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Improving the flood prediction capability of the Xinanjiang model in ungauged nested catchments by coupling it with the geomorphologic instantaneous unit hydrograph

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SUMMARY

Improving the predictive capabilities of rainfall-runoff models in ungauged catchments is a challenging task but has important theoretical and practical significance. In this study, we investigated the predictive capabilities of the conceptual Xinanjiang model (XAJ), which is widely used for flood forecasting and simulation in China, in ungauged catchments. We further produced a hybrid rainfall-runoff model (named XAJ-GIUH) by coupling the XAJ model with the geomorphologic instantaneous unit hydrograph (GIUH) to achieve improved flood predictions in ungauged catchments. The flood prediction capabilities of the original XAJ model and the XAJ-GIUH model were investigated and compared at an hourly time scale in a mountainous catchment with six nested catchments located in the south of Anhui province, China. The two models were first calibrated for each individual catchment by comparing with the observed streamflows. Then, the nested catchments were treated as ungauged and modeled using the parameter values regionalized by transposition from the downstream catchments. The results show that the performance of both models is comparable and satisfactory on different catchment scales in the case that model parameters are calibrated in each catchment. However, the models perform differently in the case that model parameters are transposed from the downstream catchments. The XAJ-GIUH model produced markedly improved estimates of peak discharge and peak time as compared to the original XAJ model in the latter case, indicating that the runoff routing is a major uncertainty source for the application of the XAJ model in this case. Coupling XAJ with topography-based GIUH has the potential to substantially improve the flood prediction capability of the XAJ model in ungauged catchments. Our analysis further reveals that the models do not necessarily perform better when the parameter values are transposed from closer donor catchment. Instead, adopting the parameter values from the catchment with more similar topographic characteristics is more likely to produce better model performance. This study implicates the necessity of including remotely sensed geomorphologic characteristics of ungauged catchments to improve flood predictions in these regions.

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1. Introduction

Floods are one of the most significant water-related natural disasters, causing serious property damage and loss of lives (WMO, 2011). To reduce the impact of flooding, operational flood forecasting systems have been developed around the world (Todini, 2005). The growing necessity of these operational systems promotes the development of rainfall-runoff models, which are commonly used in the existing systems (Todini, 2005; WMO, 2011). With the rapid development of computational technologies, a large number of studies on rainfall-runoff models for flood simulation and forecasting have been carried out over the past several decades (e.g. Beven and Kirkby, 1979; Zhao, 1992; Garrote and Bras, 1995; Singh, 1995; Todini, 1996; De Roo et al., 2000; Koren et al., 2004; Smith et al., 2004; Manfreda et al., 2005; Moore, 2007; Yao et al., 2009; Beven, 2012).

With the growing need to forecast floods at any location where there is a risk of disastrous flood events, hydrologists are widely interested in applying the rainfall-runoff models to ungauged catchments (Blöschl, 2005; Moore et al., 2006; Cole and Moore, 2009). However, it is one of the most challenging tasks in theoretical and

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operational hydrology due to the lack of hydrologic observations that could be used for model calibration. Since 2003, an initiative, decade-long plan of Predictions in Ungauged Basins (PUB) has been launched by the International Association of Hydrological Sciences (IAHS) (e.g. Sivapalan et al., 2003; Montanari and Toth, 2007; Moore et al., 2007; Wagener and Montanari, 2011; Blöschl et al., 2013; Hrachowitz et al., 2013). The decade plan has stimulated the extensive research activities in addressing the ungauged basin problem associated with considerable uncertainties and continued to push PUB to the forefront of hydrology research. Regionalization approaches, such as regression, spatial proximity and physical similarity, involving the transfer of parameter values from a donor gauged catchment to the receptor ungauged catchment, have been designed and typically used to handle the issue of PUB (e.g. Sivapalan, 2003; Wagener et al., 2004, 2007; Merz and Blöschl, 2004; Wagener and Wheater, 2006; Young, 2006; Bárdossy, 2007; Götzinger and Bárdossy, 2007; Reed et al., 2007; Norbiato et al., 2008; Seibert and Beven, 2009; Javelle et al., 2010; He et al., 2011; Beven, 2012; Yao et al., 2012; Singh et al., 2012; Yang et al., 2008, 2010, 2013).

The Xinanjiang model, which is the most popular conceptual rainfall-runoff model in China, has been extensively used for flood simulation and operational forecasting in gauged catchments since first developed in the 1970s (Zhao, 1977, 1992; Zhao et al., 1980; Zhao and Liu, 1995; Todini, 2005) and already deployed in the China National Flood Forecasting System (WMO, 2011). Although some insensitive parameters of the Xinanjiang model can be preset or estimated in terms of the implementation experience, the sensitive parameters must be calibrated based on historical streamflow data using either a trial-and-error approach and/or an automatic optimization algorithm (Lü et al., 2013). This makes it difficult to apply the Xinanjiang model to the ungauged catchments to achieve good results. Some recent studies have claimed to address the relevant issue using the regionalization approaches, but these studies mainly focused on the application of Xinanjiang model at daily time scale (Li et al., 2009; Zhang and Chiew, 2009). Since the Xinanjiang model parameters related to runoff separation and routing are sensitive to time scale, their values, which cannot be obtained in a theoretically based way of taking account of change of time-step (e.g. Moore et al., 1999), should always be adjusted through recalibration when using the model for flood simulation and forecasting at a shorter time interval. Therefore, this raises the questions whether the regionalization approaches can be successfully used in the application of the Xinanjiang model at a sub-daily time scale (e.g., commonly used time interval of 1-h with respect to flood simulation and forecasting), and how the performance of the Xinanjiang model can be improved in ungauged catchments. Unfortunately, there is little guidance in the modeling literature on these two questions.

The first objective of this paper is therefore to assess the flood prediction capability of the Xinanjiang model using the regionalization approaches at an hourly time scale. A nested region containing interior stream gauging (*hypothetical ungauged for regionalization*) stations was selected as the study region according to the recommendations of IH (1999), Smith et al. (2004, 2012) and Beven (2012). It has been shown by Merz and Blöschl (2004) that strong regional similarities exist for nested catchments and better performance can be achieved by using the parameters transposed from nested neighbors. In this study, the model parameters for the interior locations were regionalized by transposition from the downstream catchments. Results derived in this way are considered indicative of expected model performance at upstream ungauged locations, under the conditions that the model calibration may be carried out at larger spatial scales and that the calibrated parameters may be transposed to smaller spatial scales (Norbiato et al., 2008). The scale problems caused by transposing the parameters from large gauged catchments to small ungauged catchments can also be investigated in a nested catchment system (McNamara et al., 1998; Mendiondo et al., 2007; Lee et al., 2009).

Secondly, we intend to address how to improve the flood prediction capability of the Xinanjiang model in ungauged catchments using the regionalized parameters. It has been widely recognized that the simulated flood events by the Xinanjiang model are extremely sensitive to the parameters of the "lag-and-route" runoff routing method. In spite of its easy implementation, this method is not theoretically strong. Moreover, its parameters are purely empirical according to Zhao (1992) and Zhao and Liu (1995). The quantitative link between these parameters and the catchment characteristics has not been well studied for PUB. Hence, we think that it is a good starting point to use a more physically meaningful routing technique in place of the lag-and-route method. The geomorphologic instantaneous unit hydrograph (GIUH) approach based on the linearity assumption was chosen here to replace the lag-and-route component of the Xinanjiang model. The GIUH approach was first introduced by Rodriguez-Iturbe and Valdes (1979) and later generalized by Gupta et al. (1980). It has the advantage of requiring a limited number of parameters whereas the necessary geomorphologic data can be obtained from topographic maps or digital elevation model (DEM) (Ros and Borga, 1997). This approach has been reported as a powerful tool for linking the hydrologic response of catchments to their geomorphologic characteristics, which can provide an insight to the hydrologic behavior of ungauged catchments (Kumar et al., 2007). The efficiency and robustness of the GIUH approach in ungauged catchments have been tested and verified by many studies (e.g. Ros and Borga, 1997; Yen and Lee, 1997; Al-Wagdany and Rao, 1998; Rui, 2003; Fleurant et al., 2006; Kumar et al., 2007; Bhadra et al., 2008; Grimaldi et al., 2012; Hrachowitz et al., 2013).

We have noticed that there are also other physically based routing methods contributing to PUB. For example, the Horton–Izzard nonlinear storage approach (Moore and Bell, 2002; Moore, 2007), which has been used to represent network flow paths in a grid-based distributed model (Ciarapica and Todini, 2002; Moore et al., 2007; Bell et al., 2009), can be linked to the physical properties of a channel network to address the ungauged problem. Because the GIUH approach is a source-to-sink routing formulation (Moore et al., 2006), we think it is more appropriate to the semi-distributed formulation of the Xinanjiang model. Thus, we coupled the Xinanjiang model with the GIUH approach (hereinafter, referred to as XAJ-GIUH) in this study to simulate flood events. The performance of the XAJ-GIUH model was investigated to determine whether improved simulations can be obtained when using the parameters transposed from the donor catchments.

2. Study area and data

The Tunxi (TX) catchment located in the southern mountainous region of Anhui province, China is chosen as our study area (Fig. 1). It is a meso-scale catchment and has a drainage area of 2692 km^2. The long-term average annual rainfall, runoff and pan evaporation from 1982 to 2003 are 1922 mm/yr, 1279 mm/yr and 646 mm/yr, respectively. Because of the dominance of a monsoon climate, more than 60% of annual rainfall occurs during the flood season (May to August). Apart from the river gauging station at the outlet of TX, there are six interior nested stations within the Tunxi catchment, including Yuetan (YT), Wanan (WA), Chengcun (CC), Xinting (XT), Liukou (LK) and Yucun (YC) (Fig. 1). The landscape characteristics of all seven catchments are summarized in Table 1 and were derived from a DEM with a spatial resolution of 90 m (3″) provided by International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn). Station observations of rainfall,

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