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A TEST OF TWO DISTRIBUTED HYDROLOGIC MODELS WITH WSR-88D RADAR PRECIPITATION DATA INPUT

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1. INTRODUCTION AND PURPOSE

The U.S. Bureau of Reclamation (Reclamation) will test two different 2-D distributed-parameter hydrologic models in the case of a heavy rainfall over west-central Arizona. The heavy rain was produced by Tropical Storm Nora, 25-26 September 1997. The primary test area is the Santa Maria basin in West-central Arizona. The two distributed models are GSSHA and Vflo™.

The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model is a reformulation and enhancement of the distributed runoff model CASC2D (Ogden 2000). GSSHA is a physically based, two-dimensional model that operates on a raster (square-grid) representation of a watershed and is designed for long-term, large-basin simulation of rainfall-runoff and base flow processes. The model solves transport equations using finite difference and finite volume techniques and includes 2-D diffusive-wave overland flow routing and 1-D diffusive-wave channel routing. GSSHA is a process-based model where the user has the option to select the specific processes to be modeled for a particular application. Among the processes that can be simulated are precipitation distribution, snowfall accumulation and melting, precipitation interception by vegetation, surface water retention, infiltration, overland flow runoff, overland erosion and deposition, channel routing of water, channel routing of sediments, channel routing of conservative contaminants, unsaturated groundwater flow (Vadose zone modeling), saturated groundwater flow, stream recharge/discharge to groundwater, exfiltration of groundwater to land surface, and evapotranspiration (ET).

Additional information on the GSSHA model and its evolution from the Cascade of Planes, 2-Dimensional (CASC2D) model can be found in Downer et al. (2000b) and Downer et al. (2002). To facilitate the calibration process, automatic calibration using the Shuffled Complex Evolution (SCE) procedure is available for GSSHA (Senerath et al. 2000). Development of input data and model parameters from GIS inputs, as well as visualization of model outputs, is performed using the Watershed Modeling System (WMS) version 6.1, which is developed at Brigham Young University in cooperation with the U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory.

Vflo is a real-time distributed hydrologic model for managing precious water resources, water quality management, and flood warning systems. Improved hydrologic modeling capitalizes on access to high-resolution quantitative precipitation estimates from model forecasts, radar, satellite, rain gauges, or combinations in multi-sensor products. Digital maps of soils, land use, topography and rainfall rates are used to compute and route rainfall excess through a network formulation based on the Finite Element Method (FEM) computational scheme described by Vieux (2001a, and 2001b). Vflo is a new model implemented in Java™ to take advantage of secure servlet/applet technology for multi-user access. Vieux and Vieux (2002), in these proceedings, describe the Vflo model in more detail.

The overall goal of Vflo is to provide high-resolution, distributed hydrologic prediction from catchment to river basin scale. The advantage of physics-based models is that they can be setup with minimal historical data and still obtain meaningful results. Distributed models better represent the spatial variability of factors that control runoff enhancing the predictability of hydrologic processes (Vieux, 2002). Finite element solution of the kinematic wave equations is an efficient approach allowing large systems to be solved easily on single processor Intel PC's in a Windows environment, or on servers. Solution proceeds on a drainage network making the same model scalable from small catchment to major river basin. Vflo is set up using a drainage network rather than a basin approach. Vflo represents an important advance in simulating rainfall-runoff using digital data describing the Earth's terrain coupled with advances in radar precipitation detection.

We plan to integrate a distributed hydrologic model such as GSSHA or Vflo into a

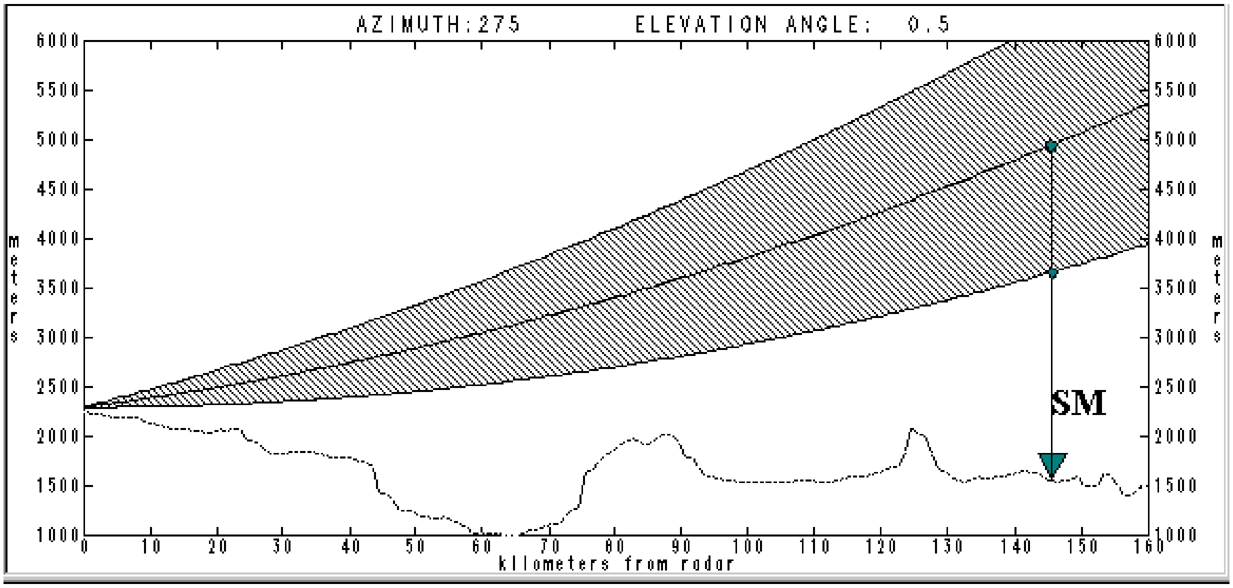

Figure 1. Representation of lowest (0.5° elevation) radar beam extent from Flagstaff AZ WSR-88D (KFSX) along azimuth 275°, which lies over the headwaters of the Santa Maria (SM) test basin. Arrow denotes location of aforesaid headwaters and line and circles above the arrow designate beam heights and width above this location (see text).

generalized watershed management framework, such as the RiverWare modeling tool (Zagona et al., 2001) currently used by Reclamation. RiverWare is a water resources management tool for operations, scheduling and planning, which builds water operations models and applies decision criteria to them. This integration may be considered analogous to the relationship of CASC2D to WMS.

Both distributed models require Geographic Information Systems (GIS) data as input, such as basin definitions, topography, soils and land use data. The following section will detail these GIS data.

2. GIS DATA INPUT

Distributed hydrologic models may require slightly different inputs and formats, but most need the same basic ingredients. Basin delineation, channel network delineation, overland flow slope, flow accumulation and drainage direction are all derived from topographic data, typically in the form of a Digital Elevation Model (DEM). Digital soil surveys may supply soil infiltration parameter estimates, and digital maps of land use/cover are generally used as the basis for estimates of surface hydraulic roughness coefficients. Arguably the most critical component is a temporally and spatially variable precipitation field. In distributed hydrologic models, such variability is accommodated by the model's spatially variable characteristics within an individual basin, derived from the aforementioned GIS input. Other factors such as temporal and spatial resolution of the input data and transformation of those data into parameters usable by the model are also crucial considerations in the modeling process.

For this preliminary comparative study, while both GSSHA and Vflo have some flexibility as to the format of GIS data that they will accept, the most important requirement of this test is that they operate from the *same* input data set. This stipulation allows for a valid comparison of the models themselves instead of the quality of their input data. From these basic data sets, the specific model parameters and inputs will be derived for the respective models. The following data sets were selected for the comparison:

- DEM data with 30 m horizontal resolution from the U.S. Geological Survey (USGS) EROS Data Center's National Elevation Dataset (NED).
- Land Use Land Cover data at 30 m resolution, from the USGS EROS Data Center's National Land Cover 1992 Dataset (NLCD).
- Soil data from the Natural Resources Conservation Service State Soil Geographic (STATSGO) database for Arizona.

- Channel cross-section data from the USGS, available for this basin only at a single stream gauge location on the Santa Maria River.

3. RADAR DATA INPUT

Radar data input is from the WSR-88D (formerly NEXRAD) Doppler radar (Crum et al. 1993) south of Flagstaff, Arizona (KFSX), which is about 150 km east of the headwaters of the test basin. The data consist of reflectivities in Level II format from the National Climatic Data Center, which have a data resolution of 0.5 dB. The beam width at the headwaters range is about 3.6 km and the lowest (0.5°) beam center altitude is about 3.4 km above ground level (Fig. 1). This location is considered to be at moderate range from the radar for precipitation estimation in the warm September atmosphere over Arizona.

The radar quantitative precipitation estimation (QPE) is accomplished via use of Reclamation's new Precipitation Accumulation Algorithm (PAA; Hunter et al. 2001). The PAA uses Eta model soundings to distinguish rain, snow, melting snow, and virga regions and applies different Z-R relationships to each, producing precipitation accumulations at the surface. In this case, the National Weather Service (NWS)-sanctioned tropical Z-R relationship ($Z = 250 R^{1.2}$) was used for all precipitation, since its phase was all liquid at the surface and was produced by a tropical storm. Finally, a single precipitation gauge/radar QPE bias (G/R) for the entire radar umbrella was calculated from all available G/R pairs. Most of the gauge data were 24-hour accumulations from NWS cooperative observers, but a few were from METAR reporting sites near airports. These steps optimized the accuracy of the precipitation field. This field was converted to a 1 km geo-referenced grid for incorporation into the hydrologic models.

4. TEST CASE DESCRIPTION

4.1 Santa Maria Basin

The Santa Maria basin is an unregulated headwater basin in West-central Arizona, flowing from elevations over 2 km west of Prescott toward the Bill Williams River at Alamo Lake, in the lowland desert of western Arizona. The Bill Williams River discharges into the mainstem of the Lower Colorado River near Lake Havasu City. The area of the Santa Maria basin is 3,727 square km. Figs. 2 and 3 show the location, hydrography and topography of the region surrounding the basin. As would be expected for the arid desert soils and steep topography of this basin, response times in the event of heavy rains are small.

An encircled red dot in Fig. 2 indicates the single active stream gauge in the basin, namely USGS 09424900 on the Santa Maria River. The elevation of this gauge is 415 m above sea level and is 17 km above the basin outlet, with a drainage area of 2,924 square km. Mean annual streamflow at the gauge varies widely from year to year - from 1967 to 1999 values ranged from zero to 232 cubic feet per second (cfs), with an average of 66 cfs. On many days in most years there is no flow. The same large variability is also evident in annual *peak* streamflows, which are presented in Fig. 4.

4.2 Synoptic and Hydrologic Characteristics of the Storm

Tropical cyclones are rare in Arizona, but occur occasionally as they make landfall from the eastern Pacific or Gulf of California. Tropical Storm (TS) Nora was an example of the latter landfall location. TS Nora's center traveled along the western Gulf of California and accelerated northward at landfall, which was near the California/Arizona border at 2100 UTC 25 September 1997 (Fig. 5 and Rappaport 1997). The most recent precipitation in the region prior to the 25th was nine days earlier, so soil conditions were dry. At that time most of the heaviest precipitation was occurring to the northeast of Nora's center, in Arizona. The storm rapidly weakened after that time and by 0000 UTC 26 September TS Nora was downgraded to the Tropical Depression category (maximum sustained surface wind speed 33 knots or less), when its center was near Parker, Arizona (PRKR in Fig. 3). Despite this weakening, Nora produced very heavy rain in and near the Santa Maria basin on both the 25th and 26th. While approximately 2-10 mm of precipitation fell in the headwaters of the basin from 1200 UTC on the 24th to 1200 UTC on the 25th, much greater amount occurred the following day, from 1200 UTC on the 25th to 1200

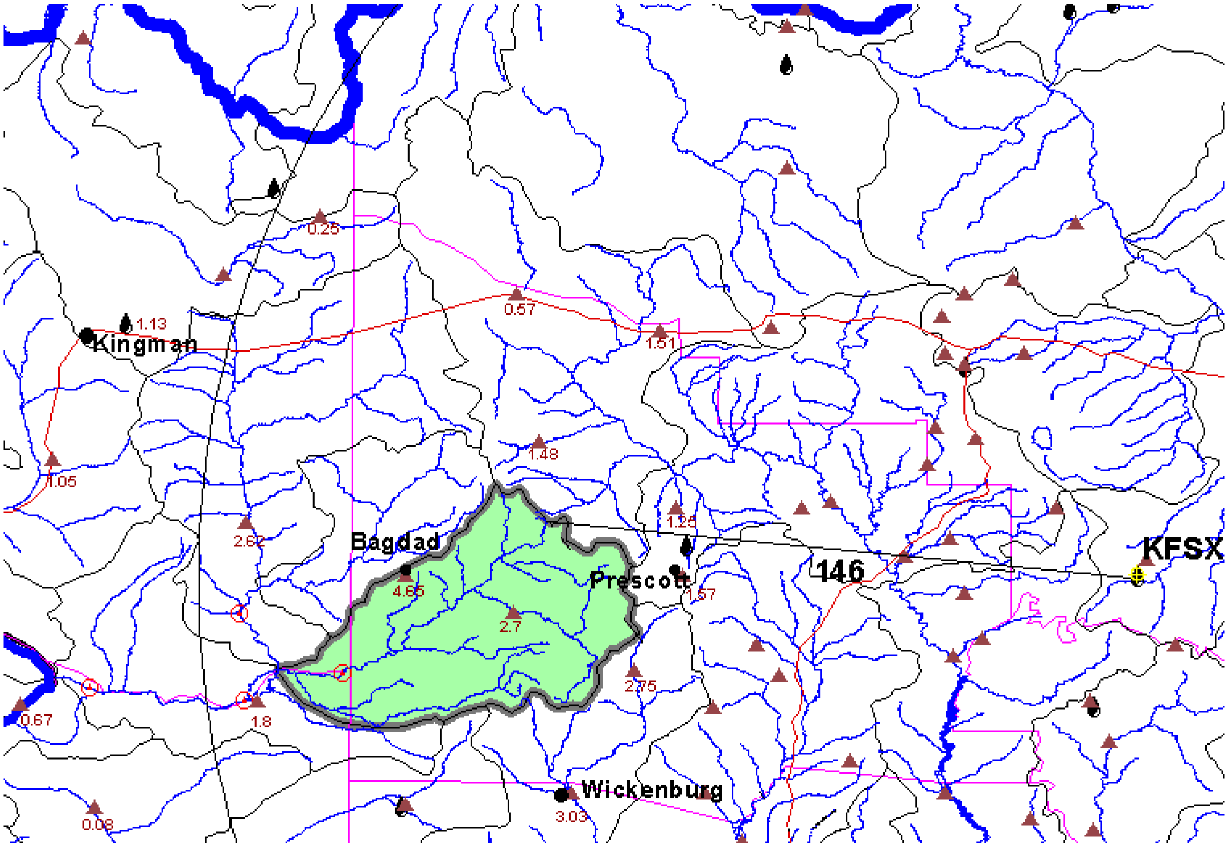

Figure 2. Map of the region surrounding the Santa Maria test basin, which is highlighted in green. Brown triangles show locations of NWS Cooperative Observing sites. Those sites with numbers underneath the symbols show active reporting sites during this event; the numbers themselves indicate 24 hour precipitation from 1200 UTC 25 September 1997 through 1200 UTC 26 September 1997. Red encircled dots pinpoint USGS streamflow gauges that report in real time. Purple lines outline counties, red lines interstate highways, and black lines other basins. The black droplet symbols show other precipitation reporting stations. The straight black line connects the KFSX radar and the headwaters of the Santa Maria basin, with the line distance indicated in km. The Colorado River is shown by the thickest blue streamlines on the western and northern fringes of the figure.

UTC on the 26th. An isohyetal analysis for the latter period is given in Fig. 6. Northward-flowing tropical moisture intercepted the elevated terrain in the headwaters (eastern and northern) portion of the basin (Fig. 3), and this upslope flow undoubtedly enhanced precipitation in those areas. This notion is supported by the highest recorded storm-total rainfall from this storm, which was in the Harquahala Mountains, 16 km southwest of Aguila (AGLA) in Fig. 3 (off the map). These mountains form an isolated southwest-northeast oriented range, with a peak elevation of 1.74 km. This orientation was optimal for barrier-perpendicular upslope flow.

Cushmeer (1999) performed an in-depth analysis of the performance of the WSR-88D at Yuma, Arizona (KYUX) during the TS Nora event. This analysis was focused on southwest Arizona, to the south of our study area. Nevertheless, this paper revealed that there was considerable underestimation of radar QPEs by the WSR-88D's Precipitation Processing Subsystem (PPS) for the tropical precipitation in the western third of the state. This underestimation occurred despite application of the NWS tropical Z-R relationship, which is intended to diminish underestimation by the default Z-R relationship ($Z = 300\ R^{1.4}$) that is normally in effect. The author cited drop breakup into small drops with low reflectivities as a likely cause for the underestimation. In this study we intend to apply the tropical relationship as a starting point for the KFSX QPEs, but we will use Reclamation's PAA (with G/R bias) rather than the PPS estimates for more accurate precipitation input.

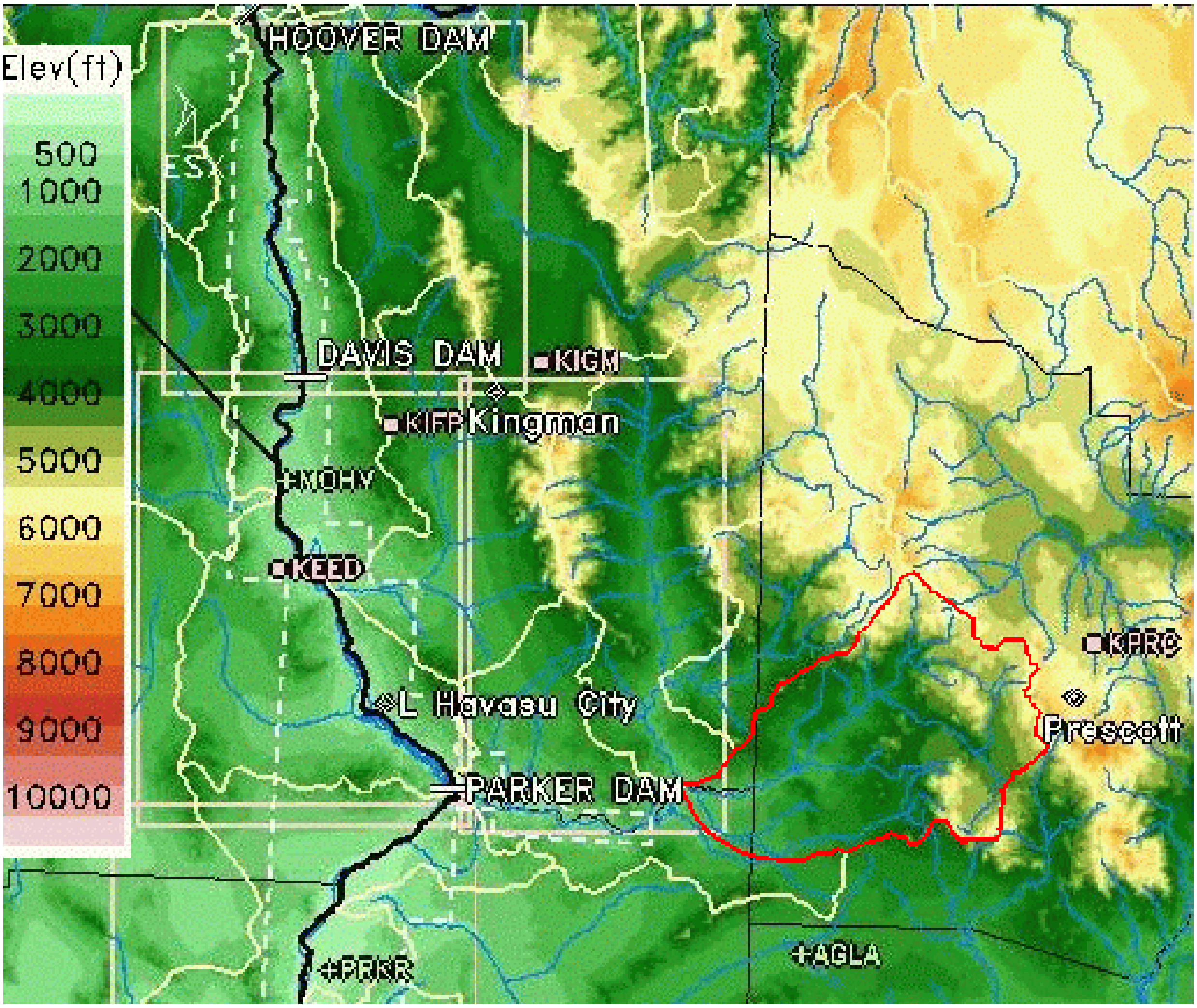

Figure 3. Topographic map of region surrounding Santa Maria basin, which is outlined in red. Color scale for elevations (in feet) is at left. State boundaries are thick black lines and county lines are thin black. Other (USGS 8-digit HUC) basin boundaries are in yellow.

Flooding, flash flooding and urban flooding occurred in and near Bagdad, Prescott, Aguila, and north of Wickenberg. The flooding and rock or mudslides closed several roads in and around these communities on the 25^{th} and 26^{th}. The flooding at Aguila was aided by the bursting of an earthen dike. The daily *mean* flow at the Santa Maria River gauge increased from zero on the 24^{th} to 69 cfs on the 25^{th} to 1910 cfs on the 26^{th}. Apparently the gauge either malfunctioned or was swept away by the river after that, as the discharge had to be estimated by the USGS for the next four days (the estimate was 450 cfs on the 27^{th}). The stream gauge on the Big Sandy River (USGS 09424450, labeled BS in Fig. 2) reported a daily mean discharge of 3510 cfs on the 26th.

5. PLANS FOR RESEARCH AND APPLICATION OF TEST RESULTS

As stated earlier, we intend to run both GSSHA and Vflo with identical GIS and radar QPE data input for this test case. This will enable a fair comparison of the performance of the two models in the arid and topographically complex Santa Maria basin of western Arizona. The two main objectives for this test are: 1) To assess if the models run sufficiently fast so as to produce output in near-real-time and 2) to see which model provides the more accurate stream flow hydrographs when compared to the USGS stream gauge data. To accomplish the latter, we will

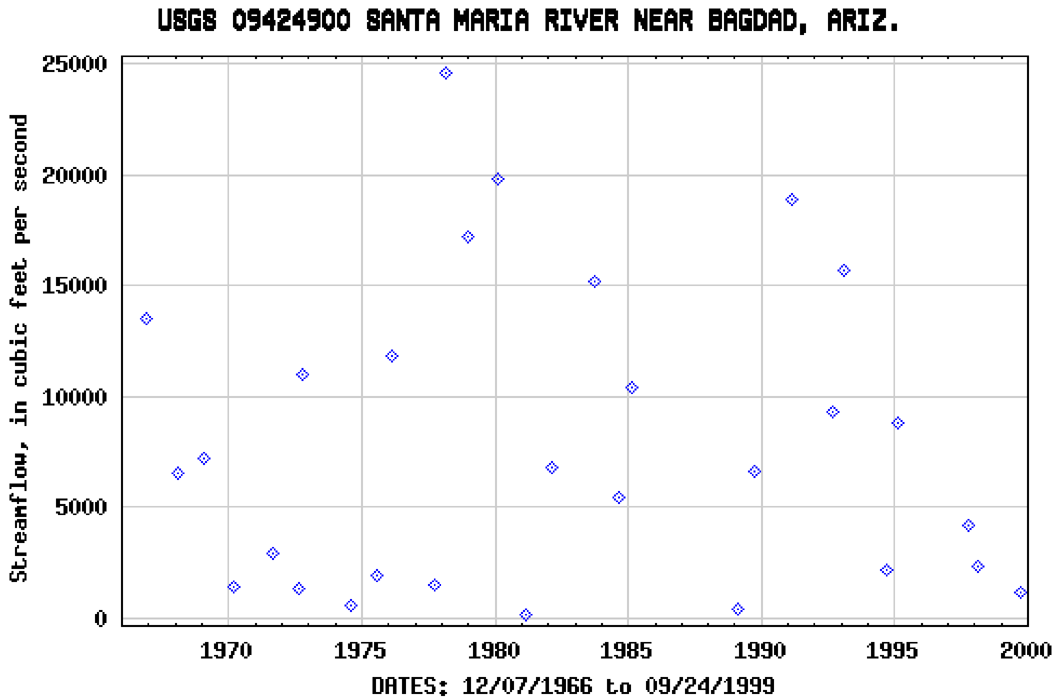

Figure 4. Peak streamflow for each year at the Santa Maria stream gauge for the given period of record. Courtesy U.S. Geological Survey.

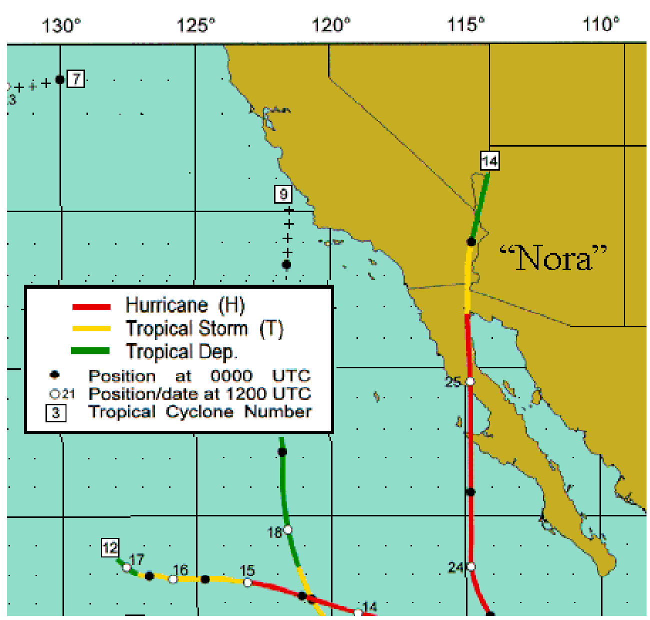

Figure 5. Track of tropical cyclone Nora, with strength categories and positions as indicated in legend. Nora is number 14. Courtesy National Hurricane Center.

T.S. Nora Precipitation (in)

25/1200Z - 26/1200Z Sept. 1997

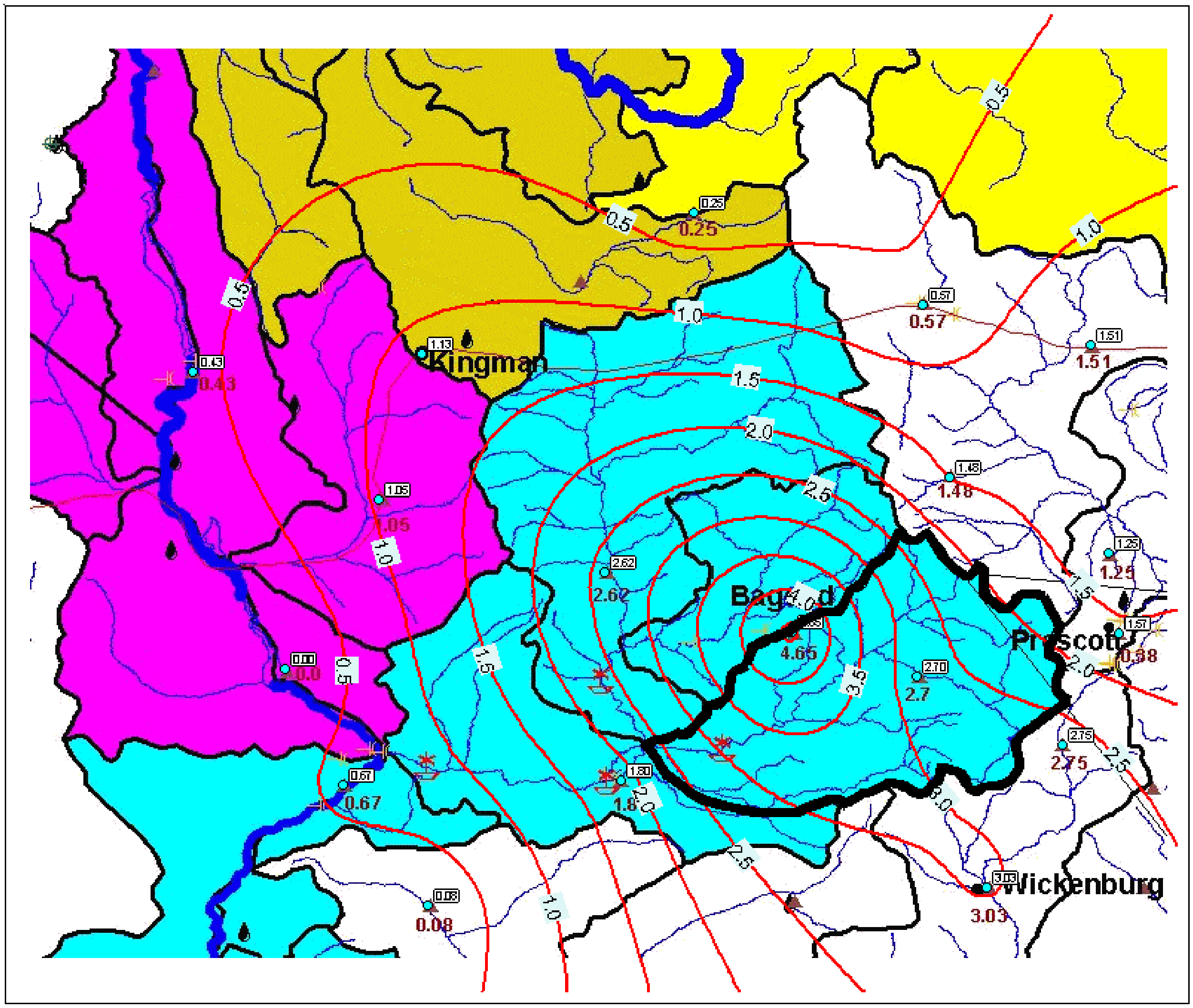

Figure 6. Isohyetal analysis (red contours) of rainfall amounts in inches (brown values), for period specified in title. Precipitation gauge data for analysis are from all available reporting sites (brown triangles and drop icons, as in Fig. 2). Heavy black line envelops Santa Maria basin. Red icons with asterisks are active stream gauges, as in Fig. 2.

employ not only the Santa Maria River gauge but also the one on the Big Sandy River near Wikieup. The Big Sandy is also an unregulated basin and is considered a backup to the Santa Maria for this test. As seen in Fig. 2, the cooperative observing site just north of the Big Sandy stream gauge reveals that heavy rain also fell in this basin (2.62 inches in 24 hours ending 1200 UTC on the 26^{th}).

The time it takes a distributed hydrologic model to execute a simulation is as important as the accuracy of its output hydrographs because of our intended application for the model. This ultimate desired application is the coupling of a distributed model with a "live" WSR-88D data feed for near-real-time hydrographs of sidewash inflows to the Lower Colorado River, for operational use. Heavy sidewash inflows can occur with widespread rainstorms such as tropical cyclones and cause unexpectedly high water volumes on the Colorado mainstem. These volumes pose a problem for Reclamation's water management in the numerous reservoirs along the mainstem. It may even cause flooding, especially in the normally low water, flood control season from January through July. Rapidly updating hydrographs produced by a distributed model, which is capable of ingesting new WSR-88D radar volume scans every 5 or 6 minutes, would provide tremendous decision assistance to Reclamation's water managers in the effective release of water from dams. Such a system could easily be transported to other regions of the United States, since radar input would be available from the operational WSR-88D network deployed throughout the country.

Preliminary testing of the Vflo model show that for 81 hours of simulation to analyze the cell located at the Santa Maria stream gauge site, the CPU time at 200 m resolution was 146 seconds; for 500 m resolution the CPU time was 24 seconds. These results were obtained on a dual-processor personal computer (PC) with an Intel® Pentium® III chip, 1.27 GHz clock speed, 2.4 Gb RAM, and MS Windows® 2000 operating system (OS). On a single-processor PC with 1.8 GHz clock speed, 0.5 Gb RAM and a Pentium® IV chip, the 500 m resolution run took 17 seconds of CPU time. Clock speed appears to be the dominant hardware factor affecting CPU usage with Vflo. Testing of the GSSHA model is still preliminary and results are pending.

While the Santa Maria not a sidewash basin directly upstream from the Lower Colorado River, it is close to that river (Fig. 3) and has similar desert soil characteristics to the sidewash basins of concern. The Santa Maria River, as noted previously, flows into the Bill Williams River. The Bill Williams basin is therefore a potential major contributing inflow to the Lower Colorado. We chose not to make that our test basin because Alamo Dam regulates it, thus making basin flows difficult to simulate using the distributed models.

Since the accuracy of any distributed hydrologic model is very dependent on the input precipitation field, Reclamation continues to seek improvements to radar QPEs. The PAA represents a major progression toward that end, but the algorithm is still under testing and development. We are currently engaged with the National Severe Storms Laboratory to develop and test a version of their Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPE-SUMS) system (Gourley, 1998; Gourley et al. 2001), which is also operating in Arizona. We intend to test both the PAA and QPE-SUMS in the hope to obtain the best possible radar QPE input for whatever distributed hydrologic model is implemented operationally as a water management tool.

As mentioned in the first section, we intend to incorporate the radar QPE-driven distributed model into a generalized river management tool such as RiverWare. The first step toward this incorporation will be done as part of Reclamation's AWARDS/ET Toolbox system (Hartzell et al. 2000).

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