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Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event

M.R. Knebl[a], Z.-L. Yang[a,*], K. Hutchison[b], D.R. Maidment[c]

[a]*Department of Geological Sciences, University of Texas at Austin, 1 University Station C-1100, Austin, TX 78712-0254, USA*
[b]*Center for Space Research, 3925 West Braker Lane, Suite 200, Austin, TX 78759-5321, USA*
[c]*Center for Research in Water Resources, University of Texas, Pickle Research Campus, Bldg 119, MC R8000, Austin, TX 78712, USA*

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Abstract

This paper develops a framework for regional scale flood modeling that integrates NEXRAD Level III rainfall, GIS, and a hydrological model (HEC-HMS/RAS). The San Antonio River Basin (about 4000 square miles, 10,000 km^2) in Central Texas, USA, is the domain of the study because it is a region subject to frequent occurrences of severe flash flooding. A major flood in the summer of 2002 is chosen as a case to examine the modeling framework. The model consists of a rainfall–runoff model (HEC-HMS) that converts precipitation excess to overland flow and channel runoff, as well as a hydraulic model (HEC-RAS) that models unsteady state flow through the river channel network based on the HEC-HMS-derived hydrographs. HEC-HMS is run on a 4×4 km grid in the domain, a resolution consistent with the resolution of NEXRAD rainfall taken from the local river authority. Watershed parameters are calibrated manually to produce a good simulation of discharge at 12 subbasins. With the calibrated discharge, HEC-RAS is capable of producing floodplain polygons that are comparable to the satellite imagery. The modeling framework presented in this study incorporates a portion of the recently developed GIS tool named Map to Map that has been created on a local scale and extends it to a regional scale. The results of this research will benefit future modeling efforts by providing a tool for hydrological forecasts of flooding on a regional scale. While designed for the San Antonio River Basin, this regional scale model may be used as a prototype for model applications in other areas of the country.

Keywords: GIS; Flood modeling; Rainfall–runoff; NEXRAD rainfall; Calibration; Validation

1. Introduction

Flooding induced by storm events is a major concern in many regions of the world (Townsend and Walsh, 1998; Dutta et al., 2000; Dolcine et al., 2001; Sheng et al., 2001; Bryant and Rainey, 2002; Horritt and Bates, 2002; Lee and Lee, 2003; Hudson and Colditz, 2003). In a time period of 6 years (1989–1994), 80% of declared federal disasters in the US were related to flooding; floods themselves average four billion dollars annually in property damage alone (Wadsworth, 1999). The extreme weather in recent years has demonstrated the necessity of reliable flood models, as emergency managers and city planners begin to realize the importance of advance warning in severe storm situations. As globally averaged temperatures increase, the potential for severe to extreme weather events increases (Becker and Grunewald, 2003; WMO, 2003). Therefore, global warming has brought further urgency to the prediction of flood levels and damages.

Flood inundation modeling requires distributed model predictions to inform major decisions relating to planning and insurance (Bates, 2004). Since the blueprint paper by Freeze and Harlan (1969), flood modeling has greatly improved in recent years with the advent of geographic information systems (GIS), radar-based rainfall estimation using next generation radar (NEXRAD), high-resolution digital elevation models (DEMs), distributed hydrologic

* Corresponding author. Tel.: +1 512 471 3824; fax: +1 512 471 9425.
E-mail addresses: mknebl@mail.utexas.edu (M.R. Knebl), liang@mail.utexas.edu (Z.-L. Yang), keithh@csr.utexas.edu (K. Hutchison), maidment@mail.utexas.edu (D.R. Maidment).

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models, and delivery systems on the internet (Garrote and Bras, 1995; Bedient et al., 2003). There are, however, major issues that limit the accuracy in flood forecasts. These issues include errors associated with the radar rainfall input (Vieux and Bedient, 1998; Borga, 2002; Grassotti et al., 2003; Jayakrishnan et al., 2004), realism of model structure (Horritt and Bates, 2002), availability of distributed data to parameterize and validate the models (Bates, 2004), and scaling theory to relate point measurements to grid-averaged quantities predicted by the models (Beven, 2002; Bates, 2004). In addition, the time required to convert the NEXRAD rainfall time series to a flood inundation map is critical in practical applications, especially during the extreme storm events that demand a highly efficient predicting capability.

Despite the progress in flood modeling research, flooding continues to plague many areas of the world, including regions such as Central Texas. In the summer of 2002, a major precipitation event caused extensive flooding, 12 deaths, and nearly one billion dollars in damage in the San Antonio River Basin, which is the case presented in this study. Urban areas such as San Antonio are especially prone to flooding due to the large proportion of impermeable surface cover such as concrete that increases the total volume of runoff and peak flows and shortens the time that the floodwaters take to arrive at peak runoff (Hall, 1984).

Recent work in the area of flood modeling has focused on developing more efficient tools for ArcGIS. Robayo et al. (2004) developed a new Map-to-Map tool that couples NEXRAD precipitation time series with GIS applications and hydrological modeling to produce a floodplain map. This Map-to-Map technology involves the creation of an ArcHydro data model in GIS, an Interface Data Model (IDM) for each outside model that shares data with the GIS, and a number of scripts to process the data in GIS. A more in-depth description of Map to Map can be found in Whiteaker et al. (in review) and Whiteaker and Maidment (2004). Successful pilot tests of the Map-to-Map tool have been made in small basins including the Salado Basin (222 square miles) and the Rosillo Basin (29 square miles). These two basins are small catchments located within the much larger San Antonio River Basin. The nearly 4000 square mile San Antonio River Basin contains numerous other small catchments, and thus demonstrates much diversity of land cover, geology, and topography.

The Map-to-Map methodology has proven successful at the local and small basin scale, but until now has not been applied to a regional scale model. As the first of a series of studies that focus on regional scale flood forecasts, this paper extends the Map-to-Map technology to the entire San Antonio River Basin. Major goals of this research include: (1) the development of a hydrological model of the San Antonio River Basin and the implementation of NEXRAD precipitation products in the model; (2) the analysis of rainfall–runoff characteristics of the basin and adequacy of current infiltration methods for describing these basin characteristics. The methodology presented in this study attempts to create a streamlined process of rainfall input and floodplain output that will enable researchers to model rainfall–runoff relations with greater efficiency and will also contribute to improvements in the ability of Texas counties to respond in the scenario of a disastrous flooding event.

The structure of the paper is as follows. Section 2 describes the major datasets used in development of the model. Section 3 outlines the parameterizations used and descriptions of both the rainfall–runoff model and the hydraulic model, and Section 4 describes the processing and calibration of the model. Section 5 discusses potential results and utility of model development, and Section 6 draws some concluding remarks.

2. Datasets

The study area selected for model development is the San Antonio River Basin, a 3921 square mile basin located in South Central Texas (Fig. 1). San Antonio, a city of 1.1 million people, is situated in the middle section of the basin. The temporal extent of the study was selected as June 30–July 9, 2002 to cover the duration of the summer storm of 2002. Heavy rainfall (3–10 in./day) was observed from days 1 to 6 (or June 30–July 5), while days 7–10 (or July 6–9) fall on days in which rainfall was minimal or zero. Days 5–7 coincide with peak stream gage heights at area stations.

Rainfall inputs to the model were processed to convert binary rainfall into a format compatible for input into the gridded hydrological model. Traditional rain gages are often sparse and do not provide a fine enough resolution for accurate runoff calculations and flood warnings (Ahrens and Maidment, 1999; Bedient et al., 2003). NEXRAD radar data have performed well in comparison studies with ground-based gages and have led to the consensus that the data are a high quality input to hydrological models (HEC, 1996a,b; Reed and Maidment, 1995). The accuracy of NEXRAD rainfall is dependent on the *Z*–*R* relationship used to convert reflectivity *Z* to rainfall rate *R*. In a case study of an extreme storm event in South Texas in October 1994, Vieux and Bedient (1998) found that use of the traditional *Z*–*R* relationship, $Z=300R^{1.4}$, caused significant errors when compared to rain gauge accumulations. The tropical *Z*–*R* relationship, $Z=250R^{1.2}$, performed much better. The tropical *Z*–*R* has been recommended for use where appropriate by the National Weather Service (NWS) since 1995; hence, the use of the more accurate *Z*–*R* relationship should reduce errors in tropical rainfall estimation for storms such as in the present study. The type of precipitation product used may also make a significant difference in output when used to drive hydrologic models. Grassotti et al. (2003) compared rainfall estimates from three different products (1) hourly 4-km resolution P1 (an update to the Stage III process) estimates, 15-min 2-km resolution NOWrad estimates, and conventional hourly rain gage