents the nonlinear relationship between soil moisture content and flow velocity.

The factor θ_t was defined as the ratio of w_t and $w_{\max,t}$, which is expressed by

$$\theta_t = \frac{w_t}{w_{\max,t}} \tag{4}$$

where w_t (mm) represents the mean tension water storage of the unsaturated region; and $w_{\max,t}$ (mm) represents the maximum tension water storage of the unsaturated region at time t.

Specifically, w_t and $w_{\max,t}$ were calculated based on the Pareto distribution function

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in this study. The Pareto distribution function has mostly been used to express the spatial variability of soil moisture capacity (Moore, 1985), which is shown in Fig. 1. As shown in the figure, the area below this curve represents the mean tension water capacity of the entire basin.

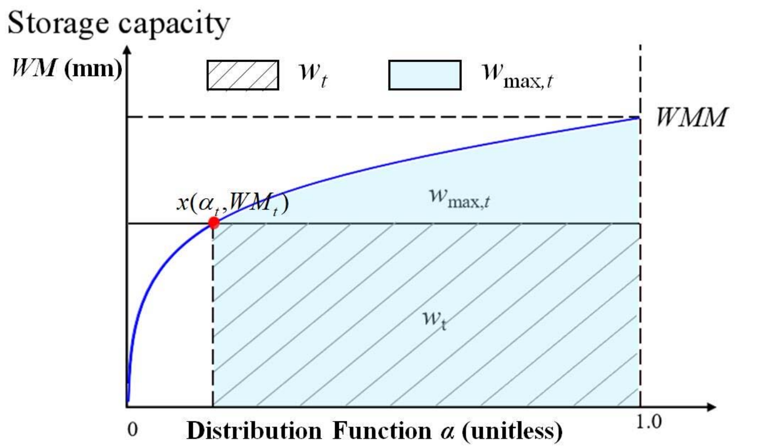

Figure 1. Watershed storage capacity curve

For the tension water storage capacity curve, the specific formula is given by

$$\alpha = 1 - \left(1 - \frac{WM}{WMM}\right)^b \tag{5}$$

where α (unitless) represents the proportion of the basin area where the tension water capacity is less than or equal to the value of the ordinate WM (mm). The tension water capacity at a point, WM, varies from 0 to a maximum WMM (mm) according to Eq. (5).

Actually, the soil moisture content in a basin varies with time. The state of the catchment at any time t can be represented by a point $x(\alpha_t, WM_t)$ on the curved line of Fig. 1 (Zhao, 1992). The area to the right and below the point x is proportional to the areal mean tension water storage (not capacity). Thus, WM_t, the ordinate of the point *x*, represents the tension water storage capacity in the basin at time *t*; w_t (mm) can be assumed to represent the mean tension water storage of the unsaturated region, and $w_{\max,t}$ (mm) represents the maximum tension water storage of the unsaturated region at time *t*. Their expressions are given by

$$\alpha_t = 1 - \left(1 - \frac{WM_t}{WMM}\right)^b \tag{6}$$

$$w_t = \left(1 - \alpha_t\right) \cdot WM_t \tag{7}$$

$$w_{\max,t} = \int_{\alpha_t}^{1} WMM\left[1 - \left(1 - \alpha\right)^{\frac{1}{b}}\right] d\alpha \tag{8}$$

Combining Eqs. (4), (7), (8), the soil moisture content can be written as

$$\theta_t = \frac{w_t}{w_{\max,t}} = \frac{\left(1 - \alpha_t\right) \cdot WM_t}{\int_{\alpha_t}^{1} WMM\left[1 - \left(1 - \alpha\right)^{\frac{1}{b}}\right] \mathrm{d}\alpha} \tag{9}$$

Substituting Eq. (6) into Eq. (9),

$$\theta_t = \frac{\left(1 - \alpha_t\right) \cdot WM_t}{WMM\left[1 - \alpha_t - \frac{b}{b+1}\left(1 - \alpha_t\right)^{1+\frac{1}{b}}\right]} = \frac{\left(b+1\right)WM_t}{WMM + bWM_t} \tag{10}$$

It can be seen from Eq. (10) that as rainfall continues, the soil moisture content in the unsaturated area continues to increase, whereas the non-runoff area continues to decrease. The ranges of θ_t is (0, 1], and with the gradual increase of soil moisture, θ_t tends to 1.

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2.2 Calculation of runoff routing based on DUH

The GIS-derived DUH method was employed for runoff routing calculations, which allowed the velocity to be calculated on a grid cell basis over the watershed. The DUH routing method is a semi-analytical form of the width function-based IUH enumerated by Rigon et al. (2016). The DUH has been used for small ungauged basins. To remove the linearity assumption, fully distributed models use routing methods which are usually computationally intensive because they solve the St. Venant equations (Bunster et al., 2019), so they are usually limited to small basins. Therefore, the DUH method is an alternative method that allows the use of distributed information in a much more efficient manner, and we apply it to different sizes of watersheds.

The core of the DUH method is to equate the probability density function of time at which the rainfall flows to the outlet of the basin to the instantaneous unit hydrograph, in which the time-area relationship is derived using the velocity field with spatial distribution characteristics. The traditional DUH method can route the time-variant spatially distributed rainfall to the watershed outlet, and such a method is a lumped linear model of watershed response (Grimaldi et al., 2010). The schematic diagram of the proposed DUH method is shown in Fig. 2.

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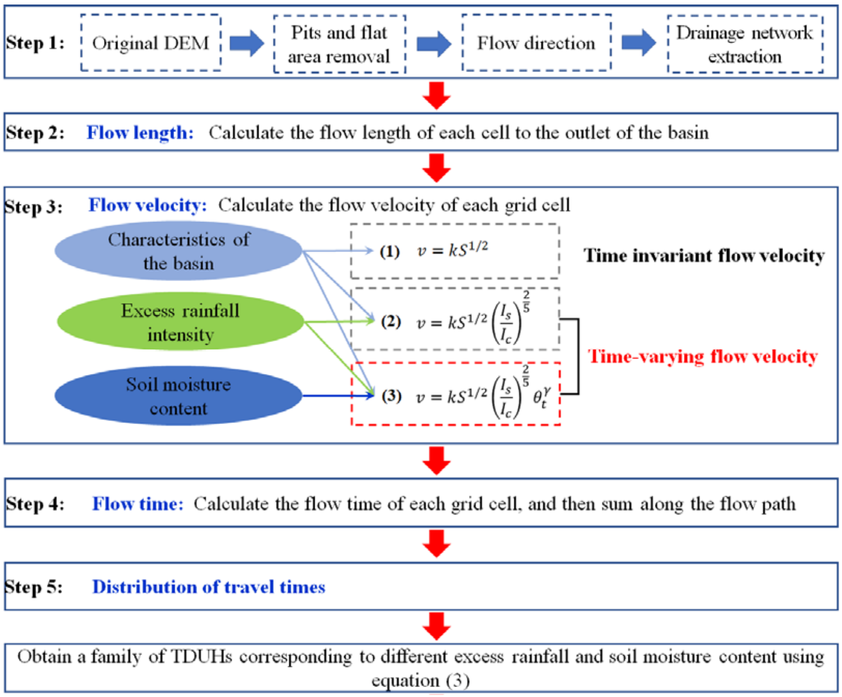

Figure 2. Schematic diagram of the DUH method considering time-varying rainfall intensity and soil moisture content, in which Eqs. (1), (2) and (3) are the time invariant flow velocity, time-varying flow velocity considering excess rainfall intensity, and time-varying flow velocity considering both excess rainfall intensity and soil moisture content. The unit hydrograph derived from the three flow velocity equations correspond to DUH, TDUH and the proposed method respectively.

The processes of the DUH method are summarized as follows.

1) The drainage network using advanced DEM pre-processing techniques is identified. More details can be found in Grimaldi et al. (2012).

2) Estimate the flow path, which is measured for each grid cell along the flow directions to the outlet of basins.

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3) Calculate the flow velocity based on the characteristics of the watershed and the spatial–temporal distribution characteristics of rainfall. Several flow velocity formulas are commonly used for deriving the spatially distributed unit hydrograph, such as the Manning' formula (Chow et al., 1988), SCS formula (Haan et al., 1994), Darcy-Weisbach formula (Katz et al., 1995), and Maidment et al. (1996) uniform flow equation.

4) To compute the total travel time τ_i of flow from each cell *i* to the outlet, we added travel times along the R_i cells belonging to the flow path that starts at that cell, given by Eq. (11) (Muzik, 1996). The travel time for each grid cell can be calculated using Eq. (12):

$$\tau_i = \sum_{i \in R_i} \Delta \tau_i \qquad (11)$$

$$\Delta \tau_i = \frac{L_i}{V} \quad \text{or} \quad \Delta \tau_i = \frac{\sqrt{2} L_i}{V} \qquad (12)$$

where $\Delta \tau_i$ is the retention time in grid cell *i*; τ_i is the total travel time along the flow path in grid cell *i*; L_i is the grid cell size; travel length in a specific grid cell is the cell size L_i when the rasterized flow is flowing along the edges of the grid, whereas travel length is $\sqrt{2} L_i$ when it is flowing diagonally.

5) Develop a cumulative travel time map of the watershed based on cell by cell estimates for hillslope velocities. The cumulative travel time map is further divided into isochrones, which can be used to generate a time-area curve and the resulting unit hydrograph (Kilgore, 1997).

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3. *Calculation of runoff generation*

The Xinanjiang (XAJ) model was used for the calculation of excess rainfall in this study. It is a conceptual hydrologic model proposed by Zhao et al. (1980) for flood forecasts in the Xinan River basin. The XAJ model has been widely used in humid and semi-humid watersheds all over the world (Zhao, 1992). It mainly consists of four modules, namely evapotranspiration module, runoff generation module, runoff partition module and runoff routing module (Zhou et al., 2019). Usually, a large watershed is divided into several sub-basins to capture the spatial variability of underlying surface, precipitation, and evaporation. In each sub-basin, the inputs of the XAJ model are the average areal rainfall as well as evaporation, and the output is streamflow. The schematic diagram of the XAJ model is shown in Fig. 3.

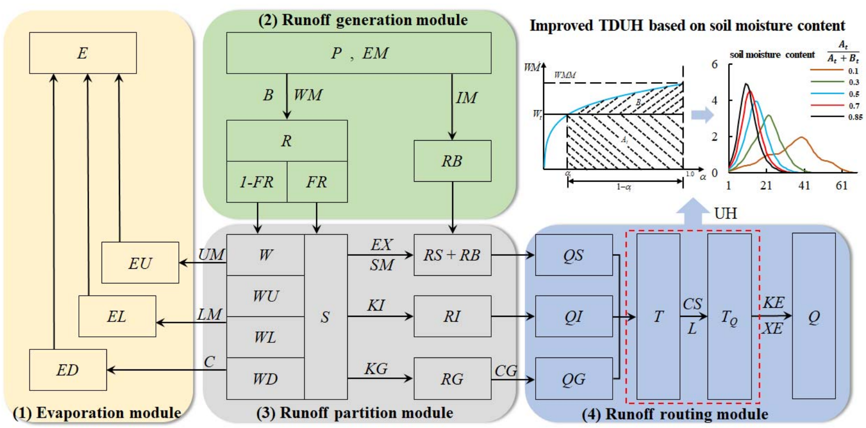

Figure 3. Schematic diagram of the XAJ model

First, for the evapotranspiration module, the soil profile of each sub-basin is divided into three layers, the upper, lower and deeper layers, and only when the layer above it has exhausted water, evaporation from the next layer occurs. Second, as for

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runoff generation in the XAJ model, a catchment is divided into two parts by the percentage of impervious and saturated areas, namely permeable and impervious areas, respectively. Since the soil moisture deficit is heterogeneous, runoff distribution is usually nonuniform across the basin. Thus, a storage capacity curve was adopted by the XAJ model to accommodate the nonuniformity of soil moisture deficit or the tension water capacity distribution. Third, the runoff partition in the XAJ model divides the total runoff into three components by a free reservoir, which consists of surface runoff (RS), interflow runoff (RI), and groundwater runoff (RG). More details can be found in (Zhao et al., 1980). Finally, the SUH, DUH, TDUH and the proposed method were used to calculate flow routing, respectively. The Maskingen method was employed to produce streamflow from each sub-basin to the outlet of the entire catchment.

4 Study area and data

The Qin River basin and Longhu River basin were selected as two case study watersheds. One is a large watershed, and the other is a small watershed. The applicability of the proposed method to different size watersheds was verified, and parameter sensitivity analysis was done to evaluate the performance of the proposed method.

The Qin River is a tributary of the Mei River, which originates from Guangdong Province, China. The river is 91 km long with a basin area of 1578 km^2. The mean slope of the basin is 1.1‰. There are 21 meteorological stations and 1 flow station (the

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Jianshan Station) in this area, as shown in Fig. 4. Using the DEM data of the Qin River basin, the whole basin was divided into 9 sub-basins, based on the natural water system, namely sub-basins 1-9 from upstream to downstream as shown in Fig. 5. Details of each sub-basin are given in Table 1.

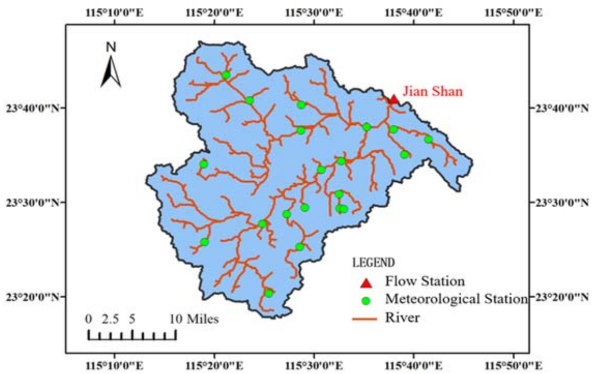

Figure 4. Distribution diagram of meteorological stations and flow stations in the Qin River basin

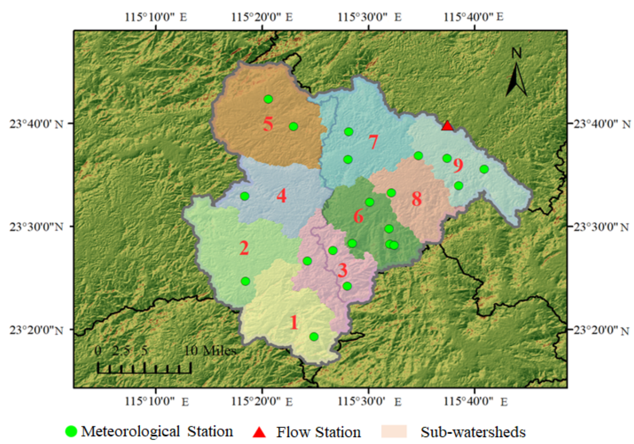

Figure 5. Sub-basins of the Qin River basin (*Note*. The satellite images for the study area are available at http://www.gscloud.cn)

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Table 1. Information on sub-basins

Sub-basins	Drainage area/km^2	Number of grids	Average slope
Sub-basin 1	175.64	176	13.29
Sub-basin 2	195.86	197	9.27
Sub-basin 3	154.97	156	12.50
Sub-basin 4	153.08	151	9.57
Sub-basin 5	147.79	147	12.49
Sub-basin 6	249.36	253	11.74
Sub-basin 7	213.34	211	10.56
Sub-basin 8	122.28	129	10.77
Sub-basin 9	166.51	161	9.74

The Longhu River basin is a small watershed, which has a drainage area of 102.7 km^2, located in the Guangdong Province, China. The length of the River is 17.4 km.

The rainfall and evaporation data from meteorological stations was collected from 1959 to 2018. The simultaneous hourly runoff data for the Jianshan Station and Longhu Station was collected as well. The antecedent precipitation was calculated, based on the daily recession coefficient of water storage in the basin.

5. Results and discussion

5.1 Calibration of parameters

5.1.1 Model calibration

The SCE-UA (Shuffled Complex Evolution Algorithm) method, developed by the University of Arizona in1992 (Duan et al., 1992), is suitable for nonlinear, high dimension optimization problems. The method has been widely used for the calibration of hydrological models (Vrugt et al., 2006; Beskow et al., 2011; Zhou et al., 2018).

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Hence, the SCE-UA method was used to optimize the parameters of XAJ model in this study.

The Nash-Sutcliffe efficiency (E_{NS}) (Nash and Sutcliffe, 1970), the Kling-Gupta efficiency (E_{KG}) (Gupta et al., 2009), and the root-mean-squared error to standard deviation ratio (R_{SR}) were chosen as criteria. Moreover, the new aggregated objective function (Brunner et al., 2021) targeted at optimizing flow characteristics was composed of these three metrics, in which E_{KG} focuses on high flows (Mizukami et al., 2019), log(E_{NS}) emphasizes low flows, and R_{SR} quantifies volume errors. Three metrics and the aggregated objective function are expressed by

$$E_{\mathrm{NS}}=1-\frac{\sum_{t=1}^{T}\left|Q_s^t-Q_o^t\right|}{\sum_{t=1}^{T}\left|Q_o^t-\overline{Q_o}\right|} \tag{13}$$

$$E_{\mathrm{KG}}=1-\sqrt{(r-1)^2+\left(\frac{\sigma_s}{\sigma_o}-1\right)^2+\left(\frac{\mu_s}{\mu_o}-1\right)^2} \tag{14}$$

$$R_{\mathrm{SR}}=\sqrt{\frac{\sum_{t=1}^{T}\left(Q_o^t-Q_s\right)^2}{\sum_{t=1}^{T}\left(Q_o^t-\overline{Q_o}\right)^2}} \tag{15}$$

$$M=0.5\times\left(1-E_{\mathrm{NS}}\right)+0.25\times\left(1-E_{\mathrm{KG}}\right)+0.15\times\left(1-\log\left(E_{\mathrm{NS}}\right)\right)+0.1\times R_{\mathrm{SR}} \tag{16}$$

where Q_o^t is observed discharge at time t; Q_s^t is simulated discharge at time t; $\overline{Q_o}$ is the mean of observed discharge; T is duration of the flood event; r is correlation coefficient between the observed and simulated flood; σ_s and σ_o are the standard deviation values for the simulated and observed responses, respectively; and μ_s and μ_o are the corresponding mean values.

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5.1.2 Calibrated parameters of runoff generation using the XAJ Model

Since the Qin River basin and Longhu River basin are in the humid area of southern China, the saturation-excess method with three-source runoff separation of the XAJ model was adopted to calculate the excess rainfall. A total of 64 isolated storms with the observed runoff responses from 1959 to 2018 were selected to calibrate and verify the model, of which 35 events were collected from the Qin River basin and 29 from the Longhu River basin. 25 and 23 flow events were used for model calibration in the Qin and Longhu River basins respectively, and 10 and 6 flow events were used for model validation in the two basins. The initial condition of the XAJ model was considered by calculating the antecedent precipitation index before each flow event (Linsley et al. 1949).

In addition, the parameters of the XAJ model and the proposed distributed unit hydrograph were calibrated separately. Since the objective of this study is to propose a new flow routing method, the runoff producing model with its parameters were not changed in order to discuss the performance of the flow routing models. The synthetic unit hydrograph, derived by historical rainfall-runoff data, was used for flow routing in the process of model calibration. The time interval was 1 hour. The flow peak, flow volume, and the occurrence time of flow peak are three main basic elements for describing the flow hydrograph, and Eq. (16) was used as the aggregated objective function. The average Nash-Sutcliffe efficiency, relative flood peak error, and peak occurrence time error obtained in the calibration period of the XAJ model are 0.84,

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10.4%, and 4.96 hours respectively for the Qin River basin. Accordingly, for the Longhu River basin, it is 0.86, 8.81%, and 2.75 hours respectively, indicating a good performance of the XAJ model. Detailed information on the calibrated parameters of the XAJ model is shown in Table 2.

Table 2. Calibrated parameters of the XAJ model

Parameters	Physical meaning	The Qin River	The Longhu River	Unit
UM	Averaged soil moisture storage capacity of the upper layer	20.05	8.24	mm
LM	Averaged soil moisture storage capacity of the lower layer	74.42	72.98	mm
DM	Averaged soil moisture storage capacity of the deep layer	26.54	22.30	mm
B	Exponential of distribution of tension water capacity	0.25	0.12	-
IM	Ratio of impervious to total areas in the catchment	0.01	0.01	-
K	Ratio of potential evapotranspiration to pan evaporation	0.85	0.89	-
C	Evapotranspiration coefficient of the deeper layer	0.15	0.12	-
SM	Free water capacity of the surface layer	45.32	50.23	mm
EX	Exponent of the free water capacity curve influencing the development of the saturated area	1.50	1.50	-
KI	Outflow coefficient of free water storage to interflow	0.38	0.13	-
KG	Outflow coefficient of free water storage to groundwater	0.26	0.65	-
CI	Recession constant of the lower interflow storage	0.85	0.83	-
CG	Recession constant of the ground water storage	0.99	0.99	-
CS	Recession constant in the lag and rout method for routing through the channel system within each sub-basin	0.46	0.7	-
KE	Muskingum time constant for each sub-reach	22.80	3.5	-
XE	Muskingum weighting factor for each sub-reach	0.13	0.12	-

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5.1.3 Calibrated Parameters of the proposed flow routing method

As mentioned in Section 2.2, the core of the DUH is the calculation of the grid flow velocity. As shown in Eq. (3), the parameters that need to be calibrated are *K*, *S*, I_c and γ, in which I_c can be determined using hourly mean rainfall intensity and flow forecast of the target basin. For the Qin River basin, I_c was set at 20 mm/h, because the mean rainfall intensity of multiple flows was about 20mm/h, and this parameter was 10 mm/h for the Longhu River basin. Additionally, parameter γ reflected the influence of soil moisture content in unsaturated regions on flow velocity. The smaller the parameter γ was, the smaller the influence of soil moisture content on the flow velocity was. When the value of γ was equal to 1, the flow velocity of grid cell was proportional to the soil moisture content factor θ_t. The parameter γ of soil moisture content was determined to be 0.5 to reflect the influence of soil moisture content on the flow velocity for the two basins. Furthermore, sensitivity analysis for this parameter was conducted in Section 5.6. In order to get the grid cell slope *S*, the slope distribution of the study areas was obtained from the DEM data of the target basin. Fig. 6(a) plots the slope distribution of the Qin River basin. The parameter *k* is the velocity coefficient, which was determined, based on different underlying surface types or different flow states (Ajward & Muzik, 2000). The parameter *k* changes with different land types, and the *k* values used in this study are given in Table 3. The land types of the Qin River basin are shown in Fig. 6(b). Then the *k* values of each grid cell were determined by combining Fig. 6(b) and Table 3.

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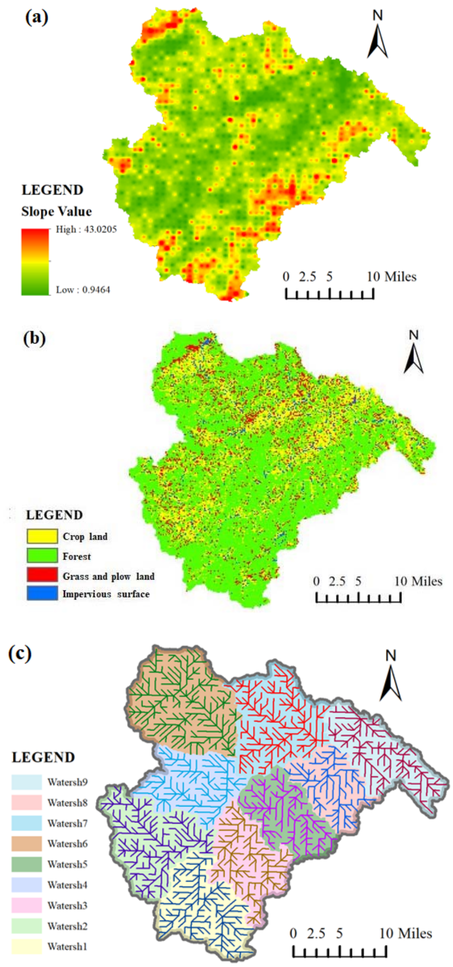

Figure 6. Slope, Land types and rasterized flow direction of the Qin River basin

(a) Slope distribution. (b) Land types. (c) Rasterized flow direction.

Table 3. Specific values of *k* for different vegetational types

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Land type	Vegetational form	*k* (m/s)
Crop land	Fallow	1.37
	Contour tillage	1.40
	Straight plough	2.77
Grass and plow land	Trample	0.30
	Lush	0.46
	Sparse	0.64
	Pasture	0.40
Forest	Dense	0.21
	Sparse	0.43
	Full of dead leaves	0.76
Impervious surface	\	6.22

The grid flow velocity was calculated by Eq. (3) with the above parameter values. Then, the flow travel time was determined by Eq. (11) and Eq. (12). It is noteworthy that the raster size of the Qin River nasin was divided into 1km×1km, and the rasterized flow direction of each sub-basin is shown in Fig. 6(c). For the Longhu River basin, the difference was that its cell size was divided into 30m×30m to evaluate the performance of the proposed method in this small watershed.

5.2 Calculation of the proposed time-varying DUH

After determining the parameters above, flow routing was calculated, based on the proposed DUH considering the time-varying soil moisture content. In order to improve the efficiency and effectiveness of the routing method, the rainfall intensity and soil moisture content parameters were discretized. Then, a simplified TDUH considering time-varying soil moisture content and TDUH were obtained in a certain range of

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rainfall intensities or soil moisture contents; these ranges are presented in Tables 4 and 5. To evaluate the performance of the proposed method, the traditional SUH, DUH and TDUH methods were used for comparison.

Table 4. The ratio of I_t to I_c of each period corresponds to the discrete rain intensity I_s

I_t / I_c (mm/h)	$0 < \frac{I_t}{I_c} \le 0.5$	$0.5 < \frac{I_t}{I_c} \le 1$	$1 < \frac{I_t}{I_c} \le 1.5$	$\frac{I_t}{I_c} > 1.5$
Discrete I_s (mm/h)	0.5	1	1.5	2

Table 5. The soil moisture content θ_t of each period corresponds to the discrete soil moisture content θ_s

Soil moisture content θ_t	$0<\theta_t \le 0.2$	$0.2<\theta_t \le 0.4$	$0.4<\theta_t \le 0.6$	$0.6<\theta_t \le 0.8$	$\theta_t > 0.8$
Discrete soil moisture content θ_s	0.1	0.3	0.5	0.7	0.85

The DUH without considering rainfall intensity and soil moisture was obtained using Eq. (1). Results of the DUH for each sub-basin of the Qin River basin are shown in Fig. 7. There is only one DUH for a specific sub-basin due to the simplification of the underlying surface, such as slope and land covers. The differences among the DUHs were mainly reflected in flow peaks and their occurrence times. It can be also seen from Fig. 7 that the peak of DUHs in sub-basins 4 and 6 were significantly lower than in others. The reason may be that the smaller mean slop values of sub-basins 4 and 6 lead to lower flow velocity, resulting in lower peak of the DUH.

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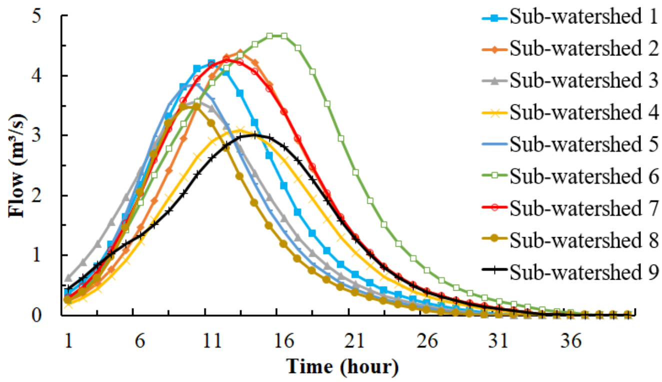

Figure 7. DUH for the Qin River basin

The TDUHs corresponding to different rainfall intensities of 9 sub-basins are shown in Fig. 8. It can be seen from Fig. 8 that different rainfall intensities corresponded to different TDUHs. The increased rainfall intensity led to higher peak and earlier peak occurrence time of the UH. This is because that a larger rainfall intensity caused a larger flow velocity according to Eq. (2). In the practical use of TDUH, the UHs need to be selected according to rainfall intensities.

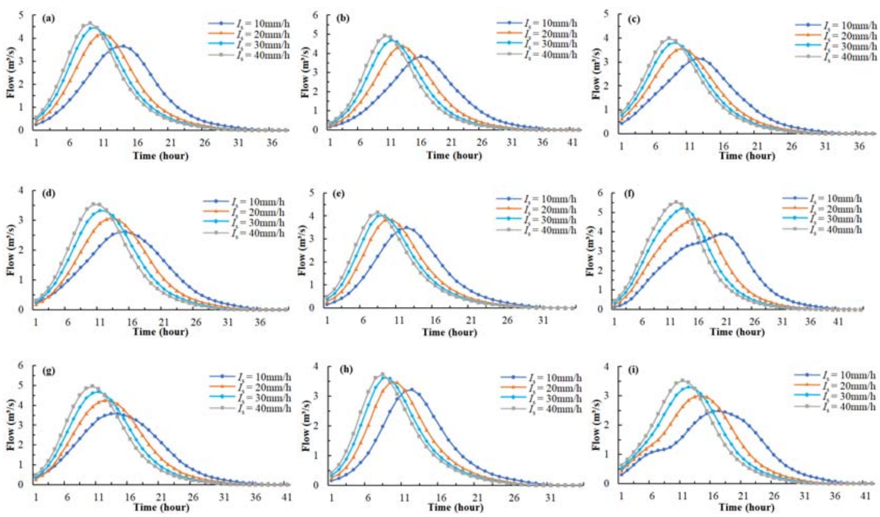

Figure 8. The TDUH for the Qin River basin. (a) Sub-basin 1. (b) Sub-basin 2. (c) Sub-

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basin 3. (d) Sub-basin 4. (e) Sub-basin 5. (f) Sub-basin 6. (g) Sub-basin 7. (h) Sub-basin 8. (i) Sub-basin 9.

The TDUH of each sub-basin was further divided according to the soil moisture content. The TDUHs considering soil moisture contents of sub-basin 1 are shown in Fig. 9. Obviously, under the same rainfall intensity, the soil moisture content was of great importance to the shape, peak value and duration of the TDUH. Specifically, when the proportion of soil moisture content θ_t increased, the proposed method considering soil moisture content was accompanied by steeper rising limb, higher peak and shorter duration. After the whole basin was saturated, the TDUH considering the soil moisture content was the same as the TDUH.

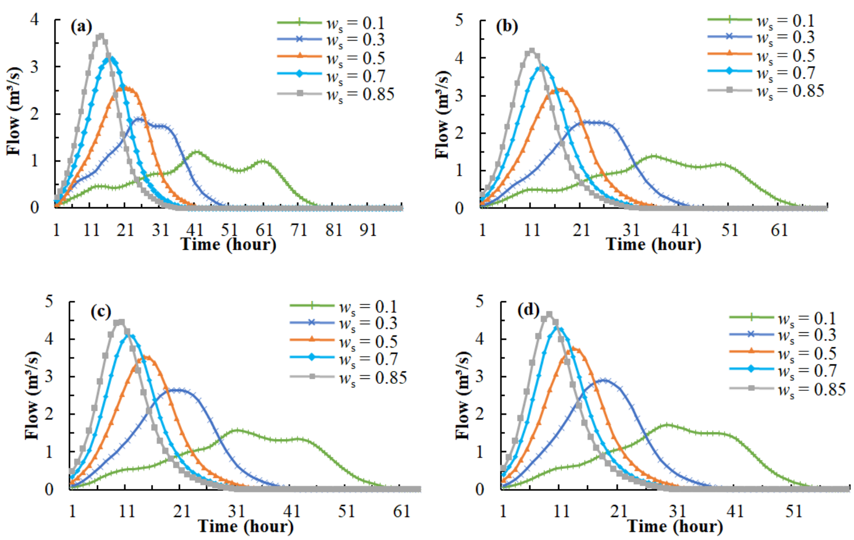

Figure 9. The TDUH considering soil moisture content for sub-basin 1 of the Qin River basin. (a) $I_s = 0.5$. (b) $I_s = 1$. (c) $I_s = 1.5$. (d) $I_s = 2$.

Similarly, the TDUHs considering the soil moisture content for the Longhu River

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basin are shown in Fig. 10. The grey line in Fig. 10(b) is the DUH, where I_s is equal to 1 and w_s is 0.85. Four grey unit hydrographs in Fig. 10(a) to 10(d) make up the TDUH without considering the soil moisture content.

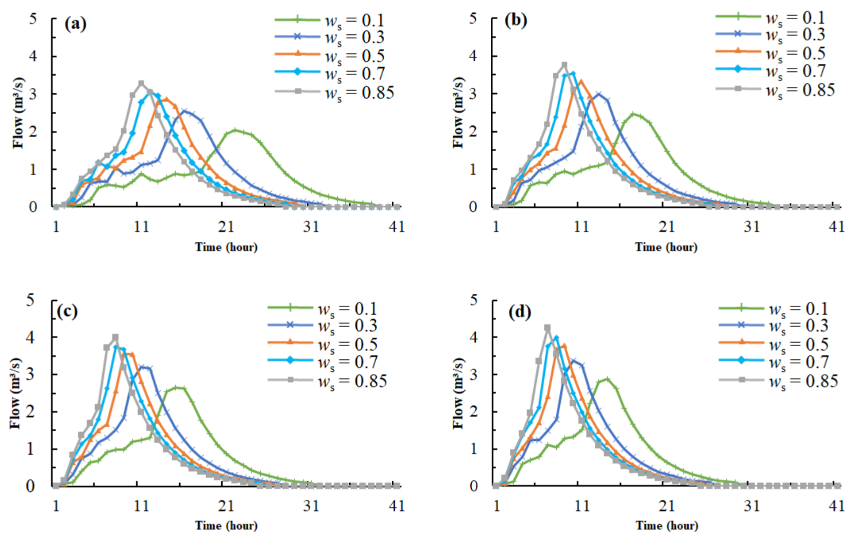

Figure 10. The TDUH considering soil moisture content for the Longhu River basin. (a) $I_s = 0.5$. (b) $I_s = 1$. (c) $I_s = 1.5$. (d) $I_s = 2$.

5.3 Comparison of flood routing methods

The runoff generation module of the XAJ model was used to calculate the excess rainfall, and the SUH, DUH, TDUH and improved TDUH considering soil moisture content were employed for flow routing calculations, respectively. Dozens of flow events were applied for model validation. Simulated results of the four methods for the Qin River basin are shown in Table 6. Three criteria were used for model performance evaluation, which included the Nash-Sutcliffe efficiency (E_{NS}), the ratio between the

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simulated and observed peak discharges (Q_p^s / Q_p^o), and the error between simulated and observed times to peak ($\left|t_p^s - t_p^o\right|$). The ratio between simulated and observed peak discharges of the proposed method ranged from 0.97 to 1.10. The average peak occurrence time error of the proposed method was 1.4h, which was the smallest among the four methods, and the mean E_{NS} coefficients of the ten flow events for validation were above 0.8. Fig. 11 shows the flow hydrographs of the four routing methods for part of the flow events (Event No. 20130720, 20130817, 20150709, 20160128, 20161021 and 20180916). It is demonstrated that the proposed method outperformed the remaining three routing methods.

In addition, the forecast results of six flow events in the Longhu River basin using the SUH, DUT, TDUH and the proposed method are presented in Table 7. Results of the proposed method generally showed the best performance, which also verified the proposed formula in the small watershed. In general, the proposed method did better simulation in this watershed than in the Qin River basin.

Table 6. Comparison of four routing methods for the Qin River basin

Event number	(Q_p^s / Q_p^o) / ($\left\|t_p^s - t_p^o\right\|$) / ($E_{NS}$)			
	SUH	**DUH**	**TDUH**	**Proposed**
20130720	1.16/1/0.44	1.13/3/0.32	1.13/3/0.31	**1.02/1/0.64**
20130817	1.06/3/0.86	1.04/7/0.61	1.01/4/0.92	**0.99/1/0.98**
20130922	0.95/2/0.82	1.07/3/0.82	**1.04/2/0.87**	0.98/3/0.85
20150709	0.83/0/0.80	1.01/2/0.87	1.26/2/0.63	**1.07/1/0.97**
20160128	0.89/2/0.93	1.09/3/0.74	0.93/1/0.83	**1.01/0/0.97**
20160827	1.14/3/0.83	1.10/2/0.75	1.12/2/0.81	**1.07/1/0.91**
20161021	0.89/1/0.89	1.08/1/0.83	**1.05/1/0.89**	1.10/2/0.91
20180606	0.84/4/0.78	1.20/3/0.68	1.13/4/0.72	**0.97/2/0.84**

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20180830	**0.97/2/0.83**	1.05/2/0.75	1.06/1/0.82	1.05/2/0.81
20180916	0.80/3/0.86	1.05/2/0.62	0.95/3/0.81	**0.97/1/0.85**
Average	0.95/2.1/0.80	1.08/2.8/0.70	1.07/2.3/0.76	**1.02/1.4/0.87**

Table 7. Comparison of four routing methods for the Longhu River basin

Event number	$(Q_p^s/Q_p^o)/(\lvert t_p^s-t_p^o\rvert)/(E_{NS})$			
	SUH	**DUH**	**TDUH**	**Proposed**
20030517	1.11/4/0.96	1.14/2/0.87	1.00/1/0.88	**1.00/2/0.97**
20060601	0.92/2/0.83	1.06/1/0.92	**1.00/1/0.96**	0.95/1/0.88
20060808	1.12/1/0.81	1.23/2/0.85	1.10/2/0.85	1.03/1/0.93
20120527	**0.96/0/0.98**	1.06/2/0.73	0.94/2/0.78	0.99/1/0.93
20130713	0.85/0/0.95	1.07/1/0.88	0.95/0/0.90	**0.91/0/0.94**
20161021	0.87/2/0.89	1.18/3/0.88	1.03/3/0.91	**1.06/1/0.94**

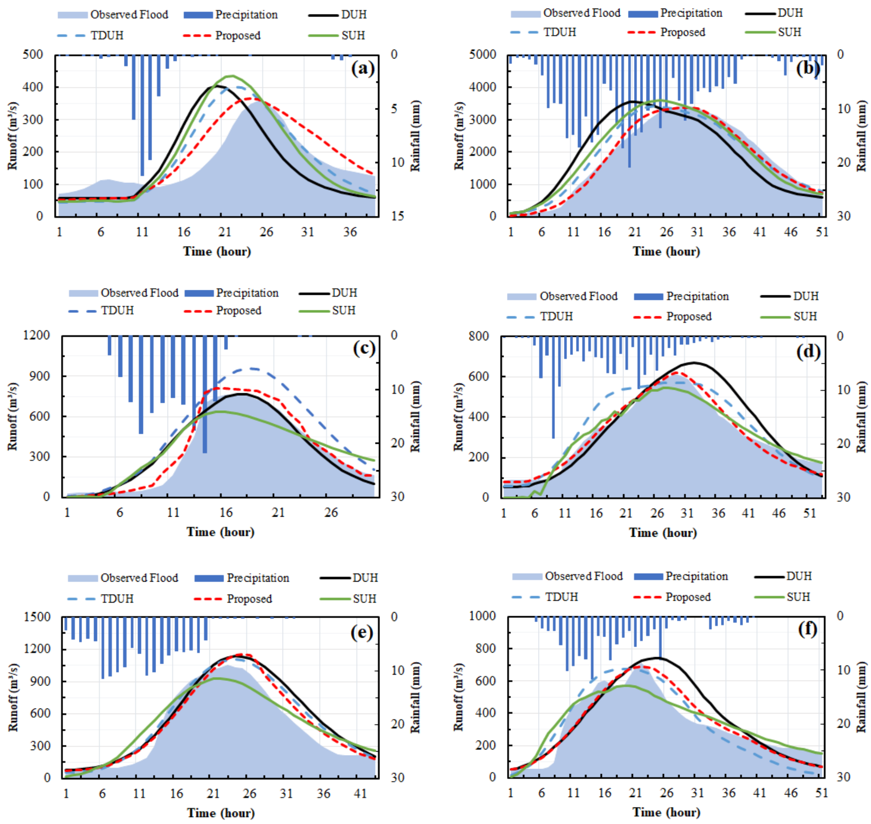

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Figure 11. Comparison of flow hydrographs obtained by the four methods. (a) Flow event No.20130720. (b) Flow event No.20130817. (c) Flow event No.20150709. (d) Flow event No.20160128. (e) Flow event No.20161021. (f) Flow event No.20180916.

For the flow event No.20161021, the simulation result of the proposed method was basically consistent with that of the TDUH method. This was because the antecedent rainfall was close to saturation under this flow event. As a result, the proposed method performed the same as the TDUH method when the watershed was saturated. For the flow event No.20180916, the simulation accuracy of the proposed method was lower than that of the TDUH. The possible reason for the inaccurate flow simulation is that the antecedent rainfall was relatively small. Because the runoff generation was not dominated by the saturation-excess, and it was not appropriate to calculate runoff with the XAJ model.

5.4 Influence of time-varying soil moisture content on flow forecasts

In order to evaluate the influence of time-varying soil moisture content on flow forecasts, three typical flow forecasting results of the proposed method were selected for comparison in the Qin River basin. Specifically, compared with the forecasting results using TDUH, the results of the flow event No.20130817 using the proposed method were relatively similar, the results of the flow events No.20150709 and 20160128 had a better performance, and the results of the flow event No.20180916 were poor. Their corresponding temporal evolution of soil moisture content in unsaturated regions were obtained. The box-and-whisker plots of soil moisture contents

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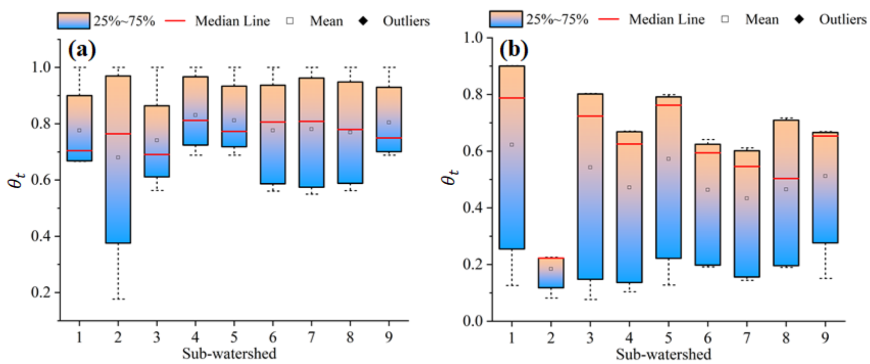
of all sub-basins for flow events No.20130817, 20150709, 20160128 and 20180916 are shown in Fig. 12. It can be seen from Fig. 12 that the soil moisture content of each sub-basin was initially low, then the soil moisture content of the sub-basin gradually increased. Meanwhile, it was obvious that θ_t was hard to reach the maximum value. For all flow events, 9 sub-basins eventually reached the saturation only under the condition of flow event No.20130817. The mean values of θ_t for flow events No.20150709, 20160128 and 20180916 ranged from 0.5 to 0.8, and the soil moisture content did not reach the maximum during the flow events. As shown from the observed flow in Fig. 10, the peak discharge of the flow event No.20130817 was larger than those of other flow events, reaching 3500 m^3/s, which meant that the watershed more probably reached saturation during the flow period.



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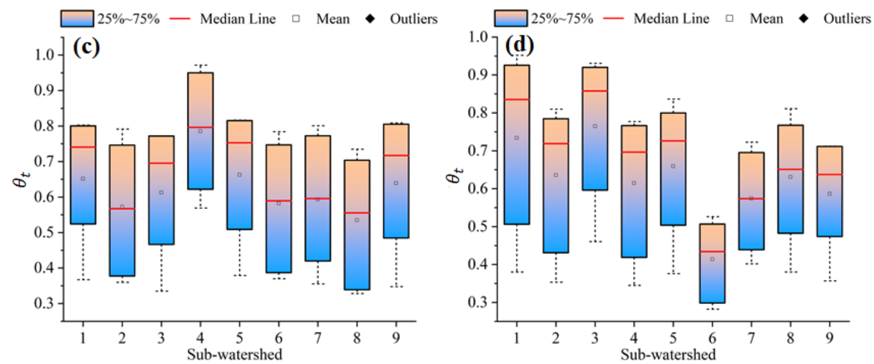

Figure 12. Distributions of time-varying θ_t at different times in each sub-basin using the proposed TDUH method. (a) Flow event No.20130817. (b) Flow event No.20150709. (c) Flow event No.20160128. (d) Flow event No.20180916. θ_t represents the ratio of current soil moisture storage to the corresponding maximum soil moisture capacity in the unsaturated region.

As discussed in Section 5.3, the results of the flow event No.20130817 using the proposed routing method showed the same behavior as did TDUH. This was because the simulation performance of the proposed method considering time-varying soil moisture content was the same as that of TDUH when the soil moisture content was closer to 1. Additionally, the forecast results of the flow events No.20150709, 20160128 with the proposed routing method were obviously better than those of DUH and TDUH. The reason can be summarized as follows. The mean values of θ_t ranged from 0.5 to 0.6 for the two flow events and the θ_t values were initially low as shown in Fig. 12. Thus, the soil moisture content had a significant impact on the shape of the hydrograph. For the flow event No.20180916, the sub-basins did not reach a global saturation, and the time-varying values of θ_t were generally high, which led to lower flow velocity than in the TDUH method. The peak occurrence times of unit hydrographs used for runoff routing calculations were general later, leading to a lag time between maximum rainfall intensity and peak discharge for the forecasting result of the flow event No.20180916.

5.5 Comparison of velocity calculated by three DUH methods

The routing method considering both time-varying rainfall intensity and soil moisture content was more accurate as discussed in Section 5.3. To evaluate the effect of time-varying soil moisture content on flow velocity, we selected a grid cell in sub-basin 3, in which slope and land type parameters were constant. Then, the flow velocity was calculated under different storm conditions. The storm events No.20130817 and 20150709 were selected and compared, because storm event No.20130817 had a high intensity and long duration, and storm event No. 20150709 had a short period of heavy rainfall. Thus, soil moisture contents during the two storm events were significantly different. Fig. 13 shows the time-varying velocity values of a grid cell for storm events No.20130817 and 20150709. For the two storm events, the mean velocity of the DUH method was the largest among the three methods, followed by the TDUH method. The velocity calculated by the proposed method considering soil moisture content was the smallest. The velocity of DUH method was constant in the two storms, and that of the TDUH method varied with the change of the excess rainfall. Meanwhile, the flow velocity of the proposed method was not only dominated by rainfall intensity, but also related to soil water content.

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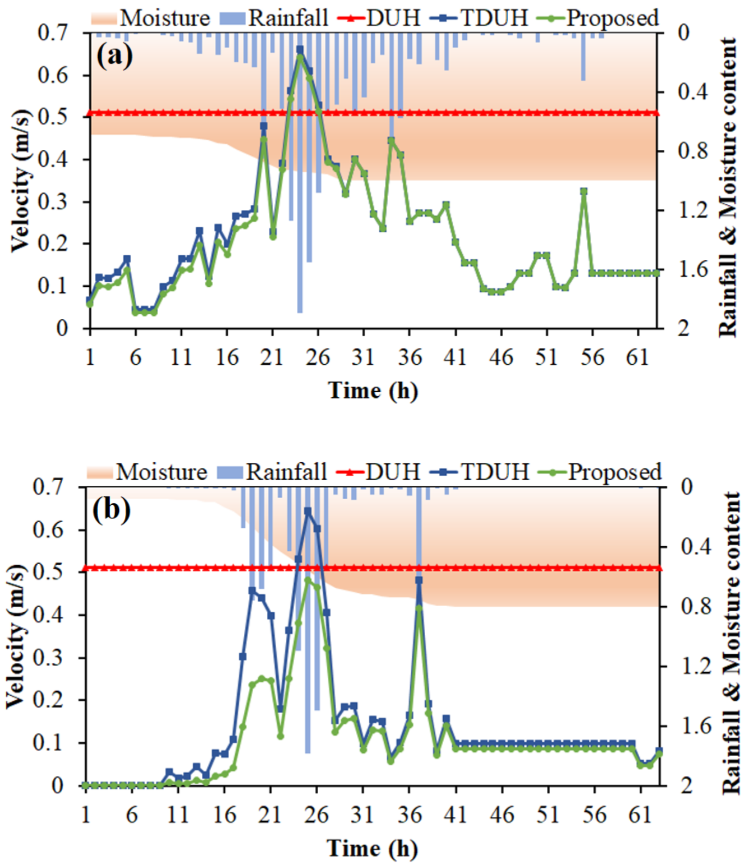

Figure 13. Time-varying velocity values of a grid cell in different storm events. (a) Time-varying velocity in storm event No.20130817. (b) Time-varying velocity in storm event No.20150709. The rainfall content is I_s, and the soil moisture content is θ_s.

For the storm event No.20130817, the initial soil moisture content was large, and it reached the maximum rapidly. The flow velocity of the proposed method was slightly smaller than that of the TDUH method at the initial stage of storm events. When the whole basin reached saturation, the flow velocities of the two methods became equal. Therefore, the differences between hydrographs were small when using the TDUH

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method and the proposed method for flow routing calculation, which led to similar forecast results.

For storm event No.20150709, the initial soil moisture content was small, and the entire basin could not reach the saturation after the rainstorm. Therefore, the grid velocity in the early stage of the storm was greatly affected by the soil moisture content. In the later stage of the rainstorm, θ_t of the watershed did not reach the maximum, and was nearly close to 1. Thus, the impact of later soil moisture content on the flow velocity was small. From the above analyses, it can be concluded that the shape and duration of the unit hydrograph were mainly related to the soil moisture content at the initial stage of a storm, and when the watershed was approximately saturated, the grid flow velocity was mainly dominated by the excess rainfall.

5.6 Sensitivity analysis for the proposed TDUH method

A sensitivity analysis for the proposed formula was conducted in the Longhu River basin. The improved method is only with two additional parameters, compared with the current model. The objective of this study is to explore the influence soil moisture content factor on the performance of the DUH model. The parameter γ in Eq. (3) mainly affected the significant degree of influence over how large that soil moisture content will be. Thus, sensitivity analysis for parameter γ was necessary. A specific grid cell in the Longhu River basin was taken as an example, where the slope of the grid cell was set to 0.22 m/m. The coefficient of flow velocity *k* and the ratio of rainfall intensity to the reference rainfall intensity I_s were assumed to be 1.5 m/s and 1,

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respectively. When parameter γ was 0.1, 0.5 and 1, respectively, the hillslope flow velocity values corresponding to different rainfall and soil moisture contents using the proposed formula are given in Fig. 14.

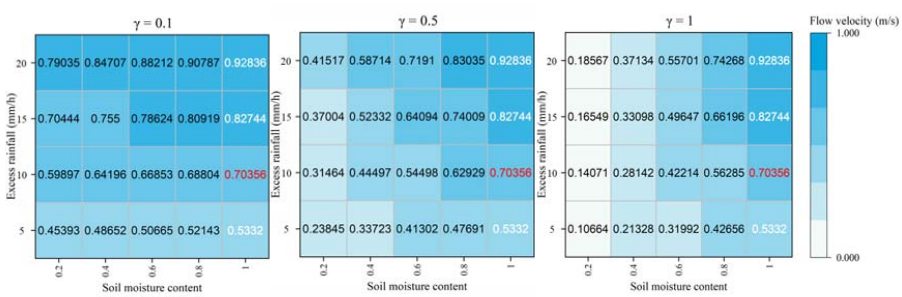

Figure 14. Time-varying flow velocity values corresponding to different parameters

It can be seen from Fig. 14 that when θ_t was equal to 1, the proposed Eq. (3) turned to Eq. (2). The flow velocity values in the last column were the same and only changed with rainfall intensities. When I_t was equal to the reference rainfall I_c, Eq. (2) turned to Eq. (1), and the flow velocity was 0.704 m/s. After introducing a soil moisture content factor into the flow velocity formula, the flow velocity values ranged from 0.107 m/s to 0.928 m/s when γ was equal to 1. The flow velocity values were significantly different corresponding to different values of parameter γ. Thus, the parameter γ significantly affected the performance of the new routing method.

Moreover, the mean flow velocity of the Longhu River basin was calculated under different rainfall intensities (e.g. $\frac{I_t}{I_c}$ = 0.5, 1, 1.5, 2, respectively). Fig. 15 plots the theoretical curve of mean velocity and soil moisture content.

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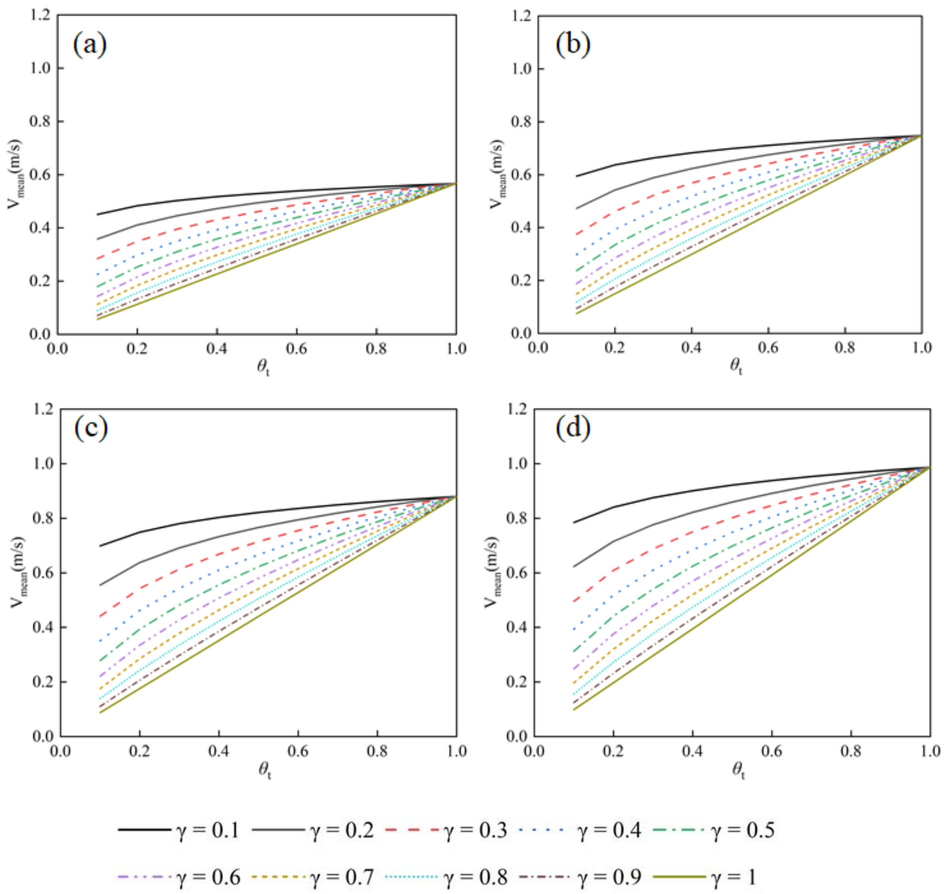

Figure 15. The theoretical curve of mean velocity and soil moisture content for the Longhu River basin. (a) $\frac{I_t}{I_c}=0.5$. (b) $\frac{I_t}{I_c}=1$. (c) $\frac{I_t}{I_c}=1.5$. (d) $\frac{I_t}{I_c}=2$.

Fig. 15 shows that the mean flow velocity ranged from 0.6 to 1 under different rainfall intensities without considering the influence of soil moisture content. After introducing this new factor into the current flow velocity formula, the mean flow velocity was significantly influenced by the exponent γ. In addition, when the soil moisture content exceeded 0.7, the variation range of mean flow velocity decreased sharply. Results showed that the influence of parameter γ on the flow velocity

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decreased gradually with the increase of soil moisture content.

5. Conclusions

An improved distributed unit hydrograph method considering time-varying soil moisture content was proposed for flow routing. The proposed method comprehensively considered the changes of time-varying soil moisture content and rainfall intensity. The response of the underlying surface to the soil moisture content was considered as an important factor. The Qin River basin and Longhu River basin were selected as two case studies. The SUH, DUH, TDUH and proposed routing methods were used for flow forecasting, and simulated results were compared. The sensitivity analysis was conducted for parameter γ. The main conclusions can be summarized as follows.

(1) The proposed runoff routing method, considering both time-varying rainfall intensity and soil moisture content, was proposed, and the influence of the inhomogeneity of runoff generation on the routing process was considered. It was found that the soil moisture content was a significant factor affecting the accuracy of flow forecasts, especially in the catchment dominated by saturation-excess runoff, and the flow velocity increased gradually with more surface runoff after considering the soil moisture content in unsaturated regions.

(2) The time-varying characteristics of the DUH can be further considered by introducing both rainfall intensity and soil moisture content into the flow velocity

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formula, which can effectively improve the accuracy of flow forecasts. Simulation hydrographs and criteria of the two case studies showed that the accuracy of the proposed method was the highest, followed by the SUH and TDUH methods, and finally the DUH method.

(3) The shape and duration of the improved TDUH considering soil moisture were mainly affected by rainfall intensity. Meanwhile, soil moisture content at initial stage of a storm also played a significant role in the characteristics of the improved TDUH. When the watershed is approximately saturated, the grid flow velocity was mainly dominated by excess rainfall.

(4) Results of sensitivity analysis showed that the accuracy of the proposed method was mainly affected by soil moisture content. The influence of parameter γ on the flow velocity decreased gradually with the increase of soil moisture content.

Data availability

Due to the strict security requirements from the departments, some or all data, models, or code generated or used in the study are proprietary or confidential in nature and may only be provided with restrictions (e.g. anonymized data).

Author contributions

Lu Chen conceived the original idea, and Bin Yi designed the methodology. Ping Jiang collected the data. Bin Yi developed the code and performed the study. Bin Yi, Lu Chen, Hansong Zhang and Vijay P. Singh contributed to the interpretation of the results. Bin

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Yi wrote the paper, and Lu Chen, Vijay P. Singh revised the paper.

Competing interests

The authors declare that they have no conflict of interest.

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