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Development and application of a storage–release based distributed hydrologic model using GIS

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SUMMARY

The objective of this paper is to present the development and application of a grid based hydrologic model using an object oriented framework within geographic information systems (GIS). The proposed model is called Storage Released based Distributed Hydrologic Model (STORE DHM). Development of STORE DHM is a part of a broader objective to develop a modular hydrologic modeling system within GIS. In this paper, the conceptual framework of STORE DHM including its application to three watersheds in Indiana is presented. The model is tested in the study watersheds by first calibrating it against observed flow hydrograph for a single event, and then verifying it for three additional storm events using both point (gauged) and continuous (radar) rainfall data. Results show that SOTRE DHM is able to predict runoff hydrographs for different types of events in terms of storm duration, peak flow magnitude and time-to-peak. The average Nash–Sutcliffe coefficient is greater than 0.8 for all runoff hydrograph during validation, and the errors in peak flow and time-to-peak predictions are within 5% and 15%, respectively. In addition, STORE DHM output is compared with outputs from two hydrologic models including Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and time variant Spatially Distributed Direct Hydrograph travel time method (SDDH). Results from these comparisons show that STORE DHM outperforms both HEC-HMS and SDDH in terms of overall hydrograph shape and flow magnitude. Although the results from application of STORE DHM are encouraging, the work presented in this paper is just an initial step towards developing a comprehensive tightly coupled GIS modeling framework for hydrology.

1. Introduction

Watershed based hydrologic models are important tools in hydrology forecasting, and water resources planning and management. A watershed scale hydrologic model is a simplified description of the hydrologic system of a watershed. Hydrologic model development is complicated by the nonlinear, time dependent and spatially varying nature of rainfall–runoff mechanism (Remesan and Shamim, 2009). Rainfall–runoff process is affected by many factors such as the rainfall dynamics, topography, soil type and land use. Significant advancements in hydrological modeling started with the introduction of unit hydrograph model and its related impulse response function (Sherman, 1932). Since then, myriad of hydrologic models have been developed, calibrated and validated for several watersheds at different scales. Developing a realistic hydrologic model requires understanding of interrelation between parameterization and scale because as the scale of the hydrologic modeling problem increases, the complexity of the model increases as well (Famiglietti and Wood, 1994).

Traditionally, statistical and conceptual hydrologic models have treated input parameters as lumped over the entire study watershed by ignoring the spatial variability of the physical system and its processes. Specifically, these models cannot accurately represent and model the spatial variation in meteorological and land surface conditions that affect various hydrologic processes, and therefore cannot guarantee realistic simulations. For example, most routines in the commonly used HEC-HMS (Hydrologic Engineering Center Hydrologic Modeling System; USACE, 1998) model does not account for spatial variations in hydrologic processes. In addition, use of HEC-HMS requires external software such as HEC-GeoHMS to produce necessary input files for the model. HEC-GeoHMS is an ArcGIS toolbar to process digital information related to topography, land use, and soil to produce input files for HEC-HMS. Nevertheless, because of their simplicity in terms of data requirements, model parameterizations and application, lumped hydrologic models such as HEC-HMS have been very popular in hydrology.

Application of semi-distributed or distributed models is complicated due to data requirements for physically based models (Koren

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et al., 2003), and parameter estimation for conceptual models (Moreda et al., 2006). To fully exploit the strength of semi-distributed and distributed models, it is necessary to provide data that can capture the spatio-temporal variations in the hydrologic system including rainfall dynamics. Difficulties related to data requirements for spatially distributed hydrologic models are addressed by the availability of continuous digital data in the form of digital elevation model (DEM) and gridded radar rainfall. In addition to the availability of geospatial data, the use of geographic information system (GIS) to process grid and vector data has led to rapid progress in grid based distributed hydrologic modeling (e.g., Maidment, 1993; Olivera and Maidment, 1999; Melesse and Graham, 2004). The use of spatially distributed topographic, soils, land use, land cover, and precipitation data in GIS ready format provides the framework for the development, verification, and eventual acceptance of new hydrologic models capable of taking full advantage of these new data, while acknowledging the uncertainty inherent in the data.

The broader goal of this study is to create a conceptual hydrologic model framework, called GIS and Hydrologic Information System Modeling Objects (GHISMO), which can utilize GIS data at different resolutions, and use these data to simulate hydrologic processes at multiple scales. GHISMO is expected to provide a platform where different models or their components can interact with each other within a GIS environment to overcome the issues related to computational requirements, scale and versatility through an object oriented design. As a first step towards accomplishing this broader goal, this paper presents the development and application of a prototype grid based hydrologic model using object oriented programming concepts. The data and computational side of GHISMO is developed by using ArcObjects (building blocks or objects of the ArcGIS software), and the conceptual model for hydrologic simulations is based on a simple storage–release approach. In the storage–release approach, each cell in a raster grid provides storage for the water draining to it from neighboring cells, and then the water is released to downstream cells based on the travel time computed by combining the continuity and Manning's equations. This paper specifically presents the conceptual framework of the prototype hydrologic model, and its application to three study sites in Indiana. The grid based hydrologic model will be referred as the Storage Released based Distributed Hydrologic Model (STORE DHM).

2. Background and related work

With the advent of GIS and remote sensing technology in topography analysis, several grid based distributed hydrologic models have been developed. These include the Système Hydrologique Europèen (SHE, Abbott et al., 1986) model, the IHDM model (Institute of Hydrology Distributed Model, Calver and Wood, 1995), the CSIRO TOPOG model (Terrain Analysis Hydrologic Model, Vertessey et al., 1993) and HILLFLOW (Bronstert and Plate, 1997), among others. These models use a grid based routing (kinematic wave or diffusive wave) approach to account for spatio-temporal variations in water movement. However, they use complex algorithms with low computational efficiency requiring large data base for calibration and large computational resources for simulation (Beven, 2002). Recently, several event based grid models have been developed that use travel time methods for routing the flow through a watershed. These include: (i) the spatially distributed unit hydrograph method by Maidment (1993; Maidment et al., 1996; Muzic, 1995; Ajward, 1996), (ii) the first passage-time response function which is derived from the advection–dispersion method by Olivera and Maidment (1999), (iii) the diffusive transport method by Liu et al. (2003), and (iv) the spatially distributed travel time method by Melesse and Graham (2004), among others. Maidment (1993) assumed time invariance velocity to get a unit hydrograph; whereas Muzic, 1995 and Ajward (1996) used continuity and Manning's equations to determine the flow velocity through each grid cell. Melesse and Graham (2004) propose an integrated technique using remote sensing and GIS datasets to compute spatially distributed excess rainfall, which is then routed by using the travel-time concept without relying on the unit hydrograph theory.

Maidment (1993) proposed a time–area method within raster GIS to derive a spatially distributed unit hydrograph. Maidment's method uses a DEM to determine the flow direction from each cell based on the maximum downhill slope, and flow velocity through each cell is estimated based on the kinematic wave assumption. The travel time through each cell is then obtained by dividing the flow distance by the flow velocity. Maidment demonstrated that if a constant velocity can be estimated for each grid cell, a flow time grid can be obtained and subsequently isochronal curves and time–area diagram can be determined for a watershed. Maidment's method is based on velocity time invariance in a linear hydrologic system.

Melesse and Graham (2004) proposed a grid based cell travel time hydrologic model that assumes invariant travel times during a storm event. The runoff hydrograph at the outlet of watershed is developed by routing the spatially distributed excess precipitation through the watershed using topographic data. Calculation of travel times from each cell to the watershed outlet requires computation of a runoff velocity for each grid cell. Velocity for each grid cell can be estimated depending on whether the grid cell represents an area of diffuse overland flow or more concentrated channel flow. This method ignores the variations in travel time during the storm because it takes average excess rainfall intensity. The advantage of Melesse and Graham's grid based travel time method is that it can create a direct hydrograph without spatially lumped unit hydrograph during a rainfall event.

The issue of invariant travel time proposed by Melesse and Graham (2004) is addressed by Du et al. (2009), who proposed a time variant spatially distributed direct hydrograph travel time method (SDDH) to route spatially and temporally distributed surface runoff to watershed outlet. In the time variant SDDH method, the cumulative direct runoff and travel time is calculated by summing the individual volumetric flow rate and travel time from all contributing cells to outlet along a flow path for a given time step. This approach, however, cannot maintain the total mass balance because a cell that receives input from multiple upstream cells gets accounted multiple times while computing the flow from upstream cells. Similarly a particular cell does not account for flow from adjacent cells while the flow is being routed from an upstream cell. For example, in Fig. 1a, water from cell A flows to the outlet cell K through cells D–E–H–K. Similarly, water from cell B reaches the outlet through E–H–K. So if the flow at the outlet from cells A and B is computed as cumulative flow along the flow path, flows from E, H and K are accounted twice, thus compromising the mass balance. As a result, this technique requires adjustment of travel time (which is mistakenly referred to as calibration) to account for high volumetric flow rates computed through repeated accumulations. To overcome these issues in grid based hydrologic models based on travel-time concept, this study proposes a simple conceptual approach for distributed event based hydrologic modeling using the storage release approach.

3. Study area and data

The methodology for STORE DHM is evaluated by applying it to multiple storm events at three study areas including Cedar Creek, Crooked Creek and Fish Creek in Indiana. Description of the study