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Watershed modeling applications with a modular physically-based and spatially-distributed watershed educational toolbox

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ABSTRACT

Introductory hydrology courses traditionally focus on process-based hydrology (i.e. precipitation, evaporation, runoff, etc.) that is ultimately unified through watershed modeling. Although physically-based and spatially-distributed hydrologic models are arguably valuable learning tools, they typically have steep learning curves and high computational costs. To overcome these common drawbacks in hydrology education, we developed the user-friendly, open-access ***Mo***dular ***D***istributed ***W***atershed ***E***ducational ***T***oolbox (MOD-WET). MOD-WET is a compilation of highly modular functions designed for process-based applications, which are integrated into a physically-based and spatially-distributed watershed model. When students use the toolbox to study individual processes, they become familiar with the fundamental components forming the hydrologic model. Student feedback indicates that this approach makes a holistic understanding of the water cycle more accessible to students. Hydrograph sensitivity to watershed characteristics (size, slope, roughness, etc.) is demonstrated. The capability of MOD-WET to model warm and cold land processes is also illustrated for a snow-covered basin.

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Software availability

Product name: Modular Distributed Watershed Educational Toolbox (MOD-WET)
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Email: huning@seas.ucla.edu and margulis@seas.ucla.edu
Year first available: 2014
Program language: MATLAB™
Program Size: 70 MB for the entire toolbox including sample datasets and outputs
Availability: http://aqua.seas.ucla.edu/margulis_intro_to_hydro_textbook.html
Cost: Free

Electronic textbook availability
Title: Introduction to Hydrology
Author: Steven A. Margulis
Year first available: 2014
Availability: http://aqua.seas.ucla.edu/margulis_intro_to_hydro_textbook.html
Cost: Free

1. Introduction

Traditionally, introductory hydrology courses present hydrologic processes (i.e. precipitation, evaporation, infiltration, snowmelt, runoff, etc.) as independent or semi-independent concepts; however, they are inherently interconnected within the water cycle. Generally, watershed modeling is briefly introduced at the end of such courses. Depending on the depth of process-based study and duration of the courses, this tends to prevent an in-depth investigation into hydrologic applications. Hydrology education at the university-level can often provide a fragmented view of the integrated hydrologic cycle rather than a holistic understanding of the system (Nash et al., 1990). Recently when more than 600 water professionals were surveyed about integrated water resources management in the United States, watershed hydrology and modeling was identified as the area of study in most educational

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need (Bourget, 2006). As we move forward, understanding hydrologic response to changes in climate and land cover becomes increasingly important; however, hydrology textbooks often provide insufficient detail regarding how to make such predictions (Seibert et al., 2013). Hydrologic models on the other hand can be used to investigate such scenarios.

Geoscience cybereducation in the form of data, modeling, and visualization should be incorporated into the curriculum to complement traditional lecture-based instruction (Merwade and Ruddell, 2012). Models designed for research and industry are often used at the university-level, but generally require a significant learning curve, and therefore a barrier, to their usage. Models designed explicitly for educational purposes have proven successful in their ability to convey complex topics in a manner that promotes student learning and discovery (e.g. Chandler et al., 2005; Crouch et al., 2008; Habib et al., 2012; Williams et al., 2009). Although numerous watershed models currently exist for research and operations (Singh and Woolhiser, 2002), hydrologic models specifically designed to be instructional tools are less common.

In recent years, there have been several attempts to utilize computer-based technologies to further hydrology and water resources education in the university curriculum. Computer games focusing on water resources management, resource allocation, decision-making, and negotiation have been demonstrated to be valuable interactive learning tools through role-playing scenarios (e.g. Hoekstra, 2012; Rusca et al., 2012; Seibert and Vis, 2012a). These efforts tend to focus on water resources management, while alternative methods have been used to teach/learn watershed hydrology. For example, watershed hydrology has been taught with a system dynamics approach (Elshorbagy, 2005). The Web-based HydroViz (Habib et al., 2012) provides learning modules that build on geospatial data and visualization to explore concepts ranging from physical watershed characteristics to rainfall-runoff modeling. Wagener and McIntyre (2007) utilized a lumped modeling framework to teach parameter identification and uncertainty in a rainfall-runoff context. Several educational versions of the conceptual HBV hydrologic model have been incorporated into the university-level curriculum (e.g. AghaKouchak and Habib, 2010; AghaKouchak et al., 2013; Seibert and Vis, 2012b). AghaKouchak and Habib (2010) used a lumped version of the HBV model, while Seibert and Vis (2012b) utilized a semi-distributed version (HBV-Light) to illustrate the interconnectivity of hydrological processes within a watershed. The HBV-Ensemble (AghaKouchak et al., 2013) was developed for studying ensemble streamflow simulations with parameter estimation and uncertainty analysis. As discussed here, the watershed models that have been used and/or were created for educational applications are typically lumped or semi-lumped/distributed conceptual models.

While conceptual models represent physical processes using a parameterized approach, physically-based models rely on the physics that governs the processes within a watershed. Seibert and Vis (2012b) reason that physically-based models tend to be more complex and have a steeper learning curve associated with them, making conceptual models easier for students to use. However, a physically-based model can arguably serve as a valuable learning tool when studying hydrology. Physically-based watershed modeling can become more feasible in an educational setting with a highly modular framework where individual codes can be used throughout a course to study individual processes. Hence, when the modules are ultimately unified in a watershed model, students are already familiar with the underlying physical processes that govern the system. This is the approach that we have taken here. This approach effectively eliminates any additional time or instruction that would be needed for students to begin running the model and studying hydrologic systems. Moreover, such a framework reduces the overall complexity of a physically-based hydrologic model and removes “black box” modeling from the classroom. This alleviates the burden on the student to master a new model while trying to understand the totality of the hydrologic system with process interactions. As a result, the primary focus can be placed on developing students' hydrologic literacy.

With the use of distributed datasets becoming more prevalent in the geosciences, it has become increasingly necessary for students to develop the skills to handle large datasets. Distributed watershed modeling provides students with an opportunity to develop such skillsets and become more adept at analyzing the spatiotemporal patterns of a dynamic system. Distributed models discretize a watershed into relatively small units at a high spatial resolution to represent the spatial variability of states and fluxes within a basin. The main drawback to spatially-distributed models is that they are many orders of magnitude more computationally expensive than lumped models that neglect the spatial distribution of states and fluxes within a basin. As the number of pixels and/or spatial resolution increases within a distributed model, the computational demand also increases. Our development of a spatially-distributed watershed model is motivated by the increased use and availability of distributed datasets from sources such as remote sensing. In the development of a distributed model, we intentionally selected and designed model components to minimize computational expense. This allows the model to be run within a classroom setting.

The primary goals of the model presented in this paper include: 1) constructing a modular toolbox for use in process-based applications, 2) developing a user-friendly, open-access model that promotes a qualitative and quantitative understanding of hydrological processes and how they change as a function of watershed properties, and 3) elucidating the underlying physical processes that can be obscured by a complicated “off-the-shelf” watershed model in an introductory hydrology course. With these aims in mind, we developed the ***Mo***dular ***D***istributed ***W***atershed ***E***ducational ***T***oolbox (MOD-WET). It consists of a modular set of functions that can be used for process-based applications and a unified framework that integrates hydrologic processes together into a physically-based and spatially-distributed watershed model. MOD-WET was conceptualized using a generic framework so that the model can be run for real or synthetic basins that are snow-covered or snow-free.

2. Model background and framework

According to Jennings (1997) and Jennings and Kuhlman (1997), software is most effective in engineering education applications if it possesses certain attributes such as easy visualization of output, detailed result and technical documentation, low cost, and information-rich examples and applications as listed in Table 1. Overall, the MOD-WET software possesses these qualities, which are summarized in Table 1 and illustrated throughout this paper. The MOD-WET framework was developed to foster an understanding of sensitivities of watershed response to inputs/parameters, hypothesis testing, etc. for use in the undergraduate curriculum. MOD-WET was also developed to facilitate student analysis of real world problems at the watershed-scale. Moreover, the toolbox and integrated model can be used as instructional tools at other levels to provide fundamental hydrology training and cultivate the hydrologic intuition necessary for future environmental and water resources professionals.

High priority has been given to the readability of the code. MOD-WET has the unique feature that it not only has a highly commented internal code, but also it has been designed in concert with a well-documented companion e-textbook (Margulis, 2014). The latter is briefly described in Section 2.1. Significant effort has

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