Journal of Hydrology 522 (2015) 645–660

Contents lists available at ScienceDirect

Journal of Hydrology

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

A holistic, multi-scale dynamic downscaling framework for climate impact assessments and challenges of addressing finer-scale watershed dynamics

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ARTICLE INFO

Article history:
Received 19 May 2014
Received in revised form 10 January 2015
Accepted 10 January 2015
Available online 20 January 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Multi-scale
Flow regime
Coupled model
Climate change
Stochastic weather generator

SUMMARY

We present a state-of-the-art holistic, multi-scale dynamic downscaling approach suited to address climate change impacts on hydrologic metrics and hydraulic regime of surface flow at the “scale of human decisions” in ungauged basins. The framework rests on stochastic and physical downscaling techniques that permit one-way crossing 10^6–10^0 m scales, with a specific emphasis on ‘nesting’ hydraulic assessments within a coarser-scale hydrologic model. Future climate projections for the location of Manchester watershed (MI) are obtained from an ensemble of General Circulation Models of the 3rd phase of the Coupled Model Intercomparison Project database and downscaled to a “point” scale using a weather generator. To represent the natural variability of historic and future climates, we generated continuous time series of 300 years for the locations of 3 meteorological stations located in the vicinity of the ungauged basin. To make such a multi-scale approach computationally feasible, we identified the months of May and August as the periods of specific interest based on ecohydrologic considerations. Analyses of historic and future simulation results for the identified periods show that the same median rainfall obtained by accounting for climate natural variability triggers hydrologically-mediated non-uniqueness in flow variables resolved at the hydraulic scale. An emerging challenge is that uncertainty initiated at the hydrologic scale is not necessarily preserved at smaller-scale flow variables, because of non-linearity of underlying physical processes, which ultimately can mask climate uncertainty. We stress the necessity of augmenting climate-level uncertainties of emission scenario, multi-model, and natural variability with uncertainties arising due to non-linearities in smaller-scale processes.

1. Introduction

Human societies require services and goods supplied by watershed systems that need to be sustainable, maintain natural structure and function, and continue to meet societal needs in the long-term (Meyer and Pulliam, 1992). However, the world is undergoing a period of rapid climate change, rarely experienced in the past (IPCC, 2001, 2007). Thus, assessments of changes in watershed systems in response to climate change have been increasing (Hanson et al., 2012; Safeeq and Fares, 2012; Wang and Alimohammadi, 2012; Beauchamp et al., 2013; Demaria et al., 2013; Lu et al., 2013; Mukundan et al., 2013; Nunes et al., 2013; Patterson et al., 2013; Shen et al., 2013; Teegavarapu, 2013; Wu et al., 2013; Schnorbus et al., 2014).

Water-related processes that are of interests to human societies mostly originate at the watershed level, and therefore physical processes in the above studies have been commonly addressed at the watershed scale. While watershed-scale assessments represent a necessary starting point, a range of processes that represent societal concern are associated with flow and hydro-geomorphic dynamics in channelized areas. Some examples in which watershed scale, hydrology-based models exhibit applicability limitations are (1) the process of flooding (where and how flood wave propagates is of most interest), (2) hydraulic phenomena such as flow discontinuity and backwater effects (e.g., when hydraulic structures such as spillways, weirs, dams, and bridges are constructed), and (3) runoff routing processes in domains of complex topography, slope transitions, and vegetated areas (Kim et al., 2012a,b, 2013; Kim and Ivanov, 2014; Warnock et al., 2014). Similarity of these examples is that the flow process exhibits characteristics that reveal limitations of hydrology models that mainly use simplified versions of governing equations representing fluid motion. One of the central reasons of limitations to describe the flow process is that commonly used simplified approaches, referred to as the “inertia-free” or the “kinematic wave” models,

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http://dx.doi.org/10.1016/j.jhydrol.2015.01.025
0022-1694/

alter the physics of flow waves that should move with finite bidirectional speeds into the waves that either have infinite, bidirectional speed or become unidirectional with a finite speed. Thus, such approximations cannot mimic real physical phenomena such as flow discontinuities, backwater, or wave reflection. A more comprehensive review of the three commonly used routing methods is provided in Warnock et al. (2014).

At the other end of research spectrum, "stream-reach based" numerical models have been often used with the purpose of identifying a more detailed level of flow characterization, i.e., extending beyond the traditional metrics of bulk flow, which can be directly attributed to major impacts on water quality, morphology, and aquatic habitat characteristics. For example, the shear stress or stream power are the most frequently used flow variables in modeling morphological processes (Bagnold, 1966; Woolhiser et al., 1990; Hairsine and Rose, 1992a), while the turbulent kinetic energy, circulation, or vorticity are some of the vital metrics that convey ecological effects of streamflow on aquatic habitat (Crowder and Diplas, 2002, 2006). However, these models, despite providing excellent results on characterization of the flow regime, have a significant drawback when applied to investigate the impact of future conditions or ungauged basins. In these circumstances, the boundary conditions are unknown at the inlet and outlet of stream reaches. Assuming artificial boundary conditions fails to connect to catchment- and larger-scale information (e.g., climate), and therefore essentially "disengages" channel flow from watershed processes (Milly et al., 2002; Arnell, 2003; Cherkauer and Sinha, 2010).

Understanding and predicting the corresponding shifts across a range of space-time scales at the relevant level of detail is one of the most fundamental, yet poorly quantified challenges facing society today. A particular difficulty is the transformation of uncertainty due to intrinsic non-linearity of a basin system (Leopold and Langbein, 1962; Zehe and Sivapalan, 2009). In order to achieve a seamless propagation of climate information into local streamflow variations and capture the uncertainty occurring from coupled hydrologic and hydraulic processes, physically-based modeling of relevant processes at a sufficient detail is needed. Explicit linkage of processes operating at different scales can incorporate the advantages of watershed-based and stream reach-based models, and thus not only enhance accuracy near channelized areas but overcome problems with specifying uncertain boundary conditions. When considered in the context of long-term effects of climate change on such important drivers as precipitation and temperature, perturbations initiated at larger scale will impact hydrological signals originating at the watershed scale. The relevant processes, especially evaporation and runoff, will subsequently alter the flow regime. The flow motion will ultimately influence sediment transport and erosion rates modifying the landscape morphology and affecting aquatic habitat at biologically relevant scales (Crowder and Diplas, 2006; Coulthard et al., 2012; Kim et al., 2013). Through this "cascade", large scale properties affect smaller-scale characteristics. Therefore, modeling the impacts of climate change on streamflow variations and flow regime requires a holistic approach, i.e., the one that incorporates relevant components from the fields of hydrology and hydraulics.

The capability to simulate processes operating at a range of temporal and spatial scales has been increasing (Ivanov et al., 2004a, 2008; Kollet and Maxwell, 2006; Kumar et al., 2009; Mirus et al., 2011; Sulis et al., 2011; Fatichi et al., 2012; Kim et al., 2012b, 2013; Chen et al., 2013; Mirus and Loague, 2013). The development of coupled models have targeted physical consistency of transferring information from larger-scale drivers to local scale dynamics with a decreasing number of simplifying approximations. Specifically, in our previous work, we developed a coupled hydrology-hydraulics model that can seamlessly handle diverse topographic transitions, including situations where the effects of inertia can become significant (Kim et al., 2012b, 2013); represent flow cumulating and diverging complexity due to topography, unsubmerged vegetation, or rock elements (Kim et al., 2012a); and extended model applicability to cases with impermeable structures (e.g., rock, vegetation or buildings) requiring a specification of boundary conditions for internal areas (Kim et al., 2012a,b). However, despite these benefits, the coupled model has been of practical value only at relatively short-time scales (daily to monthly). Such a limitation is similar for other hydraulic models based on explicit numerical schemes that constrain model applicability over longer time periods due to the issues of computational efficiency. To circumvent this difficulty, a multi-scale framework for propagating hydrologic information to flow characteristics is addressed here.

Specifically, a multi-scale modeling approach is used here in which stochastically downscaled climate information (10^5–10^6 m) permits a comparison of watershed-scale (10^3–10^4 m) hydrological regimes for present and future climate conditions, as well as their effect on details of flow hydrodynamics (10^0–10^2 m). Using analogy with climate modeling, the latter is achieved through physical downscaling of hydrologic fluxes. We refer to the concept as "Nested Dynamics Modeling" (NDM), to facilitate generality of such a downscaling approach in the fields of hydrology and ecohydrology.

First, future regional climate information is downscaled using outputs from 12 General Circulation Models (GCMs) of the third phase of the Coupled Model Intercomparison Project (CMIP3) database, the A1B emission scenario of the Special Report on Emission Scenarios (SRES, (Meehl et al., 2005)). Projections of weather variables for 3 nearby meteorological stations are generated for the present/historic and future periods using a stochastic weather generator, Advanced WEather-GENerator (AWE-GEN), combined with the Monte-Carlo simulation to produce an ensemble of alternatives of future climate (Ivanov et al., 2007; Fatichi et al., 2011, 2013). Next, a number of hydrologic and hydrodynamic metrics of channel flow are resolved by the coupled model, TIN (Triangulated Irregular Network) based Real time Integrated Basin Simulator – Flow, Erosion and Sediment Transport (tRIBS-FEaST), designed to address morphological or ecohydrologic applications. The flow process metrics obtained by propagating climate-level information through watershed and channel processes highlight the nonlinearity feature of catchments, and an inherent characteristic of climate impact studies – the uncertainty of assessments. An ungauged watershed located near Manchester, Michigan, where climatic boundary conditions for both present and future periods are not available is used as a case study. This research therefore can be considered as a template for assessments of climate impact on hydrologic and hydraulic regimes in ungauged basins.

2. Methodology

2.1. Stochastic downscaling and weather generator: AWE-GEN

A stochastic downscaling technique using a weather generator is a suitable tool for this study because weather variables such as solar radiation, relative humidity, and vapor pressure required as input by a comprehensive hydrologic model are not available from GCMs at a relevant scale. This also allows one to overcome a problem of inconsistency in observed data, when dealing with missing values or changes in observational practices. A more detailed description of how global climate information is downscaled to a local scale and how AWE-GEN stochastically generates a range of consistently inter-related weather variables can be found in Fatichi et al. (2011); an outline of the stochastic downscaling methodology is