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Estimating *a-priori* kinematic wave model parameters based on regionalization for flash flood forecasting in the Conterminous United States

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SUMMARY

This study presents a methodology for the estimation of *a-priori* parameters of the widely used kinematic wave approximation to the unsteady, 1-D Saint–Venant equations for hydrologic flow routing. The approach is based on a multi-dimensional statistical modeling of the macro scale spatial variability of rating curve parameters using a set of geophysical factors including geomorphology, hydro-climatology and land cover/land use over the Conterminous United States. The main goal of this study was to enable prediction at ungauged locations through regionalization of model parameters. The results highlight the importance of regional and local geophysical factors in uniquely defining characteristics of each stream reach conforming to physical theory of fluvial hydraulics. The application of the estimates is demonstrated through a hydrologic modeling evaluation of a deterministic forecasting system performed on 1672 gauged basins and 47,563 events extracted from a 10-year simulation. Considering the mean concentration time of the basins of the study and the target application on flash flood forecasting, the skill of the flow routing simulations is significantly high for peakflow and timing of peakflow estimation, and shows consistency as indicated by the large sample verification. The resulting *a-priori* estimates can be used in any hydrologic model that employs the kinematic wave model for flow routing. Furthermore, probabilistic estimates of kinematic wave parameters are enabled based on uncertainty information that is generated during the multi-dimensional statistical modeling. More importantly, the methodology presented in this study enables the estimation of the kinematic wave model parameters anywhere over the globe, thus allowing flood modeling in ungauged basins at regional to global scales.

1. Introduction

Providing useful estimates of the response of a hydrologic system (i.e. a catchment or watershed) at all locations (i.e. gauged and ungauged) is arguably *The Challenge* in rainfall-runoff modeling. This was the main subject of the past decade-long focus of the International Association of Hydrological Sciences (IAHS) through its Prediction at Ungauged Basins (PUB) initiative (Sivapalan et al., 2003), which, although promoted scientific productivity, was largely unsuccessful in achieving its main goal (Hrachowitz et al., 2013). The underlying challenge of PUB can be phrased as *how do we generate equally skillful model estimates at all locations regardless of whether there are measurements of the model output or not?* A key aspect involved in this challenge is the regionalization problem in hydrologic modeling, which is primarily concerned with the estimation of parameters at ungauged locations (Beven, 2011). The parameters' main role is to enable the versatility of the model in simulating a diverse set of hydrologic processes and responses, thus facilitating the application of the model at all locations.

The estimation of hydrologic model parameters has been the concentration of many studies for the past two decades or so, the majority featuring model calibration techniques (e.g., Sorooshian et al., 1993; Boyle et al., 2000; Duan, 2003; Gupta et al., 2003; Vrugt et al., 2006, 2008). However, model calibration is a technique

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primarily developed for lumped hydrologic models. This is because the spatially aggregated conceptualization of processes and parameterization in lumped models makes it difficult to employ an approach based on characterizations of the spatial variability of the basin physical structure (e.g., topography or soil texture properties such as hydraulic conductivity). Process-based distributed hydrologic models, on the other hand, are specifically designed to take advantage of the ever-increasing availability of geospatial datasets from geographical information systems and remote-sensing platforms to resolve the dominant spatial patterns of the hydrologic system. Consequently, distributed hydrologic models can be configured using *a-priori* methods for parameter estimation, which are naturally consistent with the PUB challenge and the regionalization problem.

While work on *a-priori* estimates for water balance model parameters based on soil properties have been reported to the literature (e.g. Koren et al., 2000; Yao et al., 2012), few efforts have been devoted to derive spatially-distributed flow routing parameter estimates without conditioning from calibration (e.g. Naden et al., 1999). The primary objective of routing models is to describe the space–time evolution of water flow throughout a watershed, catchment or stream network. Moreover, flow routing is essential in the description of flood wave timing, which not only establishes when a flooding event occurs, but also the magnitude and duration of the flood. Flood wave timing is critical in forecasting approaches that rely on threshold-based methodologies for detection (e.g. Reed et al., 2007). Some studies like the ones of Montgomery and Gran (2001) and Finnegan et al. (2005) have analyzed controlling factors of the downstream variability of channel characteristics related to routing parameters. Koren et al. (2004) discuss a methodology in which rating curve data at the basin outlet can be propagated upstream to populate all grids within the watershed with estimates of the flow routing parameters. However, and to the knowledge of the authors, no study has reported a methodology to estimate flow routing parameters at continental scales.

In this work, the spatial variability of parameter estimates of a physics-based distributed routing model was studied at the continental scale to devise an estimation approach based on regionalization. The choice of a physics-based model (i.e. models formulated from physical laws) is centered on the fact that model parameters are either based on or correspond to actual measurements of the physical system (Boyle et al., 2000), which facilitates the process of *a-priori* estimation. Moreover, the approach used herein to study the spatial characteristics of parameter estimates explores associations with several geophysical properties of the land surface. Using a model whose conceptualization of the physical system significantly departs from reality would prove difficult (if not impossible) to find aforesaid associations. The study was developed in the context of the Flooded Locations and Simulated Hydrographs (FLASH) project, whose main objective is "*to improve the accuracy, timing, and specificity of flash flood warnings in the US*" (NSSL, 2016). Consequently, the overall goal of this study is to find *a-priori* estimates of kinematic wave routing parameters in order to enable regional forecasting of floods and flash floods at a continental scale with a distributed hydrologic modeling system.

2. Physics-based distributed flow routing model

In general, there are two types of flow routing models: lumped routing models and distributed routing models, sometimes referred to as *hydrologic routing* and *hydraulic routing* respectively (Chow et al., 1988; Bedient et al., 2008). Lumped routing models usually employ empirical or conceptual ideas to describe the true mechanisms of water flow process in a hydrologic system. Distributed routing models, on the other hand, consider both space and time. Furthermore, and because water flow is a continuous variable, these models solve partial differential equations related to the physical laws governing the water movement mechanisms in a hydrologic system. Depending on the assumptions and approximations applicable to a particular hydrologic system, different distributed routing models can result.

The model selected herein was the kinematic wave approximation to the one-dimensional unsteady open channel flow equations developed by Barré de Saint–Venant in the 1800s (Beven, 2011). The full implementation of the Saint–Venant equations represents the closest description of the 1-D water movement in a watershed. However, the use of alternative models by simplification of the governing equations is motivated by simpler and computationally less expensive methods for distributed flow routing. Additionally, these simpler models can capture the dominant physical processes depending on specific flow conditions. Kinematic wave model is arguably the most widely used distributed flow routing method in hydrologic modeling, given its simplicity as compared to the diffusion or dynamic wave models. A general criterion to support the use of the kinematic wave approximation is based on the slope: in watersheds with predominantly steep slopes, the flow conditions are such that the kinematic wave concept reasonably approximates the unsteady flow phenomena (Ponce, 1986). Moreover, Ponce (1991) claimed that for most overland flow situations, kinematic wave approximation requirements are satisfied. Kazezyilmaz-Alhan and Medina (2007) define a minimum slope of 0.002 as a general guidance value required for kinematic wave applicability. Fig. 1 presents a map of the applicability of the kinematic wave approximation over the Conterminous United States (CONUS) based on the aforementioned criterion. It can be observed that the kinematic wave approximation applies for the majority of CONUS.

Several well-known models or modeling frameworks implement kinematic wave for the flow routing component. A list of some past studies and modeling systems employing kinematic wave are presented in Table 1. In the majority of these studies, the parameters of the routing model are derived from assumptions on the channel geometry (e.g. Feldman, 1995, 2000; Liu and Todini, 2002). In other cases, the estimation of the kinematic wave parameters relies on model calibration (e.g. Beldring et al., 2003). In this study, a methodology that does not employ assumptions of channel geometry nor relies on model calibration for the estimation of kinematic wave parameters is presented.

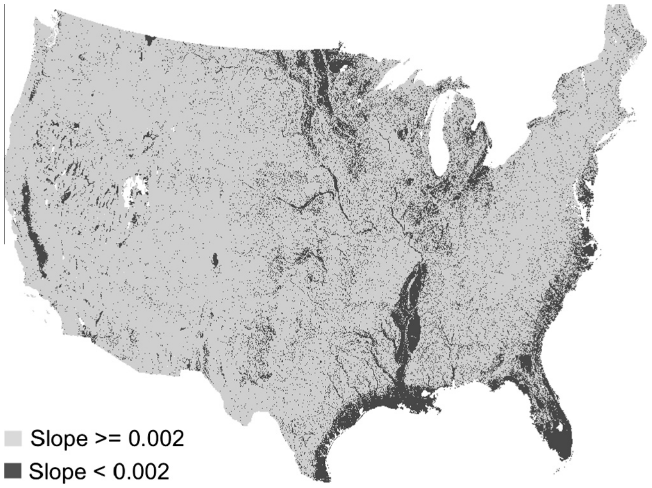

Fig. 1. Applicability of the kinematic wave approximation over the Conterminous United States based on slope. The slope grid is based on a 1-km Digital Elevation Model (DEM) grid.