ADVANCED HYDROLOGIC PREDICTION FOR EVENT-BASED AND LONG-TERM CONTINUOUS OPERATION

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Abstract Event-based and long-term continuous modeling of rainfall-runoff is associated in the same physics-based distributed model, V*flo*™. The model relies on remotely sensed precipitation from radar and rain gauges; is parameterized with widely available geospatial data describing terrain and land cover conditions; and solves the kinematic wave equations for each model grid using efficient numerical routines. Statistical analysis of model performance helps guide development and operation of the model. Distributed soil moisture in the subject basins are updated given the complex interaction of rainfall with antecedent moisture conditions. Long-term model performance is found to be consistent between the event scale and long-term inter-annual periods when calibrated to represent large events and interim periods dominated by low flow. Volume agreement is found to be 17.8 and 7.2 mm RMSE on a daily basis. Physically realistic parameters result from the calibration method applied to parameters derived from geospatial data. Urban and rural basins are simulated using a fully distributed physics-based approach.

INTRODUCTION

Advances in physics-based distributed hydrologic modeling have made it possible to support real-time decision making for reservoir operations; hydrologic analysis of storm events; long-term water balance runoff-recharge studies; and prediction of site-specific flood for stormwater and emergency management. The amount of surface runoff is simulated by numerical solution of conservation equations, parameterization from geospatial data, and inputs defined by radar, gauge, and satellite. The resulting model is applicable in rural watersheds that range in scale from headwaters to rivers, and in urban settings by explicit representation of hydraulic characteristics of urban infrastructure. Model setup is designed to use common geospatial datasets such as digital terrain, landuse/cover from satellite remote sensing, and soils information. Refinement of the model can then be made using in-country or project-specific data for operational deployment as described by Vieux et al. (2003). The model features and results for three basins using operational data streams are presented for V*flo*™ in the following sections.

Model Background Real-time V*flo*™ uses maps of data and laws of physics to solve equations that forecast flooding. The system is designed to track distributed soil moisture and runoff automatically in an unattended mode with information accessible via an intra/internet web browser. An abridged description of the model setup and data required are as follows.

1. **Geospatial Data** Geospatial data is used to setup V*flo*™ starting with a digital elevation model (DEM) for derivation of slope and flow direction (D8 or D4); remotely sensed landuse/cover for overland hydraulic roughness; impervious area and soil characteristics for derivation of Green and Ampt infiltration parameters and soil depth; channel geometry and hydraulic characteristics.
2. **Precipitation Inputs** Rainfall and snowmelt may be input on a gridded-basis as maps, or input as uniformly distributed rainfall rates/accumulations. Distributed precipitation formats

that are supported include QPESUMS format and ESRI ASCII grids. Point hyetographs may be input for subareas such as basins or uniformly over the entire domain. Snowmelt is modeled on a distributed basis using the temperature index method.

3. **Routing** The kinematic wave equations are solved on a grid cell basis within a drainage network composed of finite elements. The formulas are adapted to represent overland and channel hydraulics. Floodplain storage effects can be simulated using the Modified Puls method to account for attenuation due to temporary storage. Complex channel hydraulics are represented by: 1) rating curves for stage area/discharge, 2) surveyed channel cross-sections with slope and Manning's roughness, 3) trapezoidal cross-sections with slope and Manning's roughness.
4. **Soil Moisture and Infiltration** The theoretical basis of the infiltration module is the Green and Ampt equation, which relies on the soil properties. Infiltration rate excess runoff is computed in each grid cell as a function of soil properties and antecedent conditions. Once the soil moisture storage capacity is filled, then saturation excess runoff is computed. When the soil moisture is modeled over time, the infiltration rate is adjusted to account for a range of soil moisture. Impervious area and initial abstraction may be set to account for urbanization effects and ponding on the landsurface. The rate of soil moisture depletion is limited by the climatologically evapotranspiration (ET) rate and available soil moisture.
5. **Distributed Output** A unique feature to distributed models is the capability to output distributed runoff and other hydrologic quantities at any location. This capability supports generation of hydrographs at locations selected in the drainage network regardless of current watershed delineations. Distributed runoff is useful for debris flow forecasting where heavy rainfall, soil conditions, and slope play a role in the initiation of landslides and subsequent transport of mud and debris. Because the model outputs stage at distributed locations along the channel, inundation mapping can be accomplished that is more detailed than routing in channel reaches.

The model is applied to three basins, one urban and two rural as described in the next section. Additional information and manuals for V*flo*™ may be found at www.vieuxinc.com.

METHODOLOGICAL APPROACH

Real-time statistical analysis of model performance helps guide development and operation of the model. If the state of the soil moisture distributed across the basin is representative of actual conditions, forecasting of flooding or simulation of other significant hydrologic events can be more accurate. The model should be capable of updating soil moisture given the complex interaction of rainfall with antecedent moisture conditions that is variable in time and space. Long-term model performance can be considerably different than any given event. Consistent performance between the event scale and long-term interannual periods is a desirable feature. To achieve consistent results for both large runoff events and long-term periods, it is necessary to adjust model parameters within physically realistic ranges. Distributed model adjustment follows the method outlined by Vieux and Moreda (2003) with modification to account for long-term simulation of streamflow dominated by low-flow.

Two sources of input are tested in the model. First, a multi-sensor precipitation estimate (MPE) is used that is produced by the U.S. National Weather Service from gauge, satellite and radar data. Second, a product generated from Level 2 radar reflectivity results in gauge-corrected radar rainfall input. Simulations are conducted for three basins at the storm event time-scale and over multi-year periods. Inputs are derived from two sources: 1) Calibrated Level 2 at 1°x1km resolution, and MPE at 4x4 km resolution. Tests are designed to identify significant differences between the two model inputs and resulting calibration factors.

Sensitivity of the model in terms of long- and short-term runoff volume is examined to identify the effect of soil moisture on model performance. To facilitate the characterization of model performance a real-time statistical module is used to display model performance in terms of statistical measures and graphical output. The real-time module permits web-display of the past 30-days but it is also useful for analysis of model trials and post-analysis. Sensitivity testing is supported by a module that is operated in batch mode to run through combinations of parameter. The modules developed and used to conduct this study are described as follows:

1. **Soil moisture and Runoff Display** High-definition display of advanced runoff and soil moisture information interpretation is supported by the model and display system. This model functionality supports applications in soil moisture, recharge, and debris flow modeling in both short- and long-term timeframes.
2. **Real-time statistics** Model performance showing forecast uncertainties and statistical measures of accuracy are produced without resorting to external plotting packages. Display of statistical performance is updated at regular intervals in real-time. Statistics include a running total of volume, mean and mean-absolute percentage error, root-mean-square error (RMSE), Nash-Sutcliffe, Pearson correlation, dot plots and exceedance plots of observed and simulated volume or discharge.
3. **Sensitivity Module** Exploring parameter space of the distributed model is configured by specifying range and increment of parameters to be tested using the sensitivity module. This function helps identify the sensitivity of the model as the each parameter is varied over some physically realistic range.

Characterizing the forecast uncertainties and statistical measures of performance of distributed models was the goal of the experiment organized by the NWS and participants in the Distributed Model Intercomparison Project (DMIP) published in the Journal of Hydrology special issue (Vieux et al., 2004; and other articles contained therein). Details on the methodological basis for the V*flo*™ model and application of the model may be found in Vieux (2004) and Vieux and Bedient (2004).

RESULTS

Results presented here for selected watersheds demonstrate the importance of both event-based and long-term calibration, sensitivity, and utility of statistical measures. Notable differences in calibration occur when using either MPE or Level 2. Therefore, if the model is to be used in real-time with MPE as input, then calibration should be performed using MPE as input. The simulations presented herein are from using MPE.

Brays Bayou is a 260 km^2 urban watershed located in Houston, Texas, which causes repeated flooding of the Texas Medical Center. Clear Creek is a 290 km^2 watershed located South of Houston, Texas, and Sandy Creek located in Central Texas, has a drainage area of 900 km^2. Figure 1 presents a sample of the statistical module output for two events in Brays Bayou.

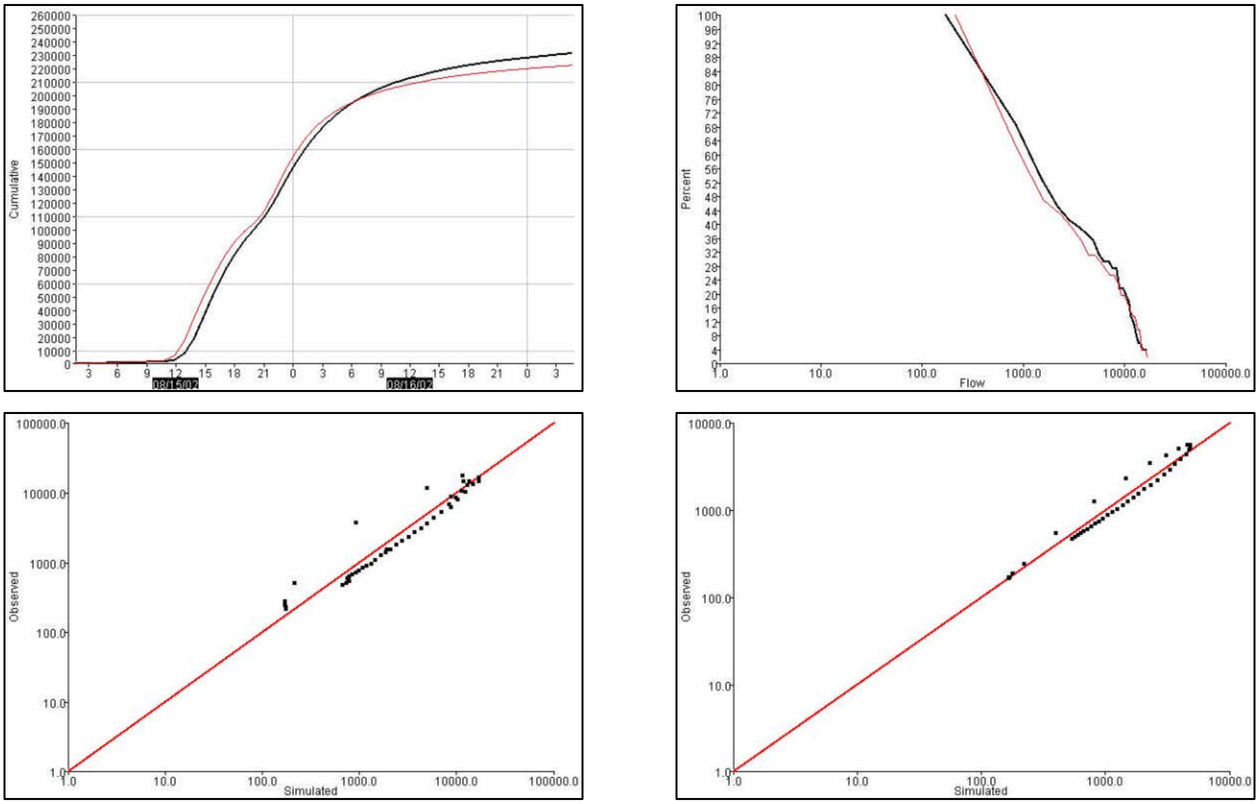

Figure 1 Sample statistics for Brays Bayou: Cumulative Volume (upper left); Percent exceedance (upper right); and Dot Plot of observed and simulated discharge for two storm events, August 15, 2001 (lower left) and Claudette (lower right).

Long-term Soil Moisture - Simulation of streamflow with operational data streams on a continuous basis has provided valuable data for characterizing initial degree of saturation for several significant runoff events, and for streamflow during long-term studies. A model version has been developed that can simulate rainfall-runoff and recharge over a long-term period, e.g., using 10-years of hourly-radar rainfall input. Long-term studies using distributed rainfall in the form of radar maps at hourly time steps is now available in archival form. This availability now supports simulations over approximately a 10-year period or longer since the inception of NEXRAD radar in the U.S. Depletion of soil moisture through evapotranspiration and replenishment by distributed radar rainfall input affects runoff volume and deep percolation/recharge. Soil properties and vegetative characteristics exert an effect on soil moisture and runoff that becomes apparent during long-term simulations. Figure 2 shows the long-term simulation of cumulative runoff volume on the left. On the right, the sensitivity of the model to evapotranspiration rate and soil moisture storage capacity, *sd*1* and *sd*1.5* is shown. Soil moisture storage capacity and evapotranspiration produce a diminishing response. As soil moisture is depleted by higher rates of ET, no further decrease in runoff volume occurs. From this analysis, a constant ET rate value is identified that minimizes volume error for the period.

The two curves produce different “optima”, which indicates that uncertainty in soil porosity or depth, i.e., soil moisture storage capacity, has some effect on the selected value of ET. Either may serve as a calibration factor, depending on which parameter is considered the most uncertain. Without detailed measurements to constrain ET, it is a likely candidate for adjustment. If soil depth and porosity were not known from soils maps, then it could be adjusted instead.

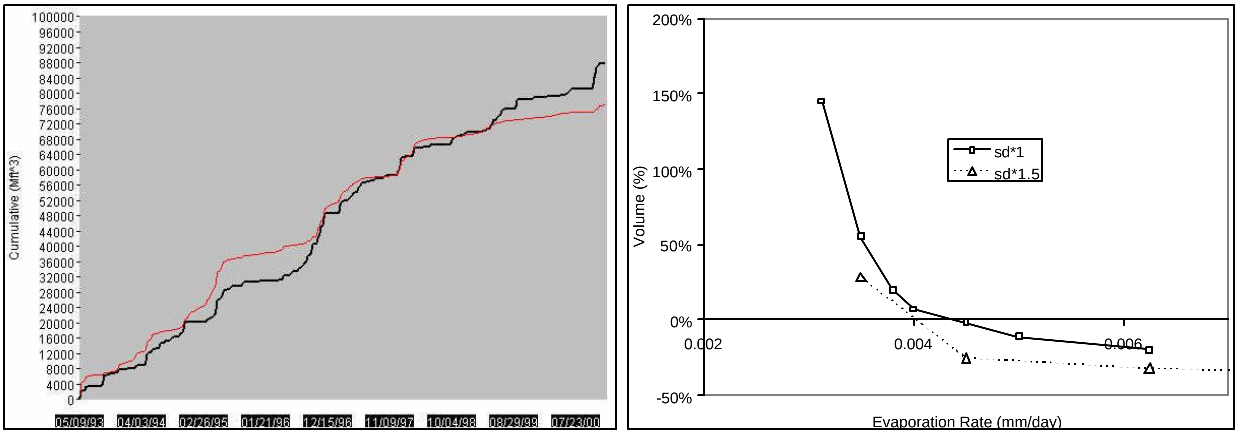

Figure 2 Statistical module output of long-term cumulative runoff volume for Sandy Creek, black simulated and red observed (left). Model sensitivity to evapotranspiration rate and soil moisture storage capacity (right).

Sensitivity Study Modeling soil moisture as a second state variable of the model makes it more useful as an operational tool in forecasting streamflow. A sensitivity study shown in Figure 3 illustrates the sensitivity of soil moisture to wetting front suction with long-term radar input. Identification of model sensitivity to parameters and inputs is important for long-term calibration. Evaluation of this state variable provides baseline information that supports operational forecasting applications.

In Figure 3, it is evident that during the year 2000 and continuing into 2001, a prolonged drought occurs, which eliminated any persistence of initial conditions from the previous year. When a very large event occurs in the first week of June 2001, the model goes from 4% to nearly 80% saturation, which then begins to rapidly decay in the summer. Over time, the effect of the wetting front suction is seen to evolve, which produces a nonlinear response in the degree of saturation. By simulating the long-term runoff and adjusting the wetting front suction, the model can be made to agree more closely with observed runoff volume. The antecedent soil moisture produced from long-term simulation is useful for constraining the initial condition of the watershed for event-based calibration.

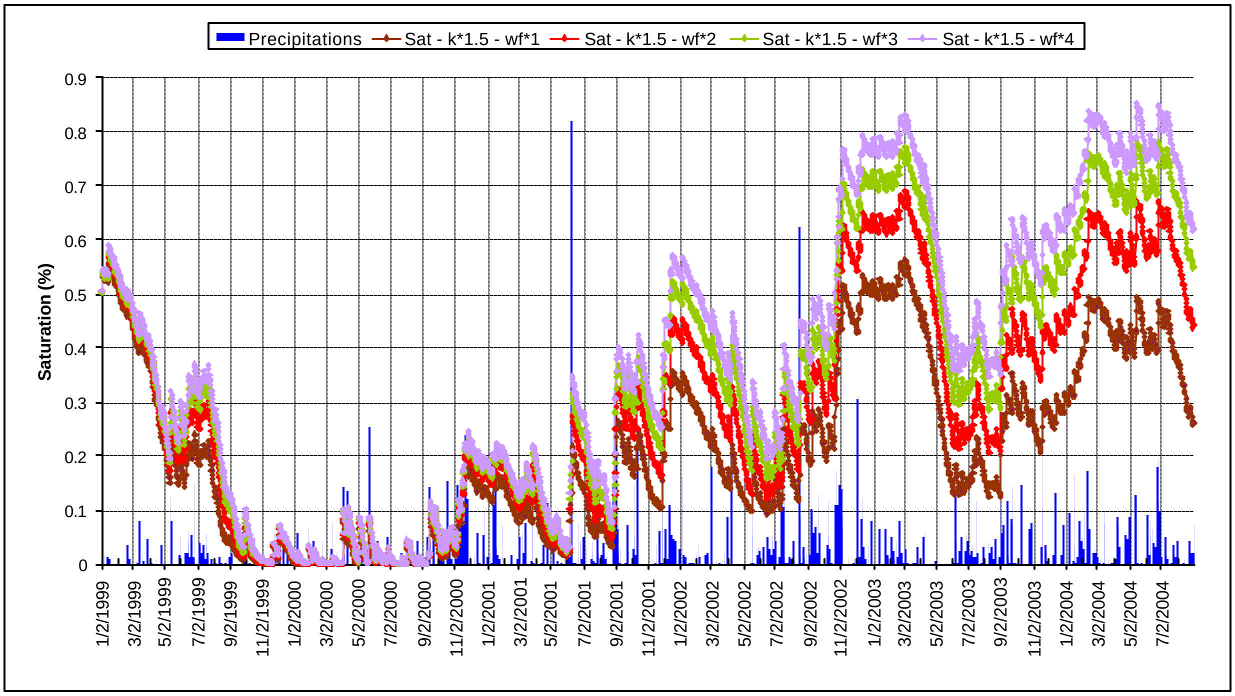

Figure 3 Soil moisture sensitivity study for Clear Creek Texas showing response of the state variable to adjustment of wetting front suction during the simulation period from 1999-2004.

Parameters controlling runoff during low flow include wetting front suction, ET rates, and soil moisture storage capacity, e.g., depth and effective porosity. For the Clear Creek watershed the long-term RMSE is computed for three periods: 1) Tropical Storm Allison, 2) Convective Event August 15, 2002, and 3) long-term period 2003-2004, which are presented in Figure 4. Adjustment of wetting front suction results in an overall volume agreement for a range of event sizes in terms of RMSE=17.8 mm on a daily basis, which corresponds to a mean absolute percentage error of 14.5%. The adjustment of wetting front suction for long-term periods has less effect on the larger runoff events because the model tends towards soil saturation. Note that this adjustment brings the long-term period 2003-2004 into agreement but with some loss in volume during the August 15, 2005 convective event.

Similar results are obtained for Sandy Creek where intermediate periods between large runoff events are calibrated. For events and interim periods ranging from 9.6 mm to 63.2 mm, the overall volume agreement is RMSE=7.2 mm on a daily basis, as shown in Figure 5. The parameter values used to achieve the calibrated results are within physically realistic limits. For Clear Creek, the wetting front suction was initially estimated from soil texture as 33.26 cm, (ranging from 11.2 to 40.67 cm), whereas after calibration, the mean wetting front suction over the basin became 133.05 cm (ranging from 44.81 – 162.66 cm), which is consistent with the high clay content soil (Vieux, 2004). In channelized cells, hydraulic roughness was initially estimated as 0.020. After calibration, the mean hydraulic roughness for the Clear Creek basin was 0.030. In Sandy Creek, the initial wetting front suction was 24.42 cm (ranging from 8.66 to 79.73 cm) and the hydraulic roughness for channel cells was initially estimated as 0.030, which was decreased to 0.015 during calibration. After calibration, the mean wetting front suction over the basin became 24.85 cm (ranging from 3.03 – 79.73 cm), which is virtually no change. Most of the calibration for this basin was achieved by adjusting ET due to its uncertainty.

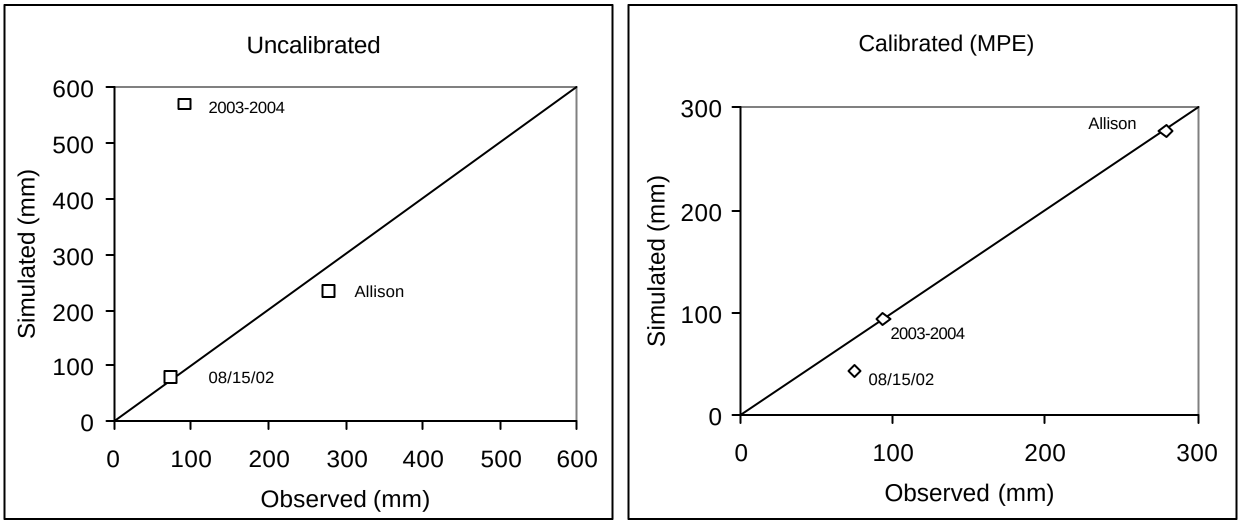

Figure 4 Event and long-term volume agreement for uncalibrated (left) and calibrated (right) for Clear Creek.

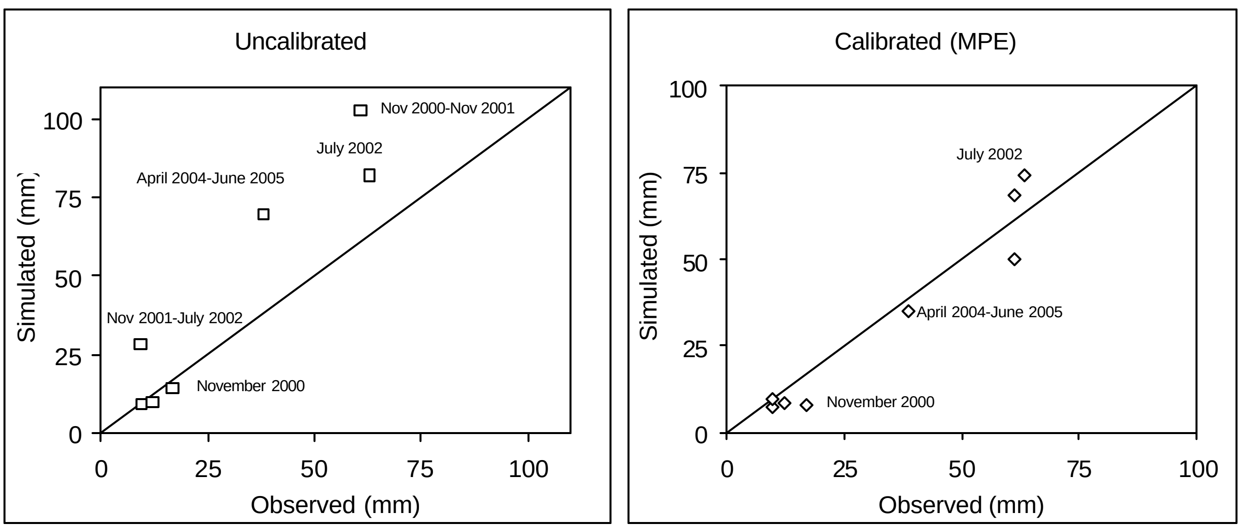

Figure 5 As in Figure 4 but for Sandy Creek during the period of 1999-2005.

Landsat imagery is used to constrain hydraulic roughness in the V*flo*™ for Sandy Creek, which is shown in Figure 6. A selected hydrograph generated by the calibrated model at Kingsland shown as red triangle on the left.

SUMMARY

Development and deployment of an operational physics-based distributed hydrologic model serves real-time decision making for reservoir operations; hydrologic analysis of storm events; long-term water balance runoff-recharge studies; and prediction of site-specific flood for stormwater and emergency management in both rural and urban basins. Results for three basins indicate that uncalibrated results can provide useful simulations. Adjustment of wetting front suction and ET is used to achieve agreement in long-term volume where low flow dominates, while maintaining consistency for larger events. Physically realistic parameters result for events ranging from low flow to tropical storms or hurricanes that achieve volume accuracy of 17.8 and 7.2 mm for Clear Creek and Sandy Creek, respectively.

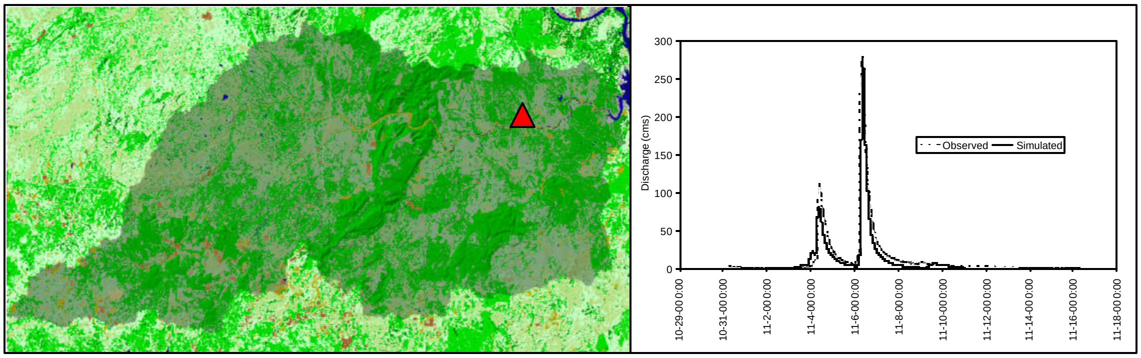

Figure 6 Landcover for Sandy Creek (Left) and selected hydrograph (Right).

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