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Technical Note

Flexibility on storage-release based distributed hydrologic modeling with object-oriented approach

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SUMMARY

With the availability of advanced hydrologic data in public domain such as remote sensed and climate change scenario data, there is a need for a modeling framework that is capable of using these data to simulate and extend hydrologic processes with multidisciplinary approaches for sustainable water resources management. To address this need, a storage-release based distributed hydrologic model (STORE DHM) is developed based on an object-oriented approach. The model is tested for demonstrating model flexibility and extensibility to know how to well integrate object-oriented approach to further hydrologic research issues, e.g., reconstructing missing precipitation in this study, without changing its main frame. Moreover, the STORE DHM is applied to simulate hydrological processes with multiple classes in the Nanticoke watershed. This study also describes a conceptual and structural framework of object-oriented inheritance and aggregation characteristics under the STORE DHM. In addition, NearestMP (missing value estimation based on nearest neighborhood regression) and KernelMP (missing value estimation based on Kernel Function) are proposed for evaluating STORE DHM flexibility. And then, STORE DHM runoff hydrographs compared with NearestMP and KernelMP runoff hydrographs. Overall results from these comparisons show promising hydrograph outputs generated by the proposed two classes. Consequently, this study suggests that STORE DHM with an object-oriented approach will be a comprehensive water resources modeling tools by adding additional classes for toward developing through its flexibility and extensibility.

1. Introduction

An object-oriented approach to hydrologic modeling increases model flexibility and reduces efforts when adapting the model for a new application, area and algorithm. Rather than replacing old code that already works, the model code can be extended using the object-oriented characteristic of inheritance (Kiker et al., 2006). An object-oriented approach allows building an incremental model that can be adapted to different watershed conditions (Wang et al., 2005). In spite of many advantages, object-oriented approach has found only limited applications in hydrologic modeling (Band et al., 2000; Kralisch et al., 2005). Band et al. (2000) introduced an object-oriented approach to simulate hydrologic processes, specifically infiltration excess overland flow and described a spatial object-oriented framework for modeling watershed system to include hydrological and ecosystem fluxes. Chen and Beschta (1999) developed 3-dimensional distributed hydrological model OWLS (the Object Watershed Link Simulation model) for dynamic hydrologic simulation and applied it to the Bear Brook watershed in Maine. Garrote and Becchi (1997) employs object oriented programming techniques with distributed hydrologic models for real-time flood forecasting. Boyer et al. (1996) presents an object-oriented method to simulate a rainfall-discharge relationship using a lumped hydrologic model. The above applications used object-oriented approach and achieved reasonable results for hydrologic simulations. However, object-oriented approach is not enough comprehensively discussed in the hydrologic literature and no general guideline exists for implementing them in hydrologic models (Wang et al., 2005; Kiker et al., 2006; Kang and Merwade, 2011).

Realization of this approach requires a modular structure, and it allows different sub-models to be interconnected depending on the

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hydrologic system. Another important aspect that must be considered in new development of hydrologic models is creating software elements that can be adapted in future projects. If a modular structure provides reusable components, both regarding development time and reliability of the software produced, the modular structure will be a useful water resources modeling platform (Goodchild et al., 1993). This also will reduce development and maintenance cost for the project. In recent years, object-oriented based hydrologic models are increasingly used in water resources research, and also the modeling paradigm in water resources is changing to the object-oriented approach (Wang et al., 2005; Kang and Merwade, 2011). Creating an incremental watershed model can be made by object-oriented design methods and using an object-oriented programming language (Wang et al., 2005), and this model can be applied to various watershed conditions.

Streamflow forecasting in hydrologic modeling is the most fundamental stage, but it cannot be easily realized due to its complicated physical process and time varying system. To implement these troublesome in streamflow forecasting, hydrologic inputs in each sub-basin mechanism under the entire basin are needed (Kang and Merwade, 2011). However, researchers are confronted with the difficulty to get realistic hydrologic inputs because inputs and outputs in hydrologic model have temporal variability and non-linear response. Several studies investigated on assessing the impacts of hydrologic inputs for hydrologic simulation (Ogden and Julien, 1993). Kang and Merwade (2014) addressed that even though precipitation input is main driver in hydrologic simulation, utilizing an effective precipitation uncertainty in hydrologic simulation is still lack of research.

The primary objective of this study is to investigate how to make an efficient model frame that can raise hydrologic modeling extensibility. The motivation to address this question is that large number of advanced technology data and multidisciplinary research approaches lead to additional computation platform that trigger wasting development cost. The STORE DHM (Kang and Merwade, 2011) is used for describing the general idea of object-oriented hydrologic model framework. Expandable user options for reconstructing missing precipitation are also described to show an object-oriented flexibility in the STORE DHM. The following section contains a general description of the study area in this research. Specific object-oriented approach in hydrology is explained in Section 3. Section 4 proposes STORE DHM object classes for hydrologic simulation. Statistic methodologies, nearest neighborhood regression (NNR) and Kernel Function (KF), are described for estimating missing precipitation in Section 5. Finally, Sections 6 and 7 present and discuss the results and conclusions, respectively.

2. Study area

The Nanticoke watershed is located in the Chesapeake Bay which spans more than 165,759 km^2. The bay connects and encompasses parts of six states – Maryland, Delaware, New York, Pennsylvania, Virginia and West Virginia. It has a great variety of ecological species, and almost 18 million people live in the Chesapeake Bay (Fig. 1a).

The Nanticoke watershed covers an area of 2142 km^2 and is characterized by an elevation ranging from 11 to 85 m above sea level (Fig. 1b), while the main river course is 10.7 km long. This region has typically four seasons with an average temperature of 1.5 °C in winter and 28 °C in summer. The average annual precipitation in the watershed was about 1080 mm from 2000 to 2015. Rainfall occurs normally from December to May (wet season), while during the dry season, from June to November, rainfall is generally concentrated in a few events. The general rainfall events in all seasons are unevenly distributed and have high intensity for a short time. These rainfall characteristics exert strong influence on the flow regimes and erosion, subsequently on sediment and nutrient delivery. The hourly precipitation data and 15 min streamflow data for the study site were obtained from the National Climate Data Center and the USGS Instantaneous Data Archive, respectively. The streamflow values for four events include both base flow and surface runoff. This study used the straight line base flow separation method for retrieving surface runoff hydrographs from streamflow. Land cover types in the Nanticoke watershed are presented as 49% agriculture, 38% forest and wetland, 9% water, and 4% urban development.

3. Object-orientated in hydrology

According to Bian (2007), object orientation involves three levels of abstraction: object oriented analysis, object oriented design, and object oriented programming. Object oriented analysis involves conceptual representation of the world including the facts and relationships about a situation. In hydrology, this would mean the conceptual representation of a watershed as a set of objects including streams and corresponding catchments. Object oriented design uses the conceptual representation from object oriented analysis to create a formal model of objects, their properties, events, and relationships. Object oriented programming involves the implementation of objects and their events to accomplish a certain task. Object orientation relies on two basic principles: encapsulation and composition. Encapsulation considers that the world is composed of objects, and that each object has an identity, properties and behavior. The properties of an object are defined by its attributes (e.g., length, area), and the behavior is represented by methods. While the value of an attribute can define the state of an object, a method can change the state of an object, and that change is referred to as an event. For example, a river object will have properties such as length and slope, methods such as RouteFlow and ComputeStorage, and routing a hydrograph through the river (by using RouteFlow method) is an event.

The principle of composition describes how objects are related through relationships including inheritance, aggregation and association. In object orientation, all objects belong to object classes, and all classes are hierarchal. A sub-class is a kind of this own super-class through inheritance and inherits all properties and methods from the super class, but also may have its own additional properties and methods. An object can also be a part of another object through aggregation, and can simultaneously maintain relationships with other objects through association. For example, an AlluvialRiver class can be a sub-class of River super class (inheritance), a River class can be a part of RiverNetwork class (aggregation) and River class is related with Watershed class through streamflow (relationship). Past studies that used object orientation for hydrologic modeling include Whittaker et al. (1991) who used object-oriented approach to model infiltration excess overland flow. Boyer et al. (1996) used object oriented approach to develop a lumped rainfall–runoff model and used object orientation to combine remote sensing and hydrologic data to develop a forecast model. Garrote and Becchi (1997), Band et al. (2000), and Wang et al. (2005) proposed object oriented frameworks for modeling hydrologic processes at watershed scale. Most of these studies used object orientation to model hydrologic processes using the concepts of inheritance and aggregation. Recently, Richardson et al. (2007) proposed a prototype geographically based object framework for linking hydrologic and biochemical processes in the sub-surface. However, the process objects were loosely coupled with geographic objects, thus there is leaving an opportunity for a tightly coupled geographically based object oriented modeling.