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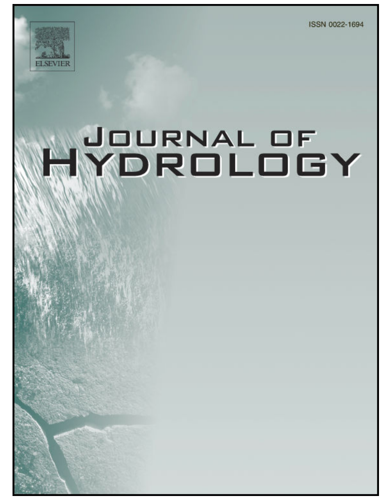

Research papers

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A multi-factor integrated method of calculation unit delineation for hydrological modeling in large mountainous basins

Bu Li[1], Xing Zhou[2], Guangheng Ni[1], Xuejian Cao[1], Fuqiang Tian[1], Ting Sun[3]

[1]State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, China

[2]Changjiang Survey, Planning, Design and Research Co., Ltd, Wuhan, China

[3]Department of Meteorology, University of Reading, Reading, UK

Correspondence to: G. Ni, ghni@tsinghua.edu.cn

Abstract: Hillslope-based distributed hydrological model has become an essential tool to simulate hydrological processes in mountainous areas, while how to properly delineate hillslope with key factors still remains to be answered. In this study, we propose a conceptually simple and computationally efficient method, the **h**illslope-asymmetry-**e**levation-band-**a**spect-based (HEA) delineation method, for large mountainous basins. Among these three factors, elevation band and hillslope aspect could represent the spatial heterogeneity of each hillslope in vertical and horizontal directions, respectively. More actual flow routing in each hillslope could be characterized due to the consideration of hillslope asymmetry and elevation band. The performance of HEA method is examined by conducting hydrological simulations with HEA-based basic calculation units (BCUs) in the Nu River basin in Southwest China. Simulated hydrographs agree well with the observations at different sites with Nash-

Sutcliffe efficiency coefficient (NSE) greater than 0.75, indicating the HEA delineation method works well for the large mountainous basins. Further numerical experiments are carried out to quantitatively investigate the role of HEA delineation factors in influencing streamflow process and the contribution of homogeneity of underlying surface and meteorological forcing in influencing streamflow process in different aspects. The results show that: the total streamflow is overestimated (underestimated) without consideration of hillslope asymmetry (aspect); while it is overestimated (underestimated) in wet (dry) season without consideration of elevation band. In addition, reduced heterogeneity in underlying surface and meteorological forcing leads to underestimated streamflow in different aspects, of which about 80% and 20% can be attributed to underlying surface and meteorological forcing, respectively.

Key words: calculation unit delineation method; distributed hydrological model; streamflow; elevation band; hillslope aspect.

Highlights:

1. A novel hillslope-based calculation unit delineation method for hydrological simulation in large mountainous basins is proposed;
2. Hillslope asymmetry and aspect are more crucial in influencing the simulation streamflow process;
3. The heterogeneity of precipitation is not the majority attribution to lead to the

streamflow influence.

1. Introduction

Mountainous areas, as one of the main landforms on the earth's surface, are the headwaters of majority rivers, providing huge water resources for human life, irrigation and hydroelectric power (Huss et al., 2017; Viviroli et al., 2011; Viviroli et al., 2007). It is thus important to understand how the hydrological processes are influenced in the mountainous basins. With meteorological data, geographic data, especially remote sensing data becoming more convenient and having higher accuracy, distributed hydrologic model has become an essential tool for hydrological studies (Han et al., 2020; Xu et al., 2014). Underlying surface of mountainous basins is known to have high spatial heterogeneity with respect to land cover, soil and topography, which in turn influences hydrological processes (DeBeer and Pomeroy, 2017; Hu and Si, 2014; Khan et al., 2014; Yang et al., 2017). As such, how to accurately discretize basins to characterize the spatial heterogeneity of underlying surface with affordable computational cost is of crucial importance in hydrological simulations using distributed hydrological models (Haghnegahdar et al., 2015; Pilz et al., 2017).

In distributed hydrological models, large mountainous basins are often delineated into sub-basins or grids (regular or irregular), to account for the spatial heterogeneity (Abbott et al., 1986; Ivanov et al., 2004; Manguerra and Engel, 1998). For natural basins, delineation into sub-basins is often preferred, since each sub-basin is most likely to be treated as the representative element for applying hydrological principles (Haghnegahdar et al., 2015). Sub-basins can be delineated into calculation units further based on different underlying surfaces and thresholds, such as Hydrological Response Units (HRUs) and Grouped Response Units (GRUs) (Flugel, 1995; Kouwen et al., 1993). Sub-basins are delineated into HRUs by a integration of soil, land cover and slope in Soil & Water Assessment Tool (SWAT) model (Manguerra and Engel, 1998). The main issue in adopting HRUs or GRUs is the lack of topological connectivity, which is important for comprehending hydrological processes in sub-basin scale (Neumann et al., 2010; Pilz et al., 2017). Another deficiency is that the factors chosen to delineate HRUs or GRUs lack considerations of spatial heterogeneity in meteorology. Furthermore, the HRUs or GRUs delineation always is based on land covers, while it is difficult to take into consideration of the land cover dynamics (Yang et al., 2019). Therefore, these methods are difficult to represent the spatial heterogeneity and connectivity in realistic hillslope scale.

To solve these issues, hillslope-based delineation methods which allow spatial topological connectivity, have been developed. Some methods utilize hillslopes as the fundamental calculation units directly (Bronstert, 1999; Zehe et al., 2001), and others delineate hillslopes into fundamental calculation units based on topography and underlying surface to reflect the spatial heterogeneity in hillslope scale further **(**Ajami et al., 2016**;** Güntner and Bronstert, 2004**;** Yang et al., 2002**;** Zehe et al., 2014**).** However, how to properly delineate hillslope with key factors into fundamental calculation units still remains to be answered. Hillslopes on two sides of river are asymmetric due to the river channel erosion. Hillslope asymmetry should be considered to capture the spatial heterogeneity on the two sides of river while many models assumed the hillslopes on two sides are symmetric (Yang et al., 2002). Elevation band is introduced to reflect the vertical variation of meteorological and hydrological conditions. Jia et al. (2006) developed the WEP model that divided sub-basins into contour bands and applied to the Yellow River basin, China successfully. Khan et al. (2014) developed an Equivalent Cross-Sections approach, which delineates sub-basins into contiguous topologically connected HRUs with respect to four landforms (upslope, midslope, footslope and alluvial-flats) successively. Ajami et al. (2016) developed the Soil Moisture And Runoff simulation Toolkit based on Equivalent Cross-Sections approach and Khan et al. (2018) applied it to a McLaughlin catchment of 459 km^2, Australia. Besides, many observational studies have demonstrated sunlit aspects are warmer and drier than shaded ones, leading to systematic differences in soil and vegetations between sunlit and shaded aspects (Brooks et al., 2015; Dearborn and Danby, 2017; Newman et al., 2014; Smith et al., 2017). Fan et al. (2019) proposed that the aspect difference of moderate and high relief can't be neglected in middle and high latitudes. For its role in identifying energy, vegetations and soil moisture to support different ecosystems, aspect information is considered as an important factor that should be included in Earth System Models and hydrological models (Chaney et al., 2018; Clark et al., 2015; Fan et al., 2019; Pelletier et al., 2018). Chaney et al. (2018) used the big data approach by integrating aspect and elevation bands to represent land heterogeneity in sub-grids of Earth System Models. However, little work is done to consider hillslope aspect explicitly and put these factors together in delineation methods for hydrological models. Therefore, based on previous studies, we develop a comprehensive delineation method to include all these important factors, and apply the method to a large mountainous basin with high spatial heterogeneity in land cover, soil, elevation and precipitation.

Investigating the roles of these delineation factors in influencing hydrological processes is important to understand the relationship between the spatial heterogeneity of topography and hydrological processes. Pilz et al. (2017) designed different discretization experiments for sensitivity analysis using WASA-WED model. It was concluded that the size of sub-basins and delineated hillslopes are the most influential factors compared with the number of landscape units and the further subdivision of terrain components. Khan et al. (2014) calculated different cross-sectional runoff to reveal that a cross section can' t characterize the hillslope and soil type is the most important condition to formulate an equivalent cross section. However, there are few studies on quantitatively and systematically illustrating the roles of delineation factors (elevation bands, hillslope aspect and hillslope asymmetry) in streamflow process. Therefore, a series of experiments were designed to characterize the impacts of individual factors on hydrological processes, especially on streamflow process.

This study aims to (1) develop a novel calculation unit delineation method and apply to a large mountainous basin and (2) clarify the individual role of various delineation factors in influencing streamflow process by practical application. Section 2 describes the development of HEA method. Section 3 focuses the methodology for hydrological model and simulation experiments design. The analysis of the method simulation performance and role of each individual factor are discussed in Section 4, followed by concluding remarks in Section 5.

2. Development of HEA-based delineation method

In this study we propose a conceptually simple and computationally efficient method, the **h**illslope-asymmetry-**e**levation-band-**a**spect-based (HEA) delineation method. Spatial variation of hillslope asymmetry, elevation difference, sun-facing or shaded, are identified as the characteristics that affect hydrological and ecological properties distribution in a river basin. The hillslopes are asymmetric in reality on two sides of river and the heterogeneity on two sides of river can be captured with consideration of hillslope asymmetry in a distributed hydrological model. The heterogeneity in hillslope scale needs to be characterized further. Elevation band and hillslope aspect are easily accessible variables to represent the heterogeneity in vertical and horizontal direction, respectively.

In this method, hillslope asymmetry, elevation and aspect are included while efforts are made to make the delineation process simple and straight with only DEM is necessarily required. The delineation procedure is summarized as follow.

During the pre-processing, based on DEM data, flow direction, slope, accumulated contribution area, and aspect are calculated for each grid with DEM data. The river network is extracted based on proper drainage area threshold value, which is the important basis for further delineation (Grieve et al., 2016; Liu et al., 2012; Noel et al., 2014). The threshold value is set based on observed channel head for geomorphological applications (Grieve et al., 2016).

In the delineation stage, the study basin is first divided into sub-basins using GIS terrain division methods based on extracted river network; then, each sub-basin is divided into two or three hillslopes, i.e. left, right, and source hillslopes; each hillslope is further discretized into continuous elevation bands with the same interval. Besides, in each elevation band, three basic calculation units (BCUs) are separated according to aspects: sunlit (south facing), shaded (north facing), or intermediate (west and east). Finally, based on the river network and landforms, the topological structures are constructed and used as basic connection relationship among the sub-basins, hillslopes, elevation bands and BCUs. The meteorological and hydrological characteristics are assumed uniform within each basic calculation unit (BCU). All these procedures are designed to characterize the spatial variation of land cover, soil type and meteorological characteristics, with the hillslope asymmetry representing spatial differences along two sides of the river, elevation-bands indicating water flowing along slope from high to low areas, and BCUs further denoting spatial differences in energy and soil moisture.

The HEA method delineation procedure is illustrated in Figure 1. Left hillslope (Figure 1b) is to the left of river flow direction and right hillslope to the right slide. Source hillslope (Figure 1b) is facing to the river origin, and not every sub-basin has source hillslope, depending on whether the river is flowing through or originated from the sub-basin. Elevation bands (Figure 1c) are delineated in each hillslope using fixed interval, numbers of elevation bands in each hillslope may be different. In each elevation band, maximum three BCUs (i.e. sunlit, shaded and intermediate aspects; Figure 1d) can be categorized according to the facing directions of grids within a hillslope. Grids of the same BCU without being spatially together are assumed to be clustered and specific location of each grid is ignored.

3. Methodology

3.1 Hydrological model

In this study, we use a modified Tsinghua Integrated Hydrological Modeling System (THIHMS) to evaluate the HEA-based method by conducting simulations of hydrological processes in the Nu River basin (Wang et al., 2006). Vegetation interception is equal to the smaller value of rainfall and interception capacity based on LAI and NDVI. Snowfall ratio in precipitation is linear in the critical temperature range and the degree day model is utilized to calculate snow and ice melting amount. Richards equation is used to simulate the movement of unsaturated soil. Use water balance equation and Darcy formula to calculate groundwater movement. The river network convergence adopts the kinematic wave equation discretized by Preissmann scheme and Manning formula.

To adopt the HEA delineation method, evapotranspiration and runoff generation processes are calculated at the BCUs scale firstly. The surface and underground runoff of BCUs in each elevation band are accumulated, and then routed to the next connected lower elevation band. There is no water exchange between the BCUs of the same elevation band. Runoff into the elevation band is redistributed to each BCU based on unit area. The runoff is routed along the elevation band until it flows into the river network. River network convergence is calculated in each sub-basin. By using the HEA method, THIHMS model could keep the spatial connectivity and reflect the realistic water flow in hillslopes.

3.2 Study area and data

3.2.1 Study area

Nu-Salween River is one of the last largely free-flowing international rivers (Grill et al., 2019), with a total length of 2,413 km, running across China, Thailand, and Burma. Nu River (Figure 2), as the upstream of Nu-Salween River, provides abundant water resource for human life and hydropower. The Nu River basin area is about 142,000 km^2 and the landform undulates greatly with elevation above sea level from 433 to 6,879 m in the study area. The annual precipitation over this area is 800–1200 mm and the dominant land cover is forest and grassland.

3.2.2 Data

In this study, we use three types of datasets as follows:

1) Surface characteristics for THIHMS:

    a. Digital Elevation Model (DEM) data of Shuttle Radar Topography Mission (SRTM) with 90 m spatial resolution for basin delineation and slope calculation. The data set is provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences. (http://www.gscloud.cn);

    b. The land cover dataset MCD12Q1 Version 51 (MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500 m SIN Grid V051) in period of 2003-2012 adopting the International Geosphere Biosphere Programme IGBP (IGBP) classification (Friedl and Sulla-Menashe, 2015);

    c. Harmonized World Soil Database version 1.2 (HWSD, Nachtergaele et al., 2008);

d. A monthly NDVI dataset with 1km spatial resolution developed by Zhou et al. (2017);

2) Meteorological forcing for THIHMS:

a. Datasets consisting of daily air temperature from 24 weather stations near the study area via the China Meteorological Administration;

b. A daily precipitation dataset with 1km spatial resolution developed by Zhou et al. (2017);

c. MODIS potential evapotranspiration (PET) product MOD16 with the spatiotemporal resolution of 500 m/8 days used for evapotranspiration calculation (Running et al., 2017).

3) Evaluation:

The streamflow data at six hydrological stations (Figure 2) provided by local institution for simulation verification.

3.3 Simulation design

In the evaluation, we conduct four suites of simulations (Table 1-2) to illustrate the effectiveness of the HEA method with the following specific aspects:

1) SHR (spatial heterogeneity representativeness case): To ensure fair comparison, the study area is delineated into the same level number of calculation units for each method, i.e. regular square grids (GRIDs; GRID scenario), sub-basins (SUBs; SUB scenario) and BCUs of the HEA method. Then the performance of the three delineation methods in characterizing the spatial heterogeneity is evaluated in terms of land use, soil, and precipitation.

2) DFT (default case): HEA method is applied in the Nu River basin to verify the applicability of HEA method based on modified THIHMS. The simulated results are also used as the control group.

3) DLF (delineation factors case): Applying HEA method to the Nu River basin enables a robust representation of spatial heterogeneity within hydrological models. However, the individual role of delineation factors isn't characterized, while it is important to advance our understanding of the relationship between the spatial heterogeneity and hydrological response. To make this analysis possible, a set of method experiments are designed to investigate the individual role of delineation factors on streamflow process. Each factor's sensitivity is explored by turning the heterogeneity of properties associated with each factor on and off. When "on" the factor is considered in delineation method; when "off" the factor isn't considered. The different method experiments (A, HE, HA and HEA) are outlined in Table 1.

4) PUS (precipitation and underlying surface case): DLF is to investigate the roles of different delineation factors in influencing streamflow process, but its contribution of the heterogeneity of underlying surface and meteorological forcing, especially precipitation is still unclear. Using the same delineation method as HEA, HEAP differs from HEA by assuming homogeneous precipitation in each elevation band. HEAP, HEA and HE methods (Table 2) are combined to investigate the contribution of underlying surface and meteorological driving condition in different hillslope aspects further.

These methods of DLF and PUS cases are based on the HEA method by neglecting the specific delineation factors (i.e. hillslope asymmetry, elevation band and hillslope aspect), or partial spatial heterogeneity. Now, we take the HA method as an example to illustrate the hillslope routing of these methods. Each hillslope will be assumed as one elevation band, when the delineation factor of elevation band is ignored. The BCUs are delineated in each elevation band based on hillslope aspect. Except it, the runoff routing and topological structures of the HA method keep consistent with the HEA method. Significantly, the parameters of these methods for hydrological simulations remain the same as those of HEA method.

Based on the above methods, the hydrological processes in the Nu River basin were simulated from 2003 to 2012 with the first two years as warm-up period. The parameter, saturated hydraulic conductivity of soil, was adjusted manually in a small range to acquire the reasonable simulation results. The following metrics are used to evaluate the performance of related methods in the later analysis:

1) homogeneity index HI

$$HI = \max\,(A_i, i = 1, l) \tag{1}$$

where l is the numbers of land cover (soil) type in each unit (i.e., sub-basin, hillslope, elevation band and BCU) and A_i is the area percentage of land cover (soil) i in the unit.

2) standard deviation STD

$$STD = \sqrt{\frac{\sum_{i=1}^{n}(P_{ai} - P_{mi})^2}{n}} \tag{2}$$

where n is the number of grids in each unit, P_a is the precipitation of 1 km grid, and P_m is the precipitation merged by sub-basins, hillslopes, elevation bands or BCUs.

3) Nash-Sutcliffe efficiency coefficient NSE (J.E.Nash and J.V.Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{t}(Q_{obs,\,i} - Q_{sim,\,i})^2}{\sum_{i=1}^{t}\left(Q_{obs,\,i} - \overline{Q_{obs}}\right)^2} \tag{3}$$

where t is the total days of simulated period, $Q_{obs,i}$ and $Q_{sim,i}$ are the observed and simulated daily streamflow; $\overline{Q_{obs}}$ is the observed average streamflow.

4) coefficient of determination R^2:

$$R^2 = \frac{\left[\sum_{i=1}^{t}\left(Q_{obs,i} - \overline{Q_{obs}}\right)\left(Q_{sim,i} - \overline{Q_{sim}}\right)\right]^2}{\sum_{i=1}^{t}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2 \sum_{i=1}^{t}\left(Q_{sim,i} - \overline{Q_{sim}}\right)^2} \tag{4}$$

where $\overline{Q_{sim}}$ is the simulated average streamflow.

5) normalized mean bias error ($nMBE$)

$$nMBE = \frac{Q_e - Q_c}{Q_c} \tag{5}$$

where Q_e is the total streamflows of method without consideration of experiment factor, and Q_c is the total streamflows with consideration of experiment factor.

6) contributions index (CI)

$$CI = \frac{\Delta Q_i}{\Delta Q_{all}} \tag{6}$$

where ΔQ_{all} is the change of average streamflow due to all study factors and ΔQ_i is the change of average streamflow due to the study factor i.

The HI and STD are used to evaluate the representativeness of underlying surface and precipitation of HEA method, and the observed streamflow data of six hydrological stations (Figure 2) is used to evaluate the performance of HEA method with indexes of NSE and R^2. The basins above Station GLH and DWJ are used to investigate the impact of delineation factors and contribution of meteorological forcing and underlying surface with R^2 and $nMBE$. Besides, the basin above Station JYQ are also utilized to investigate the impact of elevation band. The CI is utilized to quantify the contribution of underlying surface and meteorological forcing. Noteworthy, it is the simulated streamflow process with different delineation methods to be compared each other but not with observed streamflow process when investigating the impact of delineation factors and contribution of meteorological forcing and underlying surface.

4. Results and discussion

4.1 Performance of the HEA method

To adopt the HEA method in the Nu River basin, drainage area threshold and elevation band interval are set as 80 km^2 and 500 m respectively, based on the actual river network (Figure A1), the terrain with high mountain canyon, and the complex vertical distribution of precipitation (Figure B1). The Nu River basin is divided into 561 sub-basins and 1408 hillslopes (more specifically, with 286 source hillslopes, 2443 elevation bands with 500 m interval, and 4650 BCUs; see Table 3). The average area of sub-basins and BCUs are 253.1 km^2 and 30.5 km^2, respectively. The representativeness of underlying surface and precipitation, and the accuracy of simulated hydrological processes for the HEA method are evaluated as follows.

4.1.1 Representativeness of underlying surface and precipitation

In hydrological models, it is assumed the underlying surface and meteorological forcing are homogeneous in the calculation units. Thus, the more homogeneous the underlying surface and meteorological forcing are represented, the better the delineation method is. We firstly evaluate the spatial heterogeneity representativeness of BCUs with HI (Equation 1) and STD (Equation 2). As described by SHR in

Section 3.3, the study area was directly delineated into 4696 GRIDs (GRID scenario) and 4608 SUBs (SUB scenario), respectively. The comparison of HIs of land use and soil, and STD of annual average precipitation for each GRID, SUB and BCU was shown in Figure 3 and Table 4.

(1) Representativeness of underlying surface

Compared with GRIDs and SUBs, more BCUs show high HI values, indicating the BCUs perform better in representing the heterogeneity of both land use (Figure 3 (a)) and soil (Figure 3 (b)). Specifically, the average HIs of land use for GRIDs, SUBs and BCUs are 0.79, 0.78 and 0.85, respectively, while those of soil are 0.63, 0.62 and 0.64, respectively (Table 4). The average HI of both land use and soil for BCUs are higher than those of SUBs and GRIDs, indicating that the HEA method is a more efficient approach to represent the heterogeneity of underlying surface. Besides, it also demonstrates that the HEA method can better capture the heterogeneity of land use than soil, because land use is controlled by topography, especially by elevation and hillslope aspects (Pelletier et al., 2018).

(2) Representativeness of precipitation

The daily precipitation dataset of 1 km grid from 2003 to 2012 in the Nu River basin was utilized as the model input in this study. To evaluate the representativeness of precipitation for the HEA method, annual average precipitation dataset was merged based on GRIDs, SUBs and BCUs, respectively. The standard deviation (STD, Equation 2) between the initial precipitation dataset and each merged outcome was calculated. Average STD of GRIDs, SUBs and BCUs is 89.1 mm, 94.6 mm and 87.6

mm, respectively, indicating precipitation is more likely to be captured by BCUs than SUBs and GRIDs. It is probably because the method of HEA is able to capture the major vertical distribution of precipitation in hillslope scale (Figure B1), due to the consideration of the elevation band. However, the high $STDs$ indicates there is still difference between the precipitation of model input and initial dataset due to the complexity of precipitation distribution in some zones (Figure B1).

Based on the above analysis, the HEA method could better capture the spatial heterogeneity of underlying surfaces and precipitation than other methods, so fewer calculation units are needed in the THIHMS model, which makes it computationally efficient.

4.1.2 Simulated hydrological processes

The performance of HEA method in simulating the hydrological processes is examined by comparing the observed and simulated streamflow at six hydrological stations (Figure 4). In general, the HEA method works favorably in simulating hydrological processes with both NSE (Equation 3) and R^2 (Equation 4) being higher than 0.75 at six hydrological stations except for JYQ (Table 5) (Moriasi et al., 2007). It is also noting that the simulated streamflow agrees well with the observed one by reasonably capturing flood peaks with appropriate timing and magnitudes (Figure 4); while relatively poorer results are observed at JYQ, which could be due to the lack of observations as the observation out of wet seasons (i.e. July–September). The simulations results demonstrate good performance of the HEA method in modeling the streamflow process in the Nu River basin, suggesting HEA method as a reasonable approach to delineate the large mountainous basins for hydrological simulation.

4.2 Impacts of the delineation factors

Given the appealing performance of HEA method, it is thus intriguing to understand how the topographical features used by HEA method, including hillslope asymmetry, elevation and aspect, would influence the hydrological model. As such, we further investigate the role of each delineation factor in influencing the simulated hydrological processes by conducting numerical experiments with different combinations of delineation factors (Table 1).

4.2.1 Hillslope asymmetry

With consideration of hillslope asymmetry, the actual, rather than the average, routing length of flow can be characterized to ensure more reasonable overland and subsurface flow paths to rivers. Besides, the spatial heterogeneity in hydrological and meteorological characteristics on both sides of hillslopes can be captured with consideration of hillslope asymmetry.

By comparing the results between A and HA methods, we may understand the role of hillslope asymmetry in influencing streamflow process. The streamflow processes show similar patterns between A and HA methods, while the total streamflow produced by A method is apparently greater than that by HA (Figure 5a-b , and 6a), by 14% (annual 3%-26%) in DWJ, and 84% (59%-114%) in GLH. It indicates streamflow is overestimated without consideration of hillslope asymmetry, varying between different sites and years, as expected given their different heterogeneities in underlying surface and meteorological forcing (Figure 6a).

4.2.2 Elevation band

With consideration of elevation band, the vertical hillslope flows can be characterized: rainfall stored in hillslopes in wet seasons as groundwater can flow out in the dry season. Besides, the spatial heterogeneity of hydrological and meteorological forcing variables in vertical direction can be captured with consideration of elevation band.

Similarly, HEA and HA methods were designed to investigate the impact of elevation band at JYQ (upstream), GLH (downstream) and DWJ (downstream). The difference in streamflow processes between HA and HEA methods is minimal at GLH and DWJ (Figure 5c-d, and 6b) while the difference is more obvious at JYQ (Figure 7). The streamflow produced by the HA method is greater than that by the HEA method in wet seasons (May–September) but less in dry seasons (October–April). Although the total streamflow with HA and HEA method is similar, apparent seasonality is observed in their differences: without consideration of elevation band, streamflow is overestimated in wet seasons but underestimated in dry seasons. These results again suggest that consideration of elevation bands can better characterize vertical hillslope flows due to more explicit representation of storage capacity in hillslopes. We note the impact of elevation band on streamflow can be more apparent with finer intervals in the cost of higher computational load. Specific to this work in the Nu River basin, a 500-m interval considered appropriate in proper balance between good model performance and reasonable computational load.

4.2.3 Hillslope aspect

With consideration of hillslope aspect, the spatial heterogeneity in horizontal solar irradiance and its impacts on streamflow process can be more accurately captured. Such impact is investigated by comparing the results of HEA and HE methods (Figure 5e-f, and 6c): the streamflow of HE is lower than that by HEA, by 48% in DWJ and 39% in GLH. It indicates that consideration of hillslope aspect would produce higher streamflow by about 43% due to the representativeness of heterogeneity of underlying surface and precipitation in different hillslope aspects.

4.3 Comparative importance of heterogeneity between precipitation and underlying surface

Based on the analysis in section 4.2, we conclude that different delineation factors in HEA method play important but different roles in influencing streamflow process by capturing the heterogeneity in underlying surface and meteorological forcing, especially precipitation. However, comparative importance of heterogeneity between meteorological forcing and underlying surface in influencing streamflow process remains to be revealed. Considering that there is little snowfall in basins above Station GLH and DWJ, and the spatial resolution of air temperature dataset is poor, it is assumed that heterogeneity of precipitation is the majority meteorological forcing variable in this part. To illustrate the comparative importance, using HEA as the reference case, HEAP and HE are chosen in the later analysis to investigate the contributions of precipitation and underlying surface (Table 2):

1) **HEAP** differs from **HEA** by assuming *homogeneous precipitation in each elevation band* and thus can be used to investigate the role of precipitation in influencing streamflow process;

2) **HE** excludes the *heterogeneity of underlying surface in each elevation band* from **HEAP** and they are used to look into the importance of underlying surface heterogeneity.

The difference between the streamflow process with HE and HEAP is largely similar to that between HE and HEA (Figure 5g-h, and 6d). Streamflow process with HEAP method resembles that with HEA method (Figure 5i-j) while the total streamflow produced by the HEAP method is slightly less than that by HEA (Figure 6e).

Based on the simulation results, streamflow with the homogeneity of precipitation in each elevation band is underestimated slightly and the homogeneity of underlying surface is the major factor to lead to the streamflow underestimation. The Contributions Index (CI, Equation 6) is used to quantify the contributions of underlying surface and precipitation further. In this study, the CI of underlying surface and precipitation are Equation 7 and 8, respectively. The results show the contribution of underlying surface on streamflow underestimation makes up about 82%, and precipitation is about 18% in Station DWJ and the contributions are 79% and 21% at Station GLH, respectively.

$$CI_{underlying\ surfaces} = \frac{Q_{HEAP} - Q_{HE}}{Q_{HEA} - Q_{HE}} \tag{7}$$

$$CI_{precipitation} = \frac{Q_{HEA} - Q_{HEAP}}{Q_{HEA} - Q_{HE}} \tag{8}$$

where Q_{HEA}, Q_{HEAP} and Q_{HE} are average streamflow with HEA, HEAP and HE method.

Based on the analysis above, we deem it is more important to capture the heterogeneity of underlying surface for delineating sub-basins in distributed hydrological model, while the heterogeneity of precipitation in each elevation band is a less important factor in improving the hydrological simulations. Also, considering the challenge in acquisition of high resolution precipitation (especially for less gauged mountainous areas), for the sake of feasibility, we suggest more efforts should be paid on improving the representation of underlying surface heterogeneity in hydrological model.

5. Conclusion

In this study, we developed a multi-factor, i.e., hillslope-asymmetry-elevation-band-aspect-based (HEA) calculation unit delineation method for hydrological simulation in large mountainous basins, which requires only DEM data to account for heterogeneity of underlying surface while keeping the spatial connectivity. Specifically, elevation band and hillslope aspect could represent the spatial heterogeneity of each hillslope in vertical and horizontal directions, respectively. More realistic flow routing in each hillslope could be characterized thanks to the consideration of hillslope asymmetry and elevation band. Based on the HEA method, the study area is delineated into 561 sub-basins, 2,443 elevation bands and 4,650 BCUs with set of elevation band interval as 500 m, and then the hydrological simulations are conducted using THIHMS model. The good match between the simulated and observed hydrographs at 5 sites with *NSE* larger than 0.75 indicates that the HEA method works well for the Nu River basin.

Furthermore, numerical experiments are designed to investigate the roles that these three delineation factors play in influencing streamflow process. Without consideration of hillslope asymmetry, streamflow is overestimated varying from different sites and years (by annual 3–26% in DWJ, and 59–114% in GLH). Neglect of elevation band leads to the streamflow slight increase (decrease) in wet (dry) season, and the total streamflow remains the same. Streamflow is underestimated by about 39–48% if hillslope aspect is not accounted for. The underestimation can be attributed to underlying surface and precipitation by ~80% and 20%, respectively.

Overall, the HEA method proves to be an efficient and accurate method for delineation of calculation units in large mountainous basins. The influence of different delineated calculation units size will be studied in the future.

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Appendix A. The comparison of river network of HEA method and actual river network

Appendix B. The vertical distribution of precipitation in delineated hillslope scale

Reference

Abbott, M.B., Bathurst, J.C., Cunge, J.A., et al. 1986. An introduction to the European hydrological system - systeme hydrologique Europeen, SHE.1. history and philosophy of a physically - based, distributed modeling system. Journal of Hydrology 87(1-2), 45-59.

Ajami, H., Khan, U., Tuteja, N.K., et al. 2016. Development of a computationally efficient semi-distributed hydrologic modeling application for soil moisture, lateral flow and runoff simulation. Environmental Modelling & Software 85, 319-331.

Bronstert, A. 1999. Capabilities and limitations of detailed hillslope hydrological modelling. Hydrological Process 13, 21-48.

Brooks, P.D., Chorover, J., Fan, Y., et al. 2015. Hydrological partitioning in the critical zone: Recent advances and opportunities for developing transferable understanding of water cycle dynamics. Water Resources Research 51(9), 6973-6987.

Chaney, N.W., Van Huijgevoort, M.H.J., Shevliakova, E., et al. 2018. Harnessing big data to rethink land heterogeneity in Earth system models. Hydrology and Earth System Sciences 22(6), 3311-3330.

Clark, M.P., Fan, Y., Lawrence, D.M., et al. 2015. Improving the representation of hydrologic processes in Earth System Models. Water Resources Research 51(8), 5929-5956.

Dearborn, K.D. and Danby, R.K. 2017. Aspect and slope influence plant community composition more than elevation across forest-tundra ecotones in subarctic Canada. Journal of Vegetation Science 28(3), 595-604.

DeBeer, C.M. and Pomeroy, J.W. 2017. Influence of snowpack and melt energy heterogeneity on snow cover depletion and snowmelt runoff simulation in a cold mountain environment. Journal of Hydrology 553, 199-213.

Fan, Y., Clark, M., Lawrence, D.M., et al. 2019. Hillslope hydrology in global change research and Earth System Modeling. Water Resources Research 55(2), 1737-1772.

Flugel, W.A. 1995. Delineating hydrological response units by geographical information - system analyses for regional hydrological modeling using PRMS/MMS in the drainage-basin of the rever Brol, Germany. Hydrological Processes 9(3-4), 423-436.

Friedl, M. and Sulla-Menashe, D. 2015. MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006, NASA EOSDIS Land Processes DAAC.

Grieve, S.W.D., Mudd, S.M. and Hurst, M.D. 2016. How long is a hillslope? Earth Surface Processes and Landforms 41(8), 1039-1054.

Grill, G., Lehner, B., Thieme, M., et al. 2019. Mapping the world's free-flowing rivers. Nature 569(7755), 215-221.

Güntner, A. and Bronstert, A. 2004. Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas. Journal of Hydrology 297(1-4), 136-161.

Haghnegahdar, A., Tolson, B.A., Craig, J.R., et al. 2015. Assessing the performance of a semi-distributed hydrological model under various watershed discretization schemes. Hydrological Processes 29(18), 4018-4031.

Han, P., Long, D., Han, Z., et al. 2020. Improved understanding of snowmelt runoff from the headwaters of China's Yangtze River using remotely sensed snow products and hydrological modeling. Remote Sensing of Environment 224, 44-59.

Hu, W. and Si, B.C. 2014. Revealing the relative influence of soil and topographic properties on soil water content distribution at the watershed scale in two sites. Journal of Hydrology 516, 107-118.

Huss, M., Bookhagen, B., Huggel, C., et al. 2017. Toward mountains without permanent snow and ice. Earths Future 5(5), 418-435.

Ivanov, V.Y., Vivoni, E.R., Bras, R.L., et al. 2004. Catchment hydrologic response with a fully distributed triangulated irregular network model. Water Resources Research 40，W11102.

J.E.Nash and J.V.Sutcliffe 1970. River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology 10(3), 282-290.

Jia, Y., Wang, H., Zhou, Z., et al. 2006. Development of the WEP-L distributed hydrological model and dynamic assessment of water resources in the Yellow River basin. Journal of Hydrology 331(3-4), 606-629.

Khan, U., Ajami, H., Tuteja, N.K., et al. 2018. Catchment scale simulations of soil moisture dynamics using an equivalent cross-section based hydrological modelling approach. Journal of Hydrology 564, 944-966.

Khan, U., Tuteja, N.K., Ajami, H., et al. 2014. An equivalent cross-sectional basis for semidistributed hydrological modeling. Water Resources Research 50(5), 4395-4415.

Kouwen, N., Soulis, E.D., Pietroniro, A., et al. 1993. Grouped response units for distributed hydrological modeling. Journal of Water Resources Planning and Management-Asce 119(3), 289-305.

Liu, J., Chen, X., Zhang, X., et al. 2012. Grid digital elevation model based algorithms for determination of hillslope width functions through flow distance transforms. Water Resources Research 48, W04532.

Manguerra, H.B. and Engel, B.A. 1998. Hydrologic parameterization of watersheds for runoff prediction using SWAT. Journal of the American Water Resources Association 34(5), 1149-1162.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., et al. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the Asabe 50(3), 885-900.

Nachtergaele, F., van Velthuizen, H. and Verelst, L. 2008. Harmonized World Soil Database, Food and Agriculture Organization of the United Nations.

Neumann, L.N., Western, A.W. and Argent, R.M. 2010. The sensitivity of simulated flow and water quality response to spatial heterogeneity on a hillslope in the Tarrawarra catchment, Australia. Hydrological Processes 24(1), 76-86.

Newman, A.J., Clark, M.P., Winstral, A., et al. 2014. The use of similarity concepts to represent subgrid variability in Land Surface Models: case study in a snowmelt-dominated watershed. Journal of Hydrometeorology 15(5), 1717-1738.

Noel, P., Rousseau, A.N., Paniconi, C., et al. 2014. Algorithm for Delineating and Extracting Hillslopes and Hillslope Width Functions from Gridded Elevation Data. Journal of Hydrologic Engineering 19(2), 366-374.

Pelletier, J.D., Barron-Gafford, G.A., Gutiérrez-Jurado, H., et al. 2018. Which way do you lean? Using slope aspect variations to understand Critical Zone processes and feedbacks. Earth Surface Processes and Landforms 43(5), 1133-1154.

Pilz, T., Francke, T. and Bronstert, A. 2017. lumpR 2.0.0: an R package facilitating landscape discretisation for hillslope-based hydrological models. Geoscientific Model Development 10(8), 3001-3023.

Running, S., Mu, Q. and Zhao, M. 2017. MOD16A2 MODIS/Terra Net Evapotranspiration 8-Day L4 Global 500m SIN Grid V006, NASA EOSDIS Land Processes DAAC.

Smith, L.A., Eissenstat, D.M. and Kaye, M.W. 2017. Variability in aboveground carbon driven by slope aspect and curvature in an eastern deciduous forest, USA. Canadian Journal of Forest Research 47(2), 149-158.

Viviroli, D., Archer, D.R., Buytaert, W., et al. 2011. Climate change and mountain water resources: overview and recommendations for research, management and policy. Hydrology and Earth System Sciences 15(2), 471-504.

Viviroli, D., Durr, H.H., Messerli, B., et al. 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resources Research 43, W07447.

Wang, L., Ni, G.H. and Hu, H.P. 2006. Study on the interaction between surface water and groundwater in Qin River basin using a distributed hydrologic model. Journal of Tsinghua University (Science and Technology) 46(12), 1978-1981.

Xu, X., Li, J. and Tolson, B.A. 2014. Progress in integrating remote sensing data and hydrologic modeling. Progress in Physical Geography-Earth and Environment 38(4), 464-498.

Yang, D., Herath, S. and Musiake, K. 2002. A hillslope-based hydrological model using catchment area and width functions. Hydrological Sciences Journal 47(1), 49-65.

Yang, W., Long, D. and Bai, P. 2019. Impacts of future land cover and climate changes on runoff in the mostly afforested river basin in North China. Journal of Hydrology 570, 201-219.

Yang, Y., Dou, Y., Liu, D., et al. 2017. Spatial pattern and heterogeneity of soil moisture along a transect in a small catchment on the Loess Plateau. Journal of Hydrology 550, 466-477.

Zehe, E., Ehret, U., Pfister, L., et al. 2014. HESS Opinions: From response units to functional units: a thermodynamic reinterpretation of the HRU concept to link spatial organization and functioning of intermediate scale catchments. Hydrology and Earth System Sciences 18(11), 4635-4655.

Zehe, E., Maurer, T., Ihringer, J., et al. 2001. Modeling water flow and mass transport in a loess catchment. Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere 26(7-8), 487-507.

Zhou, X., Ni, G.-H., Shen, C., et al. 2017. Remapping annual precipitation in mountainous areas based on vegetation patterns: a case study in the Nu River basin. Hydrology and Earth System Sciences 21(2), 999-1015.

Abstract: Hillslope-based distributed hydrological model has become an essential tool to simulate hydrological processes in mountainous areas, while how to properly delineate hillslope with key factors still remains to be answered. In this study, we propose a conceptually simple and computationally efficient method, the **h**illslope-asymmetry-**e**levation-band-**a**spect-based (HEA) delineation method, for large mountainous basins. Among these three factors, elevation band and hillslope aspect

could represent the spatial heterogeneity of each hillslope in vertical and horizontal directions, respectively. More actual flow routing in each hillslope could be characterized due to the consideration of hillslope asymmetry and elevation band. The performance of HEA method is examined by conducting hydrological simulations with HEA-based basic calculation units (BCUs) in the Nu River basin in Southwest China. Simulated hydrographs agree well with the observations at different sites with Nash-Sutcliffe efficiency coefficient (NSE) greater than 0.75, indicating the HEA delineation method works well for the large mountainous basins. Further numerical experiments are carried out to quantitatively investigate the role of HEA delineation factors in influencing streamflow process and the contribution of homogeneity of underlying surface and meteorological forcing in influencing streamflow process in different aspects. The results show that: the total streamflow is overestimated (underestimated) without consideration of hillslope asymmetry (aspect); while it is overestimated (underestimated) in wet (dry) season without consideration of elevation band. In addition, reduced heterogeneity in underlying surface and meteorological forcing leads to underestimated streamflow in different aspects, of which about 80% and 20% can be attributed to underlying surface and meteorological forcing, respectively.

Bu Li: Methodology, Software, Data curation, Validation, Formal analysis, Visualization, Investigation, Writing- Original draft preparation, Writing - Review & Editing.

Xing Zhou: Software, Investigation.

Guangheng Ni: Conceptualization, Methodology, Supervision, Project administration, Writing - Review & Editing.

Xuejian Cao: Visualization, Writing - Review & Editing.

Fuqiang Tian: Methodology.

Ting Sun: Methodology, Visualization, Writing - Review & Editing.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights:

4. A novel hillslope-based calculation unit delineation method for hydrological simulation in large mountainous basins is proposed;
5. Hillslope asymmetry and aspect are more crucial in influencing the simulation

streamflow process;

6. The heterogeneity of precipitation is not the majority attribution to lead to the streamflow influence.

Figure 1. Workflow of the HEA method: (a) A sub-basin example (see Fig. 2 for location) for HEA delineation. (b) Hillslope asymmetry: left, right and source hillslopes are identified based on hillslope heterogeneity. (c) Elevation band classification: elevation bands (black-outlined polygons) are classified according to elevation ranges in each hillslope (colored polygons). (d) Aspect identification: elevation-band based units (colored polygons) are further separated as per aspect. Basic calculation units (BCUs) after each delineation step are shown in black-outlined polygons (d).

Figure 2. Terrain map of the Nu River basin with weather stations and hydrological stations shown in dots and triangles, respectively.

Figure 3. The numerical distribution of HI of land use (a) and soil (b), and STD of annual average precipitation (c) in GRID, SUB and BCU scenarios.

Figure 4. The comparison of simulated and observed streamflow process at six hydrological stations.

Figure 5. The streamflow processes with different experiments at Station DWJ (a, c, e, g, i) and GLH (b, d, f, h, j) in 2006.

Figure 6. The nMBE and R^2 results between streamflow processes with two delineation experiments at Station DWJ and GLH each year (2005-2012). The line is mean value.

Figure 7. The simulated streamflow processes with HA and HEA method at Station JYQ in 2006.

Figure A1: The comparison of extracted river network by the HEA method and actual river network (http://www.resdc.cn/). In the main diagram, the purple and the blue line represent the overlaps and the difference between two river networks, respectively.

Figure B1: Four typical relationships between precipitation and elevation on hillslope scale in the Nu River basin: (a) monotonically increasing in low elevation regions; (b) inversed U shape in medium elevation regions; (c) monotonically decreasing in high elevation regions; and (d) independent. The location of four typical hillslopes is shown in Figure 2.

Table 1. Design details of delineation factors case simulations. Black-outlined polygons represent BCU in different method and blue line represents the river. Colored polygons represent the elevation bands with HEA method in all sketches and white line is delineation difference between the delineation method of representation and HEA method in each sketch except that of HEA method.

Delineation Method	Hillslope Asymmetry	Elevation Band	Aspect	BCU Sketch
A	Off	Off	On	
HA	On	Off	On	

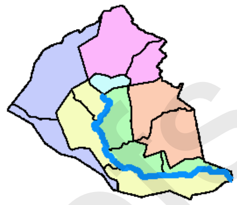
HE	On	On	Off	
HEA	On	On	On	

Table 2. Design details of precipitation and underlying surface case simulations.

Delineation Method	Precipitation	Underlying surface
HE	Off	Off
HEAP	Off	On
HEA	On	On

Table 3. The numbers of hillslopes, elevation band and BCUs in the Nu River basin with different method experiments.

Method	**Hillslopes**	**Elevation bands**	**BCUs**
A	561	561	1582
HE	1408	2443	2443
HA	1408	1408	3112
HEAP	1408	2443	4650
HEA	1408	2443	4650

Table 4. The mean HI of land use and soil, and the STD of precipitation in GRID, SUB and BCU scenarios.

Scenario	Mean HI of land use	Mean HI of soil	STD of precipitation (mm)
GRID	0.79	0.63	89.1
SUB	0.78	0.62	94.6
BCU	0.85	0.64	87.6

Table 5. The simulation results of NSE and R^2 at six hydrological stations for the period 2005-2012.

Station	NSE	R^2
JYQ	0.57	0.69
GS	0.82	0.84
LK	0.81	0.82
DJB	0.82	0.83
GLH	0.75	0.79
DWJ	0.75	0.81