Title of Paper: **Prospects for a real-time flood warning system in Arizona**

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Charlie Ester, P.E. is manager of the Salt River Project (SRP) Water Resources Operations since May, 1997. Prior to that he was a hydrologist within the same group for more than 10 years. SRP delivers more than 1 million acre-feet of water to a 240,000-acre service area. Mr. Ester leads the management team for the water supply that provides approximately 80% of the water that is used/consumed in the Greater Phoenix Metropolitan Area and reservoir operations during times of excess flow. He earned a Bachelor of Science in Hydrology from the University of Arizona.

Chuck Dempsey has been a meteorologist with the Salt River Project for 5 years. Proir to this he served 5 years at the National Severe Storms Laboratory in Norman, OK. He provides all manner of meteorological forecasts. These range from short-term temperature/thunderstorm forecasts to seasonal temperature/precipitation outlooks that are utilized in both water and power operations. He was earned a Bachelor of Science in Physics/Mathematics from the University of Arkansas and a MS in Meteorology from the University of Oklahoma. Mr. Dempsey has been a member of the American Meteorological Society since 1994.

Jean E. Vieux co-founded Vieux & Associates, Inc. in 1992. Vieux & Associates, Inc. is engineering technology company that focuses on GIS, hydrology, and radar rainfall applications. Ms. Vieux earned a Master of Environmental Science from the University of Oklahoma in 1995. Experience includes GIS analyst, prinicpal investigator and project manager for transporation planning and hydrologic applications of radar rainfall. Ms. Vieux manages day-to-day company operations.

Prospects for a real-time flood warning system in Arizona

ABSTRACT

The Salt River Project manages water resources in the 13,000 square mile Salt and Verde watersheds in central Arizona. Knowing how much and where runoff will occur given complex hydrologic and meteorological conditions requires advanced tools. This paper describes the prospects for developing real-time flash flood modeling in Arizona using advanced technology.

Implementing a real-time hydrologic prediction system is expected to improve water management and flood forecasting in the Salt and Verde watersheds and other areas in Arizona. Accurate precipitation estimates have been developed though multisensor precipitation estimates called QPE-SUMS. This information will be used in real-time to predict runoff when coupled to a suitable hydrologic model representing terrestrial characteristics.

Accurate estimation of runoff depends not only on precipitation rates and amounts, but also on terrestrial parameters such as landuse/cover, soils, complex topography and other factors influencing runoff and resulting floods. Predicting the volume of runoff and the timing and location of discharge throughout the domain encompassing the Salt and Verde watersheds will utilize a sophisticated hydrologic modeling approach coupled with QPE-SUMS.

When coupled with QPE-SUMS, such a model will help 1) manage reservoir operations, 2) minimize losses through spills, and 3) predict flood levels in selected basins. Vflo™ is a real-time distributed model implemented in Java for simulating rainfall-runoff. Parameters maps are derived from GIS or remotely sensed (GIS/RS) data and input from a combination of radar, satellite and rain gauges. The numerical solution uses the finite element in space and finite difference in time method is used to solve the kinematic wave equations. For large watersheds, days of hydrologic simulation may be accomplished in seconds making this model an ideal candidate for real-time simulation in a flash flood warning context.

Introduction

What constitutes a flood? Inundation of areas that are usually left dry is one definition. Another would be whenever river stage exceeds bankfull. Forecasting the river stage or when dry areas may become inundated depends on rainfall runoff modeling, precipitation estimation, and warning dissemination. The benefits of having this forecast ability extend beyond flood emergencies to management of water resources. In either case, the forecast of the watershed's hydrologic response is required.

Figure xx Snow on the Mogollon Rim near Oak Creek in the Verde watershed.

Figure xx Channel on the mainstem of the Verde River

Water resources management mission of SRP involves both the Salt and the Verde. Given the combined system of QPE and modeling capabilities, SRP will be able to better manage precious water resources.

[Need details here from Charlie and Chuck]

The complex hydrology and meteorology associated with the Salt and Verde is typical of many areas in Arizona. This paper is organized into sections that deal with 1) flood hazard analysis, 2) rainfall runoff modeling, 3) multisensor estimates of precipitation, and 4) the prospects for developing such a system in Arizona and elsewhere.

Flood Hazard Analysis

A complicating factor in most urban areas is the multi-jurisdictional characteristic of flooding. While the NWS is given the primary responsibility for warning the public of threats posed by severe weather, local communities and organizations have developed customized systems. Warning systems often involve several agencies and communities requiring cooperation and sharing of information or data. Radar data is made available in the US by the federal government. Though not the case in many countries, this access permits the development of customized systems that rely on federally operated radars combined with locally operated rain gauge networks.

The scope of the flood warning system depends on the type and nature of the flood hazard in the community. Defining the scope of the warning system depends on the scope and type of flooding. ADWR (1995) describe the flood hazards due to sheet flow common in Arizona and requirements for building in areas subject to flooding from a range sheet flow flood hazards that differ from riverine, alluvial fan, or other defined floodplains. Risk from sudden inundation in areas subject to poorly defined or shifting drainage channels is present in areas subject to alluvial fan flooding

Before an effective flood warning system may be instituted, the flood hazard must be defined according to depth, duration, and frequency at locations of interest, the expected magnitude and frequency of flooding, the populations exposed to the risk of being flooded, and the institutions responsible for various phases of the flood, i.e., preparedness, warning dissemination, and recovery. In the case of riverine flooding, this phase involves developing discharge-frequency and stage-discharge relationships at key locations along the river known as forecast points. Urban flooding due to its diffuse nature is more difficult to forecast except along well-defined drainage ways. Alluvial fans in the Southwestern US pose special difficulties due to the uncertainty of being flooded at any location on the alluvial fan because relatively shallow channels can shift during a flood. In all cases, the size of areas contributing runoff influence the response time after initiation of the flood-producing rainfall. USACE (1996) identifies this time period, as the *maximum potential warning time*, is related to the arrival time of the peak stage or discharge is the interval during which mitigating responses can reduce property damage, loss of life, or business interruption.

The time from the onset of rainfall to the critical flood stage depends on the location in the watershed and the intensity, duration, storm movement and spatial extent of the precipitation. Even more complicated precipitation rates result when snowmelt is coupled with intense rainfall making flood prediction a formidable problem. Storm movement and tracking may be used to extend the warning time. Extending the quantitative estimates through quantitative precipitation forecasts (QPF) have been accomplished through pattern recognition and advection, or with atmospheric modeling at the meso- or stormscale separately or together.

Rainfall Runoff Modeling

Hydrologic prediction and real-time flood warning systems require generation of a hydrograph at the desired location, e.g., at a particular location along a riverine area or the apex of an alluvial fan. To accomplish this, a rainfall-runoff model is required that is capable of taking estimates of precipitation from a variety of sensors and transforming that precipitation into runoff. To accomplish this two types of models are widely used. Historically, conceptual hydrologic models based on empirical relationships have been employed. Most of these models rely on unit hydrograph theory. More recently distributed hydrologic models that rely on conservation of mass and momentum (termed phsyics-based) to transform precipitation inputs into runoff.

Classically, hydrologic models have been optimized for point measurements, and not distributed in space and time. The most common technique in use in the US is based on the unit hydrograph approach, first proposed by Sherman (1932), the unit hydrograph technique assumes a linear response to a unit input of rainfall excess. Snyder and others contributed later improvements and modifications to the unit hydrograph approach for ungauged watersheds as described by Bedient and Huber (2001). Practical application of the unit hydrograph methods through the development of HEC-1 and HEC-HMS have been advanced by the US Army Corps of Engineers, Hydrologic Engineering Center (1981, 2000).

Deterministic physics-based models include Vflo™ (Vieux and Vieux, 2002); *r.water.fea* (*Vieux and Gauer*, 1994; *Vieux*, 2001), CASC2D (*Julien and Saghafian*, 1991; *Ogden and Julien,* 1994; *Julien, et al*., 1995), Systeme Hydrologique European (SHE) (*Abbott et al.,* 1986a,b) and the Distributed Hydrology Soil Vegetation Model (DHSVM) (*Wigmosta, et al.,* 1994). Conceptual rainfall-runoff (CRR) models include Precipitation-Runoff Modeling System (PRMS) by Leavesley et al. (1983), the Sacramento Soil Moisture Accounting Model (SAC-SMA) (*Burnash, et al.* 1973), and the HEC–HMS model (Hydrologic Engineering Center, 2000) that simulate runoff generation by a variety of conceptual parameters and route the runoff using unit hydrographs an outlet. CRR models are inherently not physics based and lump parameters at the basin or sub-basin level.

Distributed models avoid averaging parameters and input in order to more faithfully represent watershed characteristics. A computational scheme routes runoff from grid cell to grid cell or other element representative of the landscape using some set of equations termed a mathematical analogy. Moore and Grayson, (1991) describe an array of physics-based models that capitalize on digital models of elevation, GIS and remotely sensed (GIS/RS) geospatial data. The following section describes such a model that is capable of using the rich information content found in GIS/RS data.

Vflo™ Model description

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 multisensor 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 setup 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. Figure xx shows the drainage network used in Vflo™ to route runoff through overland and channel elements. Hydrographs can be simulated in real-time and post-analysis at any location where there is a channel or overland flow element. The red x-symbols designate the location of stream gauging stations.

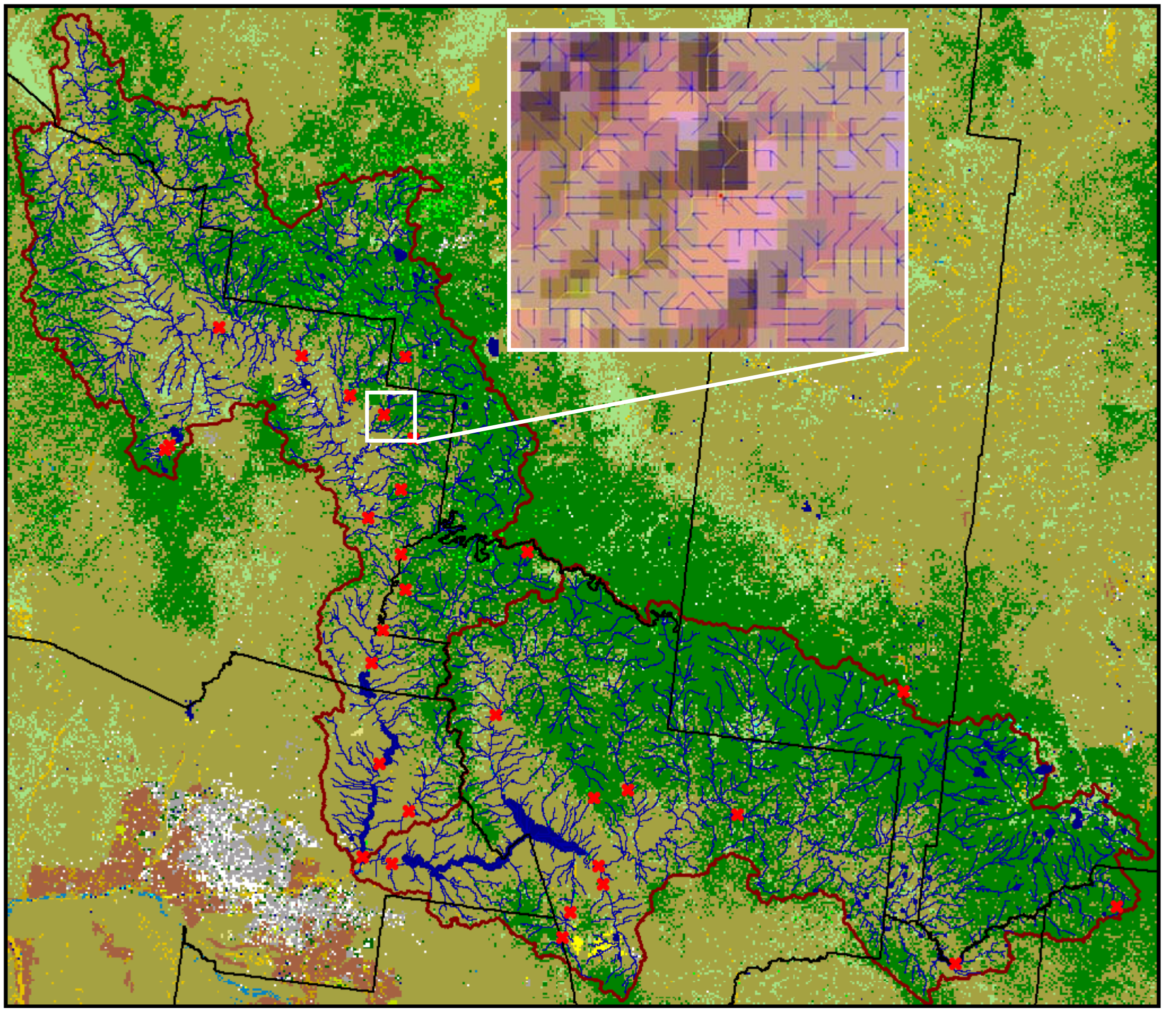


Figure 1 Salt and Verde Watershed with Vflo™ drainage network (inset).

While shown for the Salt and Verde, the system has potential for application to any location where multisensor precipitation estimates inputs are available.

Quantitative Precipitation Estimation

Precipitation inputs are widely regarded as causing the greatest uncertainty in model forecasts of stage and discharge. The required density of rain gauge networks to capture the spatial variation of convective rainfall events is usually prohibitively expensive. Several studies have found that with the use of just a few rain gauges for adjustment that radar can provide an economically feasible source of precipitation input for rainfall-runoff modeling. Crawford and Andra (1987) demonstrated that the same level of accuracy in the areal estimate of rainfall could be achieved with radar combined with just a few gauges. Amburn and Fortin (1993) demonstrated that will weather radar provides superior information about the spatial and temporal resolution of the rainfall event, estimates of rainfall accumulation can be severely biased. Wilson and Brandes (1979) states that the combination of rain gauge and radar leads to improved rainfall estimates that are better than either system alone. With the advent of satellite, radar, and rain gauge, multisensor products are being developed to overcome limitations of each data source.

Difficulties with the existing QPE produced by the NEXRAD system exist in the intermountain west due to blockages and other anomalies. In the Intermountain West (IW), the WSR-88D PPS may not adequately account for mixed-phase hydrometeors (liquid coated ice appears highly reflective to the radar). Efforts to improve on the existing WSR-88D PPS are reported by Gourley (1998) and Howard et al. (1997). This product is known as QPE-SUMS, which is under development at the NOAA-National Severe Storms Laboratory. Further information on QPE-SUMS development may be found on line at: http://www.nssl.noaa.gov/teams/western/qpe. QPE-SUMS is now operational at the Salt River Project (SRP). The overall goal of the QPE-SUMS project is to develop accurate estimates of precipitation over the Salt and Verde River Basins. The SRP operates reservoirs for power generation, water supply, and flood control. Therefore accurate estimates are crucial to efficient operation of reservoirs, managing water supply and flood warning responsibilities of SRP. An example of multi-sensor estimates of precipitation using a radar/satellite is shown in Figure XX.

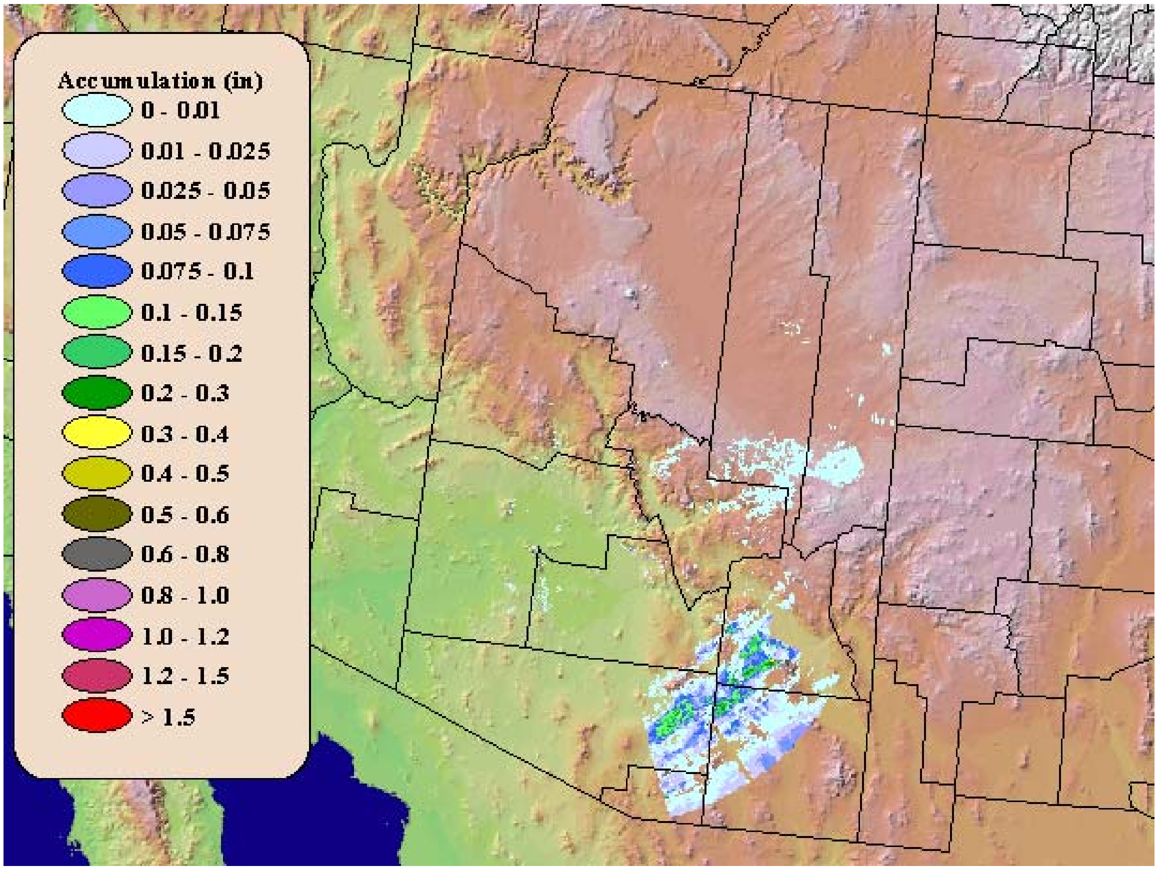


Figure xx QPE-SUMS precipitation.

Study Area

Oak Creek is located in the North Eastern portion of the Verde Watershed. Two USGS gauging stations are located on Oak Creek, Gauge 09504500 located near Cornville (355 mi^2), in Yavapai County and Gauge 09504200 near Sedona (233 mi^2), in Coconino County, Arizona. The Vflo™ interface in Figure xx illustrates the finite element connectivity of overland and channel elements in the Oak Creek and surrounding drainage areas.

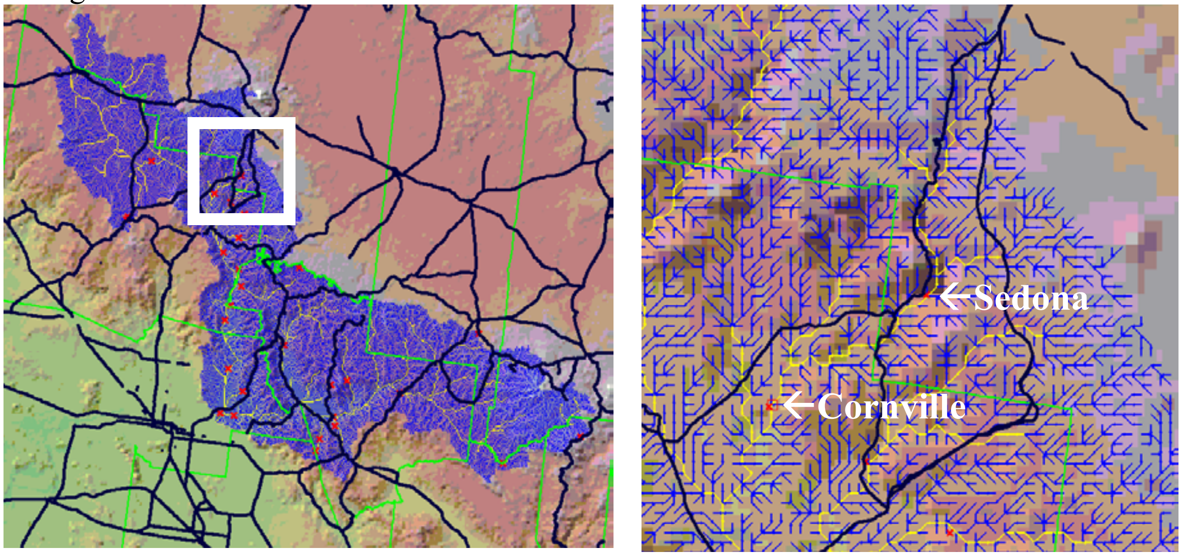
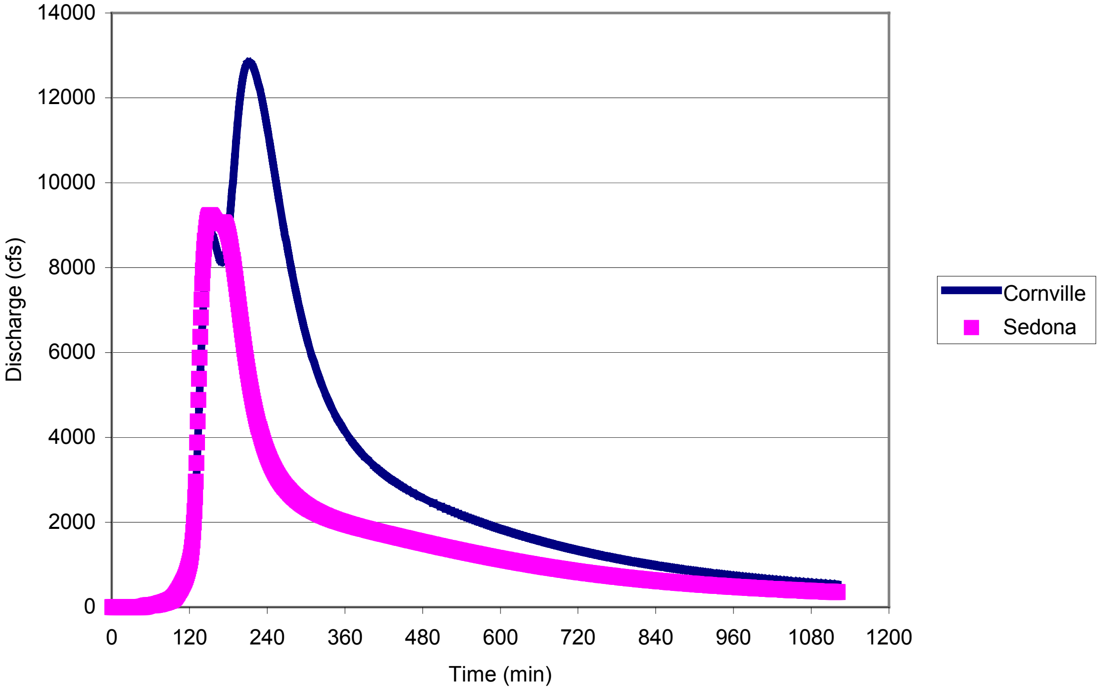


Figure xx Location of Oak Creek in relation to the Salt and Verde Watersheds (right panel). Locations of the two USGS gauging stations are shown in the left panel.

A test case is shown in Figure xx for a hypothetical storm of approximately one inch (2.54 cm) occurring in one hour. The two hydrographs were generated using an initial parameterization without calibration. The Hydro-1k DEM is used to define the drainage network, and USGS streamflow measurements to characterize the channel cross-sections. Hydraulic roughness and infiltration rates are derived from LandSat and soils maps, respectively.



Summary

Advanced technology opens new possibilities for flood warning systems customized to local watershed conditions and flood hazards. The distributed model, Vflo™ used in real-time with multisensor precipitation input allows detailed modeling of flow anywhere in a watershed. The combined system of QPESUMS and Vflo™ is operational for the Salt and Verde watersheds operated by the Salt River Project as part of its water resources management mission. Creation of local flood warning systems in Arizona and elsewhere that capitalizes on recent technological advances is now possible with this system.

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