ALTERNATIVE RIVER MANAGEMENT USING A LINKED GIS-HYDROLOGY MODEL

W. D. Rosenthal, R. Srinivasan, J. G. Arnold

ABSTRACT. *A geographic information system (GIS)-hydrologic model link was used to aid in forming input files for the hydrologic model, SWAT (Soil and Water Assessment Tool). The link and SWAT prediction of streamflow volume were then tested for the Lower Colorado River basin of Texas. With no calibration, simulated monthly streamflow volume along the river was underestimated for the extreme events, but the relationship was significant (R^2 = 0.75). Model results also suggest that urbanization further upstream can significantly affect streamflow downstream. The system is general enough to be applicable to other river systems.* ***Keywords.*** *Geographical Information Systems (GIS), Databases, Grain sorghum, Hydrologic model, Stream flow.*

Water quality assessments of river systems are becoming critical throughout the country. In 1993, the Texas legislature passed Senate Bill 818 requiring river authorities to develop river assessments by 1995. These assessments will cover the entire river basin and are to include an evaluation of best management practices to minimize nonpoint source pollution. Continuous water quality monitoring is expensive and is not currently being conducted. Therefore, simulation of the hydrologic balance and water quality parameters may be an important tool to help assess the effects of proposed changes in landuse and land management. However, to realistically simulate the effects of management scenarios, the model should accurately simulate the individual components of the hydrologic budget. This study evaluates the Soil and Water Assessment Tool's (SWAT) (Arnold et al., 1993) ability to simulate streamflow volume for the Lower Colorado River basin (LCRB) of Texas.

A distributed parameter, continuous time model, SWAT, was developed to help water resource managers assess water supplies and nonpoint source pollution on watersheds and large river basins. It is a derivative of the Simulator for Water Resources of Rural Basins (SWRRB) (Arnold et al., 1990). Arnold et al. (1987) demonstrated that SWRRB can aid in evaluation of the effects of urbanization on basin water yield and reservoir sedimentation of an urban/rural basin.

Like SWRRB, SWAT operates on a daily time step and can simulate many years using measured and/or stochastically generated weather data. The smallest unit of simulation can be either subwatersheds or grid cells. However, SWAT eliminates SWRRB's limitations on the number of subwatersheds (10) and complexity of routing that can be simulated. Therefore, the amount of time needed to develop input data sets for SWAT simulations of complex basins is large and creates practical constraints on model use. This article describes an alternative, more rapid, GIS-based method of developing SWAT input files.

Geographical information systems (GIS) can store, manipulate, and provide spatial data for a variety of display and analytical tools, including printers and simulation models. Hydrologists have linked GIS hydrologic models to facilitate model execution (Vieux, 1991). Geographic Resources Analysis Support System (GRASS) (U.S. Army, 1988) is a popular GIS that has applications as an aid in natural resource modeling. Srinivasan and Engel (1991a, b) used GRASS to provide inputs to the Agricultural Nonpoint Source (AGNPS) model (Young et al., 1989) Cushman et al. (1992) applied the link to assess phosphorus loadings from an agricultural watershed. The Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model (Beasley and Huggins, 1982) was similarly linked to GRASS (Rewerts and Engel, 1991). Both AGNPS and ANSWERS are single event distributed parameter models that require fewer inputs than continuous time distributed parameter models.

However, to evaluate a basin-scale hydrology and streamflow over time, continuous models are needed. Given the structure of SWAT, it could be linked to a raster-based GIS, such as GRASS. The objectives of this study were to:

- Test and validate the linked SWAT model for a river basin using GIS-derived inputs.
- Demonstrate the ability of the link in reducing time to develop SWAT input files. The output variable analyzed was stream flow volume.

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SWAT Command Structure

SWAT uses a command structure similar to the structure of Hydrologic Model (HYMO) (Williams and Haan, 1973) for routing runoff and chemicals through a watershed. Commands are included for routing flows through streams and reservoirs, adding flows, and inputting measured data, or point sources. The routing command language allows the model to simulate a basin subdivided into grid cells or subwatersheds. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows. Also, output data from other simulation models can be input to SWAT. Using the transfer command, water can be transferred from any reach or reservoir to any other reach or reservoir within the basin. The user can specify the fraction of flow to divert, the minimum flow remaining in the channel or reservoir, or a daily amount to divert. The user can also apply water directly to a subwatershed for irrigation.

SWAT Hydrology

Surface Runoff

Surface runoff from daily rainfall is predicted using a procedure similar to the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980). Like the CREAMS model, runoff volume is estimated with a modification of the SCS curve number method (USDA-Soil Conservation Service, 1972). The curve number varies nonlinearly from the dry condition when the soil water content is at wilting point to the wet condition at field capacity and approaches 100 at saturation.

Peak runoff rate predictions are based on a modification of the rational formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the watershed time of concentration is estimated for each storm as a function of total rainfall using a two-parameter gamma distribution.

Percolation

The percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and if the layer below is not saturated. The downward flow rate is governed by the saturated conductivity of the soil layer. Upward flow may occur when a lower layer exceeds field capacity and is regulated by the soil water to field capacity ratios of the two layers.

Lateral Subsurface Flow

Lateral subsurface flow in the soil profile (0 to 2 m) is calculated simultaneously with percolation. A nonlinear function of lateral flow travel time is used to simulate the horizontal component of subsurface flow. The magnitudes of the vertical and horizontal components are determined by a simultaneous solution of the two governing equations.

Groundwater Flow

Groundwater flow contribution to total streamflow is simulated by creating a shallow aquifer storage. Percolation from the bottom of the root zone is recharge to the shallow aquifer. A recession constant, as described by Nathan and McMahon (1990), is used to lag flow from the aquifer to the stream. The values for the recession constant range from 0.2 to 0.995.

Other components include evaporation, pumping withdrawals, and seepage to the deep aquifer.

Transmission Losses

Many semiarid watersheds have alluvial channels that abstract large volumes of streamflow. The abstractions or transmission losses, reduce runoff volumes as the flood wave travels downstream. Channel losses are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur.

Channel Flood Routing

Channel routing uses a variable storage coefficient method developed by Williams (1969). Channel inputs include the reach length, channel slope, bankfull width and depth, channel side slope, flood plain slope, and Manning's n for the channel and floodplain. Flow rate and average velocity are calculated using Manning's equation and travel time is computed by dividing channel length by velocity. Outflow from a channel is also adjusted for transmission losses, evaporation, diversions, and return flow.

Weather Variables

The weather variables necessary for driving SWAT are daily precipitation, air temperature, and solar radiation. If daily precipitation data are available, they can be input directly to SWAT. If not, the weather generator can simulate daily rainfall and temperature. Solar radiation is always simulated. One set of weather variables may be simulated for the entire basin, or different weather may be simulated for each subwatershed. The weather generator parameters would be cross-correlated for each subwatershed.

Simulations

The model was not calibrated for the runs on the basin. All inputs into the model were set up from the interface and the available database layers with no modification. Streamflow volume was the major variable studied by comparing the model estimate to historical streamflow volume at five streamgage locations.

System Description

The GIS selected for the study was GRASS. It is a general purpose, raster graphic modeling, and analysis package that is highly interactive and graphically oriented. Several agencies, such as the USDA-Soil Conservation Service, are using GRASS.

The GRASS/SWAT link (Srinivasan and Arnold, 1993) was developed to operate in the UNIX and GRASS environments. It is written in C language and is integrated with the GRASS libraries. The interface consists of these major components: (1) project manager, (2) input evaluation and aggregation, and (3) input checker. Components were designed to be modular and update database layers incrementally.

These modules can be classified into one of three categories: (1) hydrologic tools, (2) database access tools, and (3) generic aggregation tools. Within each module are associated routines.

The hydrologic tools module includes r.cn, r.stream.att, r.auto_wshd, r.fill.dir, and r.topo.att. The r.cn routine is capable of estimating curve numbers based on antecedent moisture condition (AMC) using equations from Arnold (1990) to convert from AMC II to either AMC I or AMC III. The r.stream.att routine estimates stream length, stream slope, and cross-sectional dimensions for each subwatershed and entire basin. Stream length is the distance from the starting point to the lowest point on the flow direction. Stream slope is the ratio of elevation difference between high and low points and stream length. The width and depth of the stream are exponential functions of drainage area. The r.topo.att routine estimates overland slope and slope length. The neighborhood algorithm (Srinivasan and Engel, 1991c) and unit stream power theory are used to estimate overland slope and slope length for each subwatershed, respectively. The r.auto_wshd routine delineates a watershed basin boundary

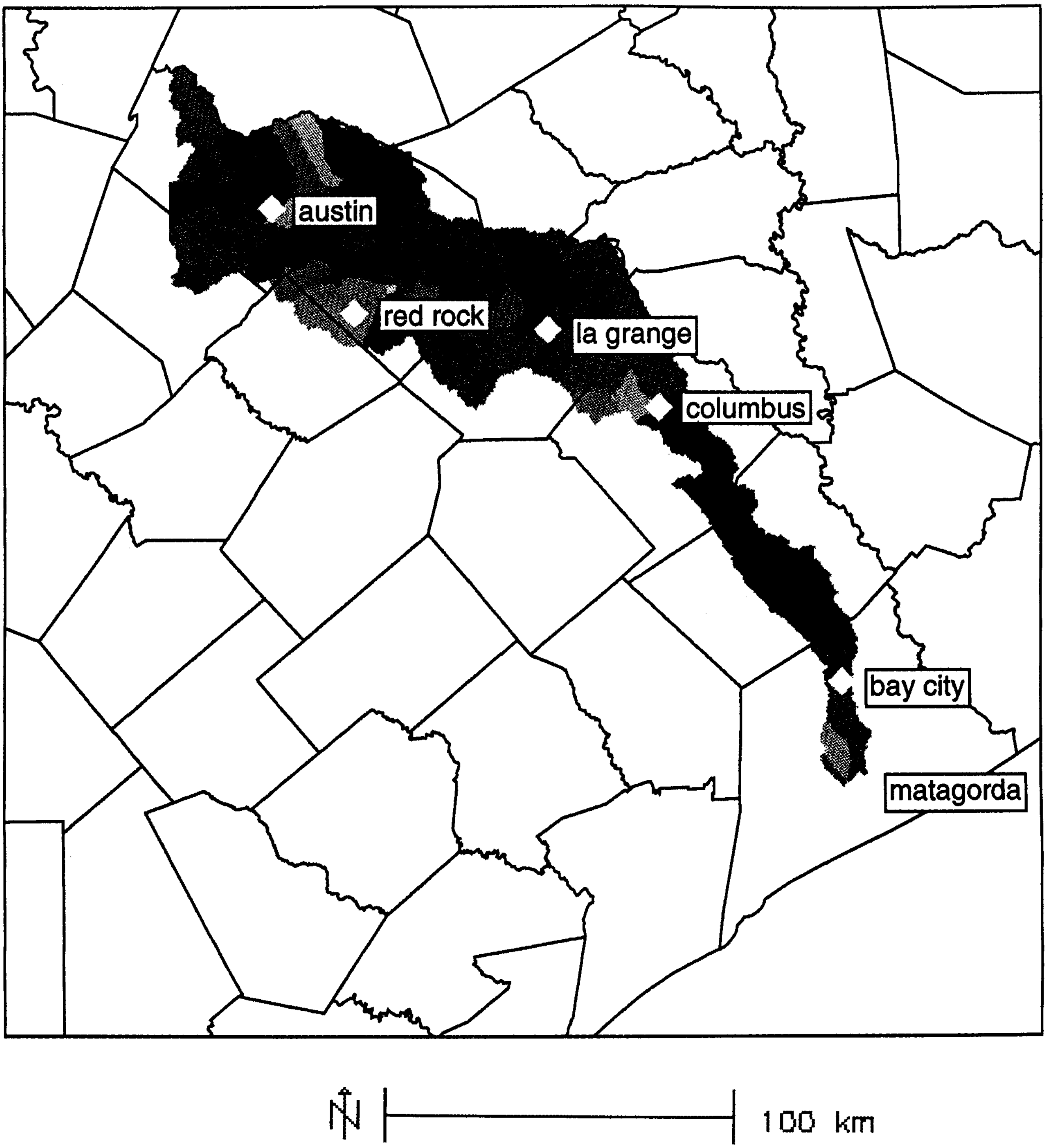

Figure 1–Display of the subwatersheds in the LCRB.

from an outlet point as specified by the user. The r.fill.dir routine generates a depressionless DEM layer and unique flow direction (aspect) layer based on work by Jensen and Domingue (1988).

Three other programs comprise the database access module: get_soil, get_weather, and get_crop. The get_soil and get_crop routines extract the soil input properties from the SOILS-5 database and creates the crop and pesticide parameters based on the type of crop. The get_weather program creates input weather generator parameters based on latitude and longitude.

The major required spatial data layers include landuse, soil groups, subwatershed boundaries, elevations, and weather station locations. In addition, reservoir inflows, pond and lake data can be input into the river system. A complete description is given by Srinivasan and Arnold (1993).

Basin Description

The river basin selected for model validation is the LCRB of Texas. Basin area of the entire Colorado River is 109 400 km^2, but only 8927 km^2 were simulated. Areal

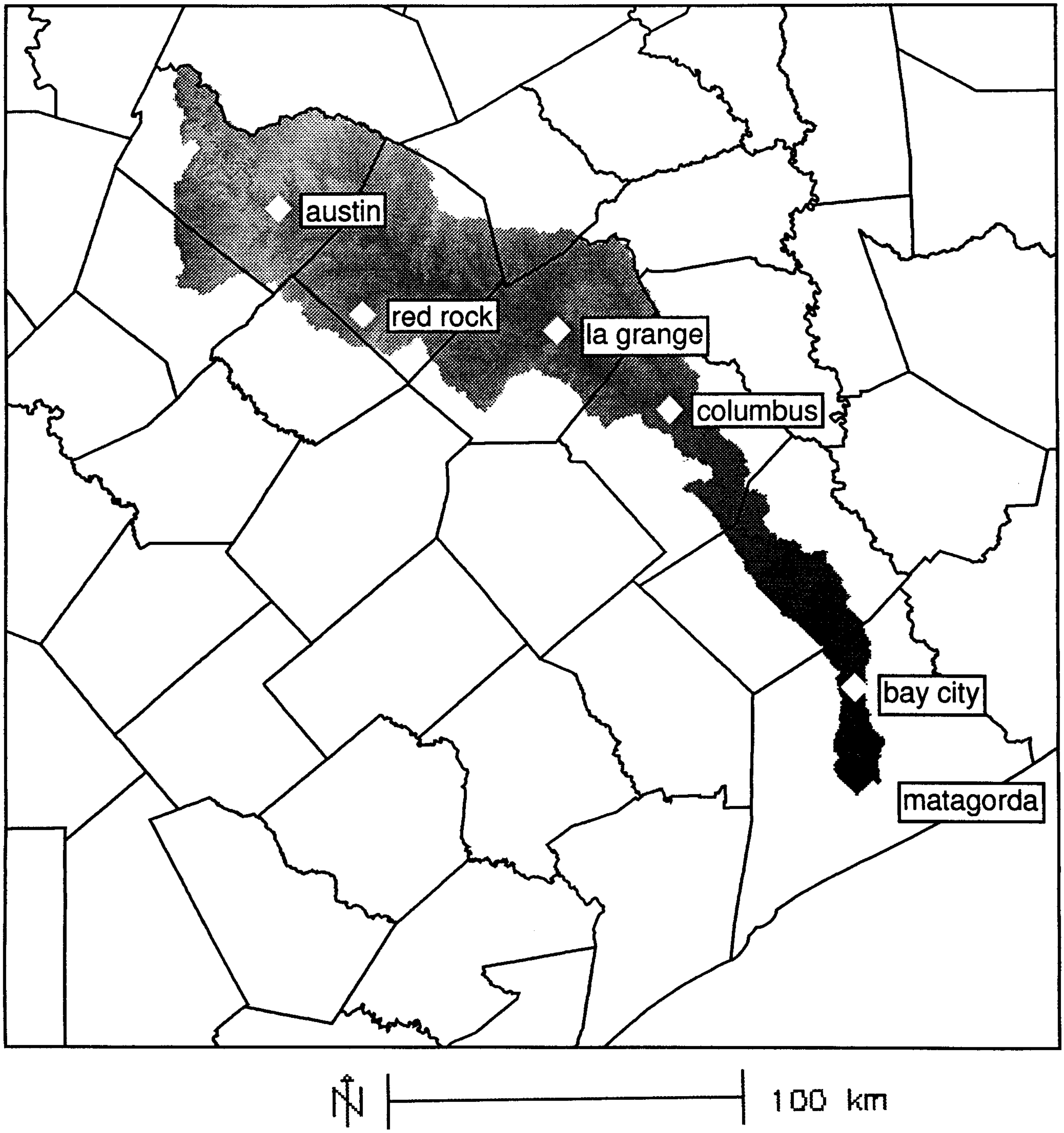

Figure 2–Display of the DEM for the LCRB.

coverage was from Lake Travis, just west of Austin, to the Gulf of Mexico at Matagorda Bay. Measured outflow volume from Lake Travis served as initial river flow input to the model. No other reservoirs were assumed to be in the river basin. Figure 1 shows the basin and subwatersheds used in modeling the basin.

Topographic Data

Elevation and slope files were extracted from the U.S. Geologic Survey Digital Elevation Model (DEM) using GRASS. The vertical resolution of the 1:250,000 DEM is 1 m. Subwatershed boundaries (fig. 2), slopes, and aspect raster maps were generated using the GRASS r.watershed module. Sixty subwatersheds were delineated with an average size of 150 km^2. The routing command file is generated from the elevation map.

Soils Data

Soils data were derived from the U.S. Soil Conservation Service STATSGO (State Soil Geographic Data Base)

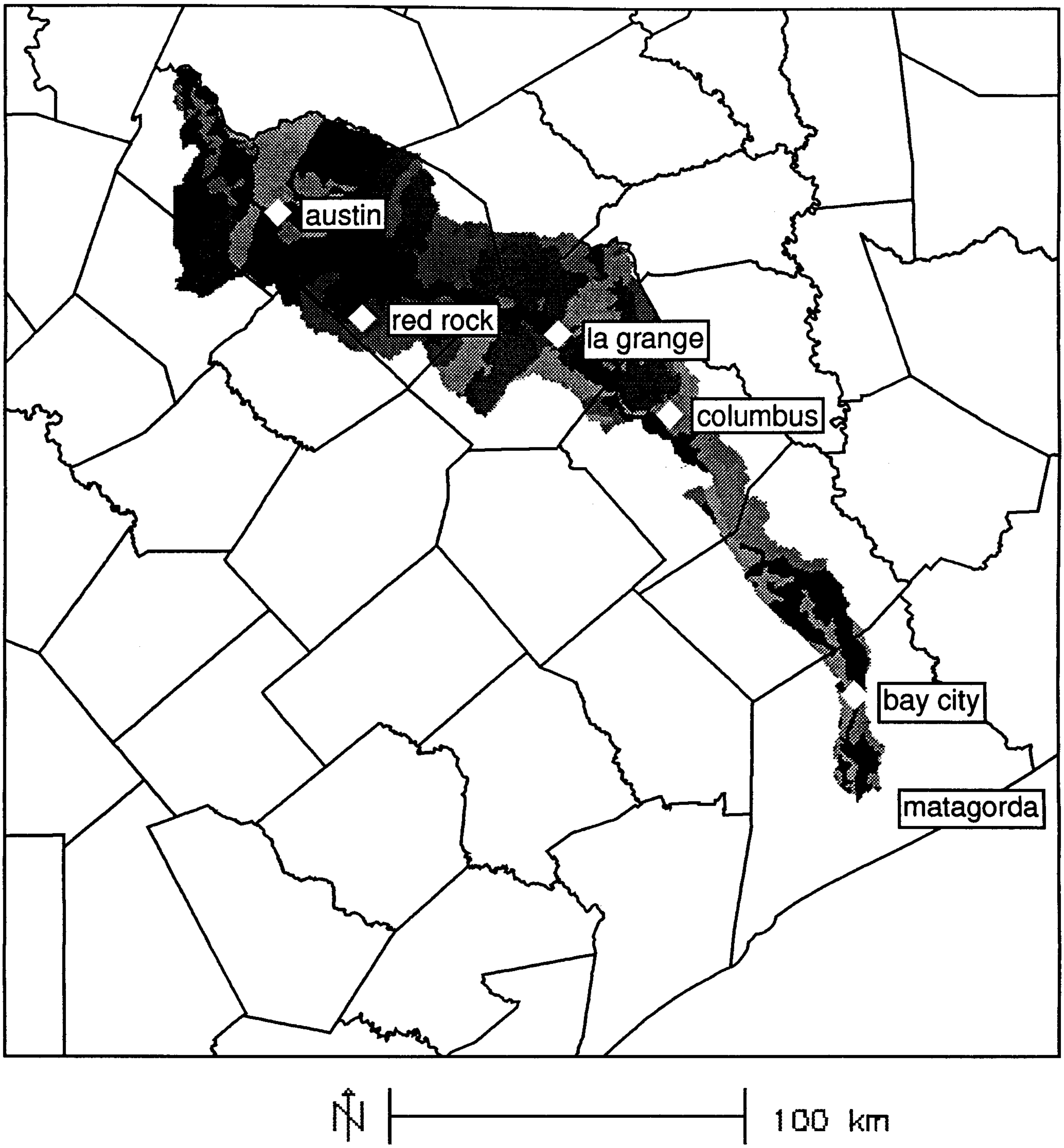

Figure 3–Display of the STATSGO soil layer for the LCRB.

spatial map (USDA, 1992). The map consists of multiple polygons describing areas of particular soil groups as digitized from the state level soil association map. Boundaries of the STATSGO polygons for the LCRB are shown in figure 3. The GRASS link used to develop the soil input (Srinivasan and Arnold, 1993) currently selects the dominant soil series within a subwatershed. It then searches the SOILS-5 attribute database for that dominant series and writes the required model input data for that series into the proper model format.

LANDUSE DATA

Landuse data were obtained from the USGS Landuse/Land cover (LULC) (USGS, 1990) spatial map which defines areas as cropland, rangeland, urban, pasture, and forest. Since the model requires more detailed information on type of crop, agricultural census data from 1980 to 1989 (U.S. Department of Commerce, 1990) of specific crop acreage for the county were overlaid onto the LULC data. Information from the resulting landuse raster map (fig. 4) was used by the model. A baseline run

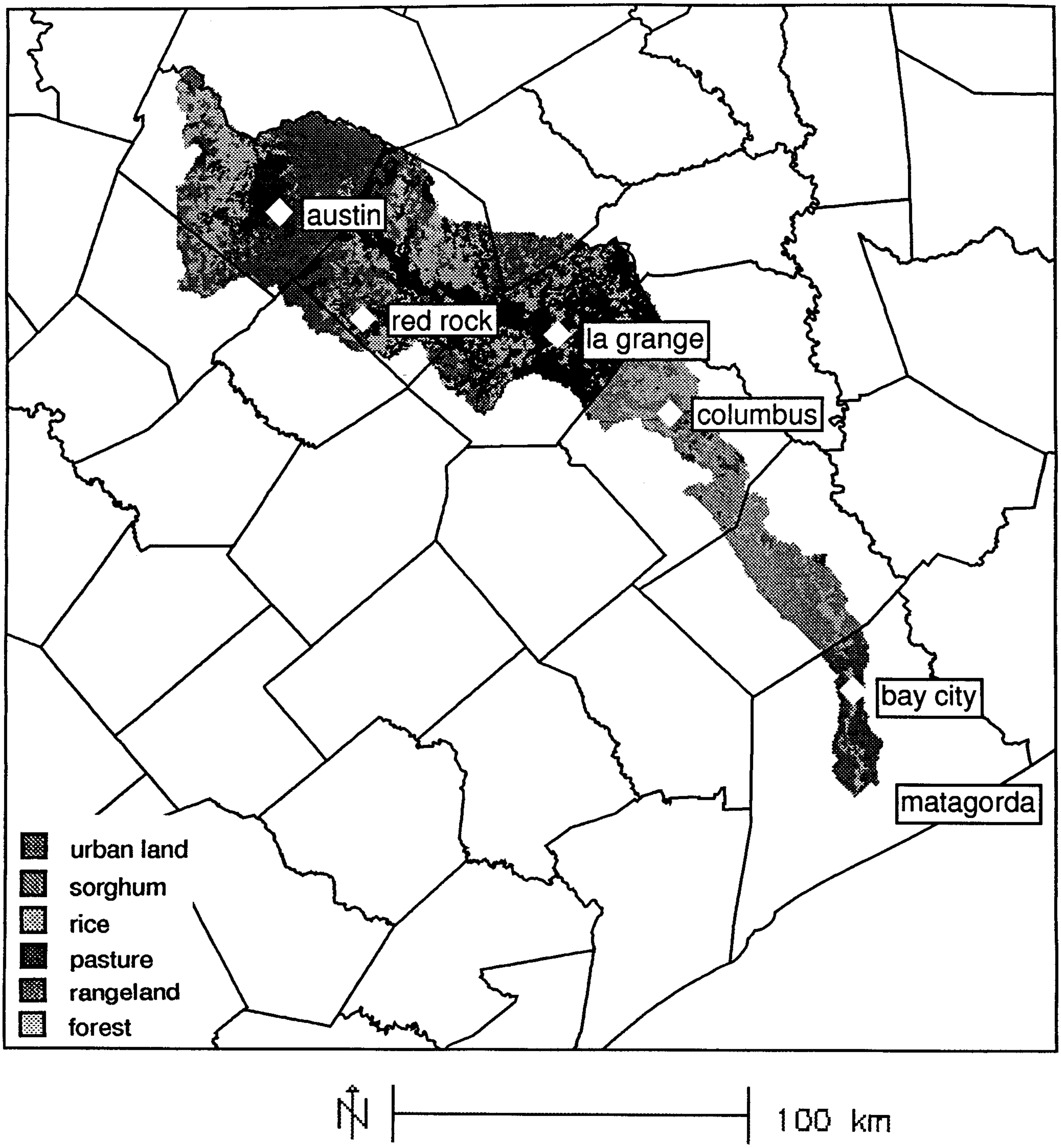

Figure 4–Display of the landuse (LULC) map for the LCRB.

was completed for present landuse conditions. Two additional scenarios were simulated. For these, landuse was modified in Wharton and Travis county to evaluate realistic agricultural practice and urban changes and their effects on downstream flow. The scenarios were selected because (1) Austin is predicted to increase in population approximately 58% by 2030 and (2) with increased surface water demands on the river, restraints on irrigation may be imposed (Texas Department of Water Resources, 1984). In Travis County, the town of Austin was expanded into four adjoining subwatersheds that were originally forest, pasture, and sorghum. With expanded urbanization, areas of impervious pavement (initial curve number was set to 100, no infiltration) increased by 721 km^2. This represents approximately 10% of the basin area. In addition, urban water withdrawals from the river system of 4×10^5/day were assumed (Lower Colorado River Authority, 1993). Second, for the base run in Wharton County, surface irrigated rice generally received water from groundwater sources. In the scenario, the model option of automatically surface irrigating rice at 90% available soil water content which implied that surface irrigated rice became dryland, thus allowing for more subsurface lateral return flow to the river to potentially meet future minimal LCRB river flows to the Gulf of Mexico.

Weather and Stream Flow Data

Measured daily precipitation and maximum and minimum temperatures were obtained from the National Weather Service. Six stations were selected to represent the basin: Austin (30° 17′N, 97° 42′W), Matagorda (28° 42′N, 95° 58′W), Bay City (28° 59′N, 95° 59′W), Columbus (29° 43′N, 96° 32′W), Lagrange (29° 55′N, 96° 52′W), and Redrock (29° 58′N, 97° 27′W). Each subwatershed was assigned to a weather station based on its closeness. Daily weather data from 1980 to 1989 for each subwatershed were collected and formatted for SWAT.

Results and Discussion

With 60 subwatersheds, the number of input files for SWAT was 600. Associated with each file are attributes that describe the subwatershed. Considering that the time to digitize an individual subwatershed would be half an hour, the total amount of time to complete the basin would be 300 h. With the GIS/model link, the time it took to create the input files was 24 h, a dramatic decrease in file development time. The same time was required to develop the other two scenario input files.

Streamflow was simulated from 1980 to 1989 for four streamgage locations on the Lower Colorado River. Figure 5 shows a plot of observed and simulated streamflows. Figure 6 shows the time series of simulated and observed monthly streamflow at Bay City. For the extreme events, simulated streamflow was approximately 60% of observed flow. The largest streamflow event occurred during month 92 (June 1987). Precipitation during this month was scattered with high intensity ranging from 102 to 490 mm. With this large range, the weather station network may not have been dense enough to pick up localized storms during that month. Tables 1 and 2 give the statistics for simulated streamflows at four gauging

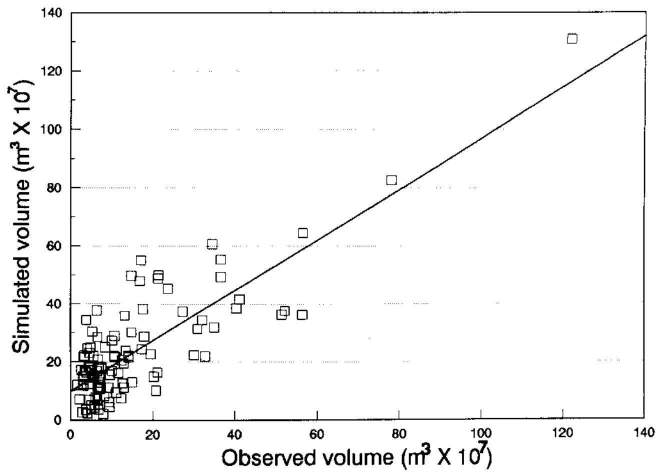

Figure 5–Observed and simulated monthly streamflows at Bay City from 1980 to 1989.

stations. Without the two extreme flow events at Bay City, the relationship decreases ($R^2 = 0.66$), but the slope increases to 0.87 and is not significantly different from 1.0. This suggests that the added groundwater flow component as described by Arnold et al. (1993) does an adequate job in simulating low flow volume.

For the scenario in Wharton county, an approximate 10% streamflow volume increase resulted from changing irrigated rice fields to dryland. The larger streamflow volume for irrigated rice was attributed to the greater evapotranspiration from the river basin. The increase in average annual evapotranspiration for the basin increased from 565 to 749 mm. In spite of this difference, this scenario did not account for other water transfers into or out of the basin for irrigation. Further studies would be needed to determine the degree of water transfer into or out of the basin.

For the scenario where Austin expanded east and west into four adjoining subwatersheds, the results (fig. 7) suggest that during extreme events throughout the basin, the flows at Bay City increased approximately 10% as a result of increased urbanization. This corresponds to the 10% increase in urban area. The overall monthly volume

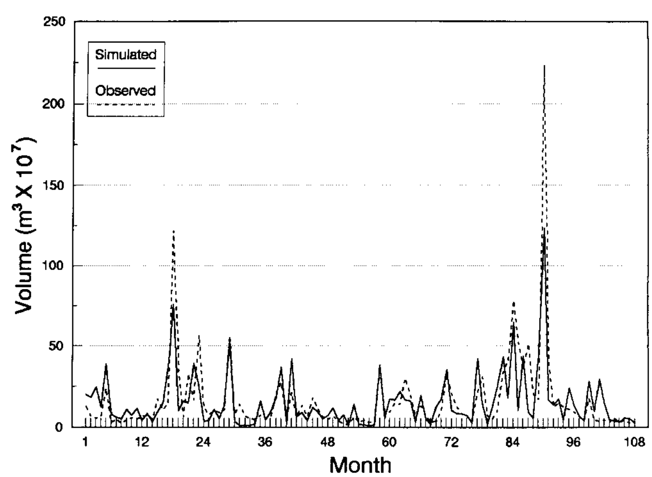

Figure 6–Time series plot of observed and simulated monthly streamflows at Bay City from 1980 to 1989.

Table 1. Statistics for average monthly streamflow (cms) at several gauge sites along the Colorado River

Location	R^2	Regression Equation
Bay City	0.75	Simulated = 0.732 ×Observed + 11.85
Wharton	0.69	Simulated = 0.67 ×Observed + 8.85
Bastrop	0.90	Simulated = 0.86 ×Observed + 1.87
Columbus	0.83	Simulated = 0.69 ×Observed + 5.977

Table 2. Statistics of measured and predicted monthly streamflow at Bay City, Tex.

Statistic	Observed	Predicted
Mean flow ($m^3s^{-1}d$)	60.5	57.8
Standard Deviation ($m^3s^{-1}d$)	97.6	74.3
R^2		0.75
Nash-Sutcliffe		0.69

average is less though (12.6×10^7 m^3 compared to 15.7×10^7 m^3 for the present conditions), primarily due to lower base flow, as a result of urban depletion. The average annual surface for the entire basin decreased from 190 to 173 mm (9% decrease). This information would be critically important in future reservoir planning based on urbanization upstream of the coast.

Conclusions

The study demonstrates that GIS can be used to efficiently collect and manage input into the SWAT hydrologic model. Even with no calibration, the model closely simulated monthly streamflow volume from 1980 to 1989 with observed values. These simulated results are based on the raw topographic, soil, landuse, and weather input information accessed by the GRASS/SWAT interface link.

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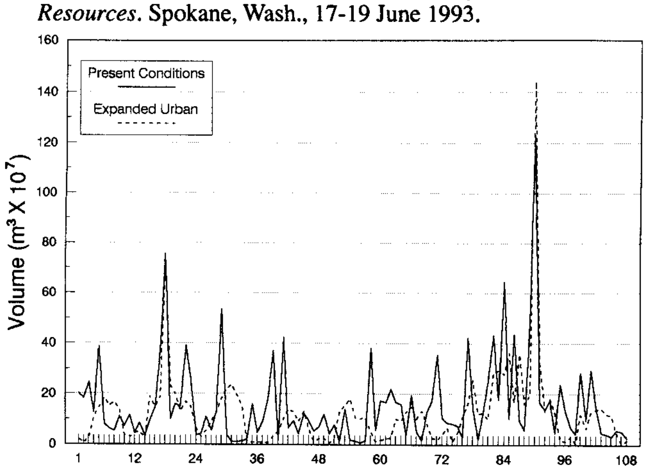

Figure 7–Time series plot of simulated present and increased urbanization monthly streamflows at Bay City from 1980 to 1989.

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