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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

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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

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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

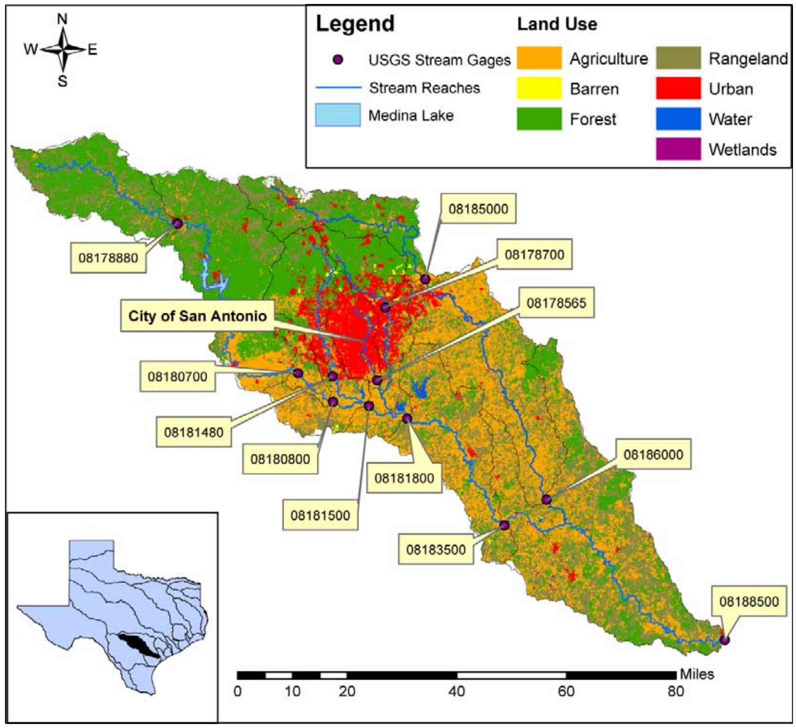


Fig. 1. Map of the San Antonio River Basin. Prominent features include the 12 subbasins and numerous river reaches delineated in this research, the 12 USGS gauging stations coinciding with outlet points of the 12 subbasins, land-cover data, and the model grid used in the study. The model grid consists of 4×4 km cells used for hydrologic processing of runoff.

observations, and found that the 4-km P1 estimates demonstrated the best agreement with rain gage observations. For the present study, NEXRAD Level III datasets over the calibration period were obtained in a 4 km gridded format from Texas' West Gulf River Forecast Center and processed into a format compatible with the hydrological model. Table 1 displays daily rainfall totals extracted from this NEXRAD data for subbasins in the study region.

Topography was downloaded from the USGS National Elevation Dataset (NED), a continuously updated grid of elevation values across the country with a minimum resolution of 30 m. The data are among the highest quality and finest resolution available at the basin scale. The preliminary model used a 30 m resolution only; DEMs of 10 m resolution where available were incorporated into later model runs. The 30 m elevation product was resampled to a 10 m grid and updated with the 10 m values where available (approximately 75% of the basin).

Twelve USGS stream flow gages with complete hydrological datasets formed a base of streamflow observations over the study region, including both discharge measurements and gage heights. These datasets were used both in parameter derivation and in calibration of the model. Information about the land surface was gathered from multiple sources. The US Department of Agriculture Soil Conservation Service (now the National Resource

Table 1
Daily rainfall totals for subbasins in the San Antonio River Basin

Subbasin ID	Precipitation (in)									
	6/30/02	7/1/02	7/2/02	7/3/02	7/4/02	7/5/02	7/6/02	7/7/02	7/8/02	7/9/02
08178880	4.30	0.84	6.98	2.09	5.57	5.67	0.05	0.09	0.03	0.09
08180700	3.83	4.81	6.27	5.50	4.26	2.69	0.00	0.03	0.17	0.13
08185000	3.87	4.35	8.92	4.48	3.25	3.15	0.01	0.07	0.14	0.19
08178700	2.92	4.36	10.16	2.70	1.56	2.31	0.05	0.03	0.04	0.33
08181480	3.76	5.31	7.08	4.38	4.73	3.19	0.03	0.01	0.05	0.29
08178565	2.10	6.47	5.94	2.43	2.18	2.58	0.06	0.00	0.00	0.37
08180800	2.86	8.03	4.20	3.92	4.88	3.92	0.00	0.00	0.00	0.22
08181800	1.10	7.57	2.88	0.91	0.52	3.02	0.01	0.00	0.00	0.40
08181500	1.61	7.17	1.62	1.71	3.64	2.92	0.03	0.00	0.00	0.48
08186000	2.27	5.15	4.11	0.50	0.11	2.73	0.11	0.00	0.00	0.25
08183500	1.74	6.52	2.70	0.90	0.14	3.18	0.04	0.00	0.00	0.21
08188500	0.61	3.89	2.62	0.11	0.10	1.96	0.15	0.00	0.11	0.69

Conservation Service) holds a database of soils data for each state, called the State Soil Geographic Database (STATSGO). These data are derived from 1:250,000 scale USGS quadrangles. The National Land Cover Dataset created by the USGS (NLCD92) contains information about the land use and cover at a 30 m resolution over most regions of the US. This dataset divides land use and land cover into 21 categories, which were aggregated as shown in Fig. 1. Finally, river geometry is necessary to run the hydraulic model; the data were obtained by combining measured survey data with cross-sections delineated from the DEM.

3. Model description

3.1. Rainfall–runoff model: HEC-HMS

Runoff is modeled using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), version 2.2.1. HEC-HMS, developed by the US Army Corps of Engineers, is designed to simulate the precipitation–runoff processes of dendritic watershed systems. HEC-HMS allows the modeler to choose between numerous infiltration loss parameterizations (HEC, 2000). However, only the gridded curve number (CN) technique enables spatially distributed infiltration calculations. Infiltration capacity is quantified in a parameter derived by the Soil Conservation Service (SCS) called the CN. The CN is a method for determining storm runoff over an area based on land use, soil and land cover type, and hydrologic soil group (US SCS, 1986). Soil groups are determined based on type and infiltrability of a soil. The infiltration loss method is derived from a set of empirical equations that define the partitioning of rainfall into infiltration and runoff,

$$Q = (P - I_a)^2/((P - I_a) + S) \tag{1}$$

$$I_a = 0.2S \tag{2}$$

$$S = (1000/\mathrm{CN}) - 10 \tag{3}$$

Substituting Eq. (2) into Eq. (1) gives

$$Q = (P - 0.2S)^2/(P + 0.8S) \tag{4}$$

where

Q = runoff in inches
P = rainfall in inches
S = potential maximum retention
I_a = initial abstraction
CN = runoff curve number

This CN parameter was derived for each grid cell using an Avenue script that combines STATSGO soils data with the land use data layer. For the San Antonio area, most soils are classified into Hydrologic Soil Group C, which corresponds to soils having a low infiltration rate when thoroughly wetted, often with impeding layers in the soil, and CN of approximately 75–90 (Chow et al., 1988). Initial abstraction is a variable parameter that takes into account losses prior to the start of runoff such as interception and depression storage. Evapotranspiration losses are considered negligible for the preliminary model due to several factors: the intensity of the storm being modeled, the continuous saturation of the air, and the resulting assumption that ET volume is negligible compared to runoff volume. Model runs testing this hypothesis demonstrated minimal to no effect on the subbasin hydrographs during the 10-day storm.

Translation of excess precipitation to runoff is accomplished using the ModClark algorithm, a version of the Clark unit hydrograph transformation modified to accommodate spatially distributed precipitation (Clark, 1945). This method convolves precipitation increments with the unit hydrograph ordinates to determine the basin hydrograph, $Q_n = \Sigma P_m^* U_{n-m+1}$, as m goes from 1 to n. Time of concentration for each cell in the basin is derived as $t_{\mathrm{cell}} = t_c^* (d_{\mathrm{cell}}/d_{\max})$, where t_c is the time of concentration for the subwatershed and is a function of basin length and slope, d_{cell} is the travel distance from the cell to the outlet, and $d_{\max}$ is the travel distance from the cell furthest from the outlet. The method requires an input coefficient for storage, R, where R accounts for both translation and attenuation of excess precipitation as it moves over the basin toward the outlet. Storage coefficient R is estimated as the discharge at the inflection point on the recession limb of the hydrograph divided by the slope at the inflection point. The translation hydrograph is routed using the equation (HEC, 2000)

$$Q(t) = [(\Delta t/(R + 0.5\Delta t)) * I(t)] + [(1 - (\Delta t/(R + 0.5\Delta t))) * Q(t-1)] \tag{5}$$

where

$Q(t)$ = outflow from storage at time t
Δt = time increment
R = storage coefficient
$I(t)$ = average inflow to storage at time t
$Q(t-1)$ = outflow from storage at previous time $t-1$

Baseflow can be an important parameter in flood studies because it defines a minimum river depth over which additional runoff accumulates. Models that neglect baseflow may underestimate water levels and therefore fail to identify inundated reaches. Baseflow is modeled using an exponential decrease function, $Q = Q_0^* \mathrm{e}^{-kt}$, where k is a fitting parameter.

3.2. Hydraulic model: HEC-RAS

The hydraulic model is based on HEC's River Analysis System (HEC-RAS), version 3.1 (HEC, 2002). HEC-RAS calculates one-dimensional steady and unsteady flow, and the model equations are also described by Horritt and Bates (2002). The hydraulic model requires as input the output hydrographs from HMS; its parameters are representative cross-sections for each subbasin, including left and right bank locations, roughness coefficients (Manning's *n*), and contraction and expansion coefficients. Roughness coefficients, which represent a surface's resistance to flow and are integral parameters for calculating water depth, were estimated by combining land use data with tables of Manning's *n* values such as that found in HEC (2002). As present engineering studies are completed throughout the basin, more detailed cross-sectional data will be incorporated into the model. Due to the regional scale of the model, channel geometry was considered only for the larger streams in the network: the San Antonio and Medina Rivers, and the Salado, Cibolo, and Leon Creeks. In order to use the RAS model to develop floodplain maps, it must be georeferenced to the basin. Hence, the DEM formed the basis for derivation of channel geometry, and was enhanced by available cross-sections from the USGS.

4. Modeling methodology

4.1. Processing steps

The development of the present flood model integrates GIS with the HEC-HMS rainfall–runoff model and the HEC-RAS river hydraulic model. Numerous past studies have shown these models to provide accurate and useful results in flood related studies (Ahrens and Maidment, 1999; Anderson et al., 2002). An additional component of this research involves Map to Map, the aforementioned tool developed for ArcGIS by the research team of Professor David Maidment of the University of Texas at Austin College of Engineering. Map to Map's model infrastructure accepts processed rainfall data, a rainfall–runoff model, and a hydraulic model, and streamlines the processes into one operation that delineates polygons showing the floodplain extents (O. Robayo, personal communication). The Map-to-Map tool was modified to meet the specific needs of the present research, including accommodations for unsteady flow and the incorporation of dissimilar precipitation products. This research tests the utility of the prototype Map to Map in regional-scale flood investigations. A flow chart outlining the fundamental steps in the model development is shown in Fig. 2.

Using ArcGIS, a geodatabase was created to contain all of the above-mentioned data. The data were imported, merged, reprojected into the Albers Equal Area coordinate system and the NAD83 datum, and clipped to the study area. While much of this functionality is available in ArcGIS, some processes required outside scripts from various authors, such as the Grid Projection Extension (author: K.R. McVay) used to process raster data.

Following collection and processing of data, the stream network was delineated. An extension of GIS called HEC-GeoHMS executes this function through a series of steps collectively known as terrain preprocessing, implying the utilization of the surface topography as the origin of the stream network. The importance of using an accurate and high-resolution DEM for hydrologic modeling is underscored by these terrain-preprocessing steps; if the DEM used is not sufficiently accurate, simulated rivers may follow very different paths from their actual pathways, and consequently watersheds will be delineated incorrectly. Two major methods exist for drainage network delineation from topography: the area-threshold method and the slope-area method. A comparison of the results obtained by the two methods has shown little difference between the two delineations (Giannoni et al., 2003). The area-threshold method was used in this study due to the gridded nature of the input datasets. In this method, water in each grid cell can potentially flow into any of the eight surrounding cells; the algorithm maps the water into a neighboring cell along the path of steepest descent. Each cell is then assigned a value according to how many cells flow into that particular cell. A threshold of upstream drainage area (in units of cells) is then specified by the modeler; every cell exceeding that threshold value becomes part of the stream network, i.e. part of the channel flow.

HEC-GeoHMS also includes functionality to delineate subbasins from the network and local topography; for calibration purposes, locations of USGS stream gages were designated as subbasin outlets. Fig. 1 demonstrates the preliminary drainage system delineated over the San Antonio River Basin.

A rainfall–runoff model simulates the runoff response of an area to a given amount and distribution of precipitation over a defined period of time. The output of the model is the discharge hydrograph at each subbasin outlet; hydrograph characteristics define each subbasin's unique runoff response due to differences in watershed properties including geology, geomorphology, and anthropogenic effects. The creation of the rainfall–runoff model requires three files of input data: a map file, a grid cell parameter file, and a distributed model file. The map model file is a background file for spatial reference around the basin. The grid cell parameter file describes the location and properties of each cell across the basin; the modeler must first derive CNs representing each grid cell for input into this file. This file was used with the ModClark method of transforming rainfall to runoff, and the grid chosen for this process was the Standard Hydrologic Grid (SHG), which uses a custom Albers Equal Area projection. The distributed model file contains the hydrologic elements and their connectivity, and links the subbasins to the gridded data in the grid cell parameter file.

Hydrographs extracted from the rainfall–runoff model were saved as time series data and inputted directly into the hydraulic model. The model computed an unsteady flow analysis to derive water levels in the river network.

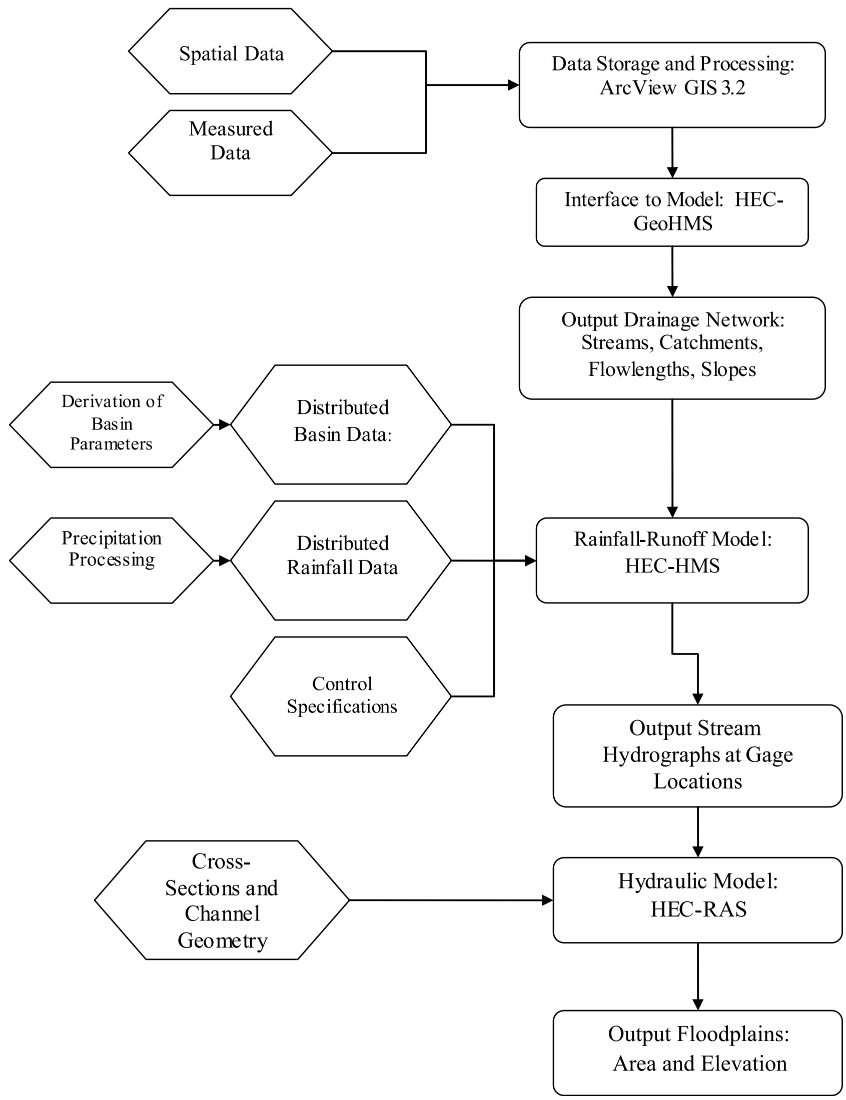


Fig. 2. Steps in model design. Spatial data such as land use and elevation were gathered in addition to measured data such as the USGS discharge time series. Processing of data was completed in ArcView GIS 3.2 and exported to the hydrological model HEC-HMS through the model interface HEC-GeoHMS. Binary files of rainfall were processed and basin parameters were derived for the study area; the hydrological model was run using these inputs. Channel geometry was derived using elevation data, and output hydrographs were then used as input to drive the hydraulic model HEC-RAS. Finally, time series of cross-section heights were processed in ArcGIS and converted to flood inundation polygons. The Map-to-Map tool used in this study connects each of these processes and allows them to run as a single process.

These water levels were then exported back to the geodatabase and overlain on the DEM. At each grid cell, water elevation was checked against the topographic elevation—if water elevation was greater than the terrain elevation, then the cell was assigned a value of 1; otherwise, the cell was assigned a value of 0. The flood polygon was then drawn by the GIS and consisted of all cells having a value of 1. The flood polygons for each reach can be displayed and analyzed in the GIS, making the model methodology very versatile and simple to apply to various applications.

4.2. Model calibration

Calibration of the model with appropriate data is a crucial step in the creation of a reliable basin representation. Watershed parameters such as infiltration coefficients, time of concentration, and baseflow may need modification to produce a best fit between model and observations. Discharge output from a rainfall–runoff model is generally calibrated with observed streamflow. During severe storms, gage capacity is sometimes exceeded and streamflow must be extrapolated to record measurements; this extrapolation carries potential error that must be taken into account in flood studies (S. Gonzales, personal communication). The hydraulic model delineating floodplain extent should be validated with an accurate image of flooding during the storm in question. Remote sensing is a valuable tool for this purpose. Several studies have utilized remote sensing data such as that from Landsat Thematic Mapper (TM) to determine the extent of floodplain inundation (Townsend and Walsh, 1998; Hudson and Colditz, 2003). The Landsat data over San Antonio (Path 27 Row 39) was processed by the Center for Space Research with an algorithm that produces spatial extent of flooding during the storm event. The satellite pass over the study area occurs once every 16 days; the one date with available Landsat data, July 8 2002, was chosen for comparison with model output. This date is several days past the storm peak, and therefore represents flood response after nearly a week of heavy rainfall.

Upon completion of model development and trial runs, the model presented in this study was calibrated against measured data to assess its ability to reproduce flooding from the July 2002 storm event. This determination involved several sets of data: the flood hydrographs produced at USGS gaging stations, and flood area as determined from Landsat TM satellite data. The output from the rainfall–runoff model was used to assess the accuracy of the model in reproducing hydrograph response, including flood peaks. Estimated parameters were modified to produce a best-fit model. It is important to note that the calibration was performed at two scales: (1) watershed parameters were modified at the subbasin scale (200 km^2 or more) and (2) CNs were modified at the ModClark grid cell scale (4 km^2).

5. Preliminary results and discussion

Preliminary results for the hydrological model showed a reasonable fit between model and observations; hydrograph shape and timing of peaks matched well, although the model tended to overestimate runoff. In the majority of subbasins, the hydrograph shape was accurately reproduced in model output. However, the model overestimated volume of runoff and frequently did not accurately define peak sharpness as observed through stream measurements. Calibration of the model improved results by greatly decreasing the volume of runoff and improving peak sharpness at most locations.

Initial calibration efforts altered the values of CNs on a regional scale (Fig. 3) and modified other watershed parameters (Table 2) for each subbasin to more accurately represent surface flow over the region. The calibration efforts have shown promising results (Fig. 4, Table 3). As an example, subbasin 08180700 initially had a percent bias of 215, a mean absolute error of 215%, and a correlation coefficient of 0.92. After calibration, these were, respectively, reduced to −1, 22, and 0.93. This reduced error is mostly due to the underestimation of peak and peak sharpness in the model. The most sensitive parameters were found to be the time of concentration of the basin, the initial abstraction (I_a), and the CN (Table 2 and Fig. 3). Modifying the time of concentration improved the timing of peaks, both absolute and in relation to other peaks. Since each subbasin has unique infiltration topography, soils, etc. the time of concentration in some basins was increased while in others was decreased from its calculated value. The initial abstraction, defined in Eq. (2), was determined in many subbasins to be too low. This value was increased to account for additional abstractions that may include detention areas or man-made structures. CNs were decreased for subbasins as necessary to optimize the model fit (Fig. 3). Decreasing the CN increased the amount of recharge into the watershed system and therefore reduced overestimation of runoff in the model. In addition, the hydrologic routing method was modified to include a greater ratio of attenuation to translation of runoff in the subbasins; this change in routing method significantly improved the model results. The results for Cibolo Creek subbasins

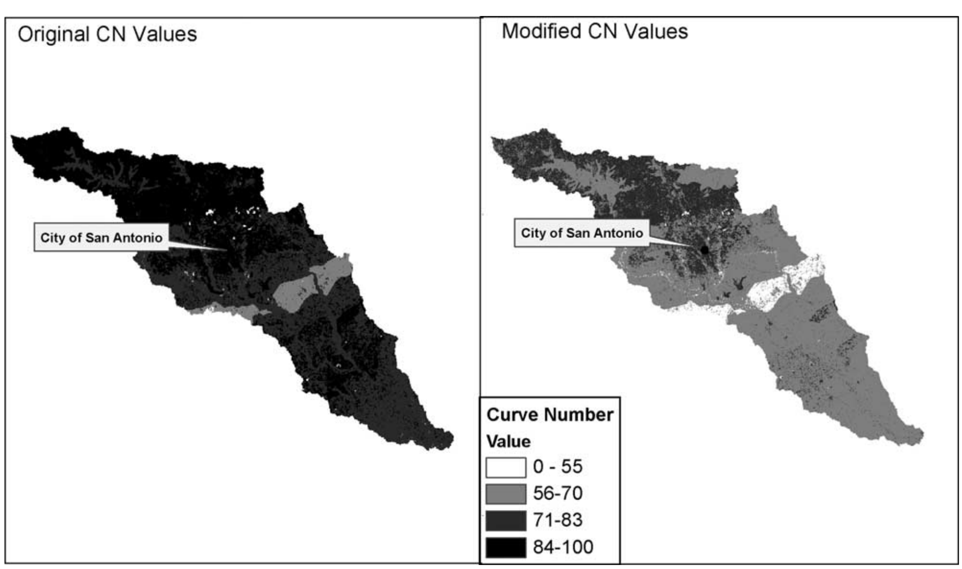
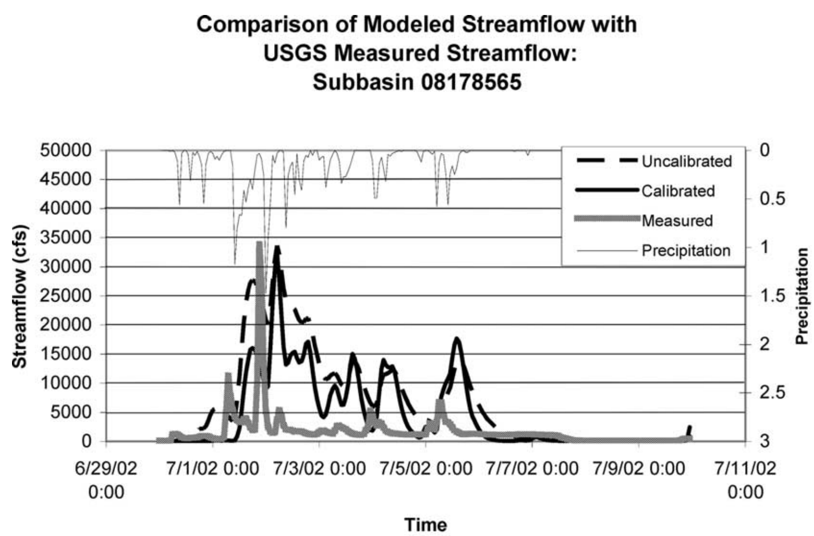


Fig. 3. Modification of curve number during model calibration. The figure on the left is the infiltration grid prior to calibration displaying the curve number distribution across the basin. The figure on the right is the infiltration grid after calibration; curve numbers were decreased approximately 20% across the basin to correct for overestimation of runoff volume in the preliminary model.

Table 2
Original and calibrated lumped subbasin parameters

Subbasin ID	Time of concentration (h)		Storage coefficient (h)		Initial baseflow (ft^3/s)		Initial abstraction ratio	
	Original[a]	Calibrated[b]	Original[a]	Calibrated[b]	Original[a]	Calibrated[b]	Original[a]	Calibrated[b]
08178880	96	5	185	20	14.94	14.94	0.20	0.35
08180700	96	10	76	35	53.78	53.78	0.20	0.40
08185000	96	4	71	20	0.0	0.0	0.20	0.35
08178700	48	6	22	10	0.0	0.0	0.20	0.38
08181480	36	10	20	10	4.98	4.98	0.20	0.38
08178565	72	5	31	8	78.67	78.67	0.20	0.38
08180800	96	134	253	345	45.8	45.8	0.20	0.20
08181800	84	465	67	445	151.4	151.4	0.20	0.30
08181500	72	109	295	349	97.6	97.6	0.20	0.30
08186000	96	588	71	567	65.73	39.83	0.20	0.25
08183500	96	482	70	480	119.5	119.5	0.20	0.30
08188500	120	930	960	1000	262.91	262.91	0.20	0.20

[a] Original parameter values.
[b] Calibrated parameter values.



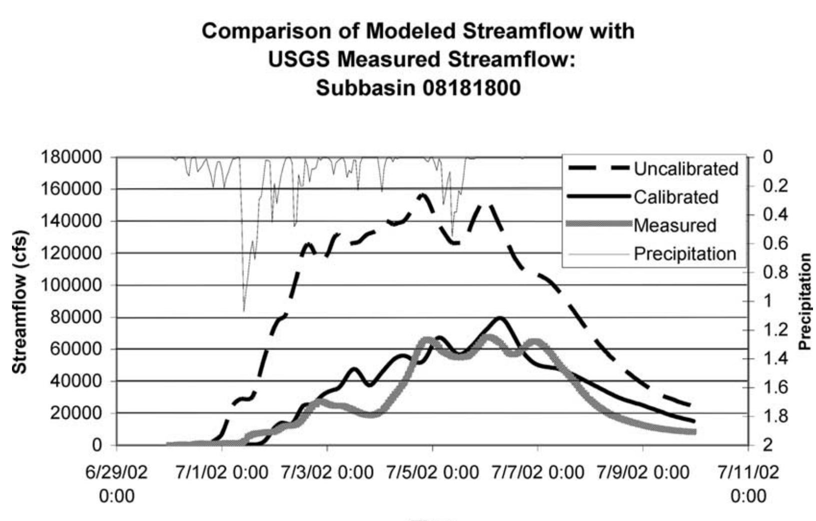


Fig. 4. Hydrologic model results and calibration for a selected downstream portion of the San Antonio River. Subbasin 08178565 is located on the San Antonio River 12 km south of downtown San Antonio, and Subbasin 08181800 is located 20 km downstream from 08178565. The figures compare measured results (hatched line) with uncalibrated (dashed line) and calibrated (solid line) modeled results. Precipitation time series are included for reference.

Table 3
Comparison of percent bias, mean absolute error, and correlation coefficient between original and calibrated simulations for the 12 subbasins

Subbasin ID	Bias (%)		MAE (%)		Correlation coefficient	
	Original	Calibrated	Original	Calibrated	Original	Calibrated
08178880	−14	−27	61	54	0.63	0.69
08180700	215	−1	215	22	0.92	0.93
08185000	54	100	102	105	0.35	0.83
08178700	314	54	350	132	0.39	0.23
08181480	151	8	156	16	0.75	0.78
08178565	285	157	311	225	0.41	0.29
08180800	158	2	158	16	0.95	0.97
08181800	197	20	197	29	0.78	0.92
08181500	208	21	208	31	0.88	0.93
08186000	28	58	44	67	0.69	0.96
08183500	237	27	237	38	0.53	0.90
08188500	447	0	359	54	0.40	0.94

The three statistical measures are defined according to Zhang et al. (2004).

(08185000, 08186000) consistently overestimate runoff in the model, even after calibration. Further calibration is necessary to reduce model error for this section of the basin. Only one subbasin, basin number 08178880, currently demonstrates a significant underestimation of runoff. This is mostly due to the large peak in measured streamflow on July 5; in the modeled hydrograph for this subbasin, the July 5 peak is much smaller. Basin 08178880, the northernmost subbasin in the study area, is one of the largest subbasins, and hence averaging of basin parameters may have lead to model error. However, it is quite likely that the extrapolation of peaks due to the exceedance of gage capacity during extreme storm flows resulted in an erroneously high measurement of streamflow during these periods (S. Gonzales, personal communication).

It is clear from the calibrated hydrographs (Fig. 4) that different subbasins show different degrees of agreement between modeled and observed discharge. There are several possible explanations for this result. Basins with a greater diversity of watershed characteristics, including topography, soils, and land use, will produce poorer results at the regional scale than more homogeneous basins. The availability of USGS streamflow data limited the number of basins for which watershed parameters (time of concentration, baseflow) could be derived. In this research it was found that averaging basin properties over larger areas appeared to decrease model accuracy. Another possible source of error is the differences in data resolutions. The NEXRAD precipitation grid is overlain on the model at a 4 km resolution. The ModClark grid, the grid at which runoff calculations are made, is at a 4 km^2 (2×2 km) resolution to match the NEXRAD data. The finer resolutions of the land cover and soils data is converted to an infiltration coefficient (CN) and averaged to get one value for each 4 km^2 grid cell. The use of data values derived at different resolutions to determine runoff may lead to errors in the outflow hydrographs. Although CN is derived from physical measurements, it is an empirical parameter and hence is a limitation in the present model. A more physically based approach to infiltration of water into soils such as the Green and Ampt parameterization (Green and Ampt, 1911) might improve model accuracy.

The final output of the model consists of flood polygons showing inundated areas over the basin. Flood inundation results were derived separately for each river reach in the San Antonio Basin. A total of six river reaches were processed over the basin; an example of floodplain output over a portion of one reach is shown in Fig. 5. The flood polygons display the model output from July 8, 2002 (Day 9 of the storm event). This day was chosen for analysis in order to compare it to the available satellite data during the storm: a Landsat TM flight over Central Texas on July 8, 2002. The Landsat TM data were processed by classifying each grid cell according to its pixel value. Histogram stretching was employed to gain a greater visual difference between pixels. A threshold pixel value was chosen and used to extract inundated cells from non-flood areas, and the result was converted to a vector shapefile in ArcGIS and overlain on the modeled flood polygon.

Results from the Landsat analysis demonstrate that the model overestimates flooding with respect to the Landsat data throughout the reach with the exception of the southernmost portion of the reach, where the model underestimates flooding. While some overestimation of flooding was expected due to the overestimation of runoff volume demonstrated in the modeled hydrographs, there are several other possible causes for the discrepancy between modeled and satellite-derived flood areas. In the Landsat image, dark blue areas signify flooded regions. Cloud shadows are represented by lighter shades of blue. It is often difficult to distinguish between water and cloud shadows on the image; in the extraction analysis, errors may occur when: (1) similar pixel values cause confusion between flooded regions and cloud shadows, (2) clouds cover a significant portion of cells that are actually flooded and therefore these cells are mistakenly identified as not flooded, and (3) areas of less intense flooding are omitted from the extraction because their values are near or equal to that of

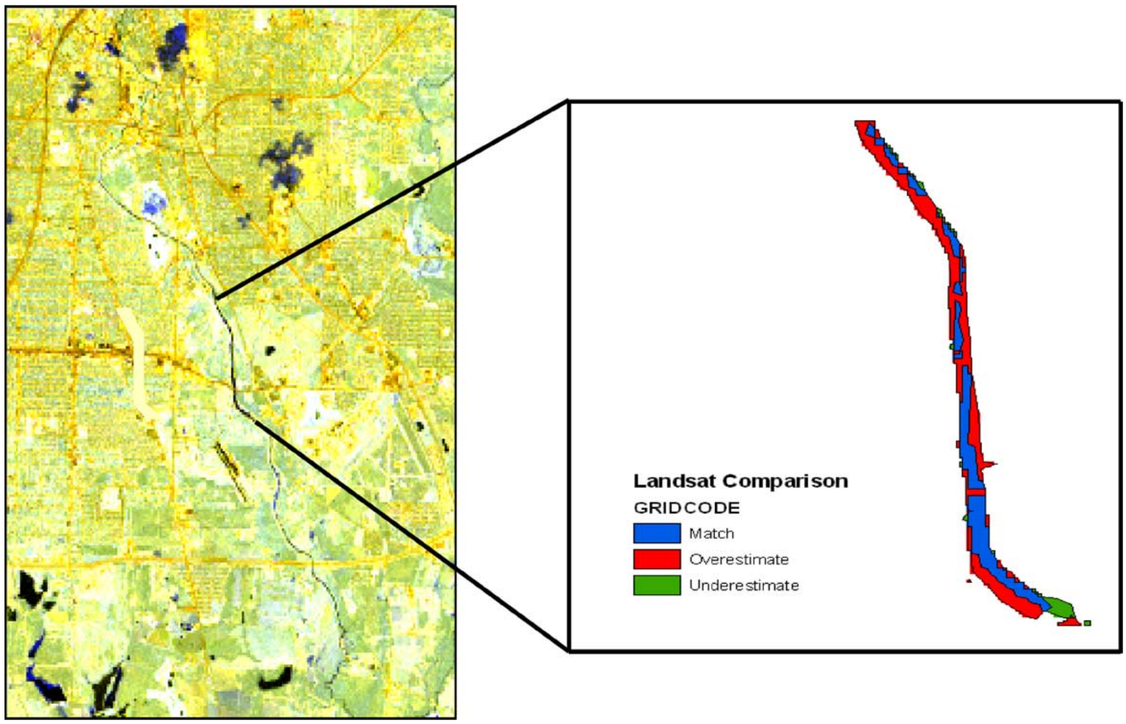


Fig. 5. Comparison of modeled flood polygon with Landsat TM data. Satellite data was acquired for July 8, 2002; dark areas show inundated regions. The inset figure displays a 2 km long stretch of the San Antonio River, 7.5 km south of downtown San Antonio, located just upstream of subbasin 08178565. The area which both model and satellite data indicate as flooded is shown in blue; red regions demonstrate model overestimation of flooding, and green regions demonstrate areas identified as flooded by satellite data but omitted by the model.

the cloud shadows. Time of image collection may also be a significant factor in model error. The Landsat image was collected 3 days after the storm peak passed over the region; the model overestimation of flooding depicted in Fig. 5 may reflect inaccuracies in the model's representation of flood dispersal following the storm peak. Analysis of the Landsat data implies that actual infiltration and dispersal of runoff is quicker than that represented in the model.

Research for the regional scale model is ongoing. Due to the highly heterogeneous nature of karstic areas in the San Antonio River Basin, groundwater recharge is difficult to quantify and a general parameterization of infiltration based on soils data such as that originally used by the SCS may be inadequate to portray this heterogeneity. Infiltration coefficients are currently being investigated to reassign CNs to the basin grid cells using a more physical basis and more detailed land cover observations. In addition, the feasibility of using various precipitation products to drive a flood model will be investigated by determining the translation of error between input (rainfall data) and output. NEXRAD and other products carry a certain degree of error; since this data drives the model, the question of interest is how this error will affect the final output. The complex hydrological processes in the model may attenuate the error; alternatively, the model may exacerbate the input error. In addition, the authors are currently working with several research groups to obtain, process, and ingest other real-time and forecast precipitation products at various resolutions into the model. With the incorporation of different precipitation products, the authors hope to demonstrate the versatility of the model.

Due to the nature of flood events and the model presented herein, this study has widespread applications in research, operations, and policy. The final result of this study is a complete hydrological and hydraulic model for the San Antonio River Basin, along with a comprehensive GIS database of the area. The model investigates several scientific questions; among these are the feasibility of incorporating rainfall real-time products into a regional flood model, and the testing of a new methodology for deriving floodplain polygons from gridded rainfall. Preliminary model runs have demonstrated a strong potential for successful hydrological modeling at the regional level. In addition, this research has displayed the capability of Map to Map to be extended upward in scale from a small catchment to a large basin. The model can be used a research vehicle for other scientific questions concerning flooding in the San Antonio River Basin region. In addition, the methodology used in this study can easily be applied to other regions of Texas, and can be extended to other areas of the nation as well.

6. Conclusions

As all areas of the country increase their level of development, infiltration capacity of the terrain decreases and the threat of flooding becomes even more pronounced. This paper presents a methodology and development of a flood model that may be incorporated into both regional hydrological studies and/or a regional alert system for hazard mitigation. The present model will have the capability to perform hydrological studies on a regional scale, and can be incorporated into or provide boundary conditions for local models as well. The successful incorporation of the Map-to-Map technology at a regional scale demonstrates the versatility of this tool for flood inundation studies at the city, county, and regional levels.

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