Journal of Hydrology 519 (2014) 1315–1327

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Assessing the impact of travel time formulations on the performance of spatially distributed travel time methods applied to hillslopes

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ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form 12 August 2014
Accepted 14 September 2014
Available online 23 September 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Michael Brian Butts, Associate Editor

Keywords:
Hydrologic modeling
Kinematic wave
Resolution
Spatially distributed
Hillslope
Upstream contribution

SUMMARY

Rainfall–runoff models are valuable tools to simulate the hydrologic response of a watershed. In recent years, Spatially Distributed Travel Time (SDTT) methods have been developed as an alternative to semi-distributed and distributed models. In these methods, the travel times of grid-cells are summed along flow paths and then convoluted to generate the hydrograph at the outlet. Some aspects of these models remain poorly understood, including the implications of different travel time formulations, the extent to which SDTT models take into account the interaction among cells, the effects of grid-cell resolution, and the validity of the kinematic wave (KW) assumptions in this context. In this study, we use an analytical approach as well as a SDTT model to investigate the significance of considering upstream contributions when calculating the travel times of cells and its influence on the computed time of concentration and overall hydrograph shape. We also analyze the effect of terrain resolution on the performance of SDTT models. Lastly, we study the validity of the KW assumptions when SDTT models are applied to a plane. Results show that considering upstream contributions when computing travel times yields much better results, increasing the modified coefficient of efficiency of the simulated hydrographs from 0.24 to 0.81 on the best case scenario. When using a travel time expression that neglects upstream contributions, finer grid cell sizes reduce the accuracy of the time of concentration and the simulated hydrograph, decreasing efficiency from 0.5 to −0.02 in the worst case scenario. Finally, the KW approximation applies to the plane irrespective of the grid-cell resolution when upstream contributions are considered in the SDTT model for a wide range of slopes and roughness coefficients.

1. Introduction

Rainfall–Runoff models are essential for the simulation of the catchment response to rainfall input and the prediction of runoff hydrographs and floods. Lumped models were initially developed for this purpose, in which the spatially-distributed properties characterizing land use, soil types, internal storage, and routing are considered through spatially-averaged parameters. In current practice, hydrological simulation is typically performed using semi-distributed models, in which the basin is divided into subcatchments or hydrologic response units (HRUs) corresponding to homogeneous areas that generate runoff and contribute through overland flow to the drainage system. The subcatchments or HRUs are conceptualized as hydrologic elements in which the upstream runoff formation and concentration is lumped and parameterized in a simple manner. This simplicity is contrasted by the representation of the hydraulics of the channel system, which are described in detail using the St. Venant's equations or their simplifications (Rodriguez et al., 2003). Thus, semidistributed approaches can neglect drainage elements and spatial heterogeneity within the subcatchments that might play an important role in generating and directing flow into the channel system (Gironás et al., 2010; Rodriguez et al., 2003).

The growing availability of digital remote-sensing data and Digital Elevation Models (DEMs) has increasingly motivated the use of distributed terrain information to extract and analyze geomorphic measures and perform distributed hydrological and hydraulic modeling (Martinez et al., 2010; Wilson, 2012). The watershed can be divided into cells with distinct parameter values that represent the spatial variations of hydrologic properties. This information can then be used in sophisticated distributed models to

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http://dx.doi.org/10.1016/j.jhydrol.2014.09.035

solve continuity and momentum equations (dynamic, diffusive, or kinematic wave equations) in each grid cell, and compute the hydrologic response at the watershed outlet (e.g., Reddy et al., 2007; Shahapure et al., 2011; Velleux et al., 2008; Vieux and Vieux, 2002). Nonetheless, these methods are computationally intensive and require advanced computing stations when dealing with large quantities of data.

An alternative approach to fully-distributed hydraulic methods is that of the Spatially Distributed Travel Time (SDTT) methods in which travel times are computed for each grid-cell and summed along flow paths to the outlet. Stormflow at any subcatchment outlet is either determined by the sum of the volumetric flow rates from all contributing cells at each respective travel time (e.g., Buchanan et al., 2012, 2013; Chinh et al., 2013; Du et al., 2009; Melesse and Graham, 2004) or the convolution of the excess rainfall and a unit hydrograph computed from the travel times to the outlet (e.g., Ajward, 1996; Gironás et al., 2009; Hall et al., 2001; Kilgore, 1997; Kute and Stuart, 2008; Lee et al., 2008; Maidment, 1993; Muzik, 1996). Finally, two other methods route the resulting unit hydrograph through a linear reservoir to provide attenuation in addition to the translation computed using the spatial map of travel times. The model by Peters and Easton (1996) considers a single velocity for all the locations, whereas Bhattacharya et al. (2012) define a travel time expression that is dependent on the contributing area and the slope.

Although SDTT methods have been shown to succeed in hydrologic modeling and hydrograph computation, there is not a total understanding of the limitations of these methods. Saghafian and Noroozpour (2010) exposed three general issues, particularly when computing travel times on hillslopes. First, the use of flow velocity rather than flood wave celerity in the travel time formulation describes the travel time of a drop of water, which is distinct from the time difference between the occurrence of an elemental effective rainfall at a location and the center of mass of the resulting runoff at the outlet. Second, neglecting the effect of any upstream flow contributions to the cell for which travel time is computed implicitly neglects the fact that hydraulic radius and flow velocity typically increase in the downstream direction, as considered in some existing models (e.g., Maidment et al., 1996; Saghafian et al., 2002). Third, the use of a single map of travel times to compute the movement of water from a location to the outlet for all excess rainfall pulses neglects the fact that rainfall intensity may change as the wave moves downstream. Saghafian and Noroozpour (2010) also pointed out that these issues may produce larger errors in the model results when the area threshold that is used to distinguish channels from hillslopes is large.

These issues and other simplifications associated with SDTT methods have been indirectly addressed to some extent by defining calibration parameters that modify the travel time expression (Du et al., 2010). Additionally, Gironás et al. (2009) hypothesized that these issues can be partially addressed in existing SDTT models by representing the majority of the flow in the basin using channels, which consider upstream contributions in the travel time formulation. Gironás et al. (2009) also developed and tested the so called Urban Morpho-climatic Instantaneous Unit Hydrograph (U-McIUH) model, which addresses the first and second issues identified in the previous paragraph. In particular, the model uses wave celerity based travel time expressions for both channels and hillslopes, which also incorporate the upstream contributing area to the cells. This approach was empirically shown to have a significant positive effect when simulating the timing of observed hydrographs for the specific case study (Gironás et al., 2009). Note that Saghafian and Julien (1995) developed an algorithm to calculate the time to equilibrium of complex watersheds, in which the effects of upstream contributing areas and rainfall intensity on the flood's celerity were considered. Thus, their work also addresses the issues previously identified, although a SDTT method was not formally developed. Nonetheless, there is a need to assess the implications of considering flow accumulation on the travel time formulae in SDTT models in a more general way. Similarly, the effect of the spatial resolution (i.e. grid-cell size) on the accuracy of SDTT results needs to be evaluated.

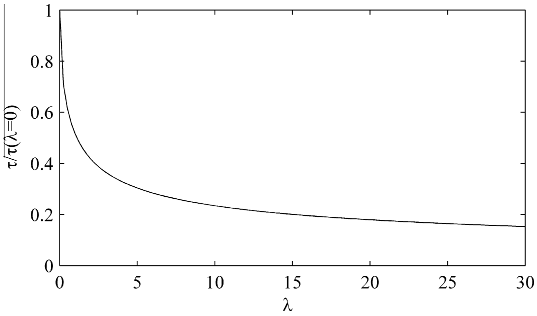

Fig. 1. The ratio of τ when λ is included and τ when λ is assumed to be 0, plotted as a function of the actual value of λ.

The overall objective of this study is to evaluate the impact of travel time formulations on the performance of SDTT methods for hillslopes. Two specific objectives are addressed: (1) the assessment of the effects of these formulations on the computed hydrologic response and (2) the characterization of the impact of grid resolution on these effects. This study will facilitate improved application of this simple distributed approach in hydrologic modeling. The analysis compares four methods that are commonly used to obtain the hydrographs from hillslopes inside a watershed. The first method is the U-McIUH, which uses travel time expressions that depend on rainfall intensity and include upstream flow contributions. The second method is obtained by neglecting upstream flow contributions in the U-McIUH expressions to imitate other existing SDTT methods. The third method is the analytical solution for a kinematic wave (KW) on a plane under constant excess rainfall, and the fourth method is a numerical implementation of complete KW routing in KINEROS2 (Woolhiser et al., 1990). These last two models will be used as the standards against which the two SDTT formulations are judged. Two synthetic unchannelized subcatchments will be used: an idealized plane with varying grid resolutions and a small dendritic-like configuration of cells that aims to include the aggregation of flow paths on an irregular hillslope. The models will be compared under four different synthetic storm events: two constant rain pulses (one longer than the catchment's equilibrium time and one shorter), a Huff precipitation event (Huff, 1967) to simulate time-varying rainfall, and an NRCS event to simulate an event with a more pronounced peak. Special attention will be given to the time of concentration, which should be well approximated by a travel time method if the method is to be successful for more general use. Additionally, for the plane, we study the effects that grid-cell size and flow accumulation have on the assumptions of KW theory, from which the travel time formulations of the U-McIUH model are derived. The outline of the paper is as follows. In the next section, we present the SDTT models and the travel time formulations tested in this study. Then, we present the case studies and the KW solutions to which the simulations are compared. The results are then discussed for each case study, and the key conclusions are summarized at the end.

2. SDTT models

Travel time expressions are a defining characteristic of SDTT models. The expressions are typically based on KW theory, given its suitability to rainfall–runoff modeling in natural and urban catchments (Overton and Meadows, 1976; Singh, 2001; Xiong