Watershed Modeling for the Santa Clara River in Southern California

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ABSTRACT

A calibrated watershed hydrologic model of the Santa Clara River (SCR) Watershed was developed for use as a tool for watershed planning, resource assessment, and ultimately, water quality management purposes. The study was a joint effort of the Ventura County Watershed Protection District (VCWPD), Los Angeles County Department of Public Works (LACDPW), and U.S. Army Corp of Engineers Los Angeles District. The modeling package used for the study was the U.S. EPA Hydrologic Simulation Program – FORTRAN (HSPF).

The SCR main stem flows east-to-west from the San Gabriel Mountains of central Los Angeles County to its mouth at the Pacific Ocean near the cities of Ventura and Oxnard. The 4,263 square kilometer watershed includes rapidly urbanizing valleys and extensive agriculture, and is subject to severe flooding and erosion. There are four large reservoirs within the watershed. Although the Santa Clara River watershed remains primarily in a natural physical state, the flow regime within the watershed is highly engineered to optimize water deliveries and aquifer recharge.

The SCR Watershed was segmented into 209 subwatersheds and 192 stream reaches, based on precipitation patterns, drainage boundaries, hydrography, stream gage locations, and impaired water segments. Each land segment was further subdivided into individual model segments based on land use/cover categories. A long-term data base of 46 years of model input data (precipitation, evaporation, diversions, POTWs, etc.) was developed. The model was calibrated and validated to observed flow at multiple locations, using both graphical and statistical model-data comparisons. Long-term simulations were run to assess the impacts of alternative conditions (baseline, natural) on flow and flood frequencies. The model was also used to generate design storm event hydrographs for selected return intervals with synthetic input rainfall hyetographs for the corresponding rainfall return period developed from available rain gage data. The design storm results were submitted to FEMA for the Flood Insurance Study currently underway.

INTRODUCTION

This study was undertaken to develop a comprehensive watershed hydrologic model of the SCR Watershed for use as a tool for watershed planning, resource assessment, and ultimately, water quality management purposes. This study was a joint effort of the Ventura County Watershed Protection District (VCWPD), Los Angeles County

Department of Public Works (LACDPW), and U.S. Army Corp of Engineers (USACE) Los Angeles District (USACE, 2003). The modeling package used for this application was the Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell et al., 2005). HSPF is a comprehensive watershed model of hydrology and water quality, that includes modeling of both land surface and subsurface hydrologic and water quality processes, linked and closely integrated with corresponding stream and reservoir processes.

Two previous HSPF studies in Calleguas Creek, adjacent to the SCR Watershed, provided the foundation for this effort. In both studies, HSPF was set up and calibrated to available flow records for recent hydrologic conditions, and customized to include consideration of localized groundwater pumping impacts and lawn/landscape irrigation practices on surface water flow levels. The Calleguas model also included consideration of diversions and deep groundwater recharge losses through the streambed. In this study, initial hydrologic parameters and the procedures for representing groundwater pumping, irrigation, and channel losses were initially based on these predecessor models but subjected to further review, refinement, and revisions as needed for the SCR watershed conditions.

The SCR is the largest river system in southern California that remains in a relatively natural state. The main stem flows east-to-west from the San Gabriel Mountains of central Los Angeles County to its mouth at the Pacific Ocean between the towns of Ventura and Oxnard (Figure 1). After descending from its mountainous headwaters, the river passes through the northern Los Angeles suburb of Santa Clarita, across the Los Angeles/Ventura County line, then transitions to the mostly agricultural valley with a series of small towns, and finally discharges to the ocean. All major tributaries flow from the north and include (from upstream to downstream) Bouquet Canyon, San Francisquito Canyon, Castaic, Piru, and Sespe Creeks. Sespe Creek lies in a relatively wet zone of the watershed and has a 100-yr peak that is about 60% of the mainstem peak even though the Sespe area is only 16% of the total. There are four major reservoirs within the tributary system. Pyramid and Castaic Reservoirs are part of the State Water Project (SWP) system and are operated by the California Department of Water Resources (CDWR). Pyramid is located on Piru Creek while Castaic is located on Castaic Creek, but the two are hydraulically connected. State water is sent through the William E. Warne Power plant into Pyramid Lake, through the Angeles Tunnel into the Castaic Power plant, and then into Castaic Lake, terminus of the West Branch of the SWP. Piru Reservoir is run by the United Water Conservation District (UWCD) and is located on Piru Creek below Pyramid Lake. UWCD's primary operational goals are groundwater recharge, public recreation, and power generation.

The watershed drainage area is about 4,263 square km, ninety percent of which consists of rugged mountains, ranging up to 2,700 meters high. Los Padres and Angeles National Forests, home to most of the major northern tributaries, comprise 47% of the watershed area. The remaining ten percent of the drainage area lies on the valley floor and coastal plain with the main stem of the Santa Clara River. The watershed is surrounded to the north, east, and south by largely undeveloped hills and canyons. The watershed is subject to severe flooding and erosion. The SCR watershed areas to be modeled in this study are shown in Figure 1 along with major waterbodies, municipalities, and other prominent features.

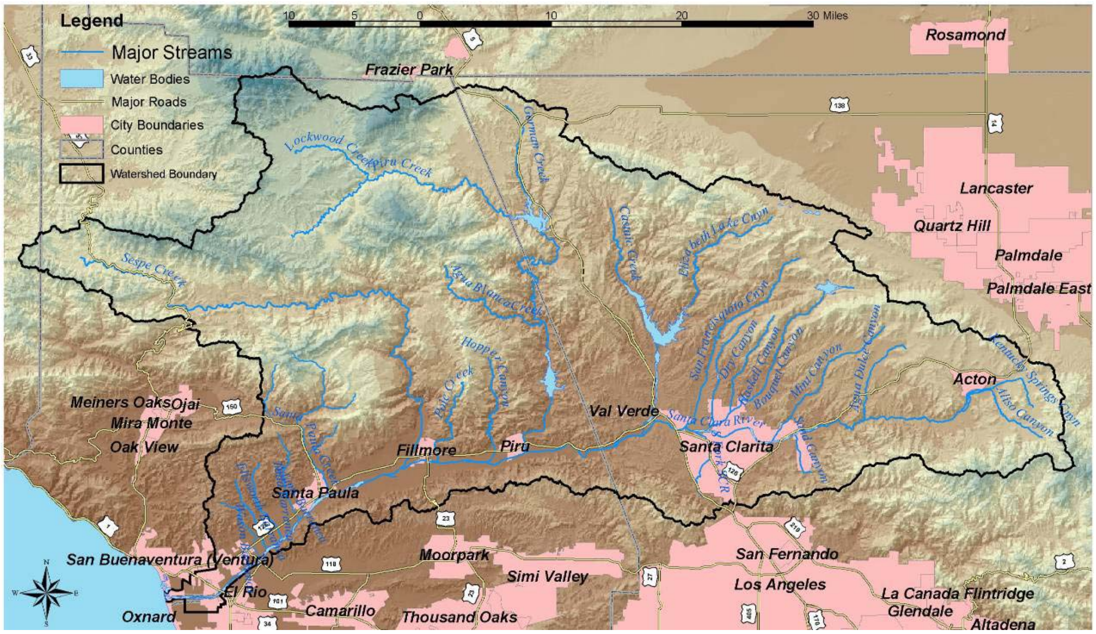

Figure 1. Santa Clara River Watershed, municipalities, and major waterbodies

One of the goals of this effort is to provide the capability to perform long-term simulations in order to assess the impacts of alternative conditions – Baseline, Natural (pre-development) Condition, Alternative Future Conditions (e.g., land use, facilities, reservoir operations) - on flow and flood frequencies. A long-term data base of 46 years of model input data (precipitation, evaporation, diversions, POTWs, etc.) with the most critical being precipitation and evaporation was developed. This data base supported long-term model runs to analyze and compare flow and flood frequencies of Natural, Current Baseline, and planned studies for Alternative Future conditions.

In addition, the model was used to generate storm event hydrographs for selected return intervals with synthetic input rainfall hyetographs for the corresponding rainfall return period developed from available rain gage data. This was performed by VCWPD and LACDPW for selected tributary and mainstem sites. The results were used by FEMA for the currently underway Flood Insurance Study update.

MODEL DEVELOPMENT

Segmentation. Subwatersheds were defined using GIS procedures and a number of data sources, including NHDPlus, Digital Elevation Models of 10 meter resolution, and GIS shapefiles of Los Angeles and Ventura Counties containing previously delineated subbasin boundaries within the more urbanized and flatter areas of the counties. The primary factors that produced the preliminary segmentation also included rain gage locations, Thiessen network boundaries, isohyetal contours, differences in slope and elevation, locations of stream gages, mainstem bridges, and locations of debris basins. The final model segmentation (Figure 2) consists of 209 model subwatersheds and 192 stream reaches.

Each model reach segment was analyzed to define its hydraulic behavior by a hydraulic function table, which defines the flow rate, surface area, and volume as a function of water depth. The function tables for the streams and rivers within the SCR Watershed model application were developed using HEC-RAS and DEMs of varying resolution. The resolution of the DEMs ranged from 5 meters in Los Angeles County to 30 meters in the mountainous northern parts of Ventura County, where less resolution was required to define the channel. Function tables for the reservoirs and lakes were developed using stage-storage and stage-surface area relationships provided in tables and figures from a variety of sources.

Since land use affects the hydrologic response of a watershed by influencing infiltration, surface runoff, and water losses from vegetal evapotranspiration, each model segment was segmented further based on land use. The SCR Watershed is a mix of urban and agricultural lowlands and upland open areas, with the latter comprising approximately 87% of the total area. Agriculture covers 4% of the watershed, concentrated along the river valley. The urban areas, including Santa Clarita, Piru, Fillmore, Santa Paula, and Ventura, are comprised of commercial/industrial, medium to high-density residential, and low-density residential areas. The primary land use coverage used in the SCR Watershed model is based on the Southern California Association of Governments (SCAG) land use designations, with coverages corresponding to land use conditions for 1990, 1993, 2001, and 2005. Although the SCAG land use data provided a reasonable mix of urban categories for the model, both the agriculture and the large upland open area groups needed better definition in order to allow their representation and contributions within the model. These areas were differentiated into categories that can better define the actual vegetation types and their characteristics using the LANDFIRE Rapid Assessment “Potential Natural Vegetation Group” coverage. Using the SCAG and LANDFIRE coverages, the final set of land uses incorporated in the model were forest/woodland, shrubland, open/grass, agriculture, low density residential, medium density residential, high density residential, and commercial/industrial.

Reservoirs. The major reservoirs (Pyramid, Piru, and Castaic) were modeled by simulating the natural runoff inputs, and defining daily interbasin transfers (i.e., imports) and reservoir releases based on observed data compiled by CADWR (2007) and USGS. Most of the imported water is ultimately used for water supply, and does not flow downstream. During calibration, the natural inflows were calibrated to maintain observed storages or water levels in the reservoirs. For the natural scenario, the reservoirs were removed and replaced with free-flowing reaches. For the Baseline Scenario – which was prior to the compilation of transfers and outflows by CADWR – a reservoir operation rule was used to compute the outflows based on simulated natural inflows.

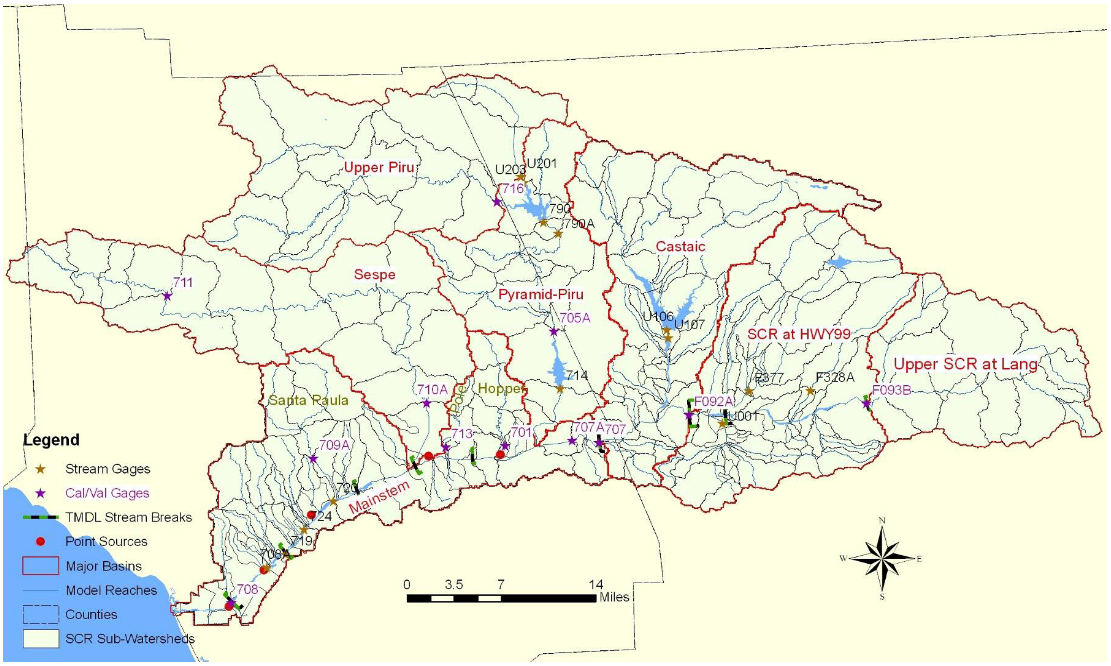

Figure 2. SCR watershed model segmentation, showing major basins and streamflow calibration locations

Rainfall and Evaporation Data. Rainfall data was developed from a database of more than 100 stations operated by Ventura and Los Angeles counties and the National Weather Service. The rainfall data development and correction task required filling-in missing data, performing QA/QC, and disaggregating daily data to hourly utilizing nearby hourly stations. The final model database consisted of 35 of these stations, which were assigned to model segments using Thiessen analysis and isohyetal information.

Evaporation data in the form of potential evapotranspiration (PET) were developed from 27 stations in and near the watershed. Most of the data were monthly totals, which were distributed to daily values using a long term daily station at Lake Cachuma, in Santa Barbara County. The PET data were further disaggregated to hourly values with a distribution function based on the pattern of daylight at the latitude of the watershed. The database was extended back to 1956 for long term runs. The final PET dataset consisted of 12 stations distributed across the watershed.

Snow. Due to the high elevations in the upper watershed, snow accumulation and melt was modeled for selected model segments in the upper Sespe and Piru Creek watersheds where significant snowfall is common. Since HSPF allows use of an optional degree-day method to simulate snow, hourly air temperature time series were required as inputs to the snow model. A database of air temperature was developed, using observed data and adjustments for elevation, where necessary.

Irrigation. The Santa Clara River watershed includes significant areas of agricultural and developed residential land, so the model considers both urban and agricultural irrigation applications for a complete water balance accounting. The approach assumed that water was applied to satisfy monthly crop and lawn evapotranspiration (ET) demands exceeding available rainfall. ET demands were computed using the "landscape coefficient" method described in the CADWR (2000) manual Water Use Classifications of Landscape Species. Daily reference ET (ETo) is given by month for each climate zone in the state. The SCR watershed is spread across a range of ETo zones, transitioning from the South Coast Marine to inland desert climates. Weighted crop coefficients were applied, and the amounts were adjusted to account for application efficiency.

Diversions and Point Sources. Several diversions and point sources were included in the model. Six diversions, including two sizable ones were defined; they are primarily used for groundwater recharge and agricultural irrigation. Most irrigation is derived from deep groundwater, and was not explicitly accounted for as diversions. Of the nine WWTP's in the watershed, only one discharges directly to the river.

Groundwater. The HSPF model represents groundwater as both a shallow, active groundwater storage that can contribute directly to streamflow (baseflow), and a deep, inactive storage that represents deep aquifers that do not contribute to streamflow. The flux into the inactive storage is represented as deep recharge. Both of these groundwater components are evaluated as part of the model calibration process and the water balance assessment.

In the SCR watershed, groundwater provides much of the water for human use through pumping from an extensive network of alluvial aquifers and the Saugus Formation in the river valley, thereby transforming deep, inactive groundwater in the HSPF model into surface water. Most of the extracted groundwater (> 90%) is used for agricultural irrigation. In this model, it was assumed that most agricultural irrigation water was derived from deep aquifers and/or local channel losses recharging the shallow alluvial aquifers. The model explicitly includes deep recharge and irrigation applications. These quantities were compared to available annual estimates for these fluxes in order to improve the accuracy of the modeled water balance.

Another groundwater-surface water interaction issue is the presence of recharge and discharge zones along the SCR channel. Areas of rising groundwater and recharge are observed at a number of locations in the watershed as shown in Figure 3. Literature documenting recharge and discharge zones of the Santa Clara River, including the model developed by McEachron (2005), was used as the basis for modeling channel gains and losses in various reaches on the mainstem and tributaries.

CALIBRATION AND VALIDATION

Model calibration and validation followed a 'weight-of-evidence' approach involving multiple graphical and statistical model-data comparisons for a comprehensive assessment of overall model performance (see Study Report, AQUA TERRA Consultants, 2009). Model parameterization was initially derived from the prior local HSPF applications, with subsequent adjustments as part of the calibration process.

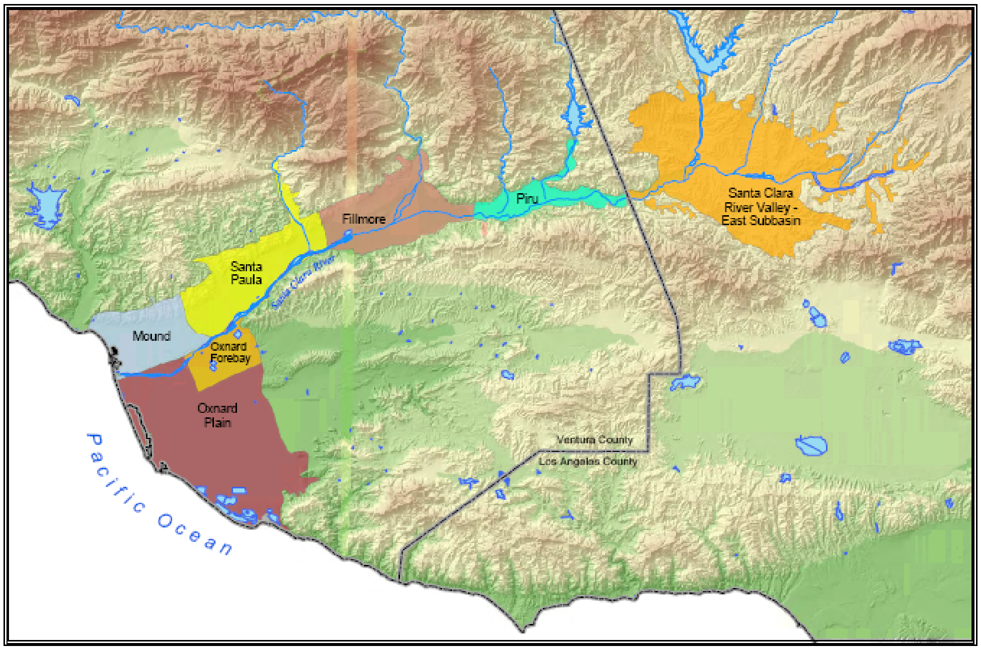

Figure 3. SCR ground water basins (from Luhdorff & Scalmanini, 2005)

Parameter adjustments focused primarily on lower zone storage and infiltration parameters, as a function of soils, land use, and slope conditions, to obtain reasonable overall water balances. Adjustments to the interflow and baseflow parameters were made to improve agreements in the flow duration curves, daily time series, and storm events. The groundwater recession and groundwater ET-related parameters are usually watershed specific, as they are a function of local groundwater and riparian conditions; therefore, they were calibrated to local conditions in each watershed.

Calibration and validation periods were based on the available meteorological, streamflow, and land use data. The data supported model simulations spanning water years (WY) 1987 through 2005; therefore, the calibration period was WY 1997-2005, and the validation period was WY 1987-1996. The later time span was selected for calibration because it covers a wider range of wet and dry years, it includes the most extensive coverage for POTW and diversion data, and it provides a starting point for future conditions. Land use coverages were available for 2001 and 1993, and so these coverages were used for the calibration and validation periods, respectively.

The approach to calibrating the watershed hydrology initially focused on the relatively natural, undeveloped areas in the upper portions of the watershed in both counties in order to provide the best estimate of hydrologic parameters without the complicating issues of irrigation, water regulations, importations, and channel losses. The major calibration/validation sites and watersheds are shown in Figure 2. Figures 4a and 4b show flow duration plots for the mainstem gage at the Ventura-Los Angeles County line for the calibration and validation periods, respectively. Figure 5 shows the hydrograph of a major storm event at the basin outlet gage near Montalvo.

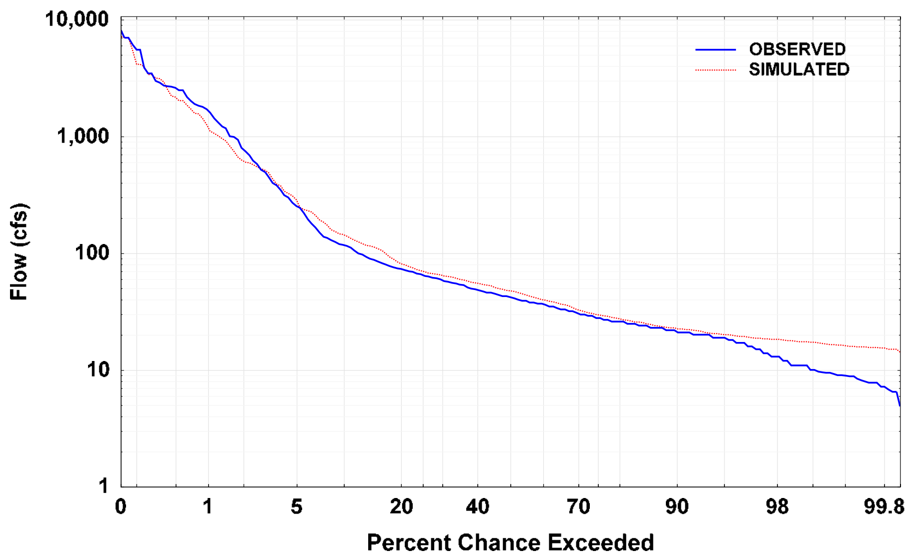

Figure 4a. Flow duration curves for SCR at County Line – calibration period

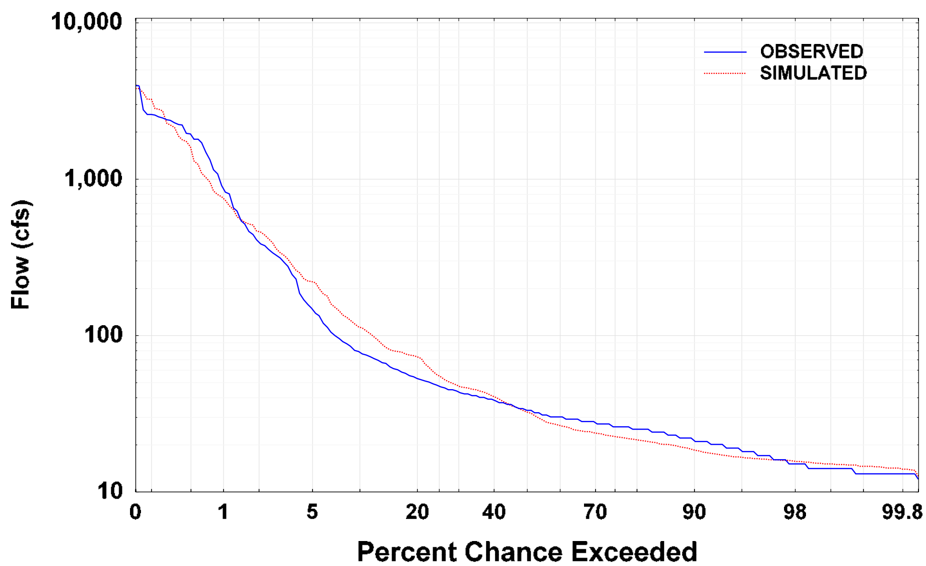

Figure 4b. Flow duration curves for SCR at County Line – validation period

Table 1 shows the 'Weight-of-Evidence' summary of the model performance metrics for the calibration and validation periods, providing the mean and range of the metrics at the various gage sites. The last column provides the qualitative assessment of the overall model performance based on how the statistical means and ranges compare to the targets proposed in the Project Plan. The model results show a range of model accuracy but the majority of the metrics show a Good-Very Good model performance. The SCR HSPF model was judged to be a robust representation of the hydrologic regime, and a viable tool for watershed management purposes.

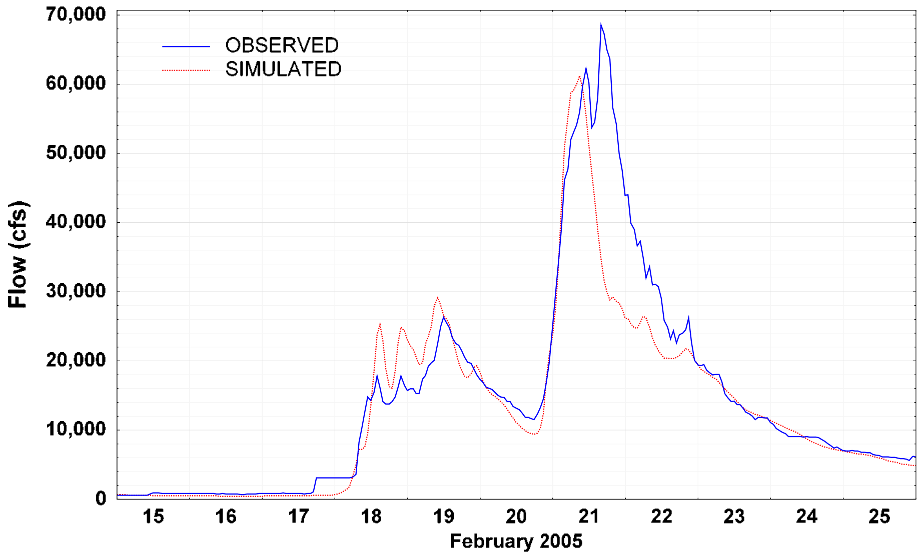

Figure 5. Hydrograph of February 2005 storm for SCR at Montalvo

Table 1. Weight-of-Evidence for SCR Watershed Model Performance

	Calibration		**Validation**		**Overall Model Performance**
	Mean	**Range**	**Mean**	**Range**	
Runoff Volume, % Δ	2.0	-7.8 - 11.8	2.7	-5.8 / 7.0	Good / Very Good
Correlation Coefficient, R:					
- Daily R	0.91	0.74 - 0.96	0.89	0.85 - 0.97	Fair / Very Good
- Monthly R	0.97	0.91 - 0.99	0.97	0.96 - 0.99	Very Good
Coefficient of Determination, R^2:					
- Daily R^2	0.82	0.55 - 0.92	0.80	0.72 - 0.94	Poor / Very Good
- Monthly R^2	0.94	0.82 - 0.99	0.94	0.92 - 0.98	Very Good
Flow-Duration	Good / Very Good		Fair / Good		Fair / Very Good
Water Balance	Good / Very Good		Good / Very Good		Good / Very Good
Storm Events:					
- Daily Storm Peak, % Δ	-6.6	-35.9 - 20.1	-7.6	-13.4 - 9.5	Fair / Very Good

SIMULATIONS OF BASELINE AND NATURAL CONDITIONS AND FLOOD ANALYSES

The long term (46 year) database of meteorologic data and other inputs was used to make long term simulations of the baseline/existing conditions and natural conditions. For the existing run, the most recent land use dataset was used, and the reservoirs for the time prior to the validation period was modeled using a set of operation rules based on knowledge of the system. In the natural run, urban and agricultural land was converted to the natural categories, and the reservoirs, irrigation, point sources and diversions were removed from the model.

The calibrated model was also used as the basis for generating design storm peaks and hydrographs for use in a hydraulic modeling study performed by the clients. The approach involved identifying a storm where saturation levels were very high across the watershed and then applying balanced design storm hyetographs for the 100-yr storm for each rain gage used in the HSPF model. The gaged tributaries with long-term records were used as calibration points in the modeling. The calibration was done by adjusting the rainfall factors applied to the rain data for each subarea and associated reach at the calibration points to establish corresponding rainfall factors that could then be applied to ungaged tributaries. The model provided 100-yr peaks at the calibration location that were within 10% or better of the results based on analyses of historic annual peak maxima. The model was then run with the appropriate rainfall distributions at 5-min timesteps for the storm of interest to provide 100-year design storm peaks at the ungaged tributaries. The 100-year peaks were converted to other return intervals of interest by using multipliers developed from flow frequency analyses of long-term Ventura County and Los Angeles County stream gages.

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