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Evaluating the effects of parameterized cross section shapes and simplified routing with a coupled distributed hydrologic and hydraulic model

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SUMMARY

With spatially distributed hydrologic models the need arises for determining the channel cross section shape for the entire stream network. In the absence of cross section data, assumed or parameterized cross section shapes are often used. The effects of parameterized cross sections are evaluated in this study by developing a modeling framework that externally couples a spatially distributed hydrologic model, HL-RDHM, with a one-dimensional unsteady hydraulic model, HEC-RAS. The evaluation emphasizes the effects of parameterized cross sections on simulated flows by focusing the analysis on the portion of the basin's main stream reach where detailed cross section data and observed streamflows (at both ends of the reach) are available, and by developing and testing three cross section scenarios. The scenarios are designed to increase sequentially, in a stepwise fashion, the complexity of the parameterized cross section, starting with a single roughness parameter and channel power law cross section shape and then including additional power law or roughness parameters. This is done stepwise to help distinguish the effects associated with each parameterization, and decide the required level of cross section detail. The scenario simulations are evaluated using split sampling, changes in measures of performance and hydrograph agreement, hypothesis tests on Nash–Sutcliffe values, and overall predictive uncertainty. The coupling framework is applied to the Blue and Illinois River basins, in Oklahoma, US. Overall, we found that in these basins the coupling tends to improve predictions when dynamic wave routing and floodplain cross section geometry are considered concurrently. For this scenario, we found that on average typical measures of model performance may be improved and, based on a quantitative and qualitative assessment, uncertainty may be reduced. We also found that dynamic wave routing does not tend to perform better than kinematic wave routing for the most basic scenarios with a single power law cross section shape. Further, results indicate that the distributed hydrologic model performance at the main outlet and at the upstream boundary of the hydraulic model, and the relative contribution of lateral inflows, are key factors that need to be considered when deciding the applicability of the coupled framework to other basins. In the future, to effectively use resources, it will be beneficial to automate the coupling and accompany its application with a priori criteria for selecting those basins where benefits are most likely.

1. Introduction

In an effort to understand and improve distributed hydrologic models, the Office of Hydrologic Development (OHD) of the National Oceanic and Atmospheric Administration's National Weather Service (NOAA/NWS) led the Distributed Model Intercomparison Project (DMIP 1) and is currently leading a second phase (DMIP 2) (Reed et al., 2004; Smith et al., 2004b, 2009). Some goals of DMIP include determining the level of model complexity needed to achieve improved predictions while keeping the parameterization costs low and identify areas in the overall modeling process to focus improvement efforts. The experience with DMIP 1 and 2 has highlighted some of the complications that can arise when trying to compare and evaluate hydrologic models (Butts et al., 2004; Reed et al., 2004; Smith et al., 2009). Factors such as high dimensionality, uncertainty (i.e. input, structural, parametric, and output), and limited data availability for model evaluation, make the identification of specific causes of model deficiency difficult (Reed et al., 2004). This suggests the need for more targeted model assessments and comparisons, where a distinct component of the model is evaluated (Reed et al., 2004). In this study we follow this suggestion through a more detailed examination of the routing technique and parameterization used in the Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM). HL-RDHM is a distributed hydrologic model developed for forecasting purposes (Koren et al., 2003, 2004). The kinematic wave routing technique implemented in HL-RDHM is common to several other distributed

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hydrologic models (e.g. see Table 1 in Reed et al., 2004). Therefore, the conclusions from our analysis here are relevant to other models as well.

With this in mind, and noting that the routing process plays an important role in hydrologic forecasting (Fread, 1981, 1993; Moreda et al., 2009), we are interested in examining ways in which the routing process may be improved. Many times there is concern that a simpler routing conceptualization may cause substantial loss of predictive capability (Horritt and Bates, 2002; Romanowicz and Beven, 2003; Cook and Merwade, 2009; Moreda et al., 2009). Further, there are aspects of the routing process that have received little attention but have, concurrently, gained a more prominent role within a spatially distributed context (Orlandini and Rosso, 1996, 1998; Koren et al., 2004). A good example of the latter is the role played by the cross section geometry in the routing of flows (Orlandini and Rosso, 1996, 1998; Koren et al., 2004). Cross section data is generally lacking but still required in a distributed context, the de facto alternative has been to use parameterized cross section shapes (e.g. Fread and Lewis, 1986; Orlandini and Rosso, 1996, 1998; Koren et al., 2004; Valiani and Caleffi, 2009), and many times a simple analytical shape is assumed. However, the effects of parameterized cross section shapes on simulated flows have been studied little and indications are that they can have an influential effect. For example, Orlandini and Rosso (1998), in a relatively recent study, showed that parameterized cross sections with vertically varying widths based on relationships of hydraulic geometry, as opposed to rectangular shapes with constant width, can lead to considerable improvement in flow simulations using a distributed model. Other studies have examined directly the role of cross section shapes but not for distributed hydrologic modeling (e.g. Keefer, 1976; Garbrecht, 1990; Myers, 1991; Ponce and Porras, 1995).

With this background, the aim of this study is to examine the effects that parameterized cross section shapes and simplified routing (i.e. kinematic wave routing instead of more general dynamic routing) have on simulated flows within the context of distributed hydrologic modeling. This study's motivation stems from the perception that using an approximate cross section shape may have a sufficient influence on routed flows to reduce gains from a more general routing method (Keefer, 1976; Myers, 1991; Ponce and Porras, 1995; Orlandini and Rosso, 1998). We seek to test this hypothesis by performing various model-based experiments while trying to emphasize conditions relevant to the use of hydrologic and hydraulic models in NWS forecasting operations.

2. Background

Much of the stage and background for this investigation is set by the results and data sets from DMIP 1 and 2 (Reed et al., 2004; Smith et al., 2004b, 2009). We use the data available to DMIP 1 participants and one of the participating models, HL-RDHM (Koren et al., 2004; Smith et al., 2004b). Next, the study area and data sets used are briefly described (see Smith et al. (2004b) for details).

2.1. Study area

The basins selected for this study are located on the Blue and Illinois River (Fig. 1a shows their location). Hereafter these basins are simply referred to as the Blue or Illinois River. Both basins are part of DMIP 1 and 2 (Smith et al., 2004b, 2009). This has the advantage that for these basins the quality of required data sets (i.e. input forcings and streamflow observations) has been thoroughly inspected and the performance of HL-RDHM has been tested beforehand (Koren et al., 2004; Reed et al., 2004; Smith et al., 2004b; Zhang et al., 2004). With this, we can draw attention to the modeling of the routing process and place less emphasis on other aspects of distributed modeling.

The Blue River basin, located in Oklahoma (see Fig. 1a), has an overall drainage area of approximately 1233 km^2. The Illinois River basin, located between the Oklahoma–Arkansas border (see Fig. 1a), has a drainage area of approximately 2484 km^2. We use two streamflow gauges for each basin, an outlet gauge located at the overall basin outlet and an interior gauge located further upstream from the outlet gauge (see Fig. 1b and c for the location of the gauges in the Blue and Illinois River basins, respectively). In the Blue River, the outlet gauge is near Blue (United States Geological Survey (USGS) gauge number 07332500), and the interior upstream gauge is near Connerville (USGS gauge number 07332390). In the Illinois River, the gauge near Tahlequah is the outlet gauge (USGS gauge number 07196500) while the interior gauge is near Watts (USGS gauge number 07195500). The along-stream distance between the two gauges in the Blue River is approximately 84.5 km. The distance is shorter in the Illinois River, approximately 71.2 km. However, the Blue River has more tributary streams (i.e. inflow locations) connecting to the main stream reach. Hereafter, for clarity, the river section between the internal and outlet gauge is referred to as the main stream reach. The stream network connectivity is shown in Fig. 1b and c for the Blue and Illinois River, respectively. The 4 km grid cell sizes in this

Table 1

Summary of the average values of NS, R_{mod}, $|\Delta Q_p|/Q_{p,obs}$, and $|\Delta T_p|/T_{p,obs}$ for the baseline simulations (KW and DW4) and the three cross section parameterization scenarios (DW1, DW2, and DW3), in both the Blue and Illinois River basins. The results for the hypothesis tests defined in (8) and (9) are also shown. For the hypothesis tests, the numbers associated with each simulation are the number of individual storm events that agree with the alternative hypothesis where the total number of events is 11 and 23 for Blue and Illinois, respectively.

Basin	Simulation	Calibration		Validation		$\|\Delta Q_p\|/Q_{p,obs}$	$\|\Delta T_p\|/T_{p,obs}$	Hypothesis test	
		NS	R_{mod}	NS	R_{mod}			Test in (8)[a]	Test in (9)[b]
Blue River	KW	0.75	0.78	0.67	0.69	0.30	0.16	–	6
	DW1	0.7	0.73	0.7	0.69	0.32	0.15	4	3
	DW2	0.71	0.73	0.74	0.7	0.30	0.17	5	2
	DW3	0.68	0.74	0.7	0.69	0.30	0.19	5	3
	DW4	0.74	0.79	0.7	0.7	0.30	0.14	6	–
Illinois River	KW	0.91	0.88	0.81	0.85	0.10	0.066	–	17
	DW1	0.95	0.93	0.84	0.83	0.14	0.081	9	13
	DW2	0.95	0.93	0.85	0.83	0.14	0.078	9	13
	DW3	0.97	0.98	0.85	0.87	0.09	0.052	17	10
	DW4	0.97	0.98	0.84	0.86	0.11	0.028	17	–

[b] Number of individual storm events i that agree with Ha: $NS_i < NS_{i,DW4}$.

[a] Number of individual storm events i that agree with Ha: $NS_i > NS_{i,KW}$.