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Estimating daily time series of streamflow using hydrological model calibrated based on satellite observations of river water surface width: Toward real world applications

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ABSTRACT

Lacking observation data for calibration constrains applications of hydrological models to estimate daily time series of streamflow. Recent improvements in remote sensing enable detection of river water-surface width from satellite observations, making possible the tracking of streamflow from space. In this study, a method calibrating hydrological models using river width derived from remote sensing is demonstrated through application to the ungauged Irrawaddy Basin in Myanmar. Generalized likelihood uncertainty estimation (GLUE) is selected as a tool for automatic calibration and uncertainty analysis. Of 50,000 randomly generated parameter sets, 997 are identified as behavioral, based on comparing model simulation with satellite observations. The uncertainty band of streamflow simulation can span most of 10-year average monthly observed streamflow for moderate and high flow conditions. Nash–Sutcliffe efficiency is 95.7% for the simulated streamflow at the 50% quantile. These results indicate that application to the target basin is generally successful. Beyond evaluating the method in a basin lacking streamflow data, difficulties and possible solutions for applications in the real world are addressed to promote future use of the proposed method in more ungauged basins.

1. Introduction

Streamflow, the volume rate of water passing a river cross section, may be the most significant hydrological variable, as it is an integrated output of the hydrological cycle at basin scale (Shamir et al., 2005). It is also a major link between continents and oceans, delivering huge amounts of particulate and dissolved material to the oceans, which strongly impact ocean chemistry and nutrients. From a terrestrial aspect, streamflow is a major source of the freshwater available for humans and regulates ecological cycles. Under climate change, frequencies of extreme climate events such as drought and flood are predicted to increase (Hirabayashi et al., 2008, 2013). Long time series of streamflow data are important to take countermeasures against such disasters. In the context of improving the ecological health and biodiversity of river basins, streamflow data are also vital to determine environmental flow (Gao et al., 2009). These data are traditionally measured by *in situ* gauging. The maintenance of gauge stations is expensive and time-consuming, which has led to a decline in coverage of monitoring networks in recent years (Fekete and Vörösmarty, 2007). Even if observations have been made, in many cases, because of political issues or conflicts of economic interests, sharing data among stakeholders is difficult (Viglione et al., 2010). Therefore, improvement of streamflow observations and estimation has long been a popular topic for hydrologists. Such improvement is one major objective of the last International Association of Hydrological Sciences (IAHS) scientific initiative “Predictions in Ungauged Basins” (PUB) (2003–2013) (Sivapalan et al., 2003). This will continue to be an important question in the new scientific initiative of the association “Panta Rhei – Everything Flows” (2013–2022) (Montanari et al., 2013), which focuses on improving the capability of predicting water resource dynamics to support sustainable societal development under a changing environment.

Given the rapid improvement of remote sensing technologies, many river hydraulic variables closely related to streamflow, such as river water-surface width, stage, channel slope, channel sinuosity and meander properties can be observed from space, especially for middle to large size rivers (Bjerklie et al., 2005; Dingman and Bjerklie, 2005). Efforts toward estimating streamflow from satellite

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observations have been made since the 1980s (*e.g.*, Usachev, 1983). In the early stage, building empirical relationships between ground-measured streamflow and observations from space (*e.g.*, Smith et al., 1995; Coe and Birkett, 2004; Bjerklie et al., 2005) was the typical approach. Results from these studies showed the great potential of remote sensing in tracking streamflow. However, empirical relationships are constrained by the characteristics of remote sensing. To monitor hydrological changes, observations at temporal resolutions from several minutes (for flood control) to daily (water resource management) are desired. The repeat cycle of a satellite determines the frequency of remote sensing observations, varying from several days to several months, such that dynamics of the hydrologic cycle between two successive observations cannot be detected (Alsdorf et al., 2007). Another usual concern is satellite observation error. When estimating streamflow using empirical relationships with remote sensing data as input, this error in satellite observations will directly propagate to the estimates.

Realizing the limitations of direct applications of remote sensing data in streamflow estimation, many researchers have recently tried to regulate hydraulic modeling using river hydraulic information from space through model calibration (*e.g.*, Stephens et al., 2012; Domeneghetti et al., 2014) or data assimilation (*e.g.*, Durand et al., 2008; Biancamaria et al., 2011; Michailovsky et al., 2013). The role of satellite observations is to make parameter values or simulation of hydraulic state variables better reflect hydrological characteristics of a basin. Streamflow is ultimately estimated by the model itself. It is common at present to incorporating satellite observations of flood inundation area, and water stage directly from radar altimetry or inferred from water surface area and high resolution topography data, into hydrodynamic or flood routing model. Because these hydraulic variables observed from space are simulated by models, such integration does not require major modifications to model structure and is easily done using calibration schemes or data assimilation techniques. Results from relevant research show that simulation uncertainty is reduced by incorporating satellite observations and estimation of streamflow is thereby improved. However, applications of such an approach to ungauged basins face many challenges. Many studies demonstrate that the greatest source of uncertainty in hydrodynamic modeling is streamflow data used as model boundary condition forcing (Schumann et al., 2009). When ground observations are unavailable, inflow is usually provided by hydrological model simulation. Therefore, assuring the accuracy of this inflow is worth addressing in such cases.

Hydrological models are common tools for estimating daily time series of streamflow. Several researchers (*e.g.*, Montanari et al., 2009; Finsen et al., 2014) have used remotely sensed hydraulic information for hydrological model calibration or data assimilation. Because the output of a hydrological model is streamflow, a necessary step is adding a hydraulic component describing the relationship between streamflow and river hydraulic variable to the hydrological model. Getirana (2010) tried to calibrate a hydrological model in the Branco River basin of the Northern Amazon basin, using water stage derived from ENVISAT altimetric data. The stage × streamflow relationship was an empirical one for the Negro River and transposed to the Branco River. Their results indicate that reasonable parameter values can be obtained from calibration using only satellite altimetric observations. They recognized that transferring the empirical relationship from a gauged basin to the target basin was a major limitation of the proposed method, and that a more generally applicable stage × streamflow relationship is desirable. Sun et al. (2010a) calibrated a hydrological model using river water-surface widths derived from Japanese Earth Resources Satellite 1 (JERS1). The at-a-station hydraulic geometry relationship was used to describe the width × streamflow relationship. In the calibration, parameters of the hydraulic relationship were tuned simultaneously with the hydrological parameters to minimize the difference between satellite observations and model-simulated river water-surface width. Using the generalized likelihood uncertainty estimation (GLUE) proposed by Beven and Binley (1992) for model calibration and uncertainty analysis, application to the Mekong Basin was successful. Compared with Getirana (2010), one advantage is that hydraulic parameter values are derived based on information from remote sensing at the river segment where the hydraulic relationship is constructed. A similar method was also successfully applied to the Mississippi Basin using river water-surface elevation derived from TOPEX/POSEIDON radar altimetric observations as calibration data (Sun et al., 2012). This method enabled a new generation of hydrological models that do not rely on any ground observations in the modeled basin, which is valuable for streamflow estimation in ungauged basins. The improvement of remote sensing and GIS techniques enable input data for hydrological models, including digital elevation model (DEM), spatial distribution of land cover and soil type, and vegetation parameters, such as Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) obtained from global datasets. Further, many satellite rainfall products are available for providing forcing to hydrological models. The method demonstrated in Sun et al. (2010a, 2012) has great potential to reduce simulation uncertainty of such new-generation models by obtaining reasonable hydrological model parameter values through calibration. However, there are still several challenges to the application of this method in need of attention. The method uses GLUE as calibration method for quantifying simulation uncertainty introduced by model structure, parameters and remote sensing data. Implementation of GLUE requires modelers to make several subjective determinations that influence ensemble prediction (Freer et al., 1996), such as prior parameter range, likelihood measure, and threshold for behavioral parameter sets. A key question is how to make reasonable choices to minimize the impact of GLUE with very limited information. Streamflow at the basin outlet is assumed to have strong correlation with river width or water level. Consequently, intermittent satellite observations are used as a surrogate to represent variations of streamflow. Whether available measurements from space are sufficient to track the amplitude and timing of streamflow variation is uncertain.As with the commonly used regionalization approach (*e.g.*, Koren et al., 2003; Merz and Blöschl, 2004), model validation is difficult, owing to a lack of streamflow data. Whether the simulation reproduces streamflow reasonably cannot be proven directly. Some alternative information should be incorporated to evaluate the reliability of streamflow estimates.

Following the concept verification of the method proposed by Sun et al. (2010a) in the Mekong Basin, the method is further explored in this study. For estimating daily time series of streamflow in a real ungauged basin (Irrawaddy basin in Myanmar), a hydrological model is calibrated using satellite observations of river water-surface width. The objective is, for the first time, evaluating the feasibility of this method for ungauged basins in which the only available data are forcing meteorological data from publicly available datasets and remotely sensed river width. More importantly, through the case study, difficulties and possible solutions for applications to the real world are illustrated and discussed to inspire future use of the proposed method in more ungauged basins.

2. Methodology

2.1. Changing calibration objective of the hydrological model to river water surface width

Based on general principles of the rainfall–runoff relationship, a hydrological model simulates water movement in the water cycle