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Chance-constrained overland flow modeling for improving conceptual distributed hydrologic simulations based on scaling representation of sub-daily rainfall variability

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HIGHLIGHTS

- We develop an improved hydrologic model considering the scaling effect of rainfall.
- A chance-constrained Hortonion overland modeling approach is proposed.
- The model improves the simulation of integral runoff volume as well as peak flows.
- A real world case study presents the applicability and adaptability of the model.
- Rainfall thresholds are crucial for representing the overland flow generation.

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ABSTRACT

Lack of hydrologic process representation at the short time-scale would lead to inadequate simulations in distributed hydrological modeling. Especially for complex mountainous watersheds, surface runoff simulations are significantly affected by the overland flow generation, which is closely related to the rainfall characteristics at a sub-time step. In this paper, the sub-daily variability of rainfall intensity was considered using a probability distribution, and a chance-constrained overland flow modeling approach was proposed to capture the generation of overland flow within conceptual distributed hydrologic simulations. The integrated modeling procedures were further demonstrated through a watershed of China Three Gorges Reservoir area, leading to an improved SLURP-TGR hydrologic model based on SLURP. Combined with rainfall thresholds determined to distinguish various magnitudes of daily rainfall totals, three levels of significance were simultaneously employed to examine the hydrologic-response simulation. Results showed that SLURP-TGR could enhance the model performance, and the deviation of runoff simulations was effectively controlled. However, rainfall thresholds were so crucial for reflecting the scaling effect of rainfall intensity that optimal levels of significance and rainfall threshold were 0.05 and 10 mm, respectively. As for the Xiangxi River watershed, the main runoff contribution came from interflow of the fast store. Although slight differences of overland flow simulations between SLURP and SLURP-TGR were derived, SLURP-TGR was found to help improve the simulation of peak flows, and would improve the overall modeling efficiency through adjusting runoff component simulations. Consequently, the developed modeling approach favors efficient representation of hydrological processes and would be expected to have a potential for wide applications.

1. Introduction

Under changing environmental conditions, hydrological models have been important tools to describe the hydrological response of climatic and landscape changes on the watersheds (Ferguson and Maxwell, 2010; Shen and Phanikumar, 2010; Tong et al., 2012). However, there are too many models confronting us, and hence, how to choose an appropriate one and to determine reasonable model configurations would be a big problem since almost all the models were established with a certain context or based on a specific watershed (Borah and Bera, 2004; Wu et al., 2007). Hydrological process representation is always formulated according to many simplifications and assumptions, and application of these models might be subject to some arguments on the rationality

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and adaptation (Beven, 2009). Besides, calibration came to be inevitable to ensure that "effective" parameter values were adopted in model application, and parameter identifiability and equifinality would be the major concerns in this regard (Zhang and Savenije, 2005). Although satisfactory simulations might be obtained through modeling operation, water balance simulations over the watershed could not be well verified as a result of a lack of detailed information on hydrologic cycle. According to Beven (1997, 2001), thus, these models should be used with care, and modifications would be necessary to suit particular circumstances.

Take the Xin'anjiang model for example, it was initially applied for inflow forecasting of the Xin'anjiang reservoir and mainly proposed for use in humid and semi-humid regions of China (Ren and Yuan, 2006; Zhao, 1992). In this model, the tension water capacity curve was employed to take the spatial heterogeneity of watershed characteristics into consideration, and runoff would only occur in areas where the soil moisture content reaches the field capacity (Ye et al., 2014). Similarly, the saturation excess overland generation was also well demonstrated by TOPMODEL (a TOPography based hydrological MODEL), which introduced a concept of hydrological similarity based on the topographic index to account for the distributed implications of hydrologic variables through indicating the spatial distribution of soil moisture deficit (Beven, 2012; Beven and Kirkby, 1979). In contrast with them, Hortonian overland flow (infiltration excess flow) was found to dominate the hydrograph of many watersheds with (semi-)arid to sub-humid climate (Stomph et al., 2002). As a matter of fact, however, the infiltration and saturation excess mechanisms are not mutually exclusive on a watershed, even at a point on a watershed (Smith and Goodrich, 2005). Johnson et al. (2003) performed hydrological simulations of a watershed in the upper part of the Irondequoit Creek basin using the Hydrological Simulation Program-FORTRAN (HSPF) and the Soil Moisture Routing (SMR) models simultaneously, surface runoff generation of which was simulated as infiltration excess and saturation excess overland flow, respectively. Although overall modeling efficiency values were comparable, simulation accuracy on a seasonal basis was highly related to the runoff-generating mechanism. In addition, the difference in the ability to predict spatial distribution of soil moisture was also significant. Therefore, a potential way to address such dilemma would combine these two kinds of overland flow generation mechanism and make full use of their roles in regulating surface runoff generation associated with specific watershed conditions.

Generally, rainfall is the most important input to hydrologic models as its resolution and quality would impose critical influence on hydrologic model's performance (Chu et al., 2012; Neary et al., 2004), and rainfall information proved to be closely related to the usefulness of watershed models. Especially for distributed hydrologic models, rainfall data are required both in the spatially and temporally distributed form. Traditionally, discrete rain gauges are able to provide accurate rainfall measurements at certain points, but interpolation or disaggregation is further needed to satisfy the required data by hydrologic models. Radar-rainfall products have demonstrated great potential for their use in hydrologic applications, while uncertainty of radar-rainfall estimates should be carefully considered, and monitoring and in situ measurement of precipitation might still be indispensable (Krajewski and Smith, 2002). Although spatial distribution of rainfall across the watershed could be better reflected through increasing rain gauges, variations in rainfall characteristics within monitoring intervals could not be explicitly indicated only based on the observations. Besides, deterministic hydrologic models are always driven with an exact rainfall input at each time step, i.e. an average used rather than varying rainfall intensities (Kavetski et al., 2011). As a result, a problem would be arisen as to how the hydrologic processes would actually respond with consideration of varying rainfall intensities instead of averaging them? Meanwhile, it further leads us to look at the simulation uncertainty due to neglecting the roles of variations in model inputs within the computation time step in mimicking runoff response (Beven, 1997, 2001, 2009).

According to the Horton's overland flow theory (Beven, 2004), infiltration excess flow is affected greatly by the rainfall intensity, and hence, consideration of varying rainfall intensity at short time-scale might lead to a distinct surface runoff response due to smaller hydrologic process representation. Kandel et al. (2003, 2005) proposed a scaling approach to capture the sub-time-step rainfall variability in rainfall-runoff and erosion modeling. A cumulative probability (CDF) distribution of rainfall intensities was introduced by them to represent the effect of temporal variability of rainfall intensities at a smaller time scale on hydrological processes, and significant improvements in the simulation of surface runoff were achieved. Note that the infiltration excess flow was the main form of surface runoff at their study site, and saturation excess flow was considered only through incorporating a simple bucket-storage capacity concept. Thereupon, surface runoff generation should further be reflected through carefully mediating infiltration excess and saturation excess flow occurring on the watershed. As far as the probabilistic form of rainfall intensity is concerned, one effective and convenient approach to deal with random uncertainty would be the chance-constrained stochastic programing approach (Jiang and Guan, 2013). In this approach, chance constraints emerge naturally as a modeling tool under various decision making circumstances (Arellano-Garcia, 2006; Li et al., 2008; Miller and Wagner, 1965), and cumulative probability level could be applied to control risk in decision making under uncertainty. Consider that infiltration excess flow is simulated based on the chance constraints between the infiltration capacity and the stochastic rainfall intensity, and overland flow generation under two kinds of mechanism would then be regulated through the rain water infiltration into soil which could be manipulated according to "the risk level" in chance constraints. Thus, a chance-constrained overland flow modeling approach would be developed to realize the simulation of surface runoff generation while taking the effect of varying sub-time-step rainfall intensities into consideration in case of no detailed rainfall data being available.

Therefore, this paper aims to develop an adaptive hydrologic modeling approach for representing adequately the process of overland flow generation and achieving improved modeling efficiency. The structure is organized as follows. The modeling framework is first formulated, including the hydrologic model and the chance-constrained overland flow modeling procedures. Then, a case study is introduced to present the study area and data, followed by the field experiments carried out to investigate the variability of the rainfall intensity. Thereafter, hydrologic simulations with various modeling schemes are performed, and the obtained results are further analyzed and discussed to illustrate the usefulness of the proposed approach. Finally, conclusions are given as well as the acknowledgements.

2. Model formulation

2.1. Hydrologic model

The applied Semi-Distributed Land-use Runoff Process (SLURP) hydrological model is a continuous and daily time step based model that requires division of a target watershed into subareas known as Aggregated Simulated Areas (ASAs), which is consistent with a subwatershed in terms of watershed subdivision (Han et al., 2013b; Kite and Kouwen, 1992; Santos et al., 2015). These subareas are further divided by ToPographic PArameteriZation (TOPAZ) into a number of units with different types of land cover based on vegetation, soil and land use conditions (Lacroix et al., 2002; Valle Junior et al., 2015). Topographic characteristics and aggregation statistics for each land cover within each ASA are also derived using the TOPAZ package, such as elevation, distance to the nearest stream and distance to downstream. In addition, each land cover is characterized by a distinct set of model parameters. With particular hydrologic response to rainfall, each land cover class within each ASA in fact functions as a Hydrological Response Unit (HRU) in the hydrologic model (Arnold et al., 1998). Hence, the