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Hydrologic Modelling of the United States with the Soil and Water Assessment Tool

R. SRINIVASAN[1], J. G. ARNOLD[2] & C. A. JONES[3]

[1]*Associate Research Scientist, Texas Agricultural Experimental Station, Temple, Texas;*
[2]*Agricultural Engineer, USDA—Agricultural Research Service, Temple, Texas;*
[3]*Associate Director, Texas Agricultural Experiment Station, College Station, Texas*

ABSTRACT *Large-area hydrologic modelling can play an important role in policy planning related to water and land management issues. Models are often required to assess the impacts and risks of management alternatives on the availability and quality of water in large and complex river systems. This paper describes the Hydrologic Unit Model for the United States (HUMUS): a decision support system designed for making national and river basin scale resource assessments. The components of the HUMUS system include: (1) the basin-scale Soil and Water Assessment Tool (SWAT) model; (2) a GIS to manage spatial inputs and outputs; and (3) relational databases of climate, soil, crop and management properties. The HUMUS system was applied and validated against flow sediment at three scales: (1) the entire conterminous US; (2) the Rio Grande/Rio Bravo river basin; and (3) The Richland and Chambers creeks watersheds. HUMUS is currently the basis of numerous impact analyses designed to improve water resources management at the local, regional, national, and international scales.*

Introduction

The availability of plentiful clean water increasingly limits economic development and environmental quality in many parts of the world. With ever greater demands on our water resources, their careful management and protection is necessary. This is especially true at the scale of large watersheds, where many users must share and protect a common resource. Such large-scale management requires in-depth knowledge of the characteristics and behaviour of watersheds and stream systems, including man-made structures such as reservoirs and large irrigation projects.

Issues affecting water resource management include increasing demands by municipalities and industries; fluctuations in water availability caused by droughts and floods; degradation of water quality due to point and non-point pollution; the need to purify return flows from municipalities, industry and agriculture; and the possible long-term impacts of climate charge on regional hydrology. Tools are needed to assess the impacts and risks of management and development alternatives on the availability and quality of water in large and complex river systems. Fortunately, recent advances in computer hardware and software, including the availability of large natural resource databases and geographic information systems (GIS), has made simulation of large hydrologic systems feasible (Arnold *et al.*, 1998a)

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This paper describes the Hydrologic Unit Model for the United States (HUMUS), a system designed to improve existing technologies for making national and river basin scale water resource assessments, considering both current and projected future climatic characteristics, water demands, point-sources of pollution, and land management affecting non-point pollution (Srinivasan *et al.*, 1993). The project was implemented as part of the United States Resources Conservation Act Assessment completed in 1997. The major cooperators in the HUMUS project were the United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) and Agricultural Research Service (USDA-ARS) and the Texas Agricultural Experiment Station, part of the Texas A&M University System (TAMUS-TAES).

The major components of the HUMUS system were: (1) the basin-scale Soil and Water Assessment Tool (SWAT) to model surface and sub-surface water quantity and quality; (2) a GIS to collect, manage, analyse, and display the spatial and temporal inputs and outputs of SWAT; and (3) relational databases used to manage non-spatial climate, soil, crop, and management data required as input to and generated as output from SWAT.

Components of HUMUS

Soil and Water Assessment Tool (SWAT)

SWAT is an enhancement of the SWRRB (Arnold *et al.*, 1990) model that allows simulation of water quality and quality in large, complex basins. A detailed description of the model is given in Arnold *et al.* (1998a). It was designed to predict the impact of topography, soils, land use, management and weather on water, sediment, nutrient (nitrogen and phosphorus), and agricultural chemical yields for large ungauged watersheds. To meet these design criteria the model (a) does not require calibration (which is impossible on ungauged watersheds); (b) uses inputs that are readily available for large areas; (c) is computationally efficient in order to simulate the interaction of hundreds of sub-basins using a daily time step, and (d) is capable of simulating hundreds of years in a continuous time mode to assess the long-term impacts of change. The command structure is used to route water, nutrients and chemicals through streams and reservoirs and to input measured data for point sources of water and nutrients. Basins can be subdivided into grid cells or subwatersheds to increase input and output detail.

Model sub-basin components can be divided into the following: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. Hydrology processes simulated include surface runoff estimated from daily rainfall using the SCS curve number; percolation modelled with a layered storage routeing technique combined with a crack flow model; lateral subsurface flow; groundwater flow to streams from shallow aquifers, potential evapotranspiration by the Hargreaves, Priestley-Taylor and Penman-Monteith methods; snowmelt; transmission losses from streams; and water storage and losses from ponds.

Weather variables that drive the hydrologic model include daily precipitation, maximum and minimum air temperatures, solar radiation, wind speed and relative humidity. A weather generator can be used to simulate all or several variables based on monthly climate statistics calculated from long-term measured data. Different weather data can be associated with specific sub-basins.

Sediment yield is computed for each sub-basin with the Modified Universal Soil Loss Equation. Soil temperature is updated daily for each soil layer as a function of air temperatures; snow, plant and residue cover; damping depth; and mean annual temperature.

Crop growth is simulated with a daily time step using a simplification of the EPIC crop model which estimates phenological development based on daily accumulation of heat units, harvest index for partitioning grain yield, Monteith's approach for potential biomass, and adjustments for water and temperature stress. Different crops, both annual and perennial, can be simulated by using crop-specific input parameters.

Nitrate losses in runoff, percolation and lateral subsurface flow are simulated. Organic nitrogen losses are estimated from soil losses and an enrichment ratio. A nitrogen transformation model modified from EPIC includes residue mineralization, HUMUS mineralization, nitrification, denitrification, volatilization, fertilization and plant uptake. Phosphorus processes include residue and HUMUS mineralization, losses with runoff water and sediment, fertilization, fixation by soil particles and plant uptake. Pesticide transformations are simulated with a simplification of the GLEAMS model approach and include interception by the crop canopy volatilization; degradation in soils and from foliage; and losses in runoff, percolation and sediment.

Agricultural management practices simulated include tillage effects on soil and residue mixing, bulk density and residue decomposition. Irrigation may be scheduled by the user or applied automatically according to user-specified rules. Fertilization with nitrogen and phosphorus can also be scheduled by the user or applied automatically.

Pesticide applications are scheduled by the user. Grazing is simulated as a daily harvest operation.

Stream processes simulated include channel flood routeing, channel sediment routeing, and nutrient and pesticide routeing and transformations modified from the QUAL2E model. Components include algae as chlorophyll-a, dissolved oxygen, organic oxygen demand, organic nitrogen, ammonium nitrogen, nitrite nitrogen, organic phosphorus and soluble phosphorus. In-stream pesticide transformations include reactions, volatization, settling, diffusion, resuspension and burial.

The ponds and reservoirs component includes water balance, routeing, sediment settling, and simplified nutrient and pesticide transformation routines. Water diversions into, out of, or within the basin can be simulated to represent irrigation and other withdrawals from the system.

Databases

Collection and organization of input data required to drive the SWAT model was a major component of the HUMUS project. For approximately 2150 hydrologic areas, also known as Hydrologic Catalogue Units (identified by eight-digit codes), information was required about historical weather, soil properties, topography, natural vegetation, cropped areas, irrigation, state and county boundaries, reservoir characteristics and agricultural practices. Both spatial data (organized in a GIS) and non-spatial data (in relational databases) were used.

Spatial databases included topography, land use, soils, state and country boundaries, watershed boundaries, stream networks, weather station locations, aquifer boundaries and stream gauge locations. Relational databases included the national resources inventory (NRI), national agricultural statistics survey (NASS), state soil survey database (SSSD) statistical weather data parameters, stream flow and reservoir operation data, and agricultural census data.

Input and Output Tools

In order to execute SWAT for complex watersheds and display output as easily understood graphics, interactive input and output tools were developed. The SWAT model is written in FORTRAN 90 language. GRASS, a public domain raster GIS, was used in the HUMUS project, though ArcInfo and ArcView can also be used. The input interface and other tools are written in C language. The input interface tools assist with preparation and extraction of data from the GIS database and consist of (1) a project manager to interact with the user, (2) a data organizer to extract and aggregate inputs for the SWAT model, and (3) a data checker to view and edit model inputs. The interface allows the user to rapidly modify management inputs for subsequent simulations and greatly reduces data collection and manipulation time.

After input data are assembled, checked and edited, the SWAT model is executed, generating large ASCII output files. The output analytical tool is then used to extract relevant outputs and organize them for output as GIS layers or for statistical or graphical analysis, including scatter plots, line graphs, pie charts, bar graphs and regression analysis. Outputs frequently selected by users include precipitation, runoff, sediment and nutrient yields, pesticide losses, evapotranspiration and crop yields. Hydrologic and water quality parameters can be analysed by basin, sub-basin, at the outlets of basins, and within channels and reservoirs. Differences between basins and stream locations can be calculated, and when validation data are available, they can be compared graphically and statistically with simulation outputs. Outputs can be analysed by month, by year, or for the entire simulation period.

Selected Modelling System Applications

The HUMUS system has been used in several national, regional and local applications.

Runoff in the Conterminous United States

The modelling system was used to simulate the hydrology, sediment and nutrient movement of all states except Alaska and Hawaii for the Resource Conservation Act Assessment (Arnold *et al.*, 1998b). Approximately 2150 eight-digit hydrologic unit areas were simulated using GIS databases at the 1:250 000 scale. Uncalibrated outputs were compared with observed runoff from 5951 stream gauging stations unaffected by reservoirs, diversions or return flows for the period 1951–80. The modelled and observed runoff data are shown in Figures 1 and 2. The uncalibrated model successfully simulated large-scale differences in runoff, including high values of runoff in the north-eastern states, Appalachian mountains, central coast of the Gulf of Mexico, and the Pacific

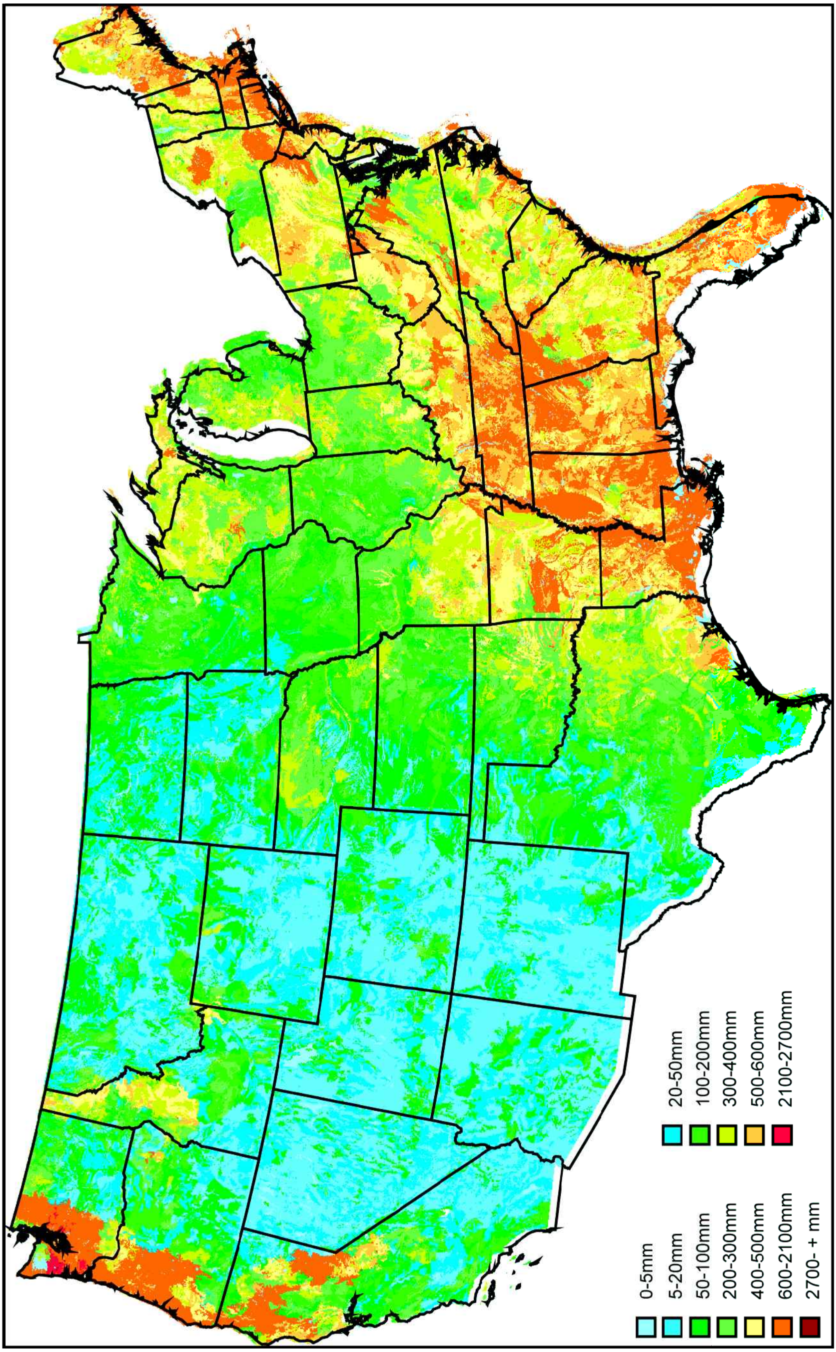

Figure 1. Average annual SWAT simulated runoff by STATSGO Polygon, Texas A&M University System.
Source: Blackland Research Center, Temple, Texas, Texas Agricultural Experiment Station.

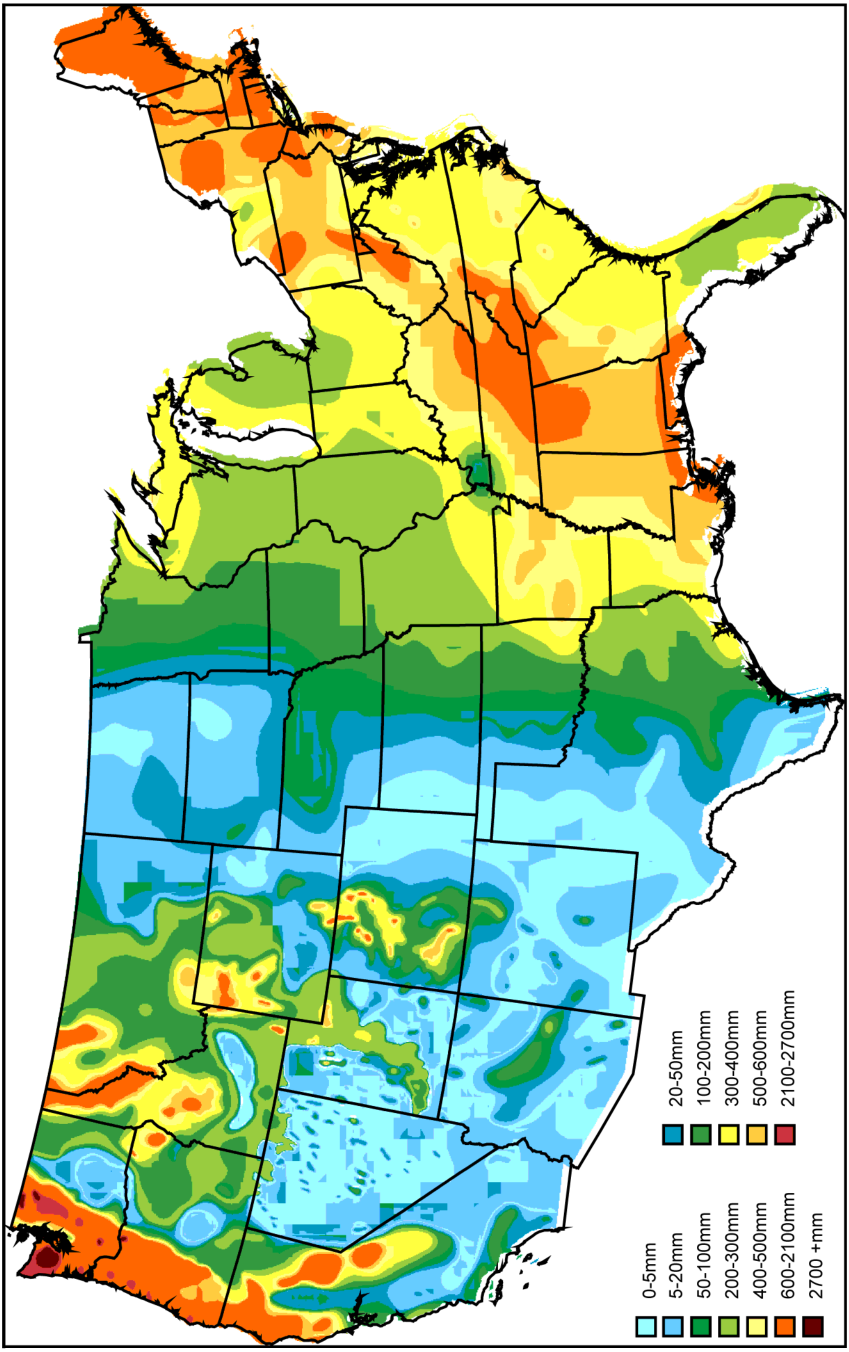

Figure 2. Average annual USGS observed runoff by STATSGO Polygon, Texas A&M University System.
Source: Blackland Research Center, Temple, Texas, Texas Agricultural Experiment Station.

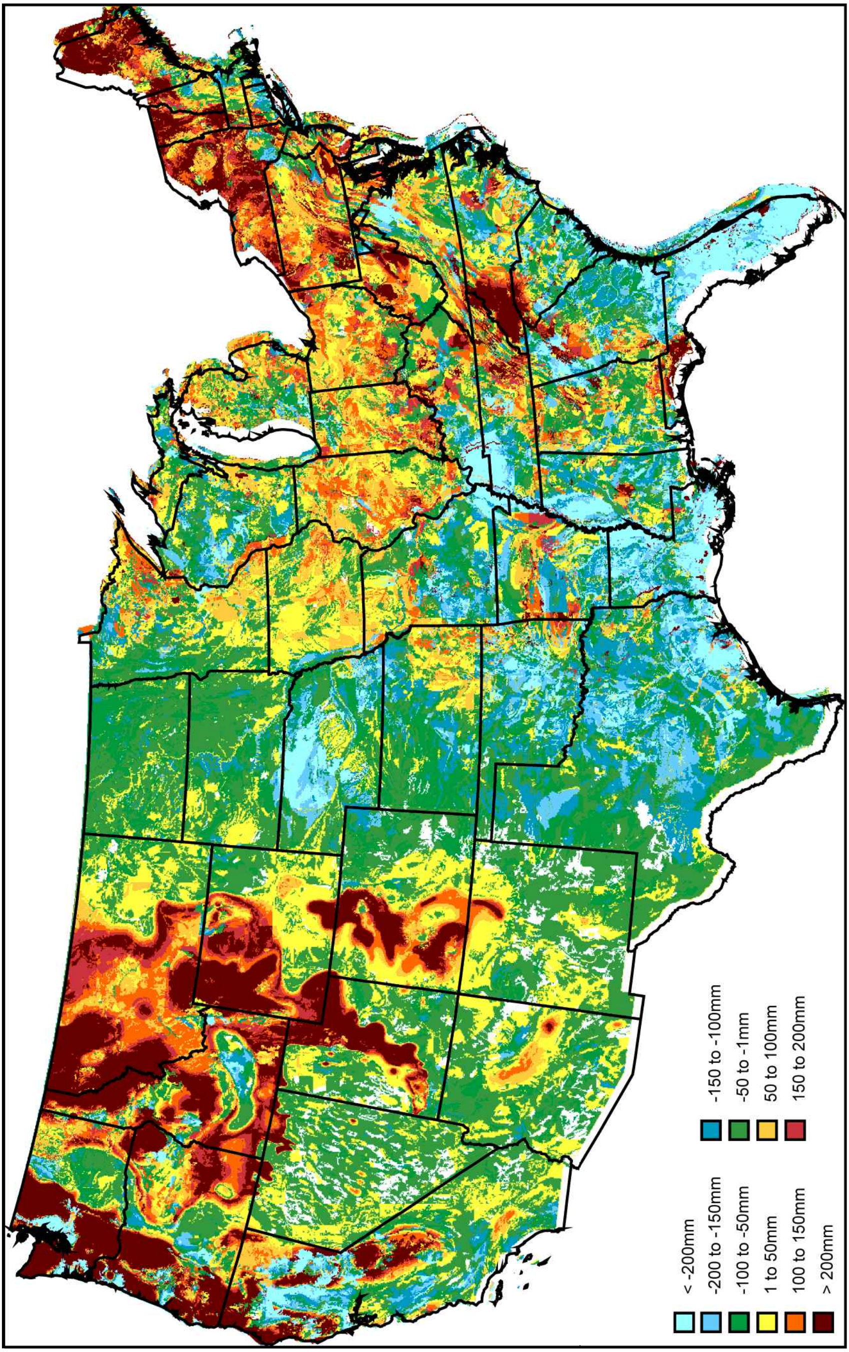

Figure 3. Difference between observed and simulated runoff, Texas A&M University System. *Source:* Blackland Research Center, Temple, Texas, Texas Agricultural Experiment Station.

Northwest. The small amounts of runoff in the Great Basin and south-western states were also simulated. The difference in observed and simulated runoff is given in Figure 3 (negative values indicate overprediction by the model). The model tends to underpredict runoff in mountainous areas. This is the result of a lack of weather data at high altitudes in mountainous areas, where most towns and weather stations are located in valleys with less annual rainfall than on mountain slopes. The uncalibrated model also overpredicted runoff in irrigated areas, where the amount of irrigated area was generally overestimated as a result of inadequate irrigation databases. In addition, the spatial resolution of the simulated data is considerably greater than the smoothed measured runoff data. This may have resulted in additional discrepancies.

Despite inaccuracies in the input data, 45% of the simulated runoff data were within 50 mm and 18% were within 10 mm of measured values. When these modelled and measured runoff data were averaged by state and regressed, the slope of the relationship was 0.95 with an R^2 of 0.78.

Runoff and Sediment Yields in Richland and Chambers Creeks, Texas

The surface hydrology, erosion and sediment transport components of the HUMUS system were tested on the Richland and Chambers creeks watershed (5×10^5 ha) of the northern Trinity river basin of Texas (Srinivasan *et al.*, 1998). GIS layers ranged from 1:24 000 scale for soils and land use to 1:250 000 scale for topography. Twelve weather stations were used in the study, four within the watershed and eight nearby. Twenty sub-basins were simulated, and each sub-basin was further subdivided into up to 30 virtual sub-units assumed to have homogeneous land use and soils. A detailed simulation of reservoir sedimentation was performed on the Mill Creek watershed, one of the 20 sub-basins in the study.

Two stream gauge stations within the watershed were used for calibration and validation of surface hydrology. For the calibration period (60 months) the model explained 84 and 87% of the variation in measured monthly runoff data for the two gauges. For the validations period (180 months) 82 and 65% of measured variation was explained.

Sediment validation was conducted by comparing simulated and measured sediment trapped by a floodwater-retarding structure in the Mill Creek watershed for two periods, 1965–68 and 1968–75. Sediment loads predicted by SWAT were 25 000 and 14 000 Mg for these two periods. These predictions compared favourably with the corresponding measured sediment loads, 29 000 and 14 000 Mg, respectively.

Hydrology of the Rio Grande/Rio Bravo Basin

Two nations and eight states (three in the United States and five in Mexico) depend on water from the Rio Grande/Rio Bravo river. This complex, mostly arid and semi-arid watershed is home to approximated 10 million people, and its water are used to meet their municipal, industrial and agricultural demands. Management of the river's waters is complicated by the highly variable climate of the region, major irrigation demands in the Lower Rio Grande Valley and the Rio Conchos (which originates in the Sierra Occidental of Mexico), substantial

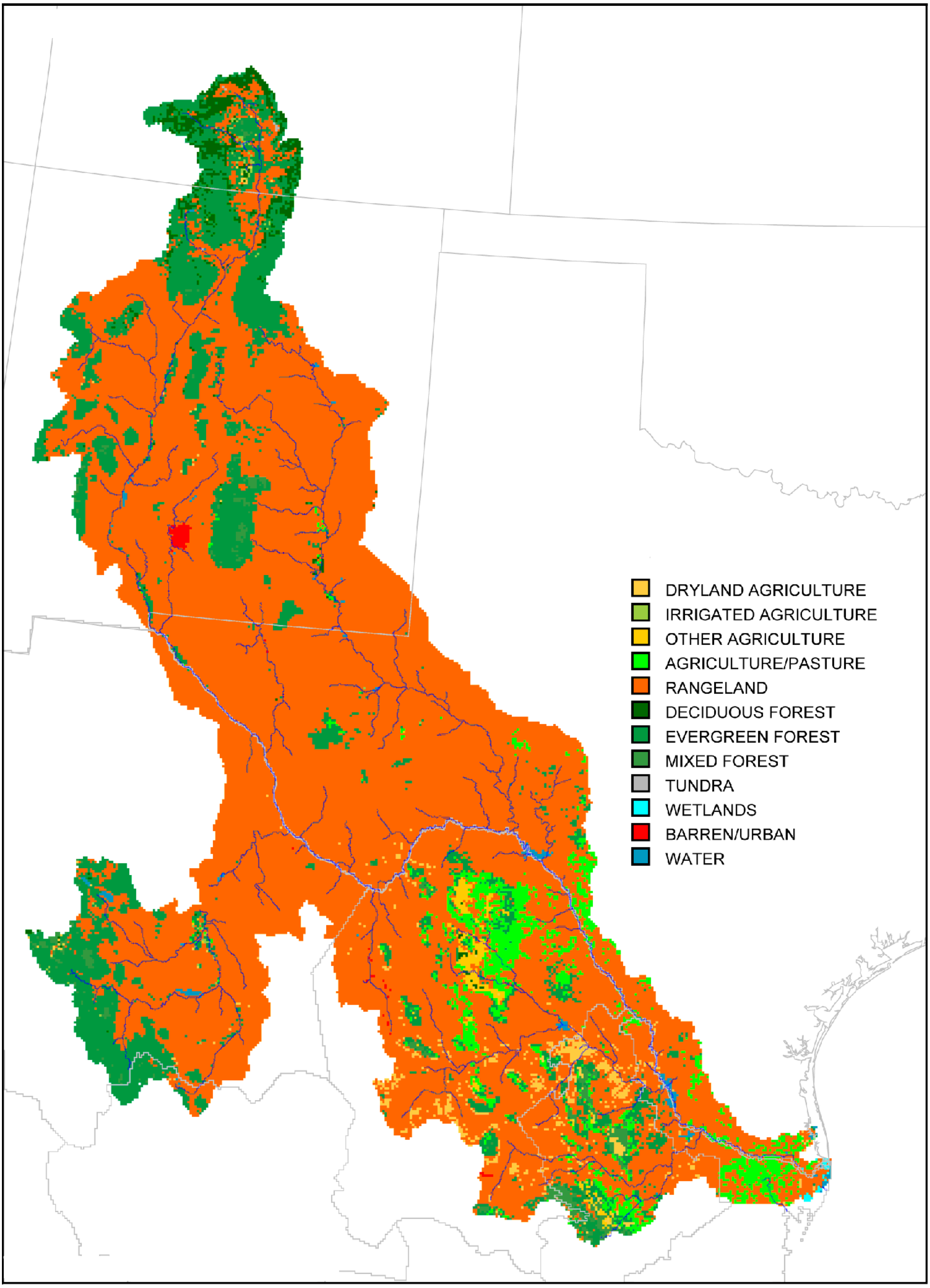

Figure 4. Land use/land cover of Rio-Grande/Rio Bravo basin, Texas A&M University System. *Source:* Blackland Research Center, Temple Texas, Texas Agricultural Experiment Station.

loads of salt from the Pecos River, declining groundwater supplies, increasing environmental requirements, operation of three major dams, inadequate municipal and industrial wastewater treatment, and binational water supply agreements. A map of the basin with its land cover is given in Figure 4.

Accurate long-term assessments of the impacts of climate, economic development, technological improvements in water management and water marketing are needed to plan for the best possible use of this scarce water resource. To meet this challenge, a team of Mexican and United States scientists representing the Mexican Institute of Water Technology (IMTA), Mexican National Institute of Forestry, Agriculture, and Livestock Research (INIFAP), Mexican National Water Commission (CNA), and Texas Agricultural Experiment Station (TAES) implemented the HUMUS system using input data from both Mexican and United States sources (Srinivasan *et al.*, 1997).

The results of this short-term effort demonstrate that international teams can effectively integrate input data from different international sources and implement the HUMUS system. Much work remains to simulate the impacts of reservoir management; industrial, municipal and agricultural demands; water treatment and reuse; and salt dynamics in this complex hydrologic system.

Opportunities for Future System Development

The HUMUS system is under continuous development by a team of USDA-ARS, USDA-NRCS, and TAMUS-TAES scientists, and as it becomes more widely understood it will be the basis of numerous impact analyses designed to improve water resource management at the local, regional, national and international scales. It has been approved by USDA-NRCS for use in water resource assessments, and the United States Environmental Protection Agency has accepted it for inclusion in the BASINS decision support system used for determination of total maximum daily loads (TMDL) of pollutants in water bodies.

Specific enhancements that are under way or have recently been completed include: linkage of SWAT input interfaces to ARC/INFO and ArcView; development of rules for selection of appropriate spatial scales for input data; linkage of SWAT with WSR-88D radar technology (formerly called NEXRAD—Next Generation Weather Radar) to estimate precipitation distribution in space and time, making real-time flood forecasting possible; improvement of stream sediment and chemical routeing; linkage of SWAT to a three-dimensional numerical groundwater model; and simulation of salt balances and transfers in soils, sub-basins and stream/reservoir systems.

Integrated management of complex watersheds for multiple objectives is a critical and growing need in many parts of the world. The HUMUS system was designed to permit users to assess the biophysical impacts of climate change, land use change, specific water resource and agricultural management alternatives, and other factors on water quantity and quality. It has been (and will continue to be) used for such assessments at the local, regional and national scales in the United States. There are excellent opportunities for scientists in many other countries to cooperate with the HUMUS development team and implement the system for regions outside the United States. Such cooperation will result in improvements in the HUMUS system and assessments leading to better water resource management.

Note

Further information can be obtained from the authors and the HUMUS home page at: http://brcsun15.tamu.edu/humus

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