UCSB NORTH CAMPUS OPEN SPACE RESTORATION PROJECT

Hydrologic Modeling Report

Prepared for
University of California Santa Barbara

June 2016

UCSB NORTH CAMPUS OPEN SPACE RESTORATION PROJECT

Hydrologic Modeling Report

Prepared for
University of California Santa Barbara

June 2016

550 Kearny Street
Suite 800
San Frnacisco, CA 94108
415.262.2300
www.esassoc.com

Los Angeles

Oakland

Olympia

Petaluma

Portland

San Francisco

San Diego

Seattle

Tampa

Woodland Hills

D140769.00

TABLE OF CONTENTS

List Of Tables

List of Figures

1 STUDY PURPOSE AND BACKGROUND

ESA is conducting analysis for the University of California, Santa Barbara to assess key physical processes in Devereux Slough (Slough) as part of the North Campus Open Space Restoration Project (Project). Fresh water inflow from the upper watershed is an important driver of hydrologic and geomorphic processes in the Slough. To support the development of a Quantified Conceptual Model (QCM) of Slough dynamics, ESA developed a continuous-simulation hydrologic model to simulate several years of flows from the upstream watershed into the Slough using the USACE's HEC-HMS (HMS) model version 4.1. This report describes the development, calibration and results of the hydrologic model. .

The Devereux Slough watershed drains approximately 3.62 square-miles. Approximately 0.98 square miles (27%) of the watershed is developed, impervious area, with the remaining approximately 3.35 square miles (73%) comprised of undeveloped or developed pervious area such as open space parks and lawns. Much of the pervious area is located in the relatively steeper Goleta hills in the upper portion of the watershed. Mean annual rainfall is approximately 16.8 inches. The two primary flowpaths draining to the Slough are Phelps Creek (also called El Encanto Creek and Phelps Ditch), and Devereux Creek. Phelps Creek drains from the north, out of steep canyons in the upper part of the watershed, passes under Highway 1 in the City of Goleta and terminates in Devereux Slough at the Pacific Ocean. Devereux Creek drains from the west out of the Sandpiper Golf Club to its confluence with Phelps Creek, approximately 2,000 feet upstream of Venoco Road. The watershed soils are typically sandy loams with low infiltration rates (NRCS, 2011; MRLC, 2015).

The continuous-simulation hydrologic model was parameterized using the Soil Moisture Accounting (SMA) routines in HMS to characterize rainfall infiltration and subsurface soil storage and conveyance. The SMA parameters include surface and canopy interception, evapotranspiration rate, soil infiltration rates and soil storage, and percolation and conveyance parameters for one shallow and one deep groundwater layer. Accounting for soil moisture is important when conducting continuous simulation modeling as antecedent moisture conditions play a significant role in watershed runoff response when several months or years are being simulated for a wide range of storm event sizes.

Many of the initial soil and landcover parameters were estimated using a combination of the National Resources Conservation Service's Soil Survey Geographic (SSURGO – NRCS, 2011) geospatial datasets and the Multi-Resolution Land Characteristic Consortium's 2011 version of the National Landcover Dataset (NLCD – MRLC, 2015). Parameters were then optimized manually and using HMS internal automation routines to calibrate the HMS model to measured data from the Devereux Creek flow gage (DV01) which was operated from 2003-2006 by the Santa Barbara Coastal Long Term Ecological Research (LTER) project. The results of the model calibration and validation are summarized below:

1. The HMS model generated similar results to measured data for the calibration period (December 2004 – March 2005). With respect to six performance metrics, the model

performance was good to very good for four metrics and satisfactory for two metrics. The Nash-Sutcliffe efficiency score, a key metric for hydrologic model calibration, was 0.653.

2. The model also performed well for the validation period (February 2006 – May 2006). Performance was very good for four metrics and satisfactory for two metrics. The Nash-Sutcliffe efficiency score was 0.754.
3. Model results consistently overestimated flows relative to the measured flow for smaller rainfall-runoff events. This may be a result of inadequate characterization of flow routing in the model, lacking data to characterize the rainfall inputs, or uncertainty in the rating curve for the streamflow gage. Each of these potential issues is discussed further in the report under Section 3.1.

The following report sections provide detailed information on the model development, results, conclusions, and next steps.

2 HYDROLOGIC MODEL DEVELOPMENT

The hydrologic model was developed in HEC-HMS (version 4.1) using the soil moisture accounting and linear reservoir routing procedures necessary for conducting continuous, rather than event-specific, hydrologic modeling. The soil moisture accounting procedure is diagrammed in the HEC-HMS technical reference manual (USACE, 2000) and is reproduced below (Figure 1).

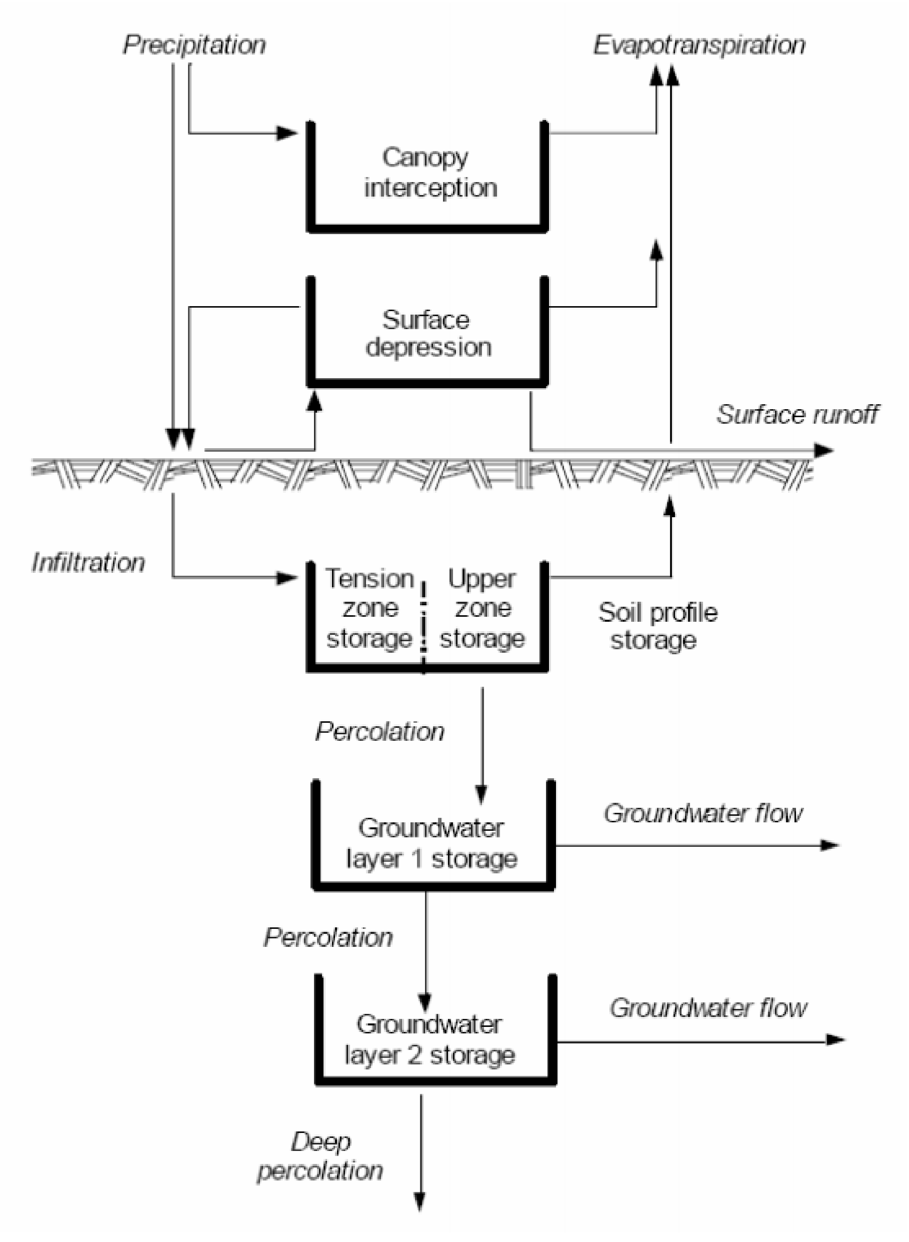


Figure 1. HEC-HMS soil moisture accounting flowchart

The model was developed using the ArcHydro and GeoHMS toolbars for ArcGIS (version 10.2) which enable automatic parameter development and data transfer from a geospatial environment into HMS. The primary components of the model developed using these tools included subbasin delineation, rainfall and evapotranspiration inputs, transformation of the effective (i.e. not infiltrated or intercepted) rainfall into a surface flow hydrograph, surface and canopy interception, soil moisture accounting, baseflow, and channel routing. The methods used to develop these components are described in the following sections.

2.1 Subbasin Delineation

The GeoHMS toolbar was used to automatically delineate subbasins based on underlying topography. Two topographic data sources were combined to cover the full drainage basin (1) 2009/2010 1-meter NOAA coastal LiDAR which covers the coastline to approximately Highway 1, and (2) 2013 USGS 10-meter raster topography from the National Elevation Dataset. Though GIS routines can be used to automatically delineate subbasins based on surface topography, this method does not always capture flow routing through the stormwater collection system. A polyline layer of storm sewers and inlets provided to ESA by the City of Goleta in February, 2016, was combined with the topography to characterize the routing within drainage areas and outfall locations in the natural channels. Finally, smaller subbasins were merged in GIS in some locations to reduce unnecessary discretization while ensuring the model captured major subbasins and junction locations. The hydrologic model layout including the final subbasins, underlying topography and the City storm drain network is shown in Figure 2.

2.2 Rainfall and Evapotranspiration

Rainfall and evapotranspiration time series data for the simulation period are required as inputs to the HEC HMS model. Several rainfall gages were assessed with respect to watershed proximity, elevation, and period of record, and ultimately two gages were selected to represent rainfall and one gage was selected to represent evapotranspiration. The model simulation period extends from October 1, 2000, to October 1, 2014 which is the period for which a full record of rainfall data is available at the gages used for modeling.

The gage characteristics are summarized in Table 1.

TABLE 1
CHARACTERISTICS FOR GAGES USED IN HYDROLOGIC MODELING

Gage name	Source	Latitude	Longitude	Mean Annual Rainfall[1]	Data used
Goleta Foothills #94	CIMIS	34.471333	119.86929	25.03	Precipitation, Evapotranspiration
LTER[2] 200	UCSB	34.415	119.846	18.49	Precipitation

[1] PRISM, 2010

[2] Santa Barbara Coastal Long Term Ecological Research (LTER) project

SOURCE: Aerial (NAIP 2014), Model Data (ESA 2016)

UCSB North Campus Open Space Restoration Project, Hydrologic Modeling . D140769.01

Figure 2
Hydrologic model development for Devereux Slough

Two forms of spatial weighting were applied to extrapolate rainfall measured at the gages to rainfall within each subbasin: (1) weighting between multiple gages based on Theissen polygons delineated around each gage, and (2) weighting to account for differences in mean annual precipitation (MAP) between the gage location and the subbasin. The Theissen weighting determined which gage record (or set of records) was applied to each subbasin, based on proximity. The MAP weighting was used to adjust gage data based on the ratio of subbasin MAP to the measured depth at the contributing gage(s). The MAP for each subbasin and rainfall gage was derived from the geospatial dataset of MAP based on gage data from 1981-2010 developed by the PRISM climate group based at Oregon State University (PRISM, 2010). This dataset was also used by NOAA as the basis for MAP in their latest rainfall Atlas for the United States—Atlas 14 (NOAA, 2011). A map of the rainfall gages, mean annual rainfall, and Theissen polygons is shown in Figure 3.

Theissen polygons contain the area that is closest to each individual gage point relative to the location of each of the other gages. The Theissen polygon for a particular gage represents the area over which that gage provides the best measure of rainfall (due to its proximity). Theissen polygons were delineated for the two gages using the ET GeoWizards toolbar (version 11.0) in GIS. The polygons were then intersected with the subbasins. The polygons are shown in Figure 3. The weight assigned to each gage was calculated by the fraction of subbasin area overlapping the Theissen polygon for a given gage. This computation is expressed in the following equation:

$$P_{SB} = P_{G1} * \frac{A_{G1}}{A_{SB}} + P_{G2} * \frac{A_{G2}}{A_{SB}} + \cdots + P_{Gn} * \frac{A_{Gn}}{A_{SB}} \qquad \text{(Equation 1)}$$

Where, P_{SB} is the computed rainfall at a subbasin (in)
P_{Gn} is the observed rainfall for gage n (in)
A_{Gn} is the coincident area of the subbasin and the Theissen polygon for gage n (ac)
A_{SB} is the area of the subbasin (ac)
n is the number of gages (in this case two)

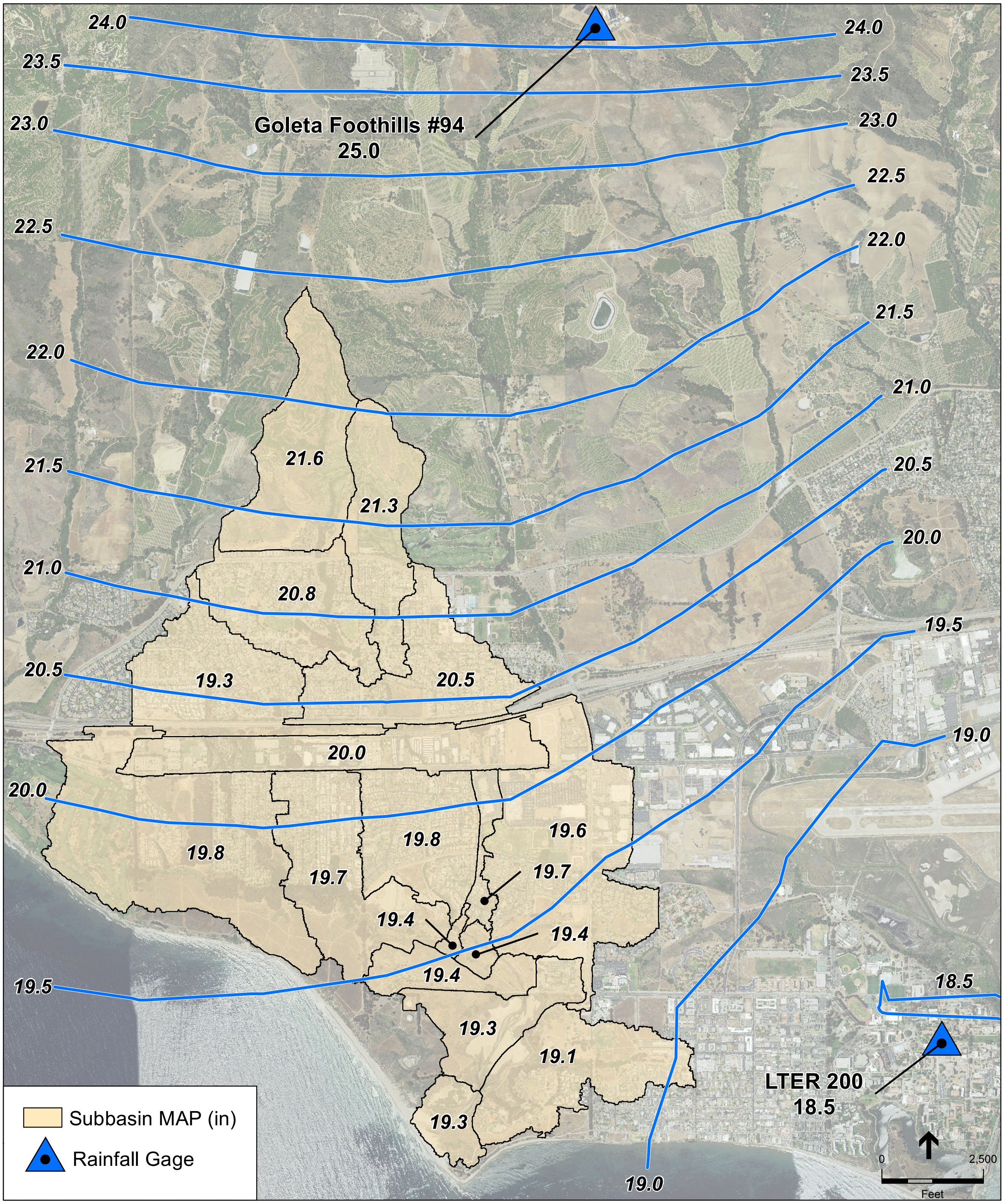
The weighted gage data were then adjusted to reflect differences in MAP between the gage location and the subbasin. The spacially weighted gage rainfall was multiplied by the MAP for a subbasin and then divided by the MAP for the gage.

The MAP weighting is expressed in the following equation:

$$P = P_{SB} * \frac{MAP_{SB}}{MAP_{G1}} + P_{SB} * \frac{MAP_{SB}}{MAP_{G2}} + \cdots + P_{SB} * \frac{MAP_{SB}}{MAP_{Gn}} \qquad \text{(Equation 2)}$$

Where, P is the spatially weighted rainfall for a subbasin (in)
MAP_{SB} is the mean annual precipitation for the subbasin (in)
n is the number of gages
MAP_{Gn} is the mean annual precipitation for gage n (in)

The gage weighting factors for the Theissen polygons and MAP are summarized in Table 2.



SOURCE: MAP (PRISM); Gage (USGS); Theissen (ESA 2016)

UCSB North Campus Open Space Restoration Project, Hydrologic Modeling . D140769.01

Figure 3

Rainfall gages, mean annual rainfall, and Theissen polygons for Devereux Slough watershed

TABLE 2
RAINFALL GAGES USED FOR HYDROLOGIC MODELING

Basin	Theissen weight		MAP (in)
	Goleta Foothills #94	LTER 200	
SB_DCREEK1	0.003	0.997	19.68
SB_DCREEK2	0.44	0.56	19.79
SB_DEV_DS1	0.00	1.00	19.29
SB_DEV_DS2	0.00	1.00	19.14
SB_DEV_DS3	0.00	1.00	19.32
SB_DEV_DS3	0.00	1.00	19.32
SB_DEV_DS4	0.00	1.00	19.38
SB_DEV_DS5	0.00	1.00	19.61
SB_DEV_DS6	0.00	1.00	19.37
SB_DEV_DS7	0.00	1.00	19.65
SB_DEV_DS8	0.00	1.00	19.41
SB_DEV_US1	0.43	0.57	19.80
SB_DEV_US2	0.99	0.01	20.04
SB_DEV_US4	0.75	0.25	20.51
SB_DEV_US5	1.00	0.00	21.28
SB_DEV_US6	1.00	0.00	20.80
SB_DEV_US7	1.00	0.00	21.58

The rate of evapotranspiration in the watershed has an impact on the soil moisture conditions during periods of low or zero rainfall. To capture this, monthly average evapotranspiration was applied for the full basin based on measured pan evapotranspiration values at the CIMIS Goleta Foothills gage. A uniform crop coefficient of 0.7 was applied based best available information from the literature. The crop coefficient is multiplied by the evapotranspiration to account for plant uptake during various seasons. The monthly evapotranspiration rates are summarized in Table 3.

TABLE 3
MONTHLY AVERAGE EVAPOTRANSPIRATION RATES AT CIMIS GOLETA FOOTHILLS #94

Month	Evapotranspiration (inches/month)	Crop Coefficient
Jan	2.35	0.7
Feb	2.68	0.7
Mar	3.87	0.7
Apr	4.86	0.7
May	5.33	0.7
Jun	4.75	0.7
Jul	5.41	0.7
Aug	5.43	0.7
Sep	4.5	0.7
Oct	3.61	0.7

Month	Evapotranspiration (inches/month)	Crop Coefficient
Nov	2.71	0.7
Dec	2.09	0.7

2.3 Transformation

HEC HMS calculates the fraction of rainfall that is not intercepted or infiltrated (referred to as "excess rainfall") and converts it to a flow rate using one of several transformation methods. Santa Barbara County uses a simplified method for transformation referred to as the Santa Barbara Urban Hydrograph (SBUH) method (Santa Barbara County, 2011). The SBUH is a simplified version of the Soil Conservation Service's (SCS) unit hydrograph methodology (NRCS, 1986). The SBUH method is not available in HEC-HMS; thus the SCS unit hydrograph method was selected. The SCS unit hydrograph equation relates flow to rainfall through a lag time (T_L) parameter which is calculated for each subbasin using the following equation:

$$T_L = \frac{L^{0.8}\left(\left(\frac{1000}{CN}-10\right)+1\right)^{0.7}}{1900(S)^{0.5}} \qquad \text{(Equation 3)}$$

Where L is the length of the longest drainage path in the subbasin (ft)
CN is the SCS Curve Number value for the subbasin (-)
S is the watershed slope (%)

The drainage path length and watershed slope for each subbasin were calculated using GeoHMS. The CN is a function of the land cover and soil conditions within each basin. ESA used 2011 landcover and impervious percent datasets from the National Landcover Dataset (NLCD) developed by the Multi-Resolution Land Characteristics Consortium (MRLC, 2015) and soil data from the NRCS Soil Survey Geographic (SSURGO) database for Santa Barbara County (NRCS, 2011). The CN method characterizes soil type by Hydrologic Soil Group (HSG) which represents the infiltration capacity of the soil. HSG groups A, B, C, and D are organized in order of decreasing infiltration rates and increasing runoff potential. The SCS curve numbers for land use categories and HSGs are outlined in Technical Release No. 55 (TR-55) (NRCS, 1986). ESA organized the NLCD land use categories into TR-55 categories as summarized in Table 4.

TABLE 4. CURVE NUMBERS FOR NLCD AND EQUIVLANET SCS CATEGORY

NLCD Land Category[1]	Equivalent SCS Category[2]	HSG			
		A	B	C	D
Barren Land	Fallow - Bare Soil	77	86	91	94
Cultivated Crops	Row Crops – Straight, good condition	67	78	85	89
Deciduous Forest	Woods - Good	30	55	70	77
Developed, High Intensity	Urban – Commercial	89	92	94	95
Developed, Medium Intensity	Residential, 1/8 acre or less	77	85	90	92

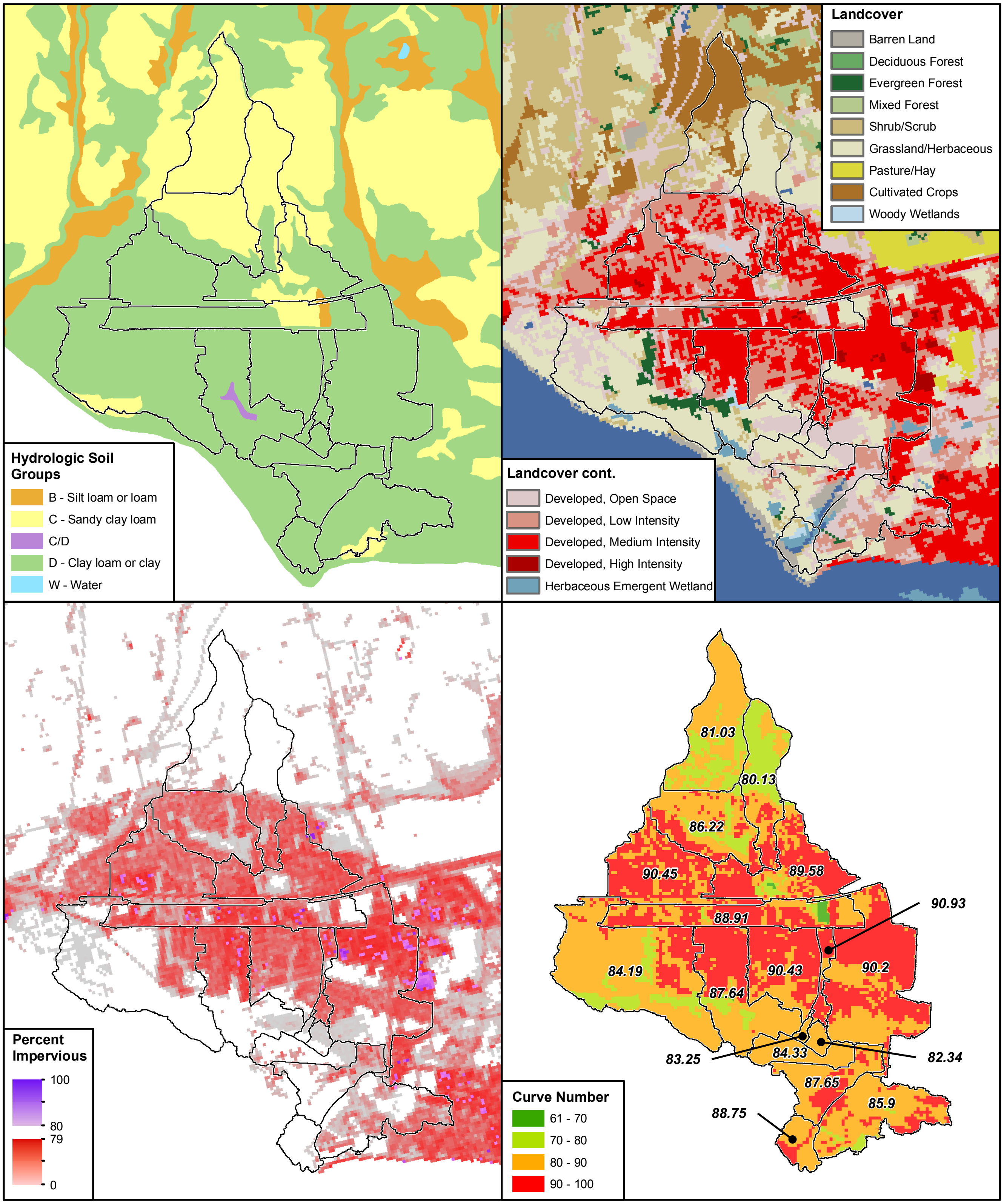
NLCD Land Category[1]	Equivalent SCS Category[2]	HSG			
		A	B	C	D
Developed, Low Intensity	Residential, ½ acre lot	54	70	80	85
Developed, Open Space	Open Space, Good	39	61	74	80
Emergent Herbaceous Wetlands	Wetland[3]	90			
Evergreen Forest	Woods - Good	30	55	70	77
Hay/Pasture	Pasture, Grassland, Good	39	61	74	80
Herbaceous	Herbaceous, Good	62	62	74	85
Mixed Forest	Woods - Good	30	55	70	77
Open Water	Water[4]	100			
Shrub/Scrub	Desert Shrub, Fair	55	72	81	86
Woody Wetlands	Wetland[3]	90			

[1] NRCS, 2015
[2] NRCS, 1986
[3] NRCS does not have a wetland class
[4] NRCS does not have a class for water

The CN was calculated for each intersection of land use category and HSG and an area weighted curve number was calculated for each subbasin. A map of the CNs and component parameters is shown in Figure 4. The parameters for the SCS unit hydrograph are summarized in Table 5.

TABLE 5. SCS UNIT HYDROGRAPH PARAMETERS

Basin	CN	L (ft)	S (%)	T_L (hr)	T_L (min)
SB_DCREEK1	87.64	7309	0.9%	1.27	76.15
SB_DCREEK2	84.19	8205	1.3%	1.32	79.18
SB_DEV_DS1	88.75	2577	1.0%	0.51	30.38
SB_DEV_DS2	85.90	5690	0.6%	1.32	79.11
SB_DEV_DS3	87.65	5070	0.6%	1.16	69.49
SB_DEV_DS4	84.33	4267	1.5%	0.72	43.06
SB_DEV_DS5	90.20	9751	0.6%	1.76	105.81
SB_DEV_DS6	82.34	1300	1.2%	0.33	20.01
SB_DEV_DS7	90.93	4344	0.8%	0.80	48.05
SB_DEV_DS8	83.25	926	1.8%	0.20	12.09
SB_DEV_US1	90.43	4947	1.2%	0.72	43.02
SB_DEV_US2	88.91	7145	1.2%	1.01	60.55
SB_DEV_US3	90.45	7460	1.5%	0.89	53.34
SB_DEV_US4	89.58	6768	1.4%	0.90	53.77
SB_DEV_US5	80.13	6347	5.4%	0.60	35.85
SB_DEV_US6	86.22	5512	3.0%	0.58	34.90
SB_DEV_US7	81.03	5944	7.6%	0.46	27.83



SOURCE: Landcover (NLCD 2011), Soils (NRCS 2011)

UCSB North Campus Open Space Restoration Project, Hydrologic Modeling . D140769.01

Figure 4

Soils, Landcover, Imperviousness, and Curve Number for Devereux Slough

2.4 Surface and Canopy Interception

A fraction of rainfall is intercepted and stored in surface depressions and on vegetation. This is represented in the model by a total volume of available surface and canopy storage in each basin. Relationships between surface slope and surface storage were presented by Fleming (2002) and are summarized in Table 6.

TABLE 6. SURFACE SLOPE AND DEPRESSIONS

Category	Slope (%)	Surface Storage (in)
Paved impervious area	NA	0.125-0.25
Flat, furrowed land	0-5	2
Moderate to gentle slopes	30-May	.25-.5
Steep, smooth slopes	>30	0.04

The NLCD 2011 impervious layer was intersected with a watershed slope raster generated in GIS and surface storage was computed for each basin. For canopy interception, ESA used the relationship between vegetation type and interception volume presented with the NLCD land use data as described by Holberg (2014) and summarized in Table 7.

TABLE 7. CANOPY INTERCEPTION FOR NLCD VEGETATION CATEGORIES

Type of Vegetation	Canopy Interception (in)
General Vegetation	0.05
Grasses and Decisuous Trees	0.08
Trees and Coniferous Trees	0.1

The relationships in Table 6 and Table 7 were used to map surface depression and canopy interception storage values throughout the basin. Area weighted composite values were calculated for each basin. The calculated values are summarized in Table 8.

TABLE 8. SURFACE DEPRESSION AND CANOPY INTERCEPTION FOR SUBBASINS

Basin	Canopy Interception (in)	Surface interception (in)
SB_DCREEK1	0.06	0.57
SB_DCREEK2	0.07	0.40
SB_DEV_DS1	0.07	0.63
SB_DEV_DS2	0.06	1.08
SB_DEV_DS3	0.06	0.54
SB_DEV_DS3	0.07	0.62
SB_DEV_DS4	0.05	0.45
SB_DEV_DS5	0.06	1.42
SB_DEV_DS6	0.05	0.33
SB_DEV_DS7	0.07	1.01

SB_DEV_DS8	0.05	0.31
SB_DEV_US1	0.05	0.48
SB_DEV_US2	0.05	0.32
SB_DEV_US4	0.05	0.43
SB_DEV_US5	0.07	0.22
SB_DEV_US6	0.05	0.32
SB_DEV_US7	0.08	0.13

2.5 Soil Moisture Accounting

Rainfall that is not directly converted to surface runoff or stored in surface depressions and canopy storage infiltrates into the soil and is stored or conveyed in the subsurface. As shown in the soil moisture accounting flowchart above, the subsurface is divided into three layers, (1) a top soil layer which includes an upper zone and a tension storage zone, (2) a shallow groundwater layer (GW1) which conveys interflow, and (3) a deep groundwater layer (GW2) which conveys baseflow. The parameters for each of these layers were calculated spatially in GIS and a lumped parameter was assigned to each subbasin. The NRCS SSURGO data was used to calculate the following parameters:

- **Maximum infiltration rate (in/hr)** – This parameter defines the rate at which water is infiltrated from into the top soil layer. The saturated hydraulic conductivity for the upper soil layer from the SSURGO data (ksat_layer1) was used to define this parameter

- **Maximum upper soil zone storage (in)** – This parameter defines the volume of available storage in the upper soil layer. The SSURGO soil porosity (wsatiated1) was multiplied by the depth of the upper soil layer (hzdepb_r) to calculate this parameter.

- **Maximum tension zone storage (in)** – This parameter defines the volume of available storage in the tension zone or the part of the soil column adjacent to the water table and wetted by capillary forces. The volume in this zone was computed using the field capacity (wthirdbar1), or porosity of the tension zone, by the depth of the upper soil layer (hzdepb_r).

- **Percolation rate (in/hr)** – This parameter describes the rate of infiltration from the upper soil layer into the GW1 layer. The average saturated hydraulic conductivity (ksat_avg) was used to define this parameter.

- **GW1 percolation rate (in/hr)** – This parameter describes the rate of infiltration from the GW1to the GW2 layer. This value is typically used for calibration and was initially set equal to the percolation rate.

- **GW2 percolation rate (in/hr)** – This parameter describes deep percolation out of the GW2 layer into deep subsurface aquifer storage. This water is ultimately lost from the system. Because this parameter is difficult to estimate it is typically set during calibration. As an initial assumption this value was set to half of the GW1 percolation rate.

The rate of flow out of the GW1 and GW2 layers was calculated using the streamflow data measured by the UCSB at Venoco road. Lohmann *et al* (1998) described a method for separating a hydrograph into a fast component, representing channel flow, and a slow component, representing baseflow. The equation for calculating the groundwater and interflow is:

$$Q_s(t) = \frac{exp(-k\Delta t)}{1+b\Delta t} Q_s(t-\Delta t) + \frac{b\Delta t}{1+b\Delta t} Q(t) \qquad \text{(Equation 4)}$$

Where, $Q_s(t)$ is the slow flow component at timestep t (cfs)

Q(t) is the total measured flow at timestep t (cfs)

K is the inverse of the recession constant for the slow flow (-/hr)

B is an equation constant

Δt is the timestep (hr)

As equation 4 describes, the slow flow decays exponentially at the rate of exp(-kΔt). The recession constant is the inverse of the decay coefficient ‘k’. Using equation 4, the baseflow, interflow, and recession constants can be calculated for specific flow events. By subtracting the baseflow from the measured flow the remaining hydrograph is surface flow plus interflow. Equation 4 can then be used to separate the interflow and calculate the interflow recession rate. An event from February, 2004 was selected to compute the baseflow (GW2) and interflow (GW1) as shown in Figure 5. Storage in the groundwater layers was calculated based on the relationship described in Sing *et al* (2015):

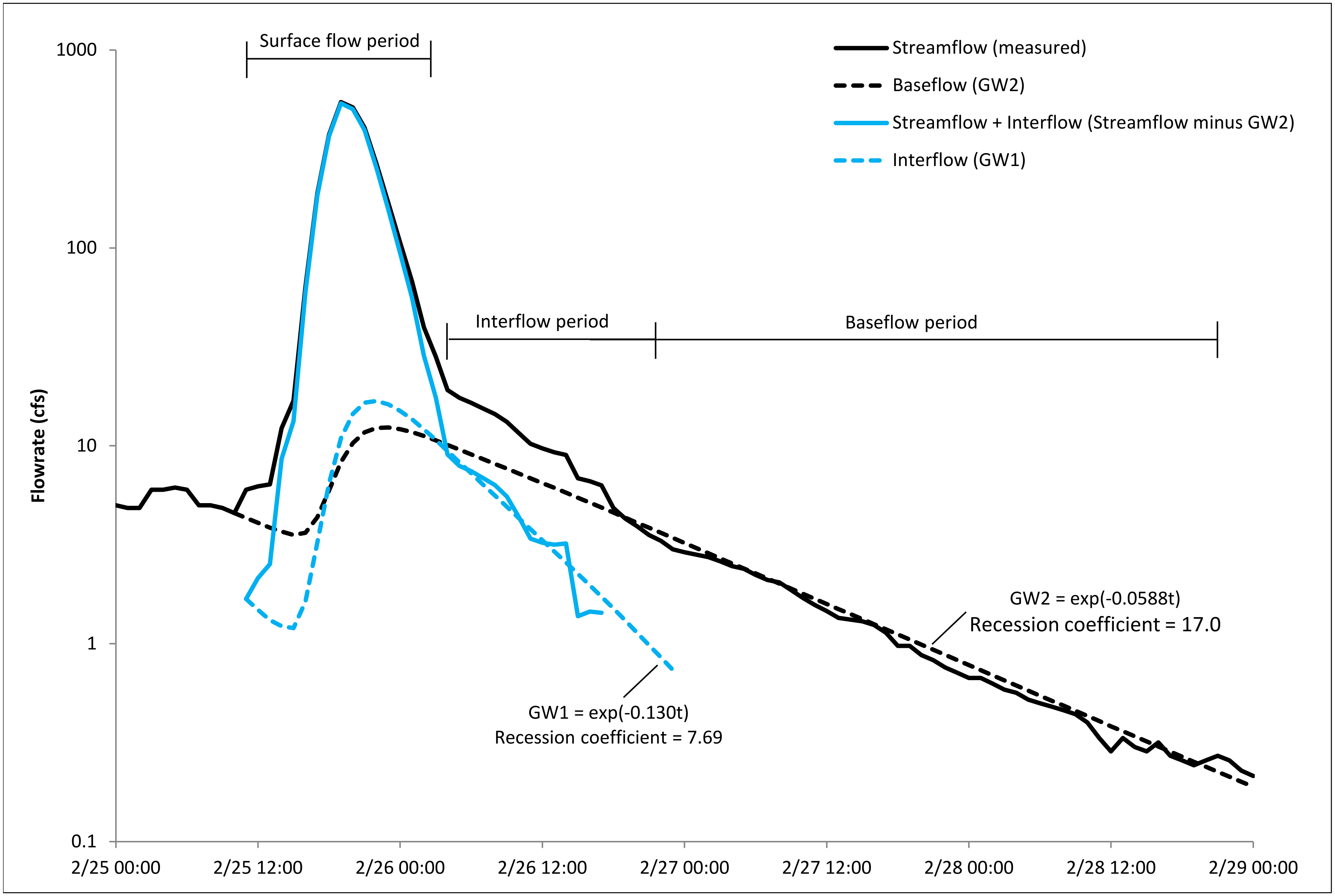
$$S = Q * k \qquad \text{(Equation 5)}$$

Where, S is the storage in either GW1 or GW2 (in)

Q is the measured flow (cfs)

k is the decay coefficient (-/hr)

Equation 5 was applied to the baseflow and interflow periods to estimate GW2 and GW1 storage respectively. The initial set of soil moisture accounting parameters is summarized in Table 9.



SOURCE: UCSB LTER (measured streamflow)
NOTE: Flow shown on semi-log plot

Figure 5
Hydrograph separation for 2004 event

TABLE 9. SOIL MOISTURE ACCOUNTING PARAMETERS

Basin	Max Infiltration rate (in/hr)	Impervious %	Soil storage (in)	Tension storage (in)	Soil Percolation (in/hr)	GW 1 Storage (in)	GW 1 Perc (in/hr)	GW1 Coefficient (hr)	GW2 Storage (in)	GW 2 Perc (in/hr)	GW2 Coefficient (hr)
SB_DCREEK1	1.33	28.03	18.19	13.27	2.01	0.03	2.01	7.69	0.009	1.00	17
SB_DCREEK2	0.88	10.88	19.48	14.15	2.18	0.03	2.18	7.69	0.009	1.09	17
SB_DEV_DS1	1.28	1.14	25.37	18.89	0.48	0.03	0.48	7.69	0.009	0.24	17
SB_DEV_DS2	1.19	18.94	26.01	19.57	0.45	0.03	0.45	7.69	0.009	0.23	17
SB_DEV_DS3	1.32	10.55	25.01	18.64	0.51	0.03	0.51	7.69	0.009	0.26	17
SB_DEV_DS3	1.82	5.47	22.72	17.09	0.86	0.03	0.86	7.69	0.009	0.43	17
SB_DEV_DS4	0.95	43.00	15.16	10.76	2.50	0.03	2.50	7.69	0.009	1.25	17
SB_DEV_DS5	3.33	3.18	16.26	12.73	1.98	0.03	1.98	7.69	0.009	0.99	17
SB_DEV_DS6	0.71	48.58	15.14	10.60	2.66	0.03	2.66	7.69	0.009	1.33	17
SB_DEV_DS7	2.49	3.00	18.20	13.86	1.71	0.03	1.71	7.69	0.009	0.85	17
SB_DEV_DS8	0.66	43.37	15.16	10.59	2.66	0.03	2.66	7.69	0.009	1.33	17
SB_DEV_US1	0.72	40.98	19.03	13.71	2.24	0.03	2.24	7.69	0.009	1.12	17
SB_DEV_US2	0.74	45.79	16.45	11.57	2.67	0.03	2.67	7.69	0.009	1.34	17
SB_DEV_US4	0.67	45.71	20.60	15.52	1.90	0.03	1.90	7.69	0.009	0.95	17
SB_DEV_US5	0.29	14.98	21.00	17.60	0.56	0.03	0.56	7.69	0.009	0.28	17
SB_DEV_US6	0.41	35.04	21.13	17.13	1.12	0.03	1.12	7.69	0.009	0.56	17
SB_DEV_US7	0.45	1.63	17.25	14.57	0.36	0.03	0.36	7.69	0.009	0.18	17

2.6 Baseflow

The linear reservoir method was selected to represent baseflow conditions. This method is typically paired with the soil moisture accounting methods as the individual reservoirs can be connected to the outflow of the individual groundwater layers. Each linear reservoir is characterized using a groundwater storage coefficient which represents the response time of the subbasin. Two linear reservoirs were used for each subbasin and the groundwater coefficients were initially set equal to the GW1 and GW2 coefficients. These parameters were then adjusted during the model calibration.

2.7 Channel Routing

The Muskingum-Cunge channel routing method was selected to represent the attenuation and conveyance processes of in-channel flow. Parameters required for this method include channel shape, length, slope, and manning’s roughness values. The physical parameters were estimated in GIS. Manning’s roughness was estimated based on typical open channel roughness coefficients (Chow, 1959) and engineering judgement. Channel cross-sections were extracted for each reach from the topography and input as 8-point sections describing the channel shape.

3 MODEL CALIBRATION

ESA used measured flow data collected by UCSB at Venoco Road from October 1, 2003 to October 1, 2006 to calibrate the hydrologic model. . The data were divided into two periods, one for calibration and one for validation. The calibration period extends from December 1, 2004 to March 1, 2005. This period covers a wide range of events and was considered suitable for calibration. The validation period extends from February 10, 2006 to May 1, 2006.

Several calibration metrics were used to evaluate the model results in comparison to the observed flow data. The primary metric used is the Nash-Sutcliffe Efficiency parameter (NSE) as recommended by the ASCE Task Committee (1993). Moriasi *et al* (2007) recommended guidelines for evaluating the calibration performance of hydrologic models. This study recommended three quantitative statistics to be used in model performance evaluations (1) the NSE parameter, the ratio of the root mean square error to the standard deviation of the measured data (RSR), and percent bias (PBIAS). Singh and Jain (2015) added additional performance metrics including percent error in flow volume (PEV), correlation coefficient (R^2), and index of agreement (d). Both studies presented performance rating categories and ranges of values for each category. The categories and ranges are summarized in Table 10.

TABLE 10. HYDROLOGIC MODEL PERFORMANCE CRITERIA

	Moriasi *et al* (2007)			Sing & Jain (2015)		
Performance Rating	NSE	RSR	PBIAS (%)	PEV	R^2	d
Very good	$0.75 < NSE \leq 1.00$	$0.00 \leq RSR \leq 0.50$	PBIAS < ± 10	PEV < ± 10	$0.75 < R^2 \leq 1.00$	$0.90 < d \leq 1.00$
Good	$0.65 < NSE \leq 0.75$	$0.50 < RSR \leq 0.60$	±10 ≤ PBIAS < ±15	±10 ≤ PEV < ±15	$0.65 < R^2 \leq 0.75$	$0.75 < d \leq 0.9$
Satisfactory	$0.50 < NSE \leq 0.65$	$0.60 < RSR \leq 0.70$	±15 ≤ PBIAS < ±25	±15 ≤ PEV < ±25	$0.50 < R^2 \leq 0.65$	$0.50 < d \leq 0.75$
Unsatisfactory	$NSE \leq 0.50$	$RSR > 0.70$	PBIAS ≥ ±25	PEV ≥ ±25	$R^2 \leq 0.5$	$d \leq 0.50$

The model results showed predominantly good to very good performance for both the calibration and validation periods. A summary of the results compared to the performance criteria is provided in Table 11.

TABLE 11. HMS HYDROLOGIC MODEL PERFORMANCE RESULTS

	Calibration period		Validation period	
Performance Metric	Value	Category	Value	Category
NSE	0.653	Good	0.754	Very good
RSR	0.59	Good	0.49	Very good
PBIAS (%)	-15%	Satisfactory	-21%	Satisfactory
PEV	-15%	Satisfactory	-21%	Satisfactory
R^2	0.83	Very good	0.87	Very good
d	0.91	Very good	0.93	Very good

A comparison between observed and simulated streamflow is shown in Figure 6 for the calibration period and Figure 7 for the validation period. As these figures and Table 11 show, the primary deviation between simulated and observed results was in the total volume.

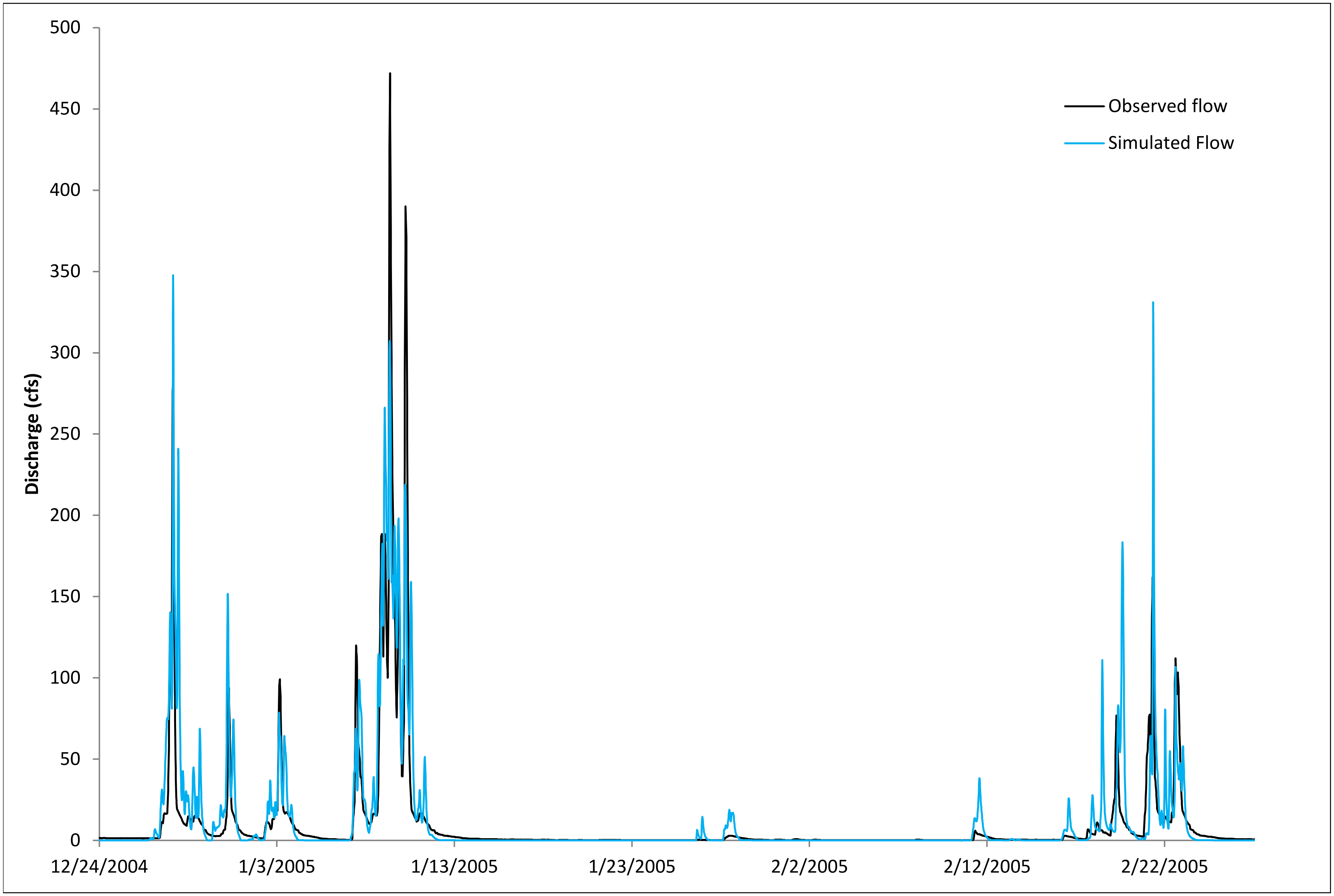


Figure 6

Hydrologic model results at Venoco Road - Calibration

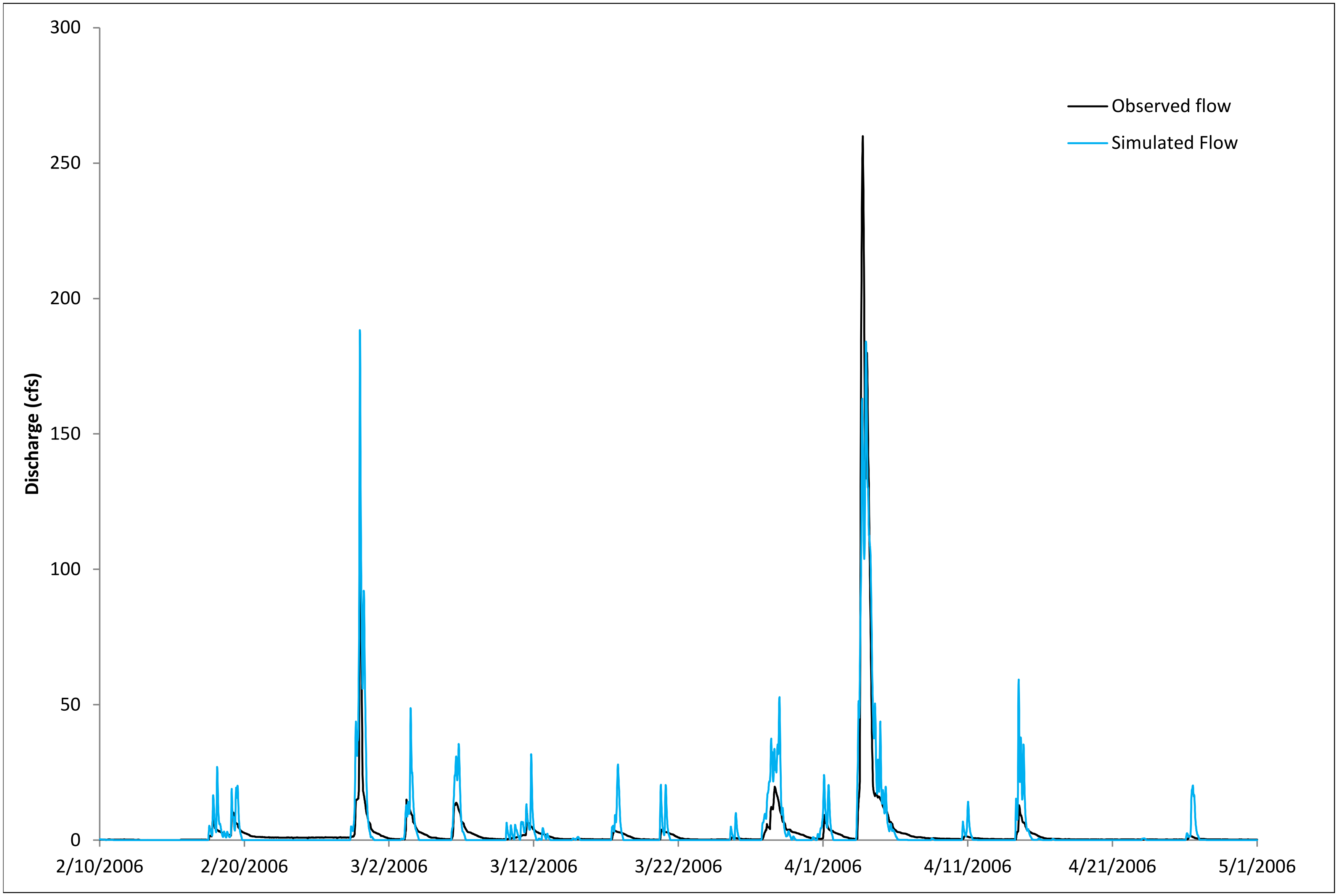


Figure 7

Hydrologic model results at Venoco Road - Validation

The model generally showed overestimates for smaller events. The potential sources for the differences between model results and measured observed streamflow as well as recommended improvements are discussed in the following section.

Ultimately, no parameters were changed from the initial parameter estimates as calibration trials did not improve the model performance. The calibrated hydrologic model was used to simulate the period from October 1, 2000 to October 1, 2014. The model results are shown in Figure 8.

3.1 Comparison with Prior Hydrologic Studies

In the summer of 2015 ESA applied a simple unit hydrograph method to estimate streamflows entering Devereux slough to support the development of the Devereux Slough QCM. This prior study was conducted with the aim of developing a representative streamflow time series for time periods where no gaged flow data exists. This study applied a simple unit hydrograph which assumed a linear rising edge and exponentially decaying trailing edge. Linear optimization was used to fit the hydrograph shape parameters based on the observed flow rate time-series during the calibration period.

Table 12 compares the performance of the unit hydrograph streamflow model vs the HMS model. We find that the Unit Hydrograph provides a comparable level of performance to the HMS model during the calibration period. Both models were found to provide satisfactory performance during both the calibration and validation period, however, the unit hydrograph does not perform as well as the HMS model during the validation period. Specifically the unit hydrograph model has a lower NSE score during the validation period, which suggests that the model is not a skillful in accurately predicting peak flows outside of the calibration period. The unit hydrograph model results also show a much larger percent bias for the validation period compared to the calibration period, which calls into question the model’s ability to produce consistently skillful estimates of cumulative streamflow for periods other than the calibration period.

TABLE 12. COMPARISON OF PERFORMANCE RESULTS FOR HMS AND UNIT HYDROGRAPH MODELS

		Calibration period		Validation period	
Metric	Satisfactory Threshold	HMS Model	Unit Hydrograph	HMS Model	Unit Hydrograph
NSE	>0.5 (larger # is better)	0.65	0.68	0.75	0.58
RSR	<0.7 (smaller # is better)	0.59	0.57	0.49	0.64
Pbias	<+/-25 (closer to 0 is better)	-15.31	6.87	-20.80	42.55
R2	>0.5 (larger # is better)	0.83	0.83	0.87	0.82
d	>0.5 (larger # is better)	0.91	0.90	0.93	0.90

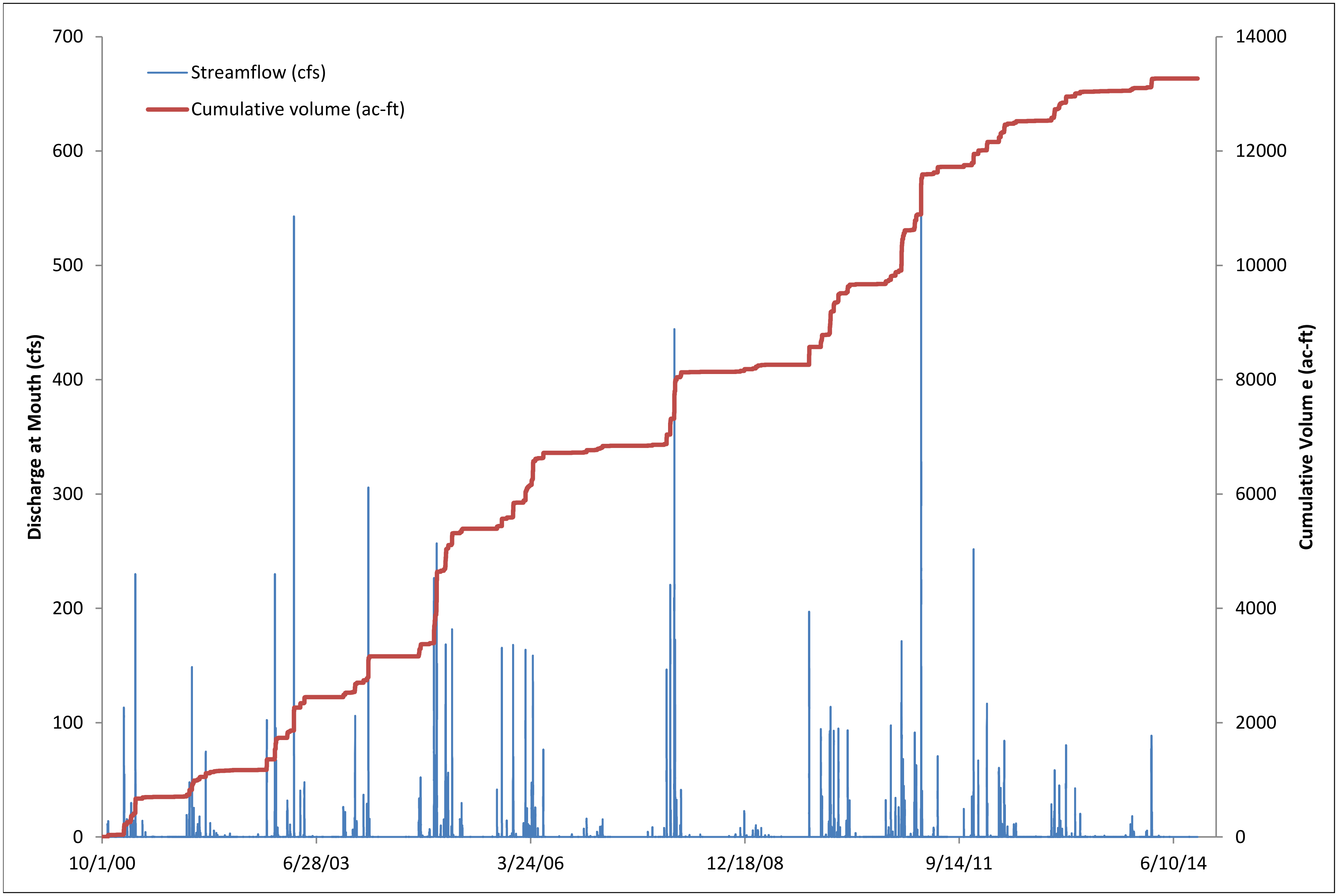


Figure 8

Hydrologic model results at watershed outlet - 2000-2014

The unit hydrograph method applied the 2015 study used optimization methods rather than watershed characteristics to develop the hydrograph shape parameters. This was based on the assumption that the available calibration dataset provides a statistically representative sample of watershed responses to rainfall. Our finding that the unit hydrograph method has weaker performance during the validation period compared to the calibration period suggests that the calibration period may not be fully representative of the range watershed conditions. This finding calls into question the quality of the unit hydrograph predictions during the time periods where no calibration/validation data is available.

The HMS model, which is based on a physical parameterization of the watershed properties which are unlikely to vary significantly over time, demonstrates consistent strong performance during both the calibration and validation periods. We therefore believe that the HMS model is most likely to provide consistently skillful estimates of streamflow for the entire simulation period.

3.2 Discussion of Model Limitations

While we believe that the HMS model was found to provide the best prediction of streamflow during the periods where gage data is not available, our review of the predicted vs. observed flow rates shows several trends that suggest the limitations of the model results. Despite these limitations we believe that model output provides the best source for inflow time-series data for the lagoon QCM modeling.

The HMS model systematically overestimates peak flows for smaller rainfall events, while underestimating flows during the falling edge of the hydrograph. Compared to model results, the observed flow record shows a much higher threshold for rainfall to generate a surface flow peak. Many of the rainfall events appear not to generate much surface flow and contribute mainly to groundwater and baseflow. This could be due either to uncertainty in the model parameterization or in the flow measurements. The primary potential sources of error in the model configuration include lack of detail in the rainfall inputs and lack of accounting for bridge crossings, culverts or other structures that may impair flow as it is routed through the watershed.

The only rainfall data available for the modeling are from gages located generally to the east of the watershed. The CIMIS rainfall gage is located approximately 3 miles to the northeast and the UCSB gage is located approximately 2 miles east of the watershed centroid. As there is no gage located within or to the west of the watershed it is difficult to evaluate how storm patterns vary between the gages and the individual subbasins. Thus, these gages may not be accurately representative of rainfall conditions within the watershed. Collecting additional rainfall data within the watershed may improve this model input. Additionally, ESA could evaluate NOAA radar rainfall in the vicinity of the watershed to evaluate how significantly storm patterns differ between the gages and the subbasins.

There are several bridge crossings in the main Devereux Slough flowpath including Highway 101, Hollister Avenue, Davenport Road, Phelps Road, and an unnamed road crossing between Sea Cove Lane and Marymount Way. These crossings may have a significant impact on peak flows by attenuating the hydrograph as flow travels downstream. The HEC-HMS model does not have an option for representing bridge crossings in the channel reaches. One potential improvement to the model would be to replace the HMS reaches with a hydraulic model to capture the channel and bridge crossing geometry and account for flow attenuation through the structures.

Apart from model configuration and input parameters, the accuracy of the flow gage could influence agreement between simulated and observed flows. Generally, streamflow is indirectly measured by directly measuring depth and estimating streamflow using a ‘rating curve’ relationship between depth and flow. The rating curve relationship is typically developed by measuring both flow and depth for a handful of discrete rainfall events and extrapolating between and above the measured points on the curve. Often the uncertainty involved in measuring the flow during a specific event reduces the accuracy of the rating curve. The metadata for the UCSB flow gage states that the rating curve was developed with “stream channel cross-sections, roughness estimates, and the HEC-RAS model”. It is unclear if flow measurements were taken in-stream to validate the rating curve. This may have a significant impact on the reliability of the measured flow data. We recommend further assessment of the rating curve to determine whether in-stream flow measurements were taken and how the rating curve was constructed. Unfortunately the channel geometry at the Venoco Road crossing has changed significantly since the rating curve was developed; consequently it is unlikely that new flow measurements would be able to inform the reliability of the rating curve used for the UCSB flow gage.

4 SUMMARY

Results of the continuous HEC-HMS model were compared to measured flow on Devereux Creek and achieved above satisfactory calibration compared to six performance metrics for calibration and validation. Correlation between model results and measured flow was good to very good for four of the performance metrics for both calibration and validation.

The calibrated hydrologic model was used to simulate a longer period (2000-2014) for which rainfall data was available. The simulated flow rates from this period will be used to drive a QCM to simulate physical processes including opening and closing of the mouth on Devereux Lagoon. We consider the calibrated HEC HMS model results to be adequate as inputs to the QCM to simulate lagoon breaching and closure processes, and to be an improvement over prior QCM inputs developed using a unity hydrograph method.

The model does show consistent overestimates of smaller flow events. This could be due to inaccurate rainfall inputs, flow attenuation in channel crossings not captured by the model, or inaccuracies in the rating curve used to estimate stream flow from stage measurements.

5 REFERENCES

ASCE, 1993. Criteria for Evaluation of Watershed Models. Journal of Irrigation and Drainage Engineering. Volume 119, Issue 3.

Chow, V.T., 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.

Fleming, M. (2002). Continuous Hudrologic Modeling with HMS: Parameter Estimation and Model Calibration and Validation. Cookeville, TN: Texas Technological University.

Holberg, 2014. Tutorial on using HEC-GeoHMS to develop Soil Moisture Accounting Method Inputs for HEC-HMS. Lyles School of Civil Engineering, Purdue University. https://web.ics.purdue.edu/~vmerwade/education/hechms_sma.pdf

Melack, J. M. . 2010. SBC LTER: Land: Hydrology: Stream discharge and associated parameters at Devereux Creek at Slough inflow (DV01). Santa Barbara Coastal LTER. doi:10.6073/pasta/d869bc9d59aba58e226b9d46ef4d4fb8

Moriasi *et al* 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE. v. 50, no. 3, p. 885-600

MRLC 2015, Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354

NOAA, 2011. NOAA Atlas 14. Precipitation-Frequency Atlas of the United States. Volume 6 Version 2.0: California.

PRISM, 2010. PRISM Climate Group, Oregon State University, www.prism.oregonstate.edu

NRCS, 1986. Urban hydrology for small watersheds (PDF). Technical Release 55 (TR-55) (Second Edition ed.). Natural Resources Conservation Service, Conservation Engineering Division

NRCS, 2011. United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Santa Rosa Watershed, CA. Available online at http://www.arcgis.com/apps/OnePane/basicviewer/index.html?appid=a23eb436f6ec4ad6982000dbaddea5ea Accessed February, 2016.

USACE, 2000. Hydrologic Modeling System HEC-HMS. Technical Reference Manual.