BIG DRAFT

Estimation of Deep Groundwater Recharge Using a Precipitation-Runoff Watershed Model Soquel-Aptos, California

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Soquel Creek Water District

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ABBREVIATIONS

AF ....acre-feet
amsl ....above mean sea level
BAG.......................................Basin Advisory Group
cfs...cubic feet per second
CWD.....................................Central Water District
DMRP...................................Drought Management and Response Plan
GIS ....geographical information system
NS ....Nash-Sutcliffe
PET ....potential evapotranspiration
PRMS.....................................Precipitation-Runoff Modeling System
SqCWD ....Soquel Creek Water District
SR...solar radiation
SR...solar radiation
USGS ....United States Geological Survey
UWMP ....Urban Water Management Plan

EXECUTIVE SUMMARY

Ensuring sustainability of Soquel-Aptos basin's groundwater supply in the face of changing environmental factors, such as climate and land use, is crucial to groundwater producers in the basin. Understanding the relationship between the amount of rainfall in any given year and the groundwater recharge that occurs as a result of that rainfall is fundamental to managing the groundwater basin effectively. Justifying pumping curtailments and planning for impacts related to future land use change are examples of management decisions that would benefit from an understanding of the rainfall-recharge relationship.

A model was developed using the USGS's Precipitation-Runoff Modeling System (PRMS) to assess the rainfall-recharge relationship. The model is a distributed-parameter, physically based hydrologic model that uses precipitation and temperature data to calculate runoff, evapotranspiration, and deep groundwater recharge. The model area contains the Soquel Creek, Aptos Creek, Valencia Creek, and portions of the Corralitos Creek and Branciforte Creek watersheds. The model was subdivided into 312 unique hydrologic response units (HRU) that were assigned hydrologic and physical characteristics based on soils, geology, land surface elevation, slope, aspect, vegetation type and density, and land use. Daily water and energy balances were calculated for each HRU over the model period (Water Year 1984 through 2009), and the sum of these area weighted responses for all HRUs results in the daily watershed response for the model area. Output from the model includes the water budget components of: precipitation, actual evapotranspiration, streamflow, and deep groundwater recharge. Calibration of solar radiation, potential evapotranspiration, and streamflow improved the model's credibility by ensuring modeled values closely matched measured values.

Total deep groundwater recharge for the portion of the PRMS model representing the District's hydrogeologic system area varied from 290 to 42,900 acre-feet per year, and averaged 10,800 acre-feet per year over the calibration period. The deep recharge by geological formations averaged: 6,600 acre-feet per year in the Purisima Formation, and 4,200 acre-feet per year in the Aromas Red Sands. The PRMS deep recharge estimate was slightly higher than the 9,900 total deep recharge estimated in 2004 by Johnson and others.

The rainfall-recharge relationship established by the PRMS model was used to develop drought curtailment criteria to support Soquel Creek Water District's

Drought Management and Response Plan (DMRP) and Urban Water Management Plan (UWMP). Model output was used to identify the frequency and severity of historic periods of below average deep groundwater recharge. To facilitate identifying multi-year periods of below average deep groundwater recharge, the model was extended to cover a 69 year period from Water Year 1942 to Water Year 2010. The extended model water budget was used to determine the long-term rainfall-recharge relationship.

The average deep groundwater recharge was 10,400 acre-feet for the extended model, similar to the 10,800 acre-feet estimated for the calibration period. The median annual deep groundwater recharge for the extended model was 5,900 acre-feet. Of the 69 years, 64% of years are below average recharge, highlighting that average recharge is influenced by relatively infrequent high recharge years.

Model output showed that a year with below average recharge has between a 19% and 36% probability of having the recharge shortfall made up the following year. These statistics support basing drought curtailment criteria on multi-year periods of below average recharge. Cumulative multi-year shortfalls exceeding 10,500 acre-feet are recommended for Stage 1 drought curtailments, and shortfalls exceeding 21,000 acre-feet are recommended for Stage 2 drought curtailments.

Two potential methods are available to evaluate future deep groundwater recharge. The first is to use the historical rainfall-recharge relationship from PRMS to identify multi-year rainfall amounts that signal deep recharge shortfalls exceeding 10,500 and 21,000 acre-feet. The second is to annually update the PRMS model to dynamically estimate the deep groundwater recharge shortfall.

Other uses of the calibrated PRMS model are to (1) evaluate changes in groundwater recharge and runoff in response to predicted climate change; (2) evaluate changes in groundwater recharge and runoff in response to increased urbanization or land use change such as deforestation; and (3) provide input to a groundwater flow model.

SECTION 1
INTRODUCTION

1.1 BACKGROUND AND PURPOSE

Central Water District (CWD), City of Santa Cruz Water Department (City), and Soquel Creek Water District (District) all rely on groundwater from the Soquel-Aptos Basin for all or part of their water supply. As such, protecting and managing the groundwater resource is a high priority. CWD and the District are members of the Soquel-Aptos Groundwater Management Basin Implementation Group (BIG). City staff join staff from CWD and the District to form the Soquel-Aptos Groundwater Management Basin Advisory Group (BAG).

To ensure the groundwater resource's sustainability considering changing environmental factors such as climate and land use changes, the three agencies co-funded this study to estimate the spatial and temporal variation of deep groundwater recharge in the basin. Furthermore, by gaining an understanding of the relationship between recharge and rainfall, it is possible to use this understanding to assist in making management decisions regarding when to call for pumping curtailments in the basin.

This study has the following enhancements compared to previous recharge studies:

- Recharge is calculated daily over many years. This allows for an understanding of how recharge changes with precipitation and land use changes.
- Recharge can be analyzed for specific areas. Recharge over the Purisima A-unit outcrop can be differentiated from recharge over the Purisima BC-unit outcrop or recharge over the Aromas Red Sands.
- Deep recharge for the Soquel-Aptos area is estimated using a tool that can be updated in the future, and can be modified as new data become available.
- The recharge data can be used as input to a groundwater flow model.

The term groundwater recharge has previously been defined differently in different reports and contexts. For this report, the terms may not be consistent with those used previously. It is important that the semantics of recharge are clearly laid out at the outset to avoid confusion.

Groundwater recharge is water added to an aquifer. Not all water recharged to an aquifer is available for groundwater extraction, as some of it naturally discharges as baseflow to streams or is used by phreatophytes. Deep recharge is what is theoretically available for extraction by wells. However, as Johnson et al. (2004) pointed out, the relative amounts of baseflow and deep recharge can be altered by groundwater pumping. Deep groundwater recharge should not be confused with sustainable yield. Estimating deep groundwater recharge, as groundwater recharge less baseflow to streams and use by phreatophytes, is the purpose of this report.

1.2 PROJECT SCOPE

During the development of the scope for this study, various USGS recharge models were reviewed for applicability for estimating deep recharge in the Soquel-Aptos area. Based on guidance provided to the District's Board, it was decided to use the United States Geological Survey's (USGS) Precipitation-Runoff Model System (PRMS) for this study. One of the main reasons for using PRMS was that it includes baseflow as a component of calibrated streamflow. Being able to specifically identify and remove baseflow from water recharged to the aquifer is fundamental to estimating deep groundwater recharge.

The general scope of work that was approved for this project involved obtaining and reviewing background information and model input data; converting data into the correct formats; and developing and calibrating the model. Results of the modeling were used to provide supporting information for drafting a Drought Management and Response Plan (DMRP) that can be incorporated into the Urban Water Management Plan (UWMP).

The reporting portion of the scope included preparing this report and presenting results to the District's Board and to the Basin Advisory Group (BAG).

1.3 PREVIOUS STUDIES

The most recent deep groundwater recharge estimates of 6,100 acre-feet per year for the Purisima outcrop area, and 2,900 acre-feet per year for the Aromas outcrop area were developed by Johnson et al. in 2004. The District has been using these estimated average numbers to manage its pumping. During work for this report, a computational error in Table 5-11 of Johnson et al. (2004) was discovered. This error resulted in Johnson et al. estimating 900 acre-feet per year less recharge in the Purisima Formation than there should have been. Correcting this error results in a previously estimated total deep recharge of 9,900 acre-feet per year.

Prior to 2004, a number of other studies on sustainable yield and groundwater recharge had been completed for aquifers within the Purisima Formation and Aromas Red Sands in the Soquel-Aptos area. Johnson et al. (2004) provides a summary of those studies; and the reader is directed to that report if more information on studies prior to 2004 is needed.

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SECTION 2
DESCRIPTION OF STUDY AREA

2.1 LOCATION AND PHYSIOGRAPHY

The study area is located east of the City of Scotts Valley, and extends eastwards to the City of Watsonville. It includes a small portion of the City of Santa Cruz, and the communities of Soquel, Aptos, Day Valley, Corralitos, Freedom, Aptos Hills-Larkin Valley, Rio del Mar, La Selva Beach, Amesti, Capitola, Opal Cliffs, Twin Lakes, and Live Oak. These communities all lie between the Santa Cruz Mountains to the north and the Pacific Ocean to the south (Figure 1). The study area was selected to coincide as much as possible with hydrologic boundaries. Figure 1 shows major hydrologic units from CalWater (NRCS, 2008). Where necessary, partial hydrologic units were included to ensure that all aquifers supplying the three agencies' public supply wells were part of the study area. In the eastern part of the study area, a straight line from the Corralitos Creek streamflow gage was used to cut through the relatively large hydrologic unit that flows southeastwards to the Pajaro River.

The general topography of the study area is represented by the basemap digital elevation model (DEM) in Figure 1. The Santa Cruz Mountains, in the northeast of the study area, rise up to 3,160 feet above mean sea level (amsl). Flowing from the mountains to the ocean are several well established watersheds with relatively steep topography, including Soquel Creek, Aptos Creek, and Valencia Creek. In the lower relief eastern part of the study area, streams flow into the Pajaro River before flowing into the ocean (Figure 1).

2.2 LAND USE

Current land use within the study area is predominantly forests, with most urban development taking place along the coast and along transportation corridors. There is limited agricultural activity in the Pajaro Valley portion of the study area. Figure 2 is a 2009 aerial photograph, and Figure 3 provides 2001 USGS 1-km gridded land use/ land cover data (Anderson et al., 1976).

Figure 1: Soquel-Aptos Area

Figure 2: 2009 Aerial Photograph

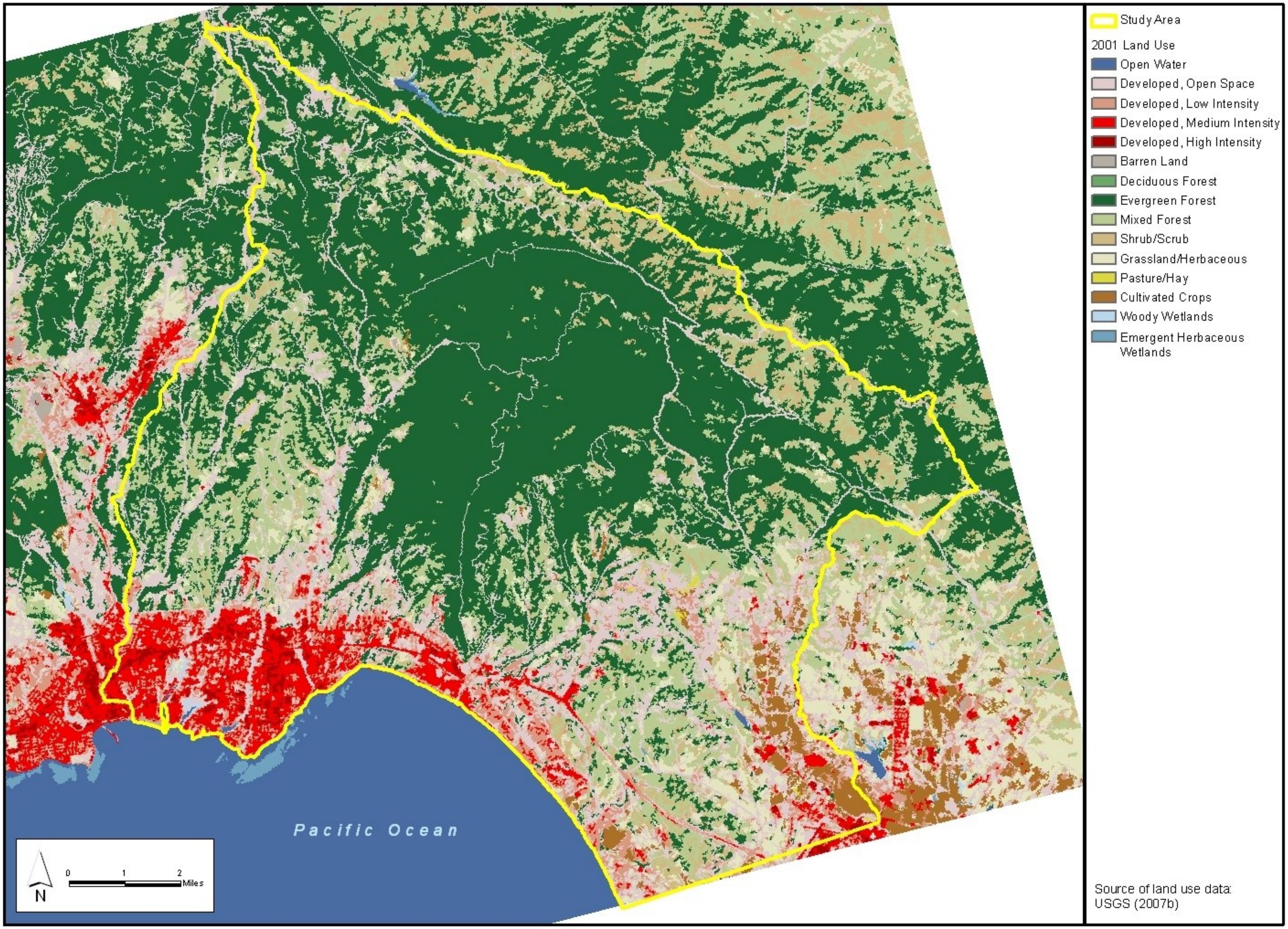

Figure 3: 2001 Land Use

2.3 Geology and Hydrostratigraphy

The predominant geologic formation outcropping in the study area is the consolidated to semi-consolidated Purisima Formation sediments of marine origin (Figure 4). The Purisima Formation is overlain by poorly consolidated Aromas Red Sands in the eastern third of the Soquel-Aptos area, and by relatively shallow alluvial and terrace deposits elsewhere. Hard rock formations, in the upper Santa Cruz mountains comprise mudstone, shale, siltstone, conglomerate and sandstone. The Zayante Fault, which cuts across the Purisima Formation in the study area, is the most significant structural feature (Figure 4). The sections below describe in more detail the geologic formations from youngest to oldest.

2.3.1 Aromas Red Sands

The poorly consolidated Aromas Red Sands consist of interbedded fluvial, marine, and aeolian sands with lenses of silt and clay. As a result of this complex depositional history, the Aromas Red Sands contain significant heterogeneities and cannot be easily subdivided into meaningful hydrostratigraphic units.

2.3.2 Purisima Formation

The late Miocene to Pliocene age Purisima Formation is a sequence of grey, sometimes described as blue, moderately consolidated, silty to clean, fine to medium sandstones containing siltstone and claystone interbeds.

Johnson et al. (2004) developed the current hydrostratigraphic model of the Purisima Formation by dividing it into hydrostratigraphic units that define regional aquifers and aquitards. The hydrostratigraphic units of Johnson et al. are defined for the Purisima south of the Zayante Fault from youngest to oldest as follows:

Aquifer F

This unit consists of alternating moderately coarse- and fine-grained zones. Johnson et al. (2004) identifies this aquifer as the upper portion of the Purisima F unit that is often screened in conjunction with the lower Aromas Red Sands.

Aquifer DEF

This moderately coarse aquifer includes intermittent fine-grained zones. The top of this aquifer seems poorly defined; Johnson et al. (2004) does not identify a distinct marker or aquitard separating this aquifer from the overlying Aquifer F.

Aquitard D

This aquitard is the fine-grained unit between the BC and DEF aquifer units. Few production wells are screened across this unit.

Aquifer BC

This is a moderately coarse-grained unit with a distinct 15- to 20-foot thick coarse-grained unit at the top of the unit.

Aquitard B

This unit is the fine-grained unit between the A and BC aquifer units. Few production wells are screened across this unit.

Aquifer A

This distinct aquifer is the most consistently coarse-grained aquifer within the Purisima Formation. It is sometimes divided into an upper and lower zone with the lower zone being more coarse-grained.

Aquifer AA

This unit comprises a sequence of interbedded, moderately coarse- and fine-grained zones underlying the well defined A-unit. A fine-grained zone 20 to 70 feet thick divides the AA-unit from the overlying A-unit.

Aquitard Tp

This unit consists of fine-grained sediments near the base of the Purisima Formation that act as an aquitard where present.

AQUIFER TU

The Tu aquifer comprises the lower part of the Tertiary age sediments below the base of the Purisima Formation. This aquifer has only been observed in deep wells and is limited in extent.

PURISIMA NORTH OF THE ZAYANTE FAULT

Hydrogeologically, the Purisima Formation occurring north of the Zayante Fault has been undifferentiated with respect to hydrogeology (Johnson et al.., 2004). The USGS classifies it as "Tp" and describes it as very thick bedded siltstone containing thick interbeds of fine-grained sandstone.

2.3.3 OTHER HARD ROCK FORMATIONS

The hard rock formations north of the Zayante Fault extend to the Santa Cruz Mountain watershed divide (Figure 4). They comprise uplifted, steeply dipping and folded sediments of Tertiary marine mudstone, shale, siltstone, conglomerate and sandstone; and Cretaceous sandstone and shale. Tertiary formations include: Lompico Sandstone, Lambert Shale, Vaqueros Sandstone, Zayante Sandstone, San Lorenzo Formation, Butano Sandstone, and mudstone of Maymens Flat area; the one Cretaceous formation is shale and sandstone of Nibbs Knob area.

These hard rock formations are generally regarded as non-water bearing in the study area. Johnson et al. (2004) pointed out that some of the Tertiary mudstones and shales may be difficult to distinguish from the lower parts of the Purisima Formation.

2.4 SOILS

Soils in the study area are shown on Figure 5. The spatial dataset is from the Soil Survey Geographic (SSURGO) database developed by the Natural Resources Conservation Service (NRCS). Within the study area there are 31 different soil types. More details on soil types can be found at the NRCS website cited in the reference section.

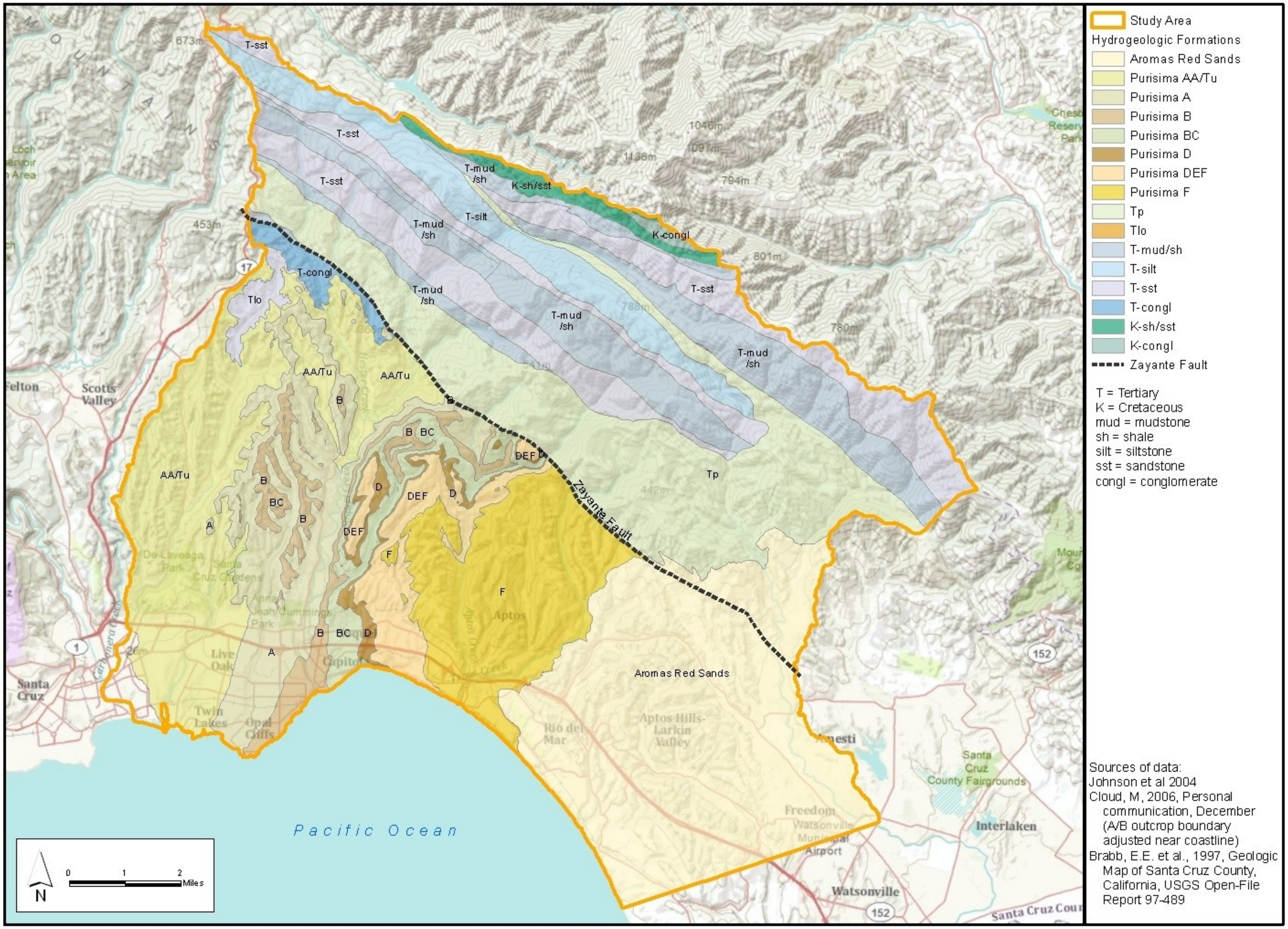

Figure 4: Hydrogeologic Map

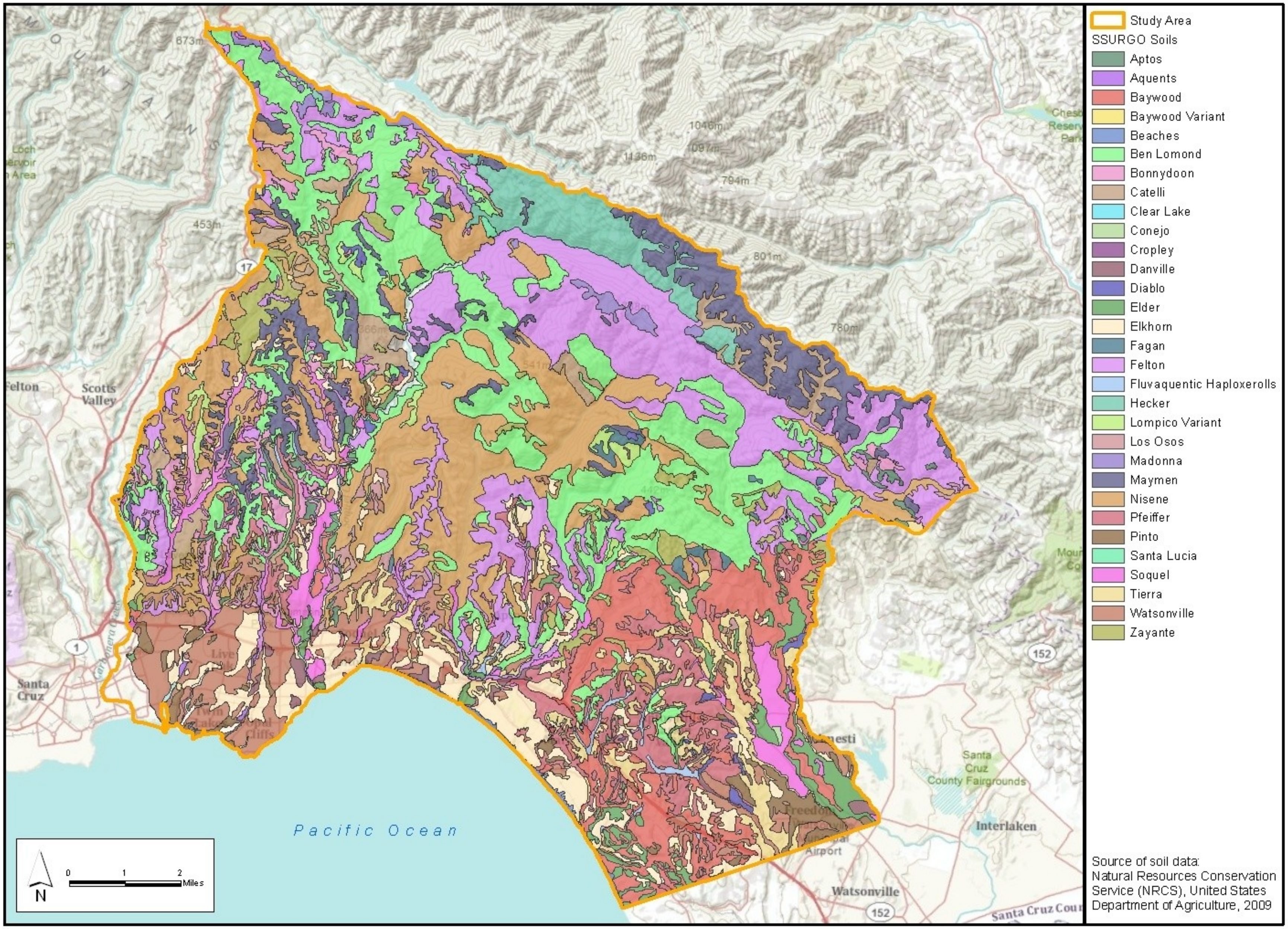

Figure 5: Soils

2.5 Climate

2.5.1 Precipitation

The Soquel-Aptos area has a Mediterranean-type climate, and receives the majority of its rainfall between September and March. The higher elevations in the Santa Cruz Mountains experience over 16 inches more rainfall than the coastal areas. At higher elevations, snow falls have occasionally been recorded.

The average water year precipitation at the Santa Cruz Co-op station in the City of Santa Cruz is 30.3 inches. The maximum precipitation that occurred between Water Year 1942 and 2010 was 59.9 inches in 1998 (Figure 6). The minimum precipitation during this time period was 14.8 inches in 1977.

The cumulative departure from mean water year precipitation shows a number of wet and dry climatic cycles (Figure 6). From 1942 to 1958 rainfall was above average; from 1959 to 1994 a prolonged dry cycle prevailed, being interrupted from 1982 to 1986. Since 1995, a wetter cycle has been experienced with more close to normal rainfall occurring.

2.5.2 Temperature

Temperatures in the study area are generally mild due to buffering by the Pacific Ocean. Winter temperatures typically range from 40 to 70˚ Fahrenheit, and summer temperatures from 60 to 90˚ Fahrenheit (Figure 7).

2.6 Hydrology

The study area contains a number of major streams that flow into the ocean. Soquel Creek has the largest complete catchment in the study area; measuring approximately 42 square miles (Figure 1). The two main upper tributaries of Soquel Creek are the West Branch and East Branch; Bates Creek is a lower tributary.

Other smaller streams whose watersheds are completely covered by the model include Aptos Creek and Valencia Creek. Valencia Creek flows into Aptos Creek half a mile before Aptos Creek enters the ocean.

The watersheds of two other streams, Branciforte Creek and Corralitos Creek, are only partially included in the model. Corralitos Creek flows out of the study area's southeast corner, and into the Pajaro River before flowing into the ocean. Similarly, Branciforte Creek flows out of the study area and into the San Lorenzo River before flowing into the ocean.

The USGS, County and District operate streamflow gages on the major creeks in the study area (Figure 1). As indicated on Figure 1, only five of these gages are currently operational. Flows in the study area are characterized as flashy, with relatively high flows in the winter rainfall months, and low to no flows for the rest of the year.

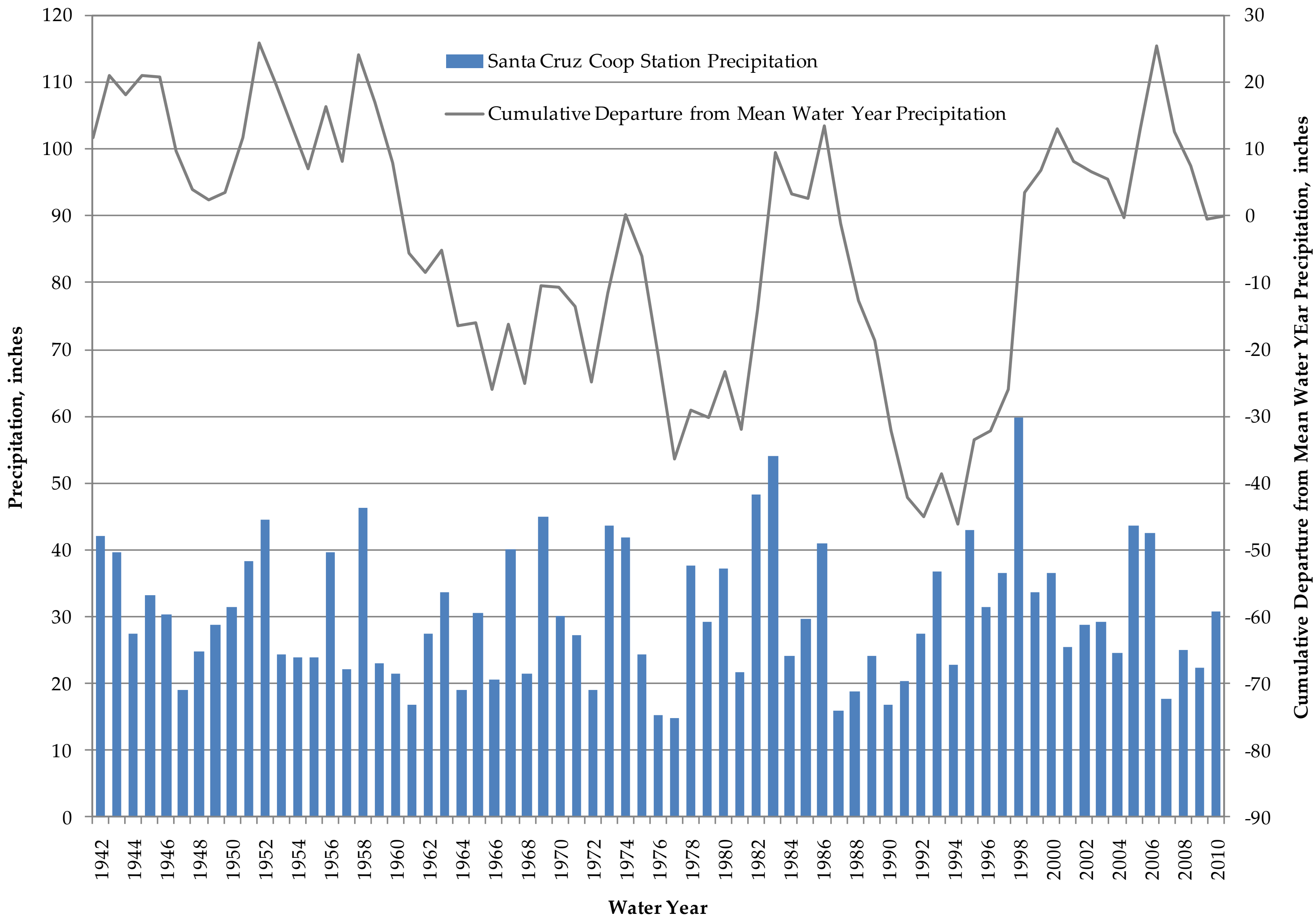

Figure 6: Santa Cruz Co-op Station Precipitation

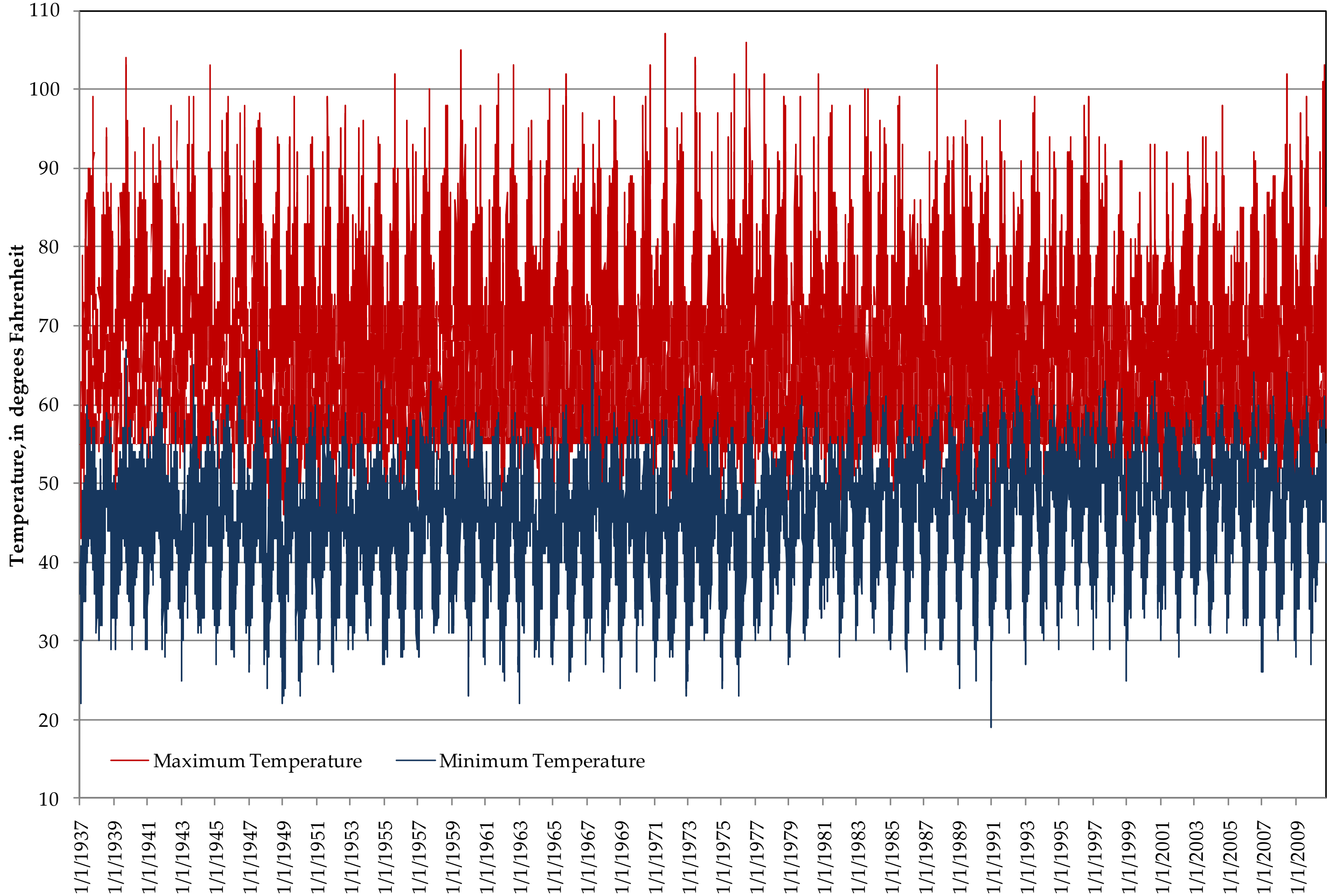

Figure 7: Santa Cruz Co-op Station Daily Maximum and Minimum Temperature

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SECTION 3
PRECIPITATION-RUNOFF WATERSHED MODEL

3.1 WATERSHED PROCESSES

The model used to simulate hydrologic inflows and outflows in the study area was the USGS's Precipitation-Runoff Modeling System (PRMS). PRMS is a distributed-parameter, physically based hydrologic model. The model was first developed in 1983 (Leavesley, et al., 1983), and has since undergone numerous improvements, both conceptually and programmatically. Version PRMS-2010 was used for the Soquel-Aptos model.

The hydrologic processes simulated by PRMS are shown in Figure 8 and Figure 9. A series of reservoirs (impervious zone, soil zone, and groundwater) are used to route water from the surface to the subsurface. The PRMS model requires daily precipitation and minimum and maximum temperatures as input. The model estimates streamflows from the sum of surface runoff, soil water discharges, and shallow groundwater discharges. These estimated streamflows are compared to measured streamflows during model calibration. The groundwater sink shown in Figure 8 is equivalent to deep groundwater recharge.

3.2 HYDROLOGIC RESPONSE UNITS

PRMS requires that the model area be divided into discrete units that are assigned physical characteristics such as slope, aspect, elevation, vegetation type, soil type, land use, and precipitation. These units are called hydrologic response units (HRU). Daily water and energy balances are calculated for each HRU, and the sum of these area weighted responses for all HRUs results in the daily watershed response for the model area. The steps taken to delineate the HRUs were:

1. Start with CalWater Committee watersheds (NRCS, 2008);
2. Split CalWater watersheds into left and right stream banks. This ensures that HRUs are delineated based on differences in aspect.
3. Generate smaller watersheds using hydrologic modeling of a digital elevation model (DEM) in GIS. The hydrologic modeling splits watersheds into sub-watersheds of equal contributing area.

4. Delineate contributing areas to streamflow gages used in model calibration. This resulted in each gage being located at the outlet of an HRU;
5. Subdivide HRUs to honor aquifer outcrop boundaries. Each HRU overlies only one hydrostratigraphic outcrop;
6. Further delineate HRUs based on distinct land use differences;
7. Any of the resultant HRUs that were less than 0.12 square miles were incorporated into the most suitable adjacent HRU to ensure that HRUs were not too small. This combining of HRUs was done in a fashion that ensured that resultant aquifer outcrop areas represented by the HRUs were similar in size to the actual aquifer outcrop areas.

The HRU delineation process produced 312 HRUs (Figure 10). Due to HRU complexity, subbasin designations and cascading parameters were assigned to each HRUs to better represent the streamflow network.

Each HRU was assigned to a unique subbasin. Subbasins consist of groups of HRUs which all contribute to streamflow at a gage (Figure 10). There are eleven subbasins in the study area: ten subbasins have gages at their outlet, and one is ungaged and for the most part flows into the ocean.

Cascading instructions define where water leaving an HRU moves to. This is essential for setting up stream networks in the model. The cascading instructions inform the model whether runoff, soil water, and shallow groundwater from every HRU should flow either to a stream segment or another downslope HRU. Furthermore, each stream segment is assigned a downgradient stream segment into which it flows. Stream segments that are used to link the network of HRUs together are shown on Figure 10.

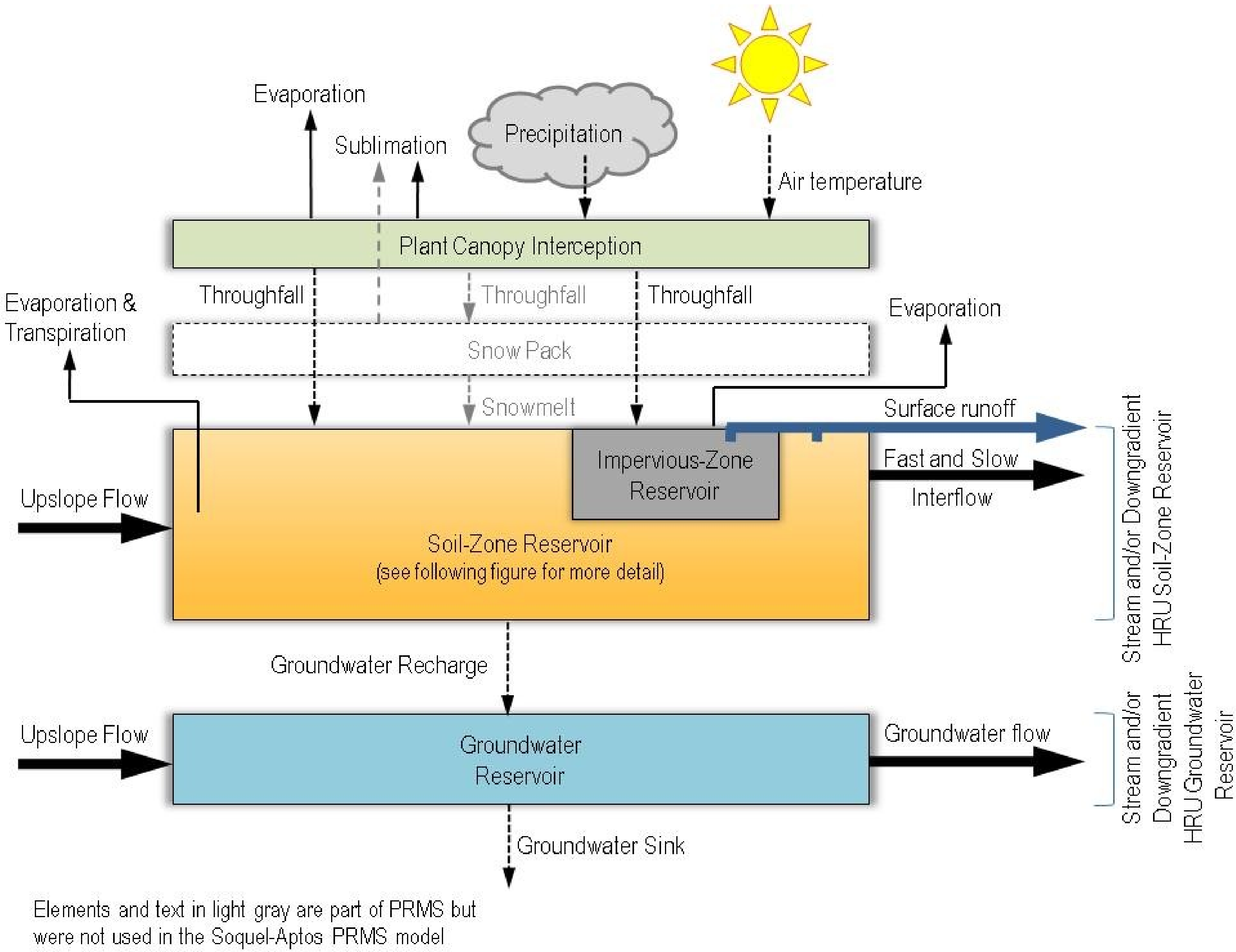


Figure 8: Overview of the Precipitation-Runoff Modeling System Conceptualization of HRU Components and Fluxes

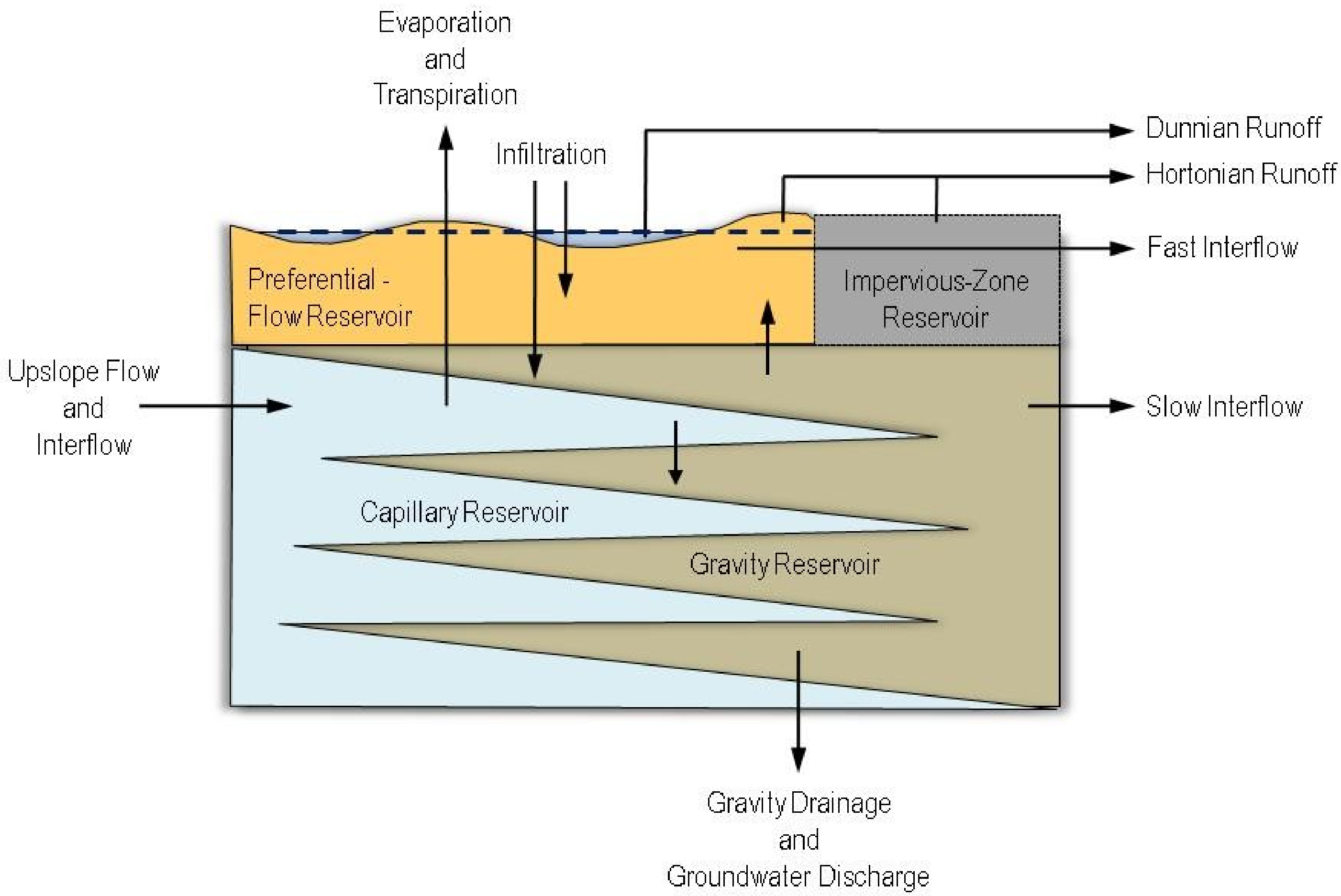


Figure 9: Soil-Zone Reservoir Inflows and Outflows

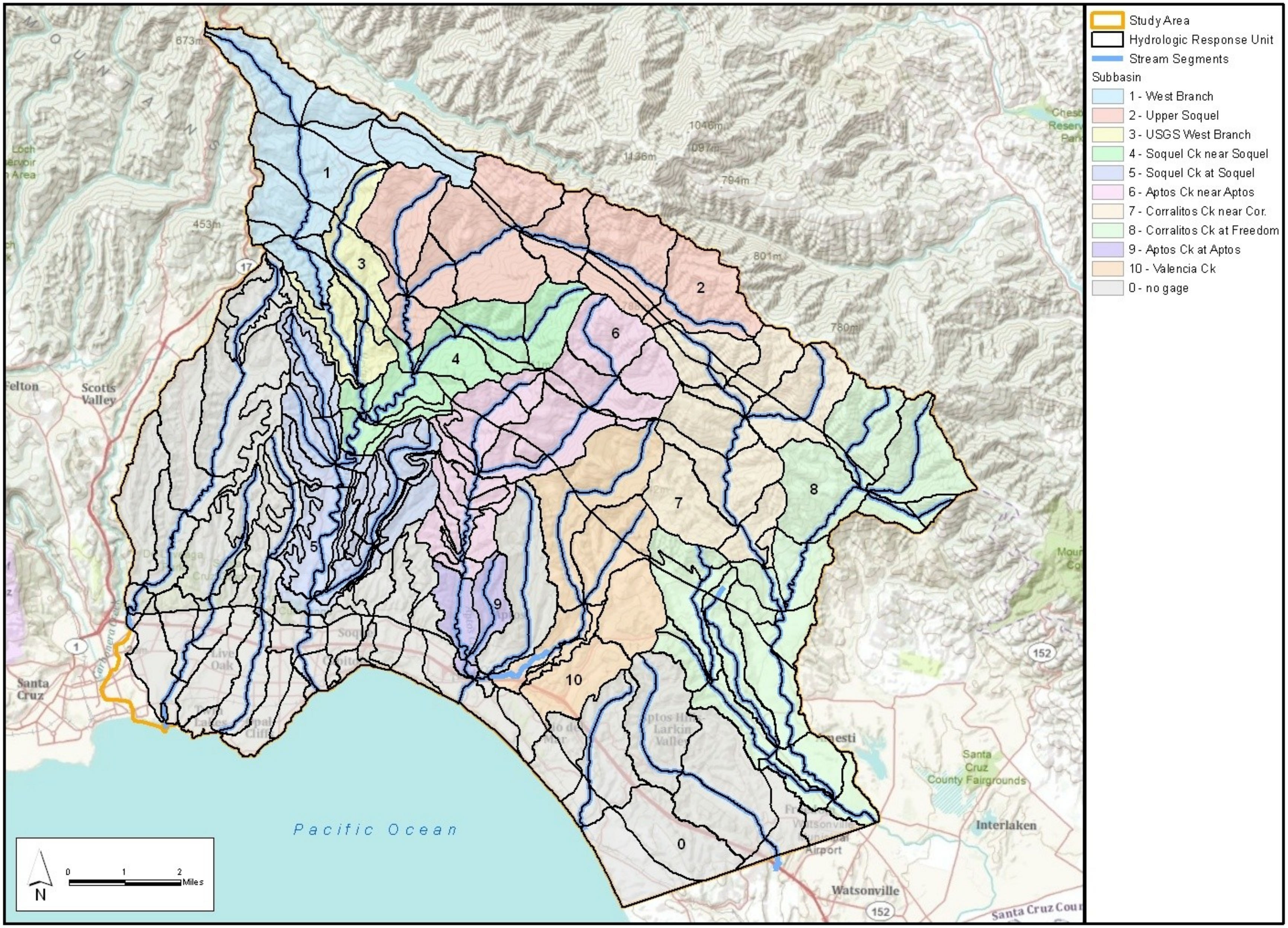


Figure 10: Hydrologic Response Units, Subbasins and Stream Network

3.3 SELECTION OF PRMS MODULES

PRMS uses different software modules to simulate various water and energy processes. Each module requires specific input to execute, and computes outputs which are can be used as input to other modules. The modules selected for the Soquel-Aptos PRMS were based on the availability of data and appropriateness for local conditions. Modules used in the Soquel-Aptos PRMS are summarized in Table 1.

Table 1: Modules used in Soquel-Aptos PRMS

Module Name	**Module Description**
basin_prms	Defines shared watershed-wide and HRU physical parameters and variables
cascade_prms	Determines computational order of the HRUs and groundwater reservoirs for routing flow downslope
obs_prms	Reads and stores observed data from all specified measurement stations
obs_adjust_prms	Checks for missing values and quality control of measured data
soltab_hru_prms	Computes potential solar radiation and sunlight hours for each HRU for each day of the year
temp_1sta_prms	Distributes maximum and minimum temperatures to each HRU using temperature data measured at one station and an estimated monthly lapse rate
precip_dist2_prms	Determines the form of precipitation and distributes it to each HRU using an inverse distance weighting method
ddsolrad_hru_prms	Distributes solar radiation to each HRU and estimates missing solar radiation data using a maximum temperature per degree-day relation
potet_jh_prms	Determines whether current time period is one of active transpiration, and computes the potential evapotranspiration using the Jensen-Haise formulation (Jensen and Haise, 1963)
intcp_prms	Computes volume of intercepted precipitation, evaporation from intercepted precipitation, and throughfall that reaches the soil or snowpack
srunoff_smidx_casc	Computes surface runoff and infiltration for each HRU using a non-linear variable-source-area method allowing for cascading flow
soilzone_prms	Computes inflows to and outflows from soil zone of each HRU and includes inflows from infiltration, groundwater, and upslope HRUs, and outflows to gravity drainage, interflow, and surface runoff to downslope HRUs

Module Name	Module Description
gwflow_casc_prms	Sums inflow to and outflow from PRMS groundwater reservoirs; outflow can be routed to downslope groundwater reservoirs and stream segments
strmflow_prms	Computes daily streamflow as the sum of surface runoff, shallow-subsurface flow, detention reservoir flow, and groundwater flow

Source: (USGS, 2011)

3.4 MODEL PARAMETERS

Model parameters are inputs that are assigned to each HRU, groundwater reservoir, stream segment, and cascade. Parameters values remain fixed throughout a PRMS simulation. There are over 240 parameters required for PRMS. Many parameters were assigned using spatial datasets that represent soils, geology, land surface elevation, slope, aspect, vegetation type and density, and land use. Parameters that cannot be spatially derived were assigned default values. The final PRMS calibrated parameter file is provided on the accompanying data CD.

The general procedure provided in the USGS's online instructions for GSFLOW model input preparation (USGS, 2010) was used to determine spatial parameters for each HRU. Model Builder in ArcGIS was used to automate the process. The four main spatial datasets used were:

1. USGS 1-arc second DEM (USGS, 2007a),
2. USGS 30-meter gridded land use/ land cover (USGS, 2007b),
3. SSURGO soils database (NRCS, 2009), and
4. USGS 30-meter gridded tree canopy density (USGS, 2007b).

Figure 11 graphically shows the attributes and parameters derived from the four spatial datasets. For example, the SSURGO dataset was used to determine depth of soil, available water content, and percentage of sand and clay for each HRU. These attributes were then used to calculate the PRMS parameters required for the soil zone module, such as soil type, soil moisture maximum, and soil recharge maximum.

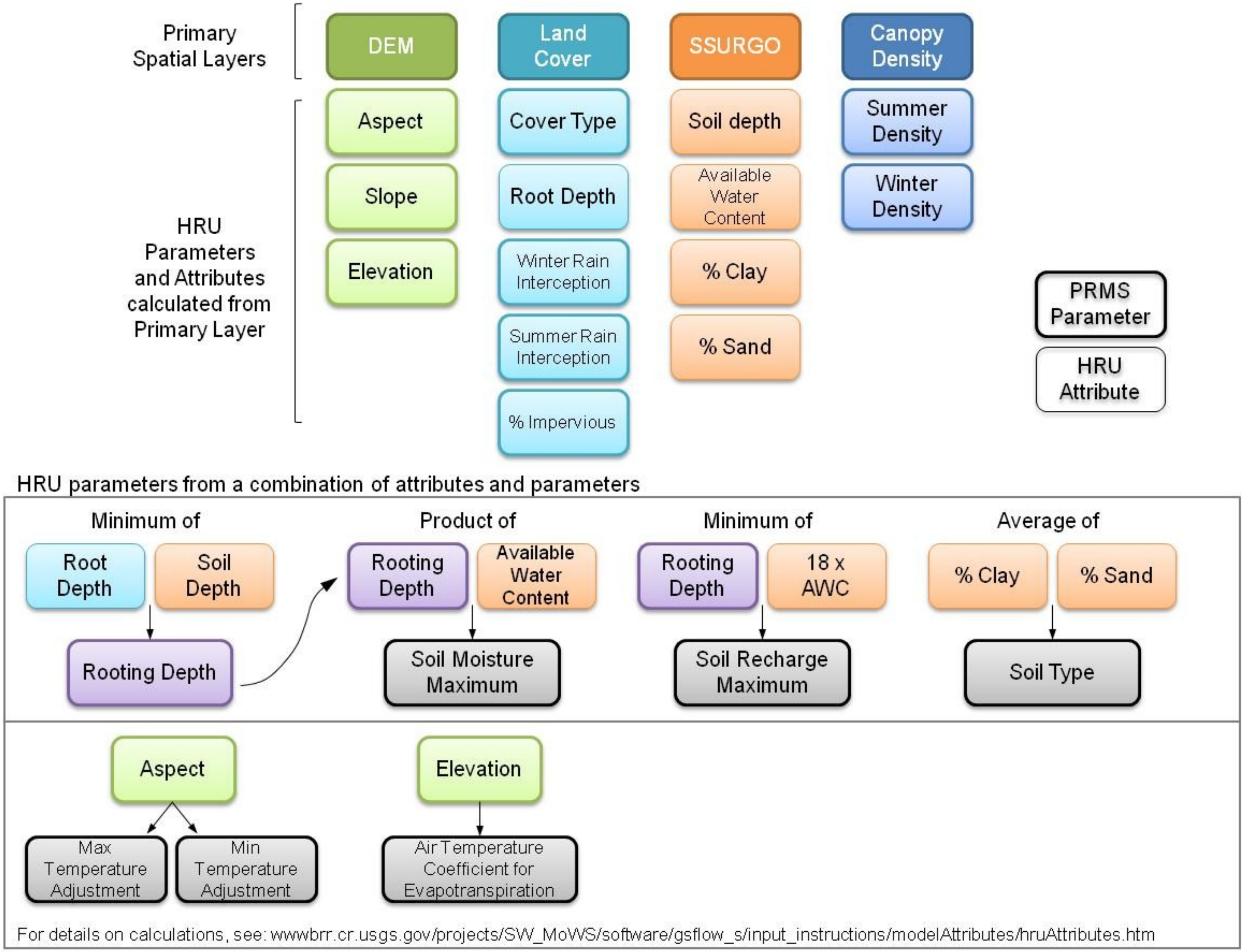


Figure 11: HRU Parameters from Spatial Data

3.5 Calibration Model Period

After evaluating all the available input and calibration data, a model period from October 1, 1983 to September 30, 2009, i.e., Water Year 1984 to Water Year 2009, was selected as the calibration period.

Both dry and wet hydrologic cycles occurred between Water Year 1984 and Water Year 2009. The average annual precipitation during this time period was within one inch of the long-term average precipitation. By selecting this model period, the goal of selecting a time period that is representative of historical conditions was achieved.

3.6 Input Data Sources

Data required for PRMS can be separated into three main categories. The first category is daily climate data, such as precipitation, pan evaporation, solar radiation, and maximum and minimum temperature. These inputs are distributed by PRMS according to user-selected distribution methods (Table 1). The second category is daily streamflow which is used as targets against which to compare model simulated streamflow. The third category is spatial data related to the physical environment within the study area such as topography, soil type, land use, and vegetation.

3.6.1 Climate Data

Daily precipitation data were obtained from NOAA cooperative network and District stations.

Table 2 summarizes the available precipitation used for watershed modeling. As is typical with climate data, there were some days with missing data. Where precipitation data were missing, it was first established from the other station locations whether the missing day was a rainfall day or not. If rainfall did occur on that day, a value was estimated using the normal-ratio method. This method used a weighted average based on annual precipitation.

The distribution of rainfall to HRUs was based on inverse distance weighting the six precipitation stations. Average annual precipitation is shown on Figure 12.

Table 2: Summary of Precipitation Stations

Station Name	Station Number	Source	Date Range	Annual Average** (inches)
Santa Cruz	047916	NOAA Co-op	1893 - present	29.3*
Felton	043004	NOAA Co-op	9/1/2000 - 8/29/2008	45.3*
Ben Lomond	040673	NOAA Co-op	1/1/1937 - present	49.0*
Watsonville Water Works	049473	NOAA Co-op	1/1/1908 - present	21.6*
Mancarti	NA	SqCWD	10/1984 – present	36.5
Krager/Longridge	NA	SqCWD	10/1984 – present	37.4

* Source of Data: Western Regional Climate Center

** Average listed is for entire period of record

Temperature data were used from the Santa Cruz station (NOAA Co-op 047916) which has records from 1893 to the present. Temperature data were also available for other weather stations, however, for the temperature distribution method selected in PRMS, only one temperature station was required.

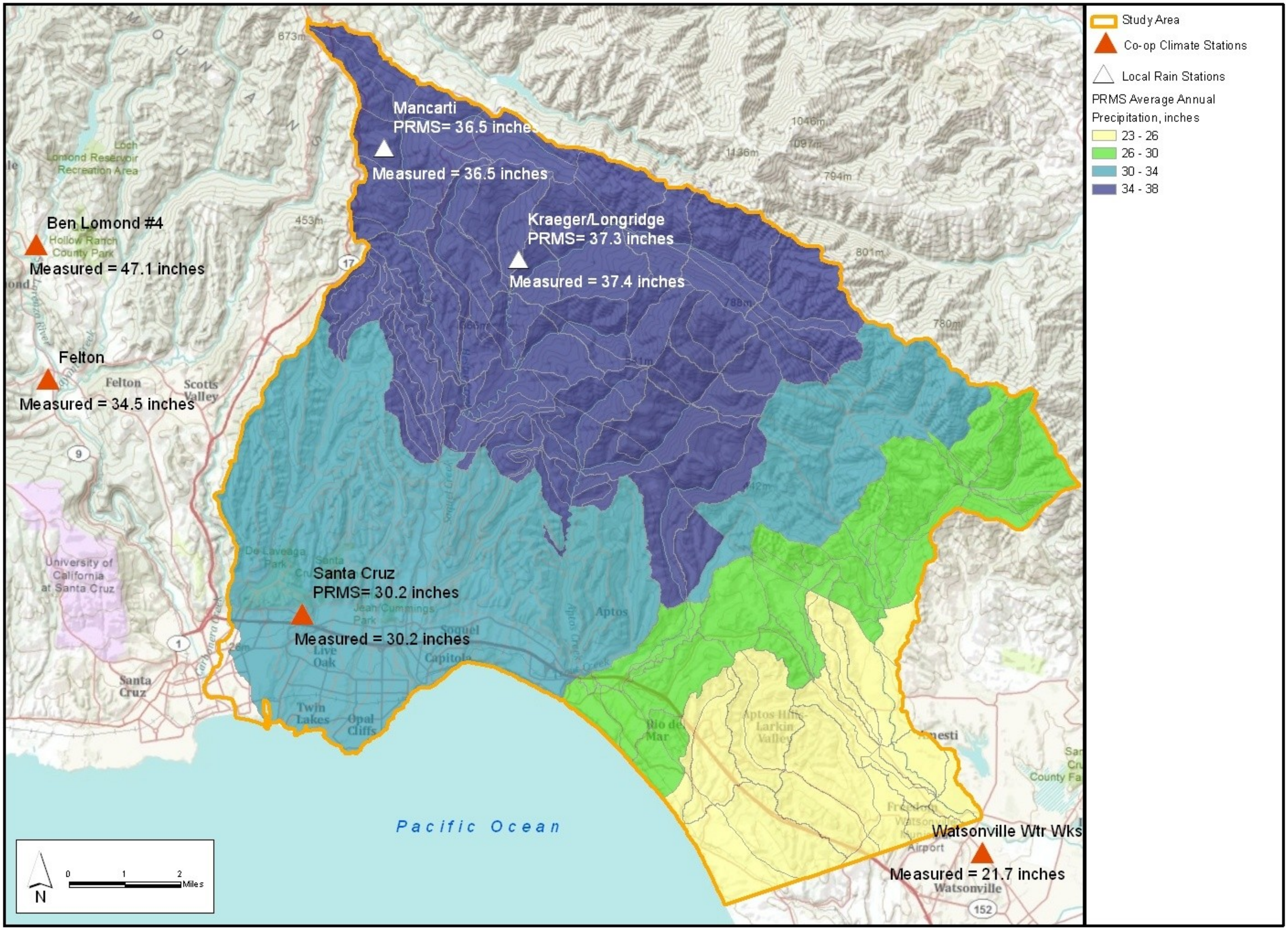


Figure 12: Average Annual Precipitation Distribution by HRU

3.6.2 STREAMFLOW DATA

There are a number of USGS streamflow gages in the study area. However, most of the gages are inactive, with only two being currently operational (Table 3 and Figure 1). The District operates two streamflow gages within the Soquel Creek watershed (Table 3 and Figure 1).

Table 3: Summary of Study Area Streamflow Gages

Station Name	Report Station Number	USGS Station Number	Source	Dates Operational
West Branch	1	NA	SqCWD	11/11/1983 - present[1]
Upper Soquel Creek	2	NA	SqCWD	10/1/1983 - 1/30/1986 11/21/1986 - present[2]
West Branch Soquel Creek near Soquel	3	11159800	USGS	10/1/1958 – 10/6/1972
Soquel Creek near Soquel	4	11159940	USGS	10/1/1968 – 9/30/1972
Soquel Creek at Soquel	5	11160000	USGS	5/1/1951 – present
Aptos Creek near Aptos	6	11159690	USGS	10/1/1971 – 9/30/1985
Corralitos Creek near Corralitos	7	11159150	USGS	10/1/1957 – 10/11/1972
Corralitos Creek at Freedom	8	11159200	USGS	10/1/1956 - present
Aptos Creek at Aptos	9	11159700	USGS	10/1/1958 – 10/6/1972
Valencia Creek (County)	10	NA	County	Unknown Data provided by County from 10/1/2008 to 12/31/2009

[1] Two periods (2/24/2003-4/15/2003 and 4/5/2007-5/3/2007) were estimated by Kraeger using watershed rainfall and potential evapotranspiration. This was necessary due to data errors related to instrument or gage failure (Kraeger, 2009).

[2] Six periods (7/20/2002-10/28/2002, 11/28/2005-12/19/2005, 12/19/2006-1/26/2007, 2/25/2009-4/30/2009, 6/27/2009-7/31/2009, and 9/4/2009-10/30/2009) were estimated by Kraeger using watershed rainfall and potential evapotranspiration. This was necessary due to data errors related to water flowing under the weir or uncertainty of the pressure sensor location (Kraeger, 2009 and Kraeger, 2010).

The streamflow data were used by PRMS as calibration targets. Due to the fact that only two gages have complete records for the entire model period, synthetic data were generated for other gages to ensure that calibration targets were more widespread throughout the study area. Synthetic data were not generated for the Valencia Creek gage due to the short period of available data from that gage.

Synthetic data were produced based on linear regressions from double-mass curves. Double-mass curves were generated between gages with incomplete records and one of the two gages with complete records for the concurrent data period. Double-mass curves for Soquel Creek near Soquel (Gage 4), Aptos Creek gages (Gages 6 and 9) and District gages (Gages 1 and 2) were based on the Soquel Creek at Soquel gage (Gage 5). A double-mass curve for the Corralitos Creek near Corralitos gage (Gage 7) was based on the Corralitos Creek at Freedom gage (Gage 8). Appendix A contains charts with all double-mass curves used for synthesizing streamflow data.

Linear regression equations were developed for each of the double-mass curves. The equations are shown on the charts in Appendix A. For the District's Upper Soquel Creek gage, only the period after 11/21/1986 was used for the linear regression because the gage was at a different location prior to that date. The double-mass curves were extrapolated to the entire model calibration period based on the linear regression equation. Daily streamflow were synthesized from the extrapolated double-mass curves. Charts for all daily streamflow used by PRMS, including synthesized data are shown in Appendix B.

3.6.3 SPATIAL DATA

Section 3.4 described the spatial data used as input for PRMS.

3.7 MODEL CALIBRATION

Calibration of initial PRMS parameters was accomplished using a step-wise approach. Solar radiation and potential evapotranspiration were calibrated by hand adjusting specific parameters. Mean monthly solar radiation (SR) data were obtained using the multiple linear regression method from 217 climate stations across the country described by Hay et al. (2006). These values compared well to the SR recorded at the De Lavega CIMIS station near the Santa Cruz Co-op station. Figure 13 shows the mean monthly distribution of SR for the study area.

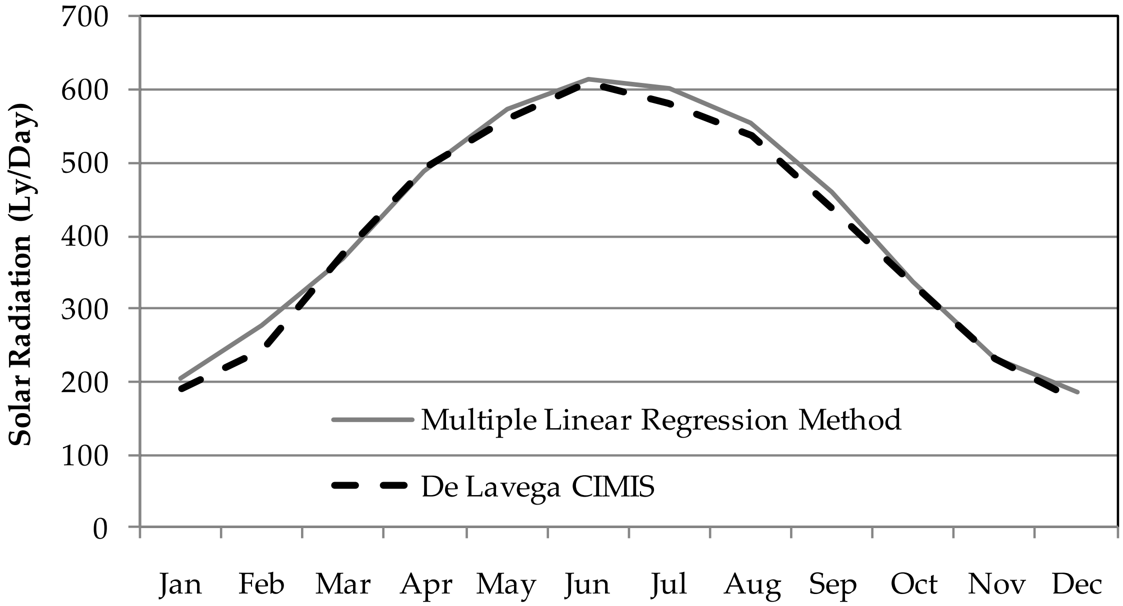


Figure 13: Mean Monthly Solar Radiation for Calibration

Evaporation data for monthly potential evapotranspiration (PET) were not available at any of the climate or CIMIS stations in the vicinity of the study area. In-lieu of observed data in the study area, mean monthly PET values were calculated from PET maps provided by the NOAA National Weather Service (NWS). The NWS derived the PET values from the free water evaporation atlas of Farnsworth et al. (1982). Figure 14 shows the mean monthly distribution of PET for the study area.

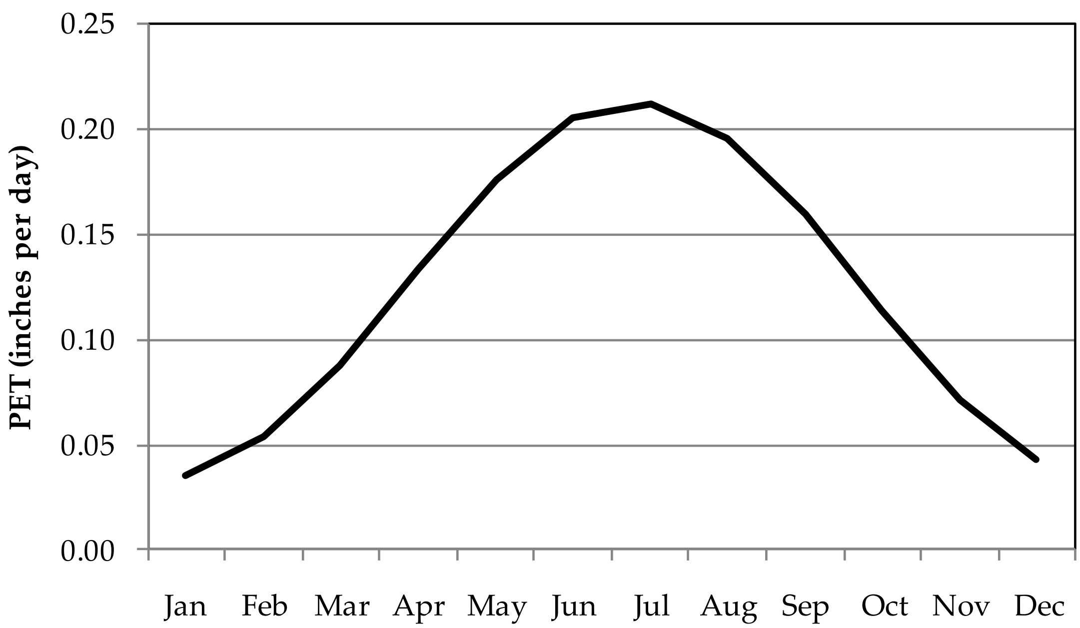


Figure 14: Mean Monthly Potential Evapotranspiration for Calibration

The calibration process for SR and PET involved changing monthly parameters until a good match between measured and calibrated values was found (Figure 15 and Figure 16). Table 4 lists the parameters adjusted for SR and PET.

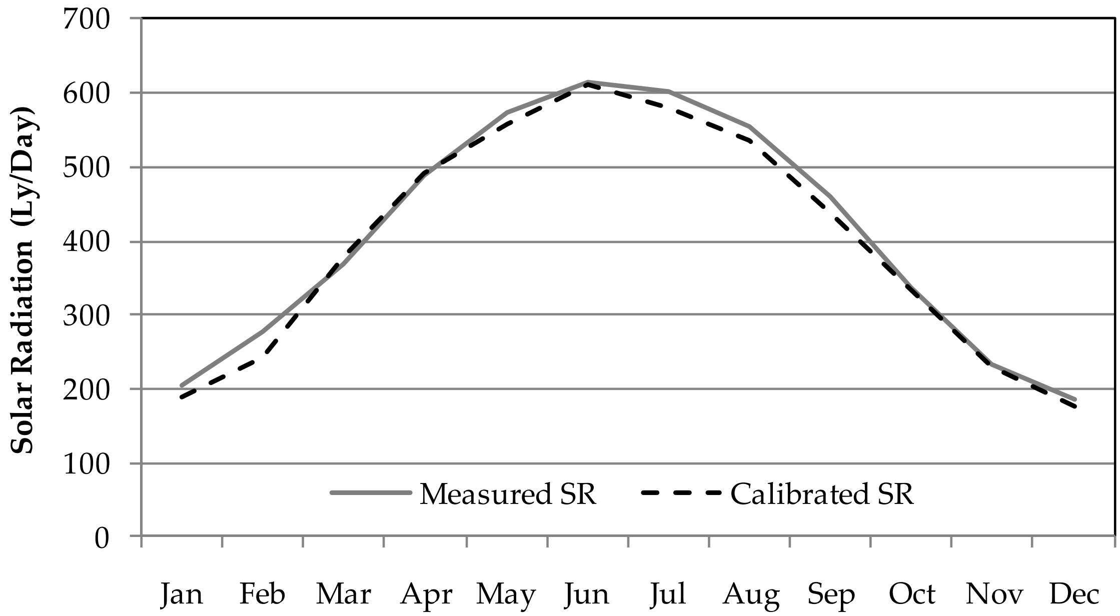


Figure 15: Measured and Calibrated Basin Mean Monthly Solar Radiation

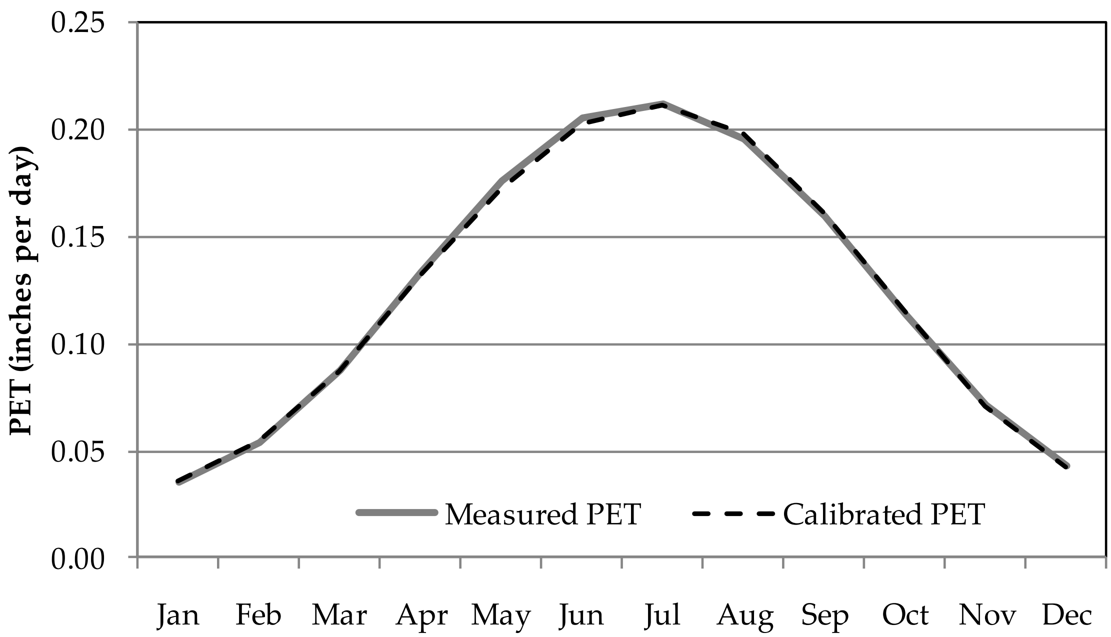


Figure 16: Measured and Calibrated Basin Mean Monthly Potential Evapotranspiration

The second phase of calibration involved the use of Parameter Estimation (PEST) software (Watermark, 2004; Watermark 2008) to optimize PRMS parameters to achieve the best match between measured and simulated streamflow at ten gages throughout the model area. The PRMS parameters calibrated during this phase included primarily soil-zone parameters (Table 4). Due to the varying geology in the area, the best results were found when the model area was subdivided into calibration zones based on geology (Figure 17). The PEST setup enforced no relationship between these zones besides what was informed by the calibration data.

Calibration accuracy was first estimated by visually comparing measured streamflow with simulated streamflow at each of the ten gages. When comparing daily streamflow, the important features to observe on the hydrograph are: peak flows, low flows or baseflow, and the shape of the storm recession part of the hydrograph.

Figure 18 provides an example of the daily measured and simulated hydrographs for the main Soquel Creek and Corralitos gages. Due to the size and complexity of the study area, it is difficult to get an exact match for all daily streamflow measurements, and therefore an effort was made to ensure that measured and simulated monthly and annual streamflow matched well. Figure 19 through Figure 28 provide graphical calibration results for monthly and annual streamflow at each of the ten gages used as calibration targets. The upper left graph in each figure compares measured and simulated average annual flow rates. The upper right graph in each figure compares measured and simulated average monthly flow rates. The center graph on each figure compares measured and simulated average flow rates for each individual month in the simulation. Overall calibration statistics are shown on Figure 29.

Table 4: Calibration Parameters

Target	Parameters Calibrated	Parameter Range	Parameter Description
Mean SR	dday_intcp (month)	-54.5 – -12.5	Intercept in temperature degree-day relation
	dday_slope (month)	0.264 – 0.868	Slope in temperature degree-day relation
Mean Monthly PET	jh_coef (month)	0.007 – 0.013	Coefficient used in Jensen-Haise PET calculation
Streamflow	carea_max (all)	0.282	Maximum possible area contributing to surface runoff expressed as a portion of the HRU area
	fastcoef_lin (zone)	0.002 – 0.033	Coefficient to route preferential-flow storage down slope
	fastcoef_sq (zone)	0.108 – 1.0	Coefficient to route preferential-flow storage down slope
	gwflow_coef (zone)	0 – 0.126	Groundwater routing coefficient
	imperv_stor_max (zone)	0.421 – 1.0	Maximum impervious area retention storage for each HRU
	pref_flow_den (zone)	0 – 0.288	Preferential-flow pore density
	sat_threshold (zone)	15.306 – 999	Soil saturation threshold, above field-capacity threshold
	slowcoef_lin (zone)	0.001 – 0.003	Coefficient to route gravity-flow storage down slope
	slowcoef_sq (zone)	0 – 0.038	Coefficient to route gravity-flow storage down slope
	smidx_coef (zone)	0 – 0.001	Coefficient in non-linear contributing area algorithm
	smidx_exp (zone)	0.2 – 0.355	Exponent in non-linear contributing area algorithm
	soil_moist_max (zone)	7.877 – 20.0	Maximum available water holding capacity of soil profile. Soil profile is surface to bottom of rooting zone
	soil_rechr_max (zone)	0.001 – 10.0	Maximum value for soil recharge zone (upper portion of soil moisture zone where losses occur as both evaporation and transpiration)
	ssr2gw_rate (zone)	0 – 0.054	Coefficient in equation used to route water from the subsurface reservoirs to the groundwater reservoirs
	ssr2gw_exp (zone)	0.043 – 3.0	Coefficient in equation used to route water from the subsurface reservoirs to the groundwater reservoirs

month = different value for each month
all = same value for all HRUs
zone = calibrated by zone

As a more quantitative measure of how well the model predicted streamflow, the Nash-Sutcliffe goodness of fit (NS) statistic was calculated for each of the gages. This statistic has been used previously in other PRMS models to evaluate the performance of the PRMS calibration (Hay et al., 2006; Dudley, 2008; Viger et al., 2010). The NS statistic provides a measure of whether the PRMS model is a better predictor of annual streamflows than the average streamflow. The NS value is calculated for each water year as follows (Moriasi et al., 2007; Nash and Sutcliffe, 1970):

$$NS = 1.0 - \sum_{n=1}^{ndays} (MSD_n - SIM_n)^2 / \sum_{n=1}^{ndays} (MSD_n - MN_n)^2$$

where MSD = measured daily runoff values,
SIM = simulated daily runoff values,
MN = average of the measured values, and
n = the number of values out of a total of n days (ndays).

An NS value of one indicates a perfect fit between observed and simulated. A value of zero indicates that predicting annual streamflows with the PRMS model is as good as using the average value of all the observed data. Any value above zero is considered acceptable, and indicates that predicting annual streamflows with the PRMS model is better than using the average value of all the observed data..

Figure 19 through Figure 28 include the Nash-Sutcliffe results for each gage.

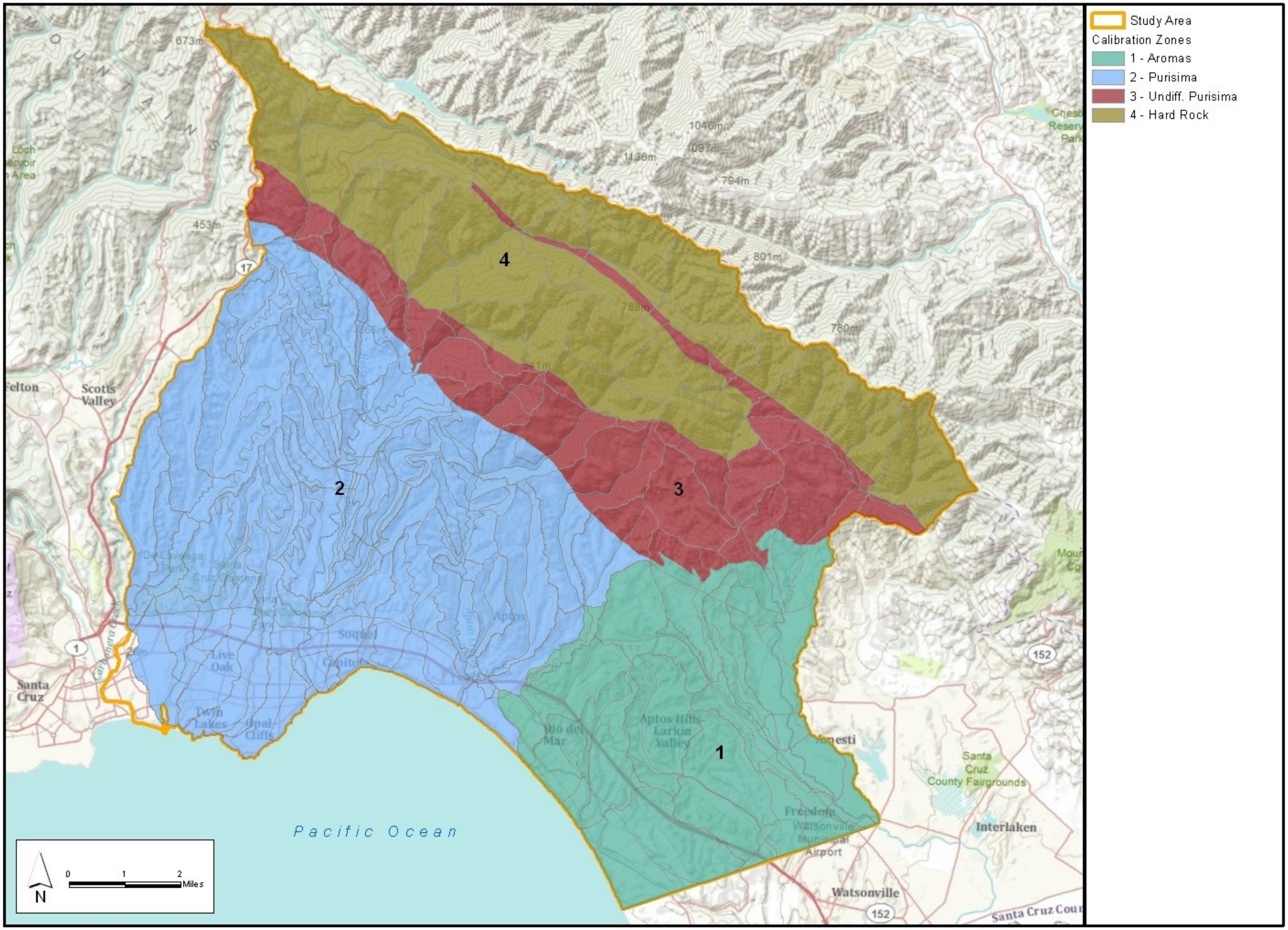


Figure 17: Calibration Zones based on Geology

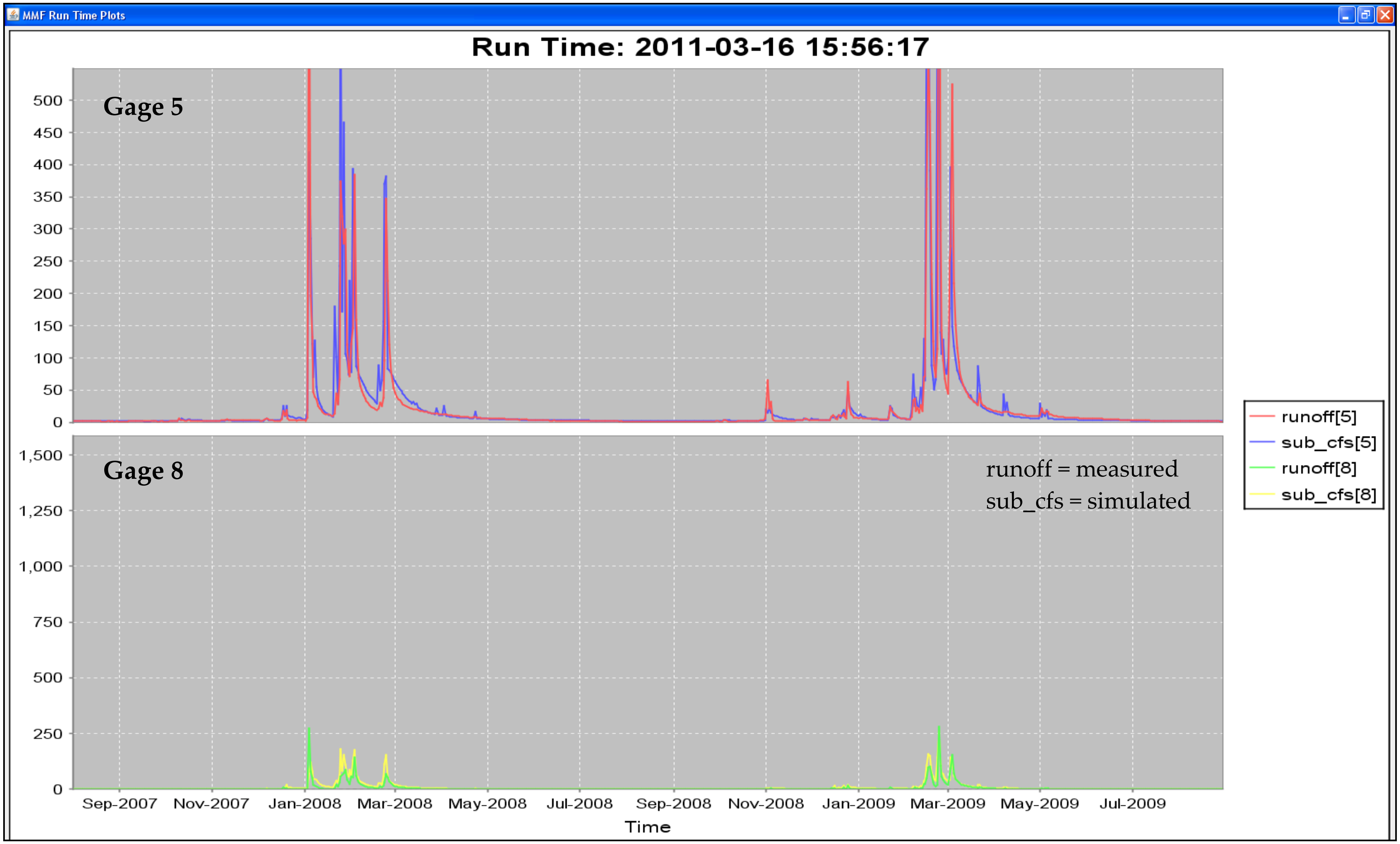


Figure 18: Example of Calibration Output for Daily Streamflow at the Soquel Creek at Soquel Gage (Gage 5) and Corralitos Creek at Freedom Gage (Gage 8)

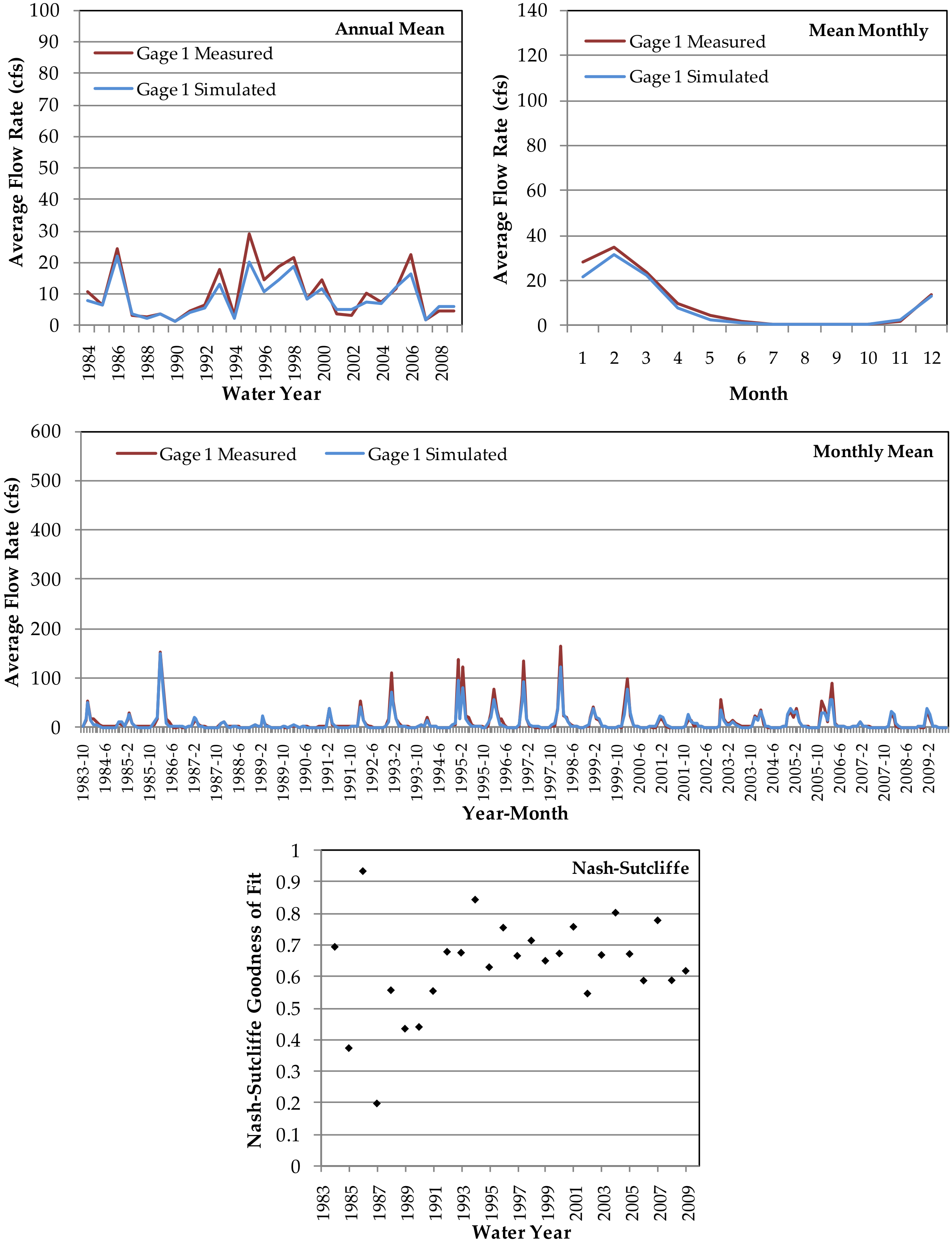


Figure 19: Gage 1 – West Branch Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

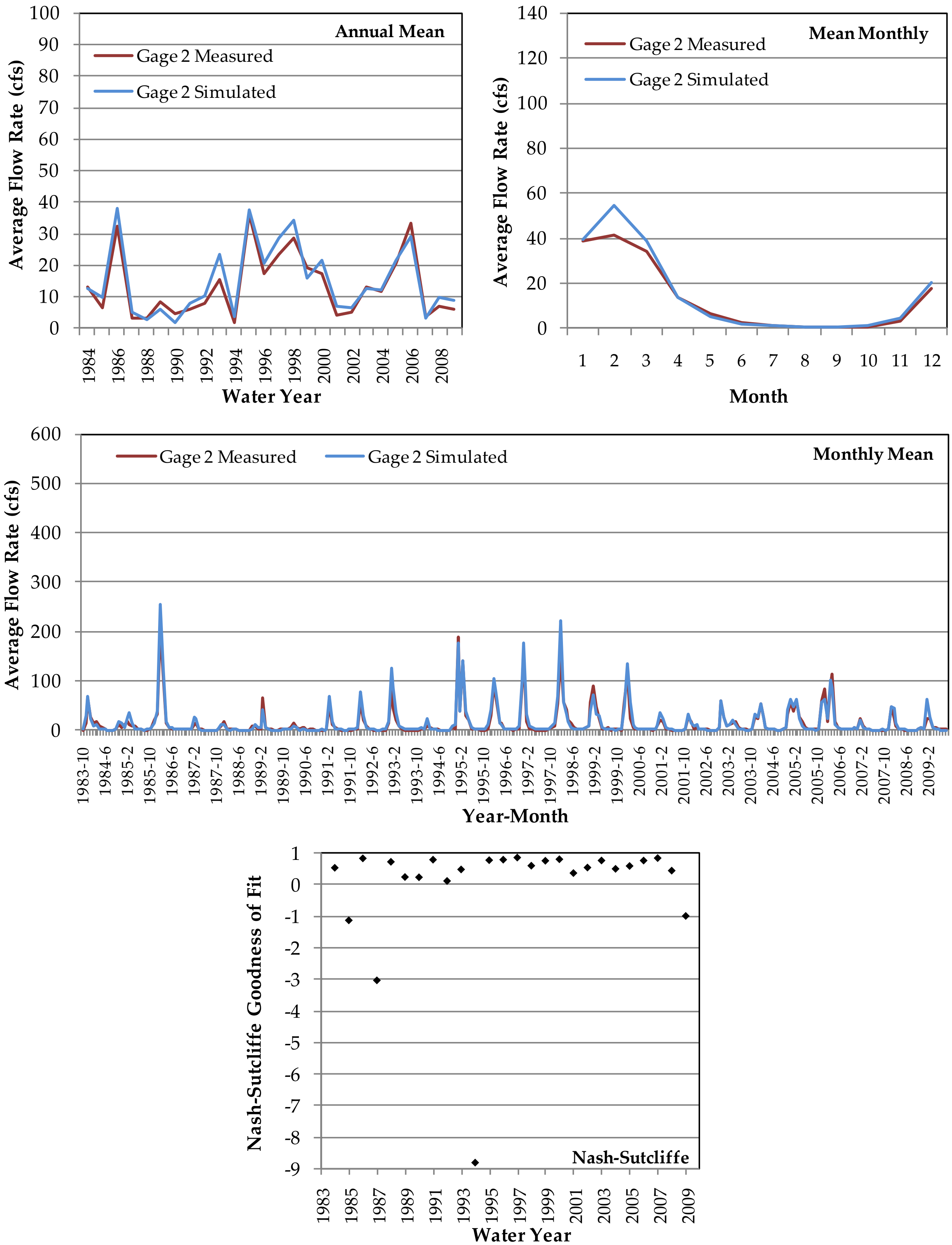


Figure 20: Gage 2 – Upper Soquel Creek Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

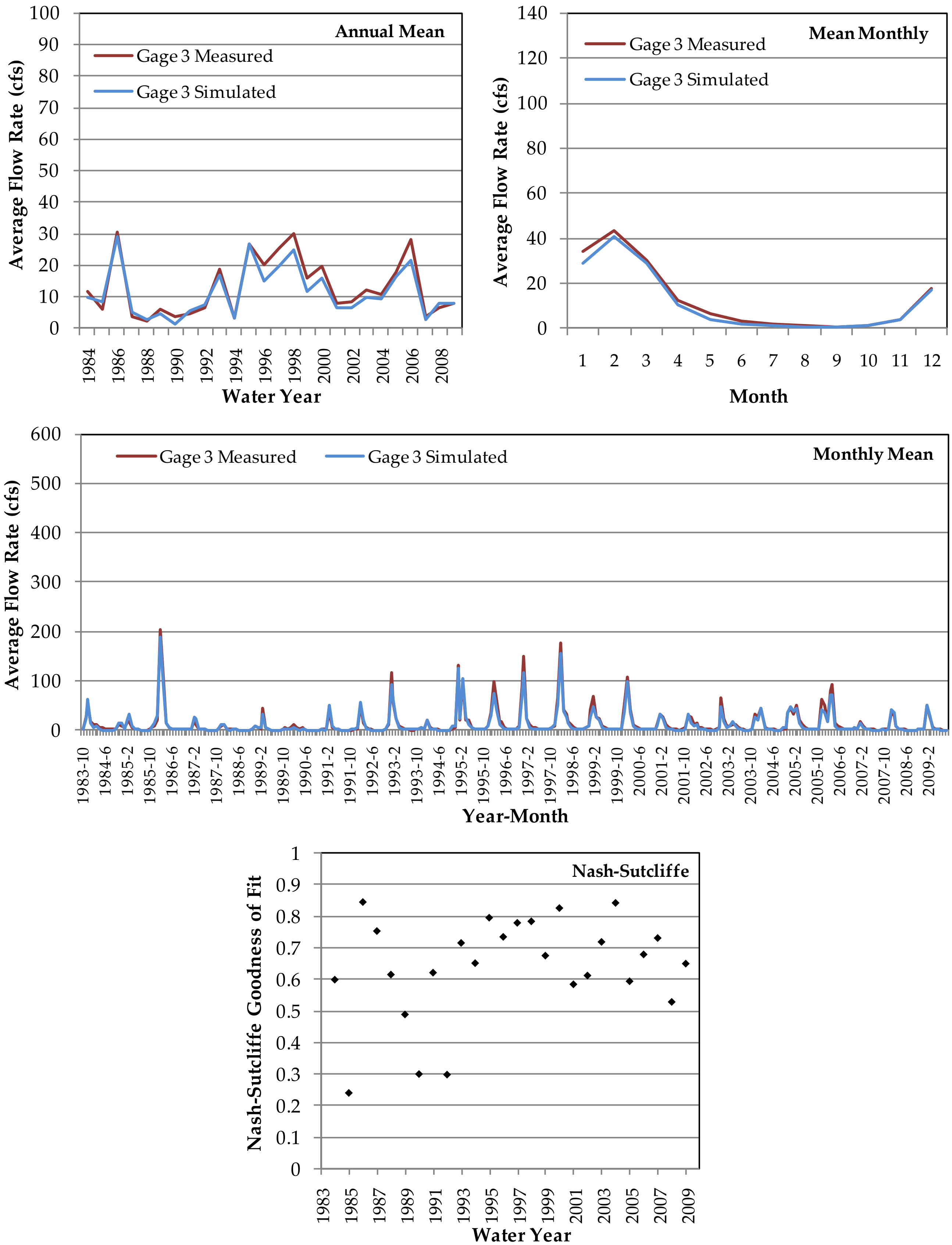


Figure 21: Gage 3 – West Branch of Soquel Creek near Soquel Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

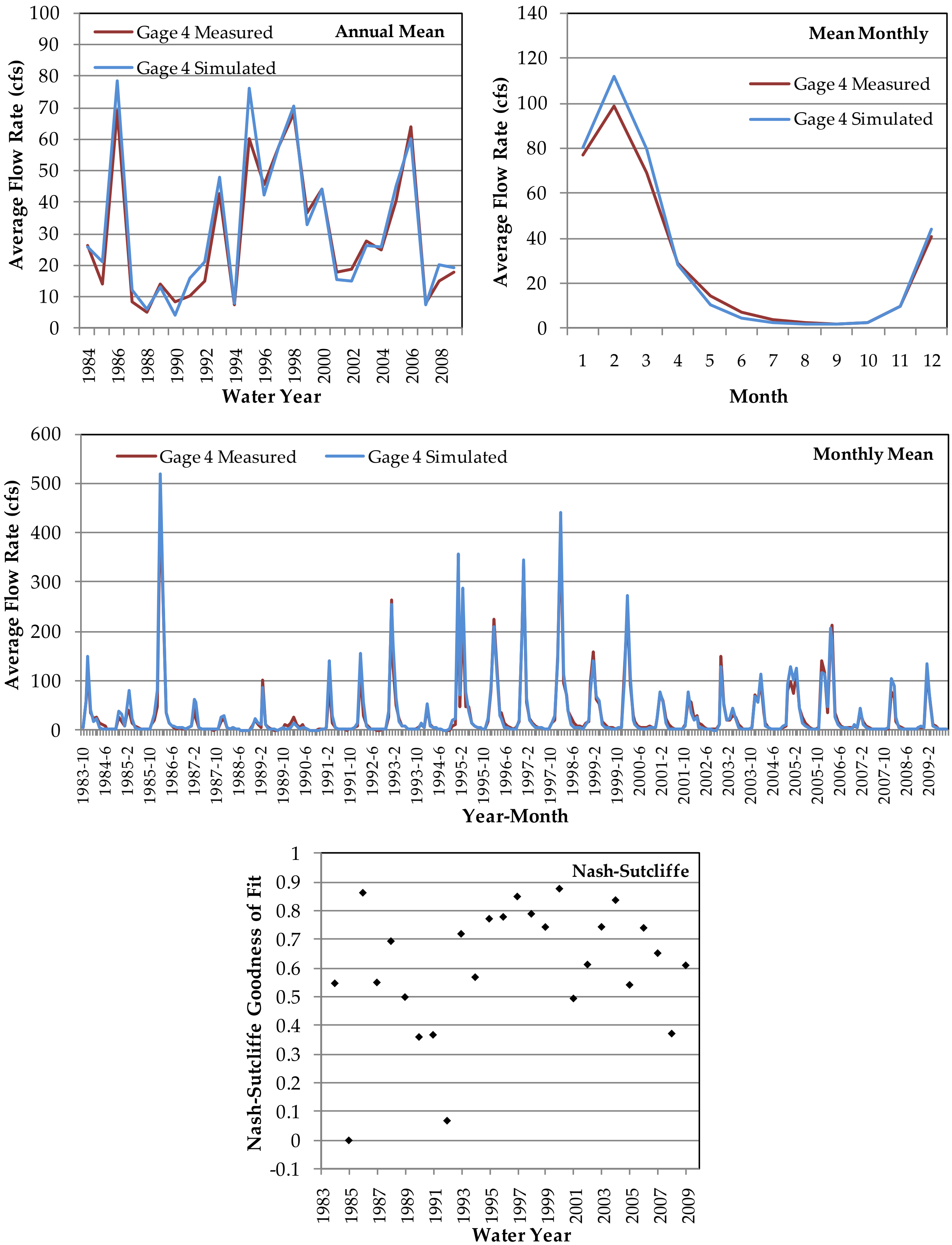


Figure 22: Gage 4 – Soquel Creek near Soquel Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

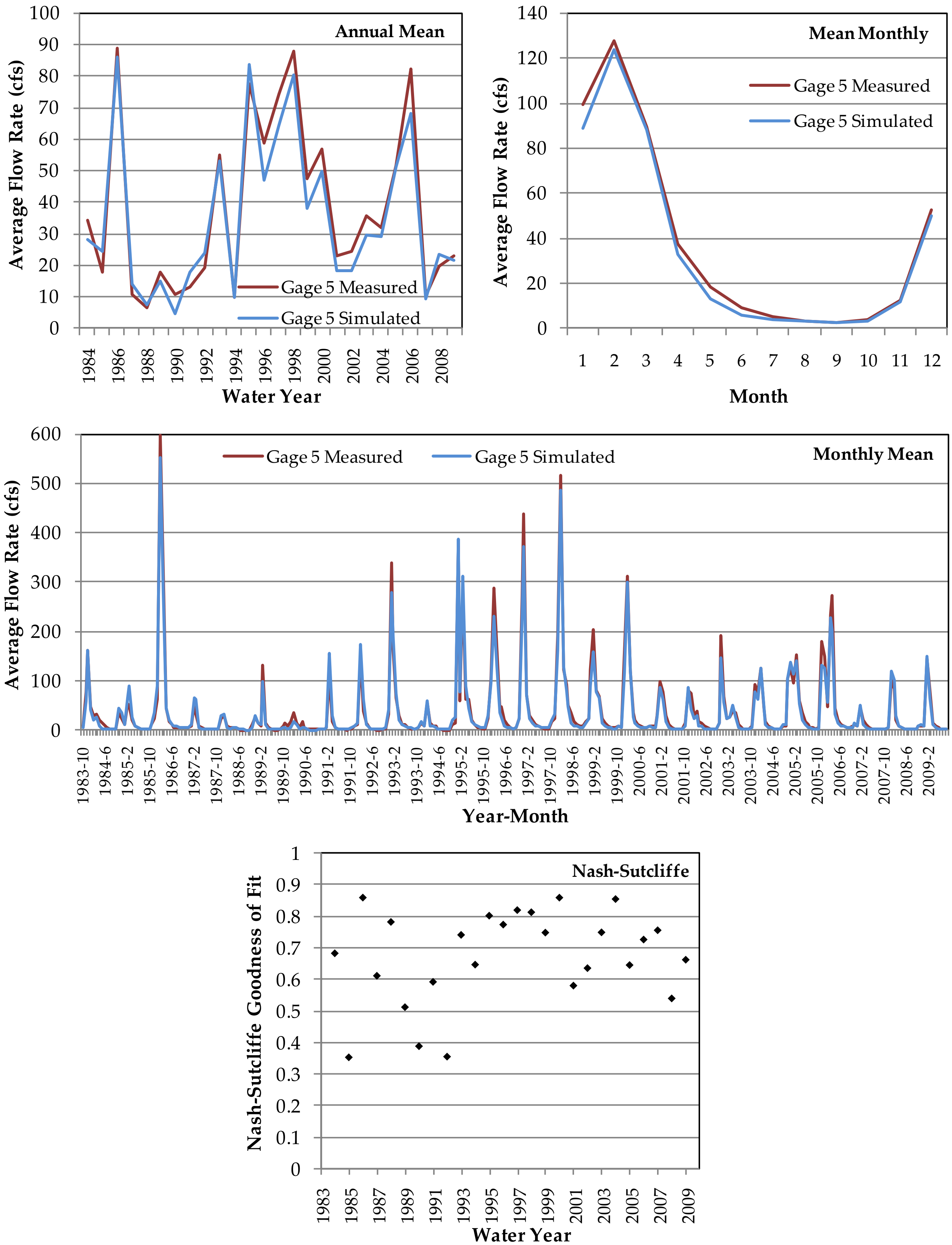


Figure 23: Gage 5 – Soquel Creek at Soquel Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

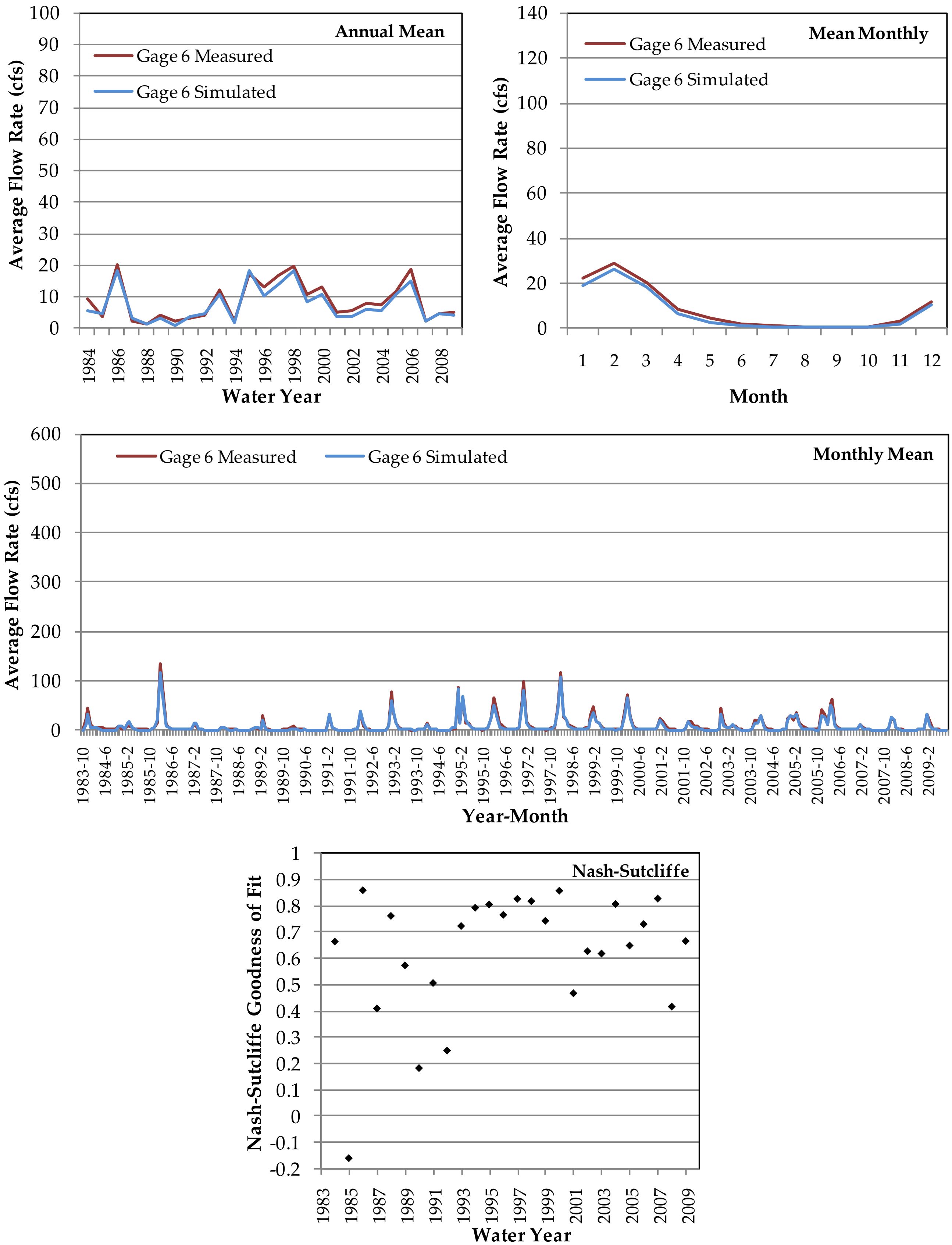


Figure 24: Gage 6 – Aptos Creek near Aptos Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

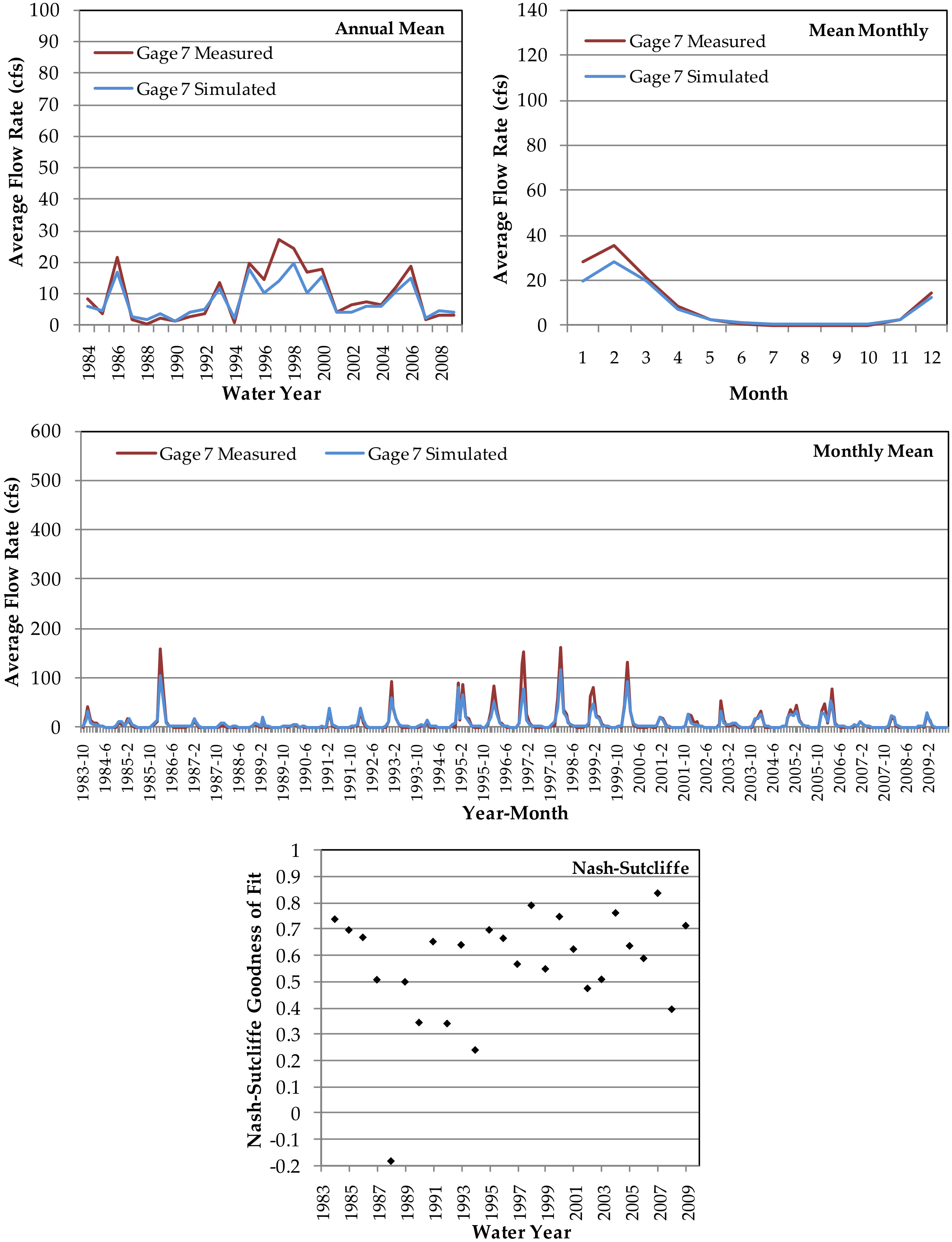


Figure 25: Gage 7 – Corralitos Creek near Corralitos Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

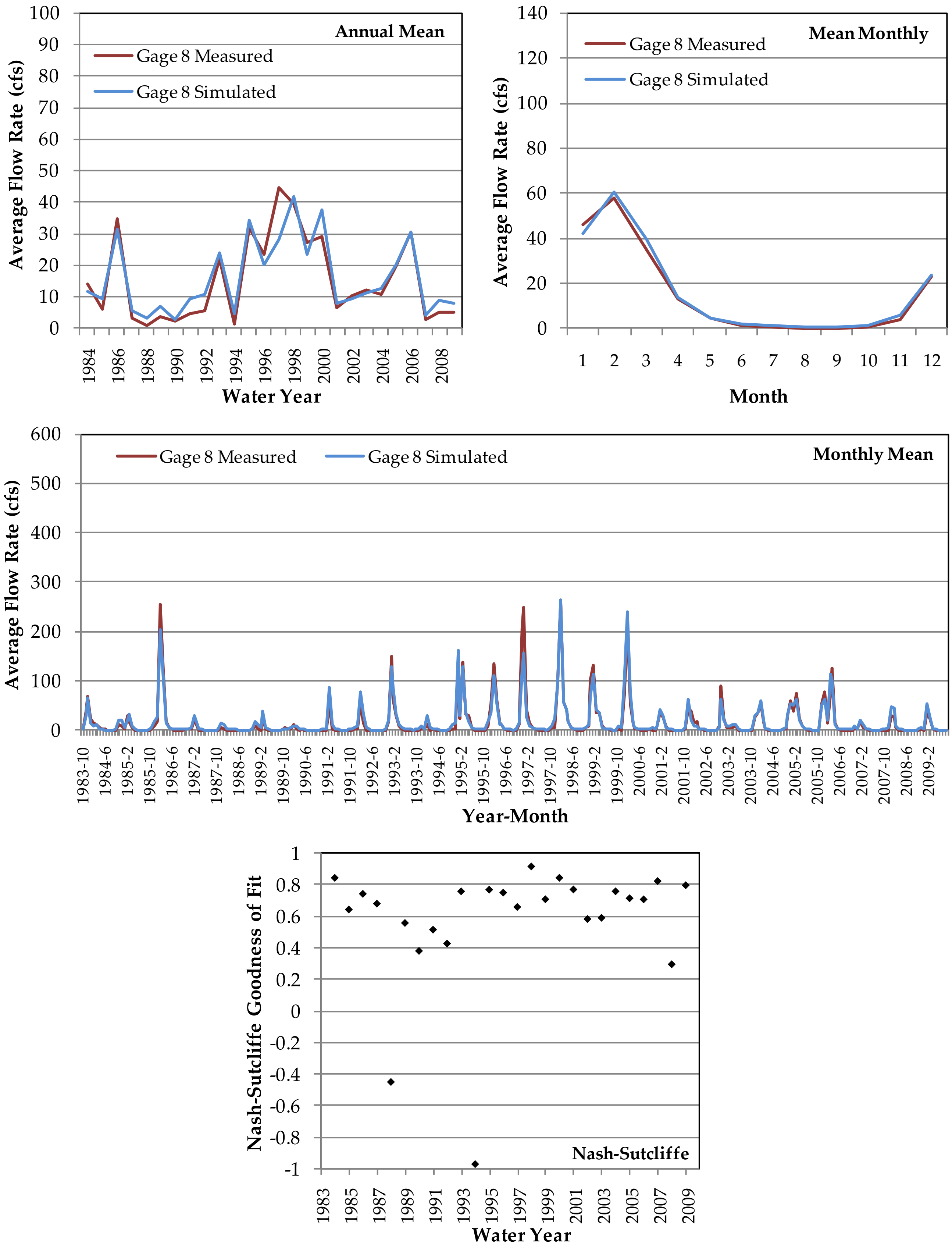


Figure 26: Gage 8 – Corralitos Creek at Corralitos Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit

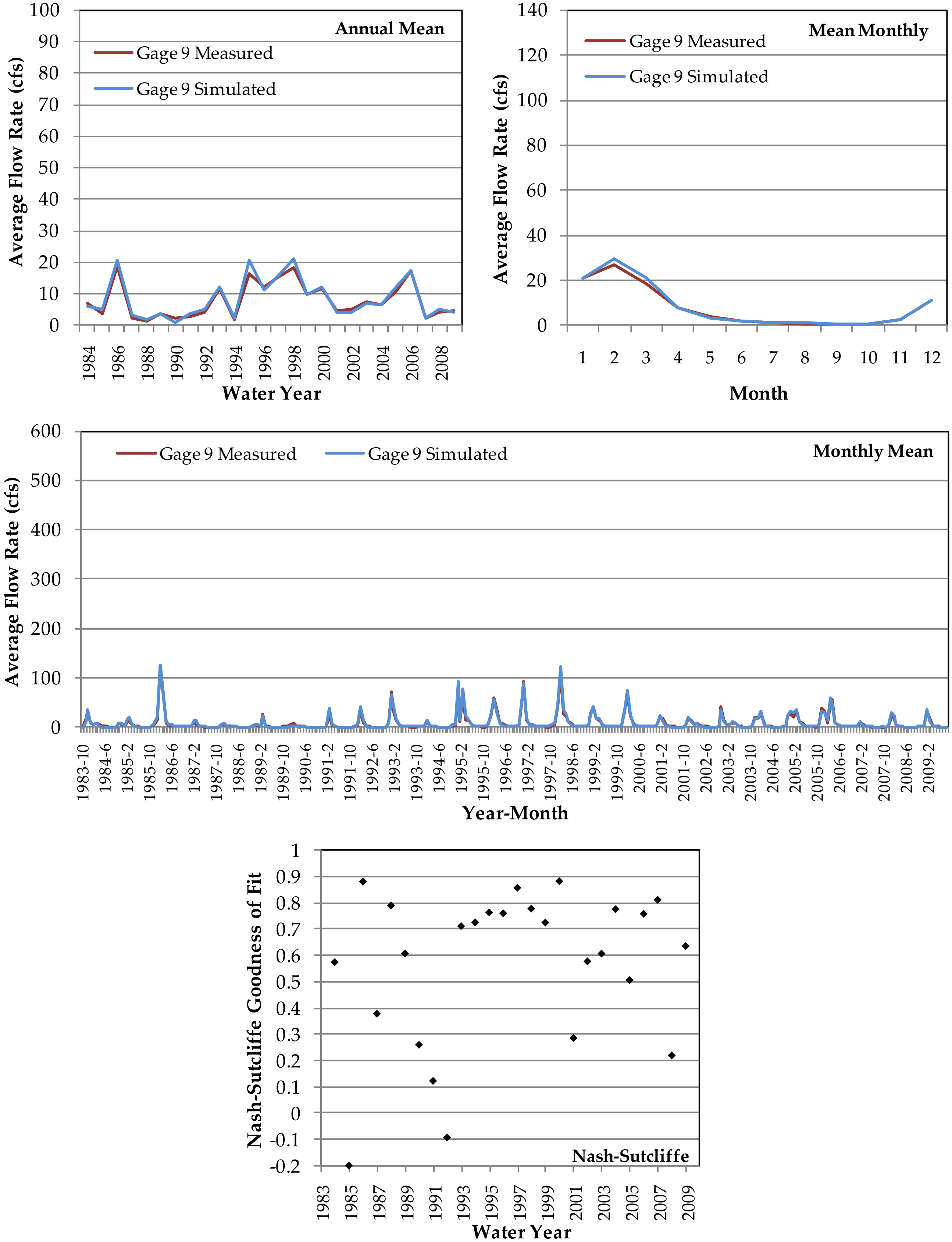
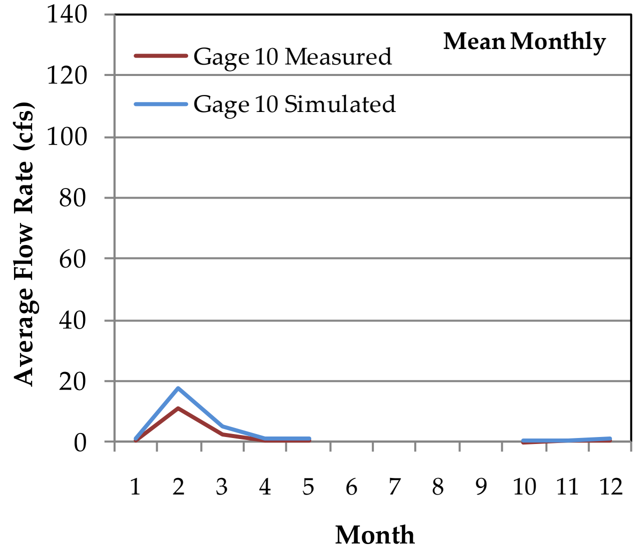


Figure 27: Gage 9 – Aptos Creek at Aptos Calibration: Annual Mean, Mean Monthly, Monthly Mean, Nash-Sutcliffe Goodness of Fit



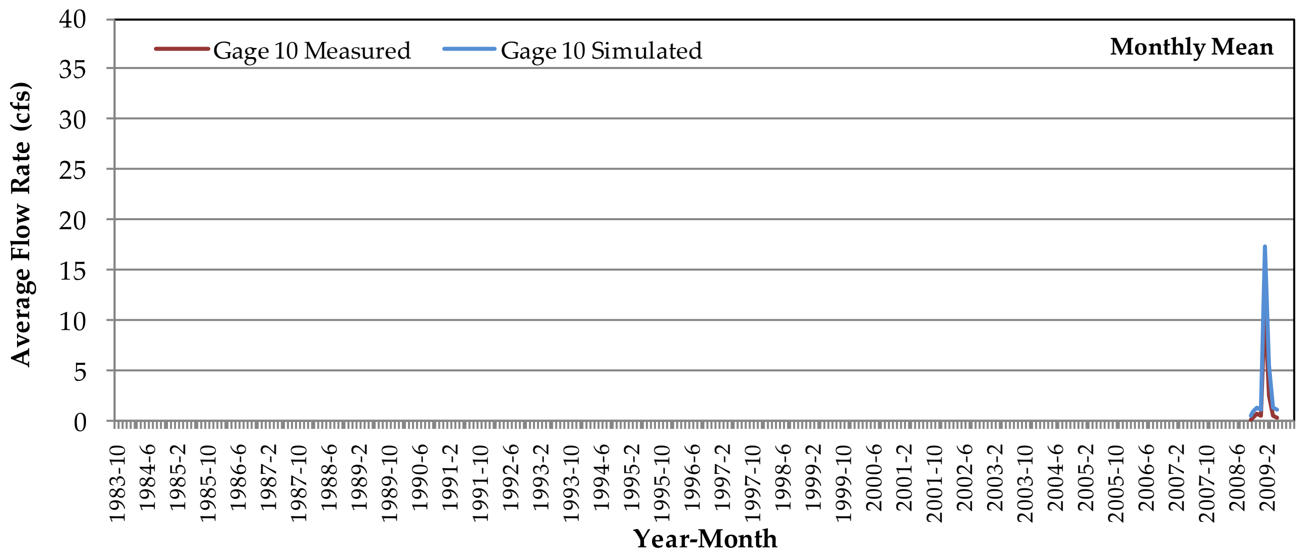


Figure 28: Gage 10 – Valencia Creek Calibration: Mean Monthly, Mean Monthly

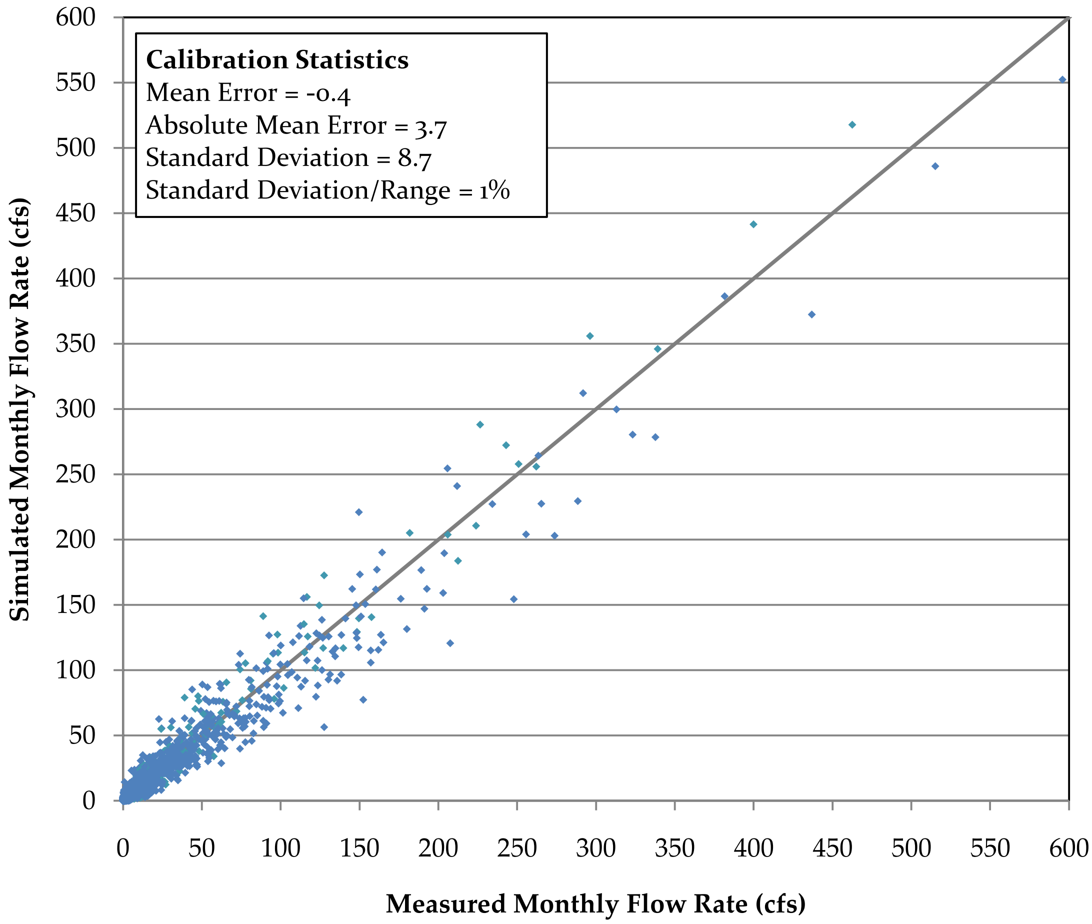


Figure 29: Overall Comparison of Measured and Simulated Streamflow

Evident from the calibration charts shown above, the model is well calibrated. Instances where the annual NS values were less than one are all due to high flow events. After examining particular years with less than zero NS values, it was found that the NS for that year could be increased to greater than zero with the improvement of specific daily events. Table 5 lists those years where the NS was less than zero, and identifies the largest daily streamflow differences between measured and simulated for that year. If simulated streamflow on these days matched measured values, the NS would be above zero for that year.

Table 5: Summary of Years Where Nash-Sutcliffe (NS) is Less than One

Gage	Water Year When Nash-Sutcliffe < 0	Dates that Results in NS < 0
1	1989	3/9/1989
2	1985 1987 1994 2009	2/7/1985, 3/6/1985, 3/26/1985 2/9/1987, 2/11/1987, 2/13/1987, 3/5/1987 2/7/1994, 2/17/1994, 2/18/1994, 2/19/1994 2/15/2009, 2/22/2009
4	1985	3/26/1985
6	1985	3/26/1985
7	1988	12/9/1987, 12/11/1987, 12/16/1987, 12/28/1987
8	1988 1994	12/9 – 12/12/1987, 12/16/1987, 12/28-12/31/1987 2/17/1994, 2/20 – 2/26/1994

SECTION 4
MODEL APPLICATIONS

4.1 WATER BUDGET

The model water budget comprises precipitation, streamflow, evapotranspiration (ET), and deep groundwater recharge. Simplistically, precipitation falls on the land surface and is routed to runoff and ultimately streams, is lost through evapotranspiration, and what remains in the ground after baseflow reaches the streams becomes deep groundwater recharge. Both model-wide and individual HRU output can be generated by the model. Although the model-wide output is available, this report focuses on the output from a smaller area delineated by Johnson et al. (2004), hereafter referred to as the District's hydrogeologic system area (Figure 30).

To obtain the output for the hydrogeologic system area, a subgroup of HRUs coinciding with the area were identified. The hydrogeologic system area is further divided into Purisima Formation and Aromas Red Sands areas. Table 6 summarizes the average annual (water year) water budget from the PRMS model and compares it with the water budget calculated by Johnson et al. (2004).

The PRMS model and Johnson et al. (2004) use different methods and assumptions to apportion deep groundwater recharge between the Purisima and Aromas. Therefore, the results shown in Table 6 for the Purisima and Aromas are not directly comparable. The PRMS model uses the Aromas Red Sands outcrop to define the area for Aromas deep recharge (Figure 4), which includes all of the HRUs on the eastern bank of the Valencia Creek watershed (Figure 10). Johnson et al. (2004) assigned 10% of deep recharge in the Valencia Creek watershed to the Aromas. As a result, the PRMS model includes 1,700 acre-feet per year in deep recharge from the Valencia Creek watershed in the Aromas total while Johnson et al. (2004) includes only 113 acre-feet per year in deep recharge from the Valencia Creek watershed in the Aromas total.

Table 6: Hydrogeologic System Area Average Annual Water Budget Summary

Method	Aquifer Outcrop	Precipitation	Streamflow	Evapo-transpiration	Deep Groundwater Recharge
		Acre-Feet per Water Year			
Johnson et al. (2004)	Purisima	93,500	24,700	61,800	7,000 (6,100)
	Aromas	18,900	1,800	14,200	2,900
	Total	**112,400**	**26,500**	**76,000**	**9,900 (9,000)**
PRMS	Purisima	91,300	24,500	60,500	6,600
	Aromas	19,200	2,100	12,200	4,200
	Total	**110,500**	**26,500**	**72,700**	**10,800**

Notes: The values in parenthesis are values from the Johnson et al. (2004) report that are in error. The values above the parenthesized values are the corrected values.
Totals may not add up due to rounding errors.
Purisima area = 51 square miles, Aromas area = 14 square miles

Comparing the two water budgets, the difference in deep groundwater recharge is 1,800 acre-feet per year, which is due to differences in values for precipitation and ET. The correct amount of ET is always a difficult component to estimate, however PRMS uses a more sophisticated method than what was used by Johnson et al. (2004) and therefore considered more accurate. Furthermore, annual values of ET range from 17 to 24 inches, which is within the expected ET rates in the Soquel-Aptos area.

The variation of deep groundwater recharge throughout the model period is shown on Figure 31. The chart shows how total deep recharge fluctuates annually in response to rainfall. Over the 26 year period, maximum annual deep recharge is 42,900 acre-feet and the minimum is 290 acre-feet. The average is 10,800 acre-feet per year.

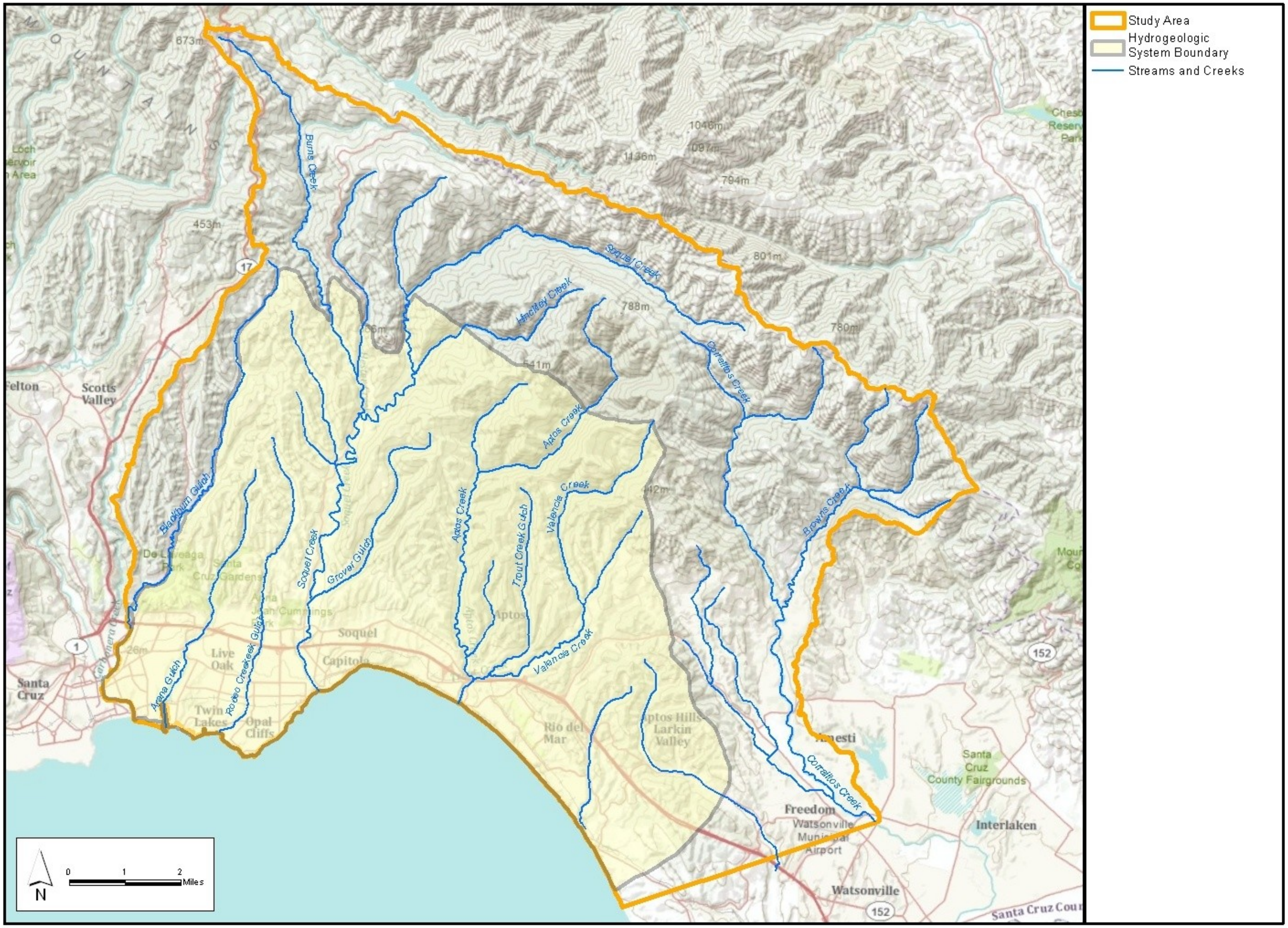


Figure 30: Soquel Creek Water District Hydrogeologic System Area

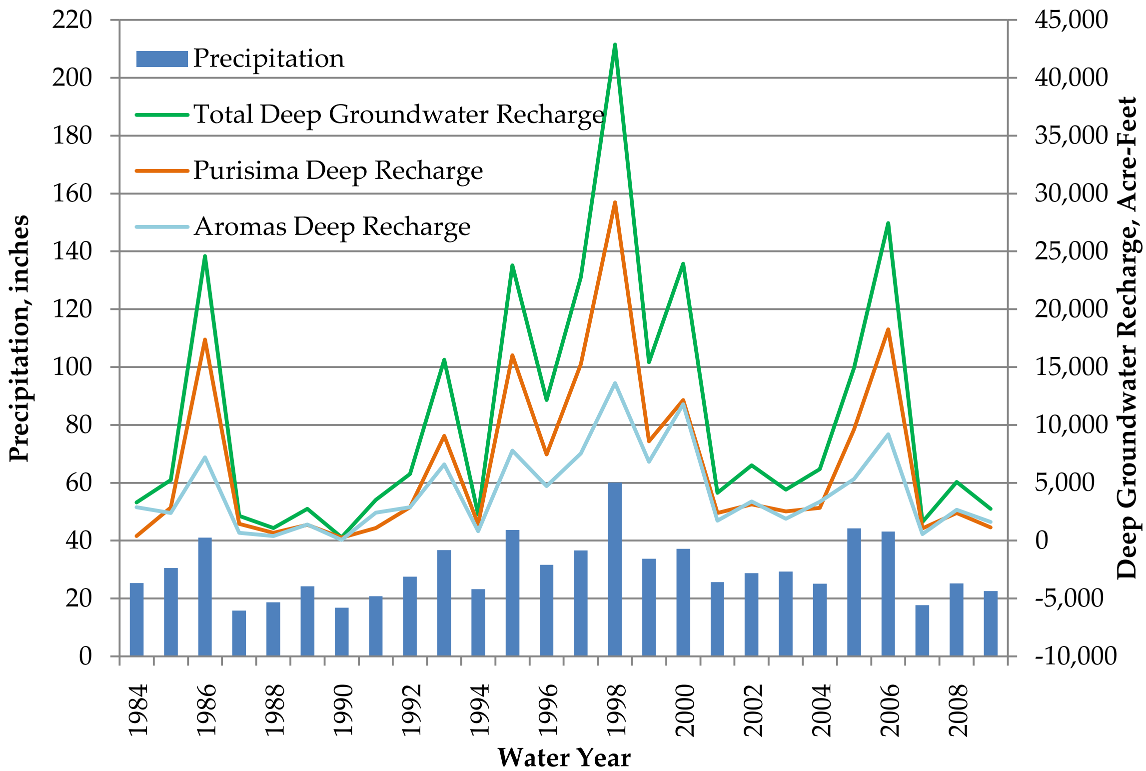


Figure 31: Deep Groundwater Recharge - 1984 to 2009

By selecting the HRUs that coincide with different aquifer outcrop areas (Figure 4) the amount of deep groundwater recharge received by each aquifer was determined. Table 7 lists the average deep recharge for each of aquifers. As expected, the aquifer outcrops with the largest areas have the most deep aquifer recharge.

Table 7: Hydrogeologic System Area Average Deep Groundwater Recharge for Outcropping Aquifers

Aquifer Outcrop	**Average Deep Groundwater Recharge (Acre-Feet per Year)**
AA	1,600
A	1,300
BC	500
DEF	900
F	1,400

4.2 PRECIPITATION PATTERNS

An attempt was made to evaluate the effect of rainfall intensity on modeled deep groundwater recharge. However, initial results were inconclusive and no clear relationship could be found. We recommend that a longer period of record be evaluated to establish whether such a relationship exists.

Due to the model's daily time step limitation, it cannot be used to evaluate changes in recharge due to changes in storm intensity. To achieve this, an hourly time step would be needed, which is not supported by the current PRMS software (PRMS-2010). As such, any analysis of rainfall intensity will be limited to daily data.

4.3 CRITERIA FOR DROUGHT CURTAILMENT

In its 2005 Urban Water Management Water Plan (UWMP), the District includes provisions for declaring a precautionary drought curtailment. However, criteria for when and to what degree to declare a drought curtailment have not been developed. Because the District's current water supply is exclusively from groundwater, developing these criteria is not necessarily straightforward; a period of lower precipitation does not immediately lead to a reduction in water supply as it would for a surface water source such as the City of Santa Cruz's San Lorenzo River source. The District's groundwater basin has built in storage. Although a period of lower precipitation would lead to decreased deep groundwater recharge of the aquifers, the District could maintain water production by pumping the groundwater in storage.

Annual groundwater recharge was chosen instead of groundwater elevations as a measure of drought conditions because groundwater elevations in many wells are sensitive to nearby pumping, and less sensitive to recharge fluctuations. Therefore groundwater elevation fluctuations are not a measure of drought, but rather a measure of pumping changes. Furthermore, groundwater levels at the District's coastal monitoring wells have been below elevations that protect the basin from seawater intrusion (HydroMetrics WRI, 2011). Low elevations cannot be considered an emergency, or an unusual condition.

Results from the PRMS model were evaluated to identify the frequency and severity of historic periods of below average deep groundwater recharge. Based on this evaluation, a deep groundwater recharge shortfall of 10,500 acre-feet is suggested as a criterion for drought curtailment. The PRMS model results were also used to establish the amounts of rainfall that signals a deep groundwater recharge shortfall of at least 10,500 acre-feet.

4.3.1 EXTENDED MODEL PERIOD

To facilitate identifying multi-year periods of below average deep groundwater recharge, the PRMS model was extended. The extended PRMS model starts in Water Year 1942 and ends in Water Year 2010. Water Year 1942 was chosen as the start because daily rainfall data at the Ben Lomond cooperative rainfall station was sporadic prior to 1942. Input data for the six precipitation stations and one temperature station, used as PRMS input, were added to the calibrated model for the 1942 – 1983 water years, and for Water Year 2010. Where data were missing, the same normal-ratio method was used to synthesize data as described in Section 3.6.1. The extended model used the same model parameters that were established during the 1984 to 2009 calibration period.

4.3.2 EXTENDED MODEL DEEP GROUNDWATER RECHARGE

Total deep groundwater recharge estimated by the PRMS model from Water Year 1942 to 2010 is shown in Figure 32. Long-term average annual deep groundwater recharge was estimated to be 10,400 acre-feet, similar to the 10,800 acre-feet estimated for the calibration period. However, the median annual deep groundwater recharge was estimated to be 5,900 acre- feet: half of the years provide less than 5,900 acre-feet of recharge. The skewed distribution of annual total deep recharge is shown in Figure 33; in 64% of years, annual recharge is below average. Basin management has traditionally been based on total long-term groundwater recharge represented by the average, but the average is influenced by relatively infrequent high recharge years.

To evaluate the severity of a period of below average deep groundwater recharge, the deep recharge shortfall is defined as the additional deep recharge over the period needed to bring recharge up to the average deep groundwater recharge. Figure 33 shows that there is a 36% probability that any year's recharge will exceed the average recharge of 10,400 acre-feet. Furthermore, there is a 19% probability that any year's deep groundwater recharge will exceed two times the average, which would make up for a previous year of zero recharge. Therefore, any single year with below average recharge (10,400 acre-feet per year) has between a 19% and 36% probability of having the single year shortfall made up the following year.

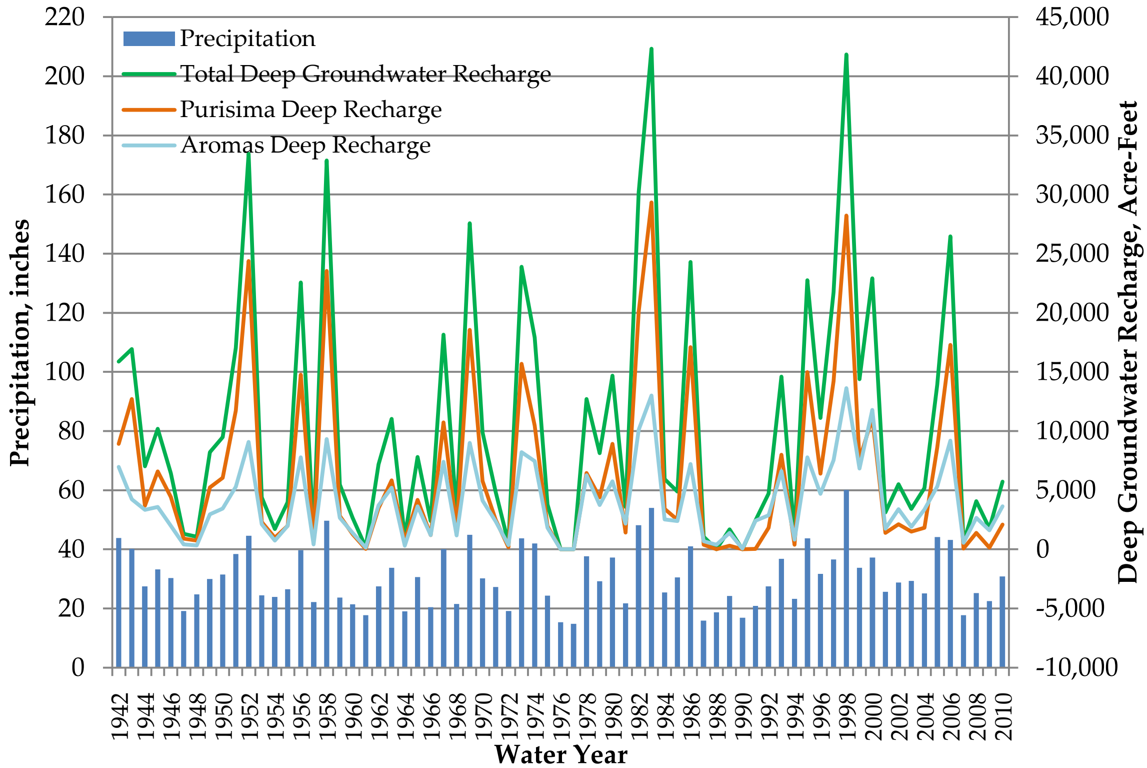


Figure 32: Total Deep Groundwater Recharge – 1942 to 2010

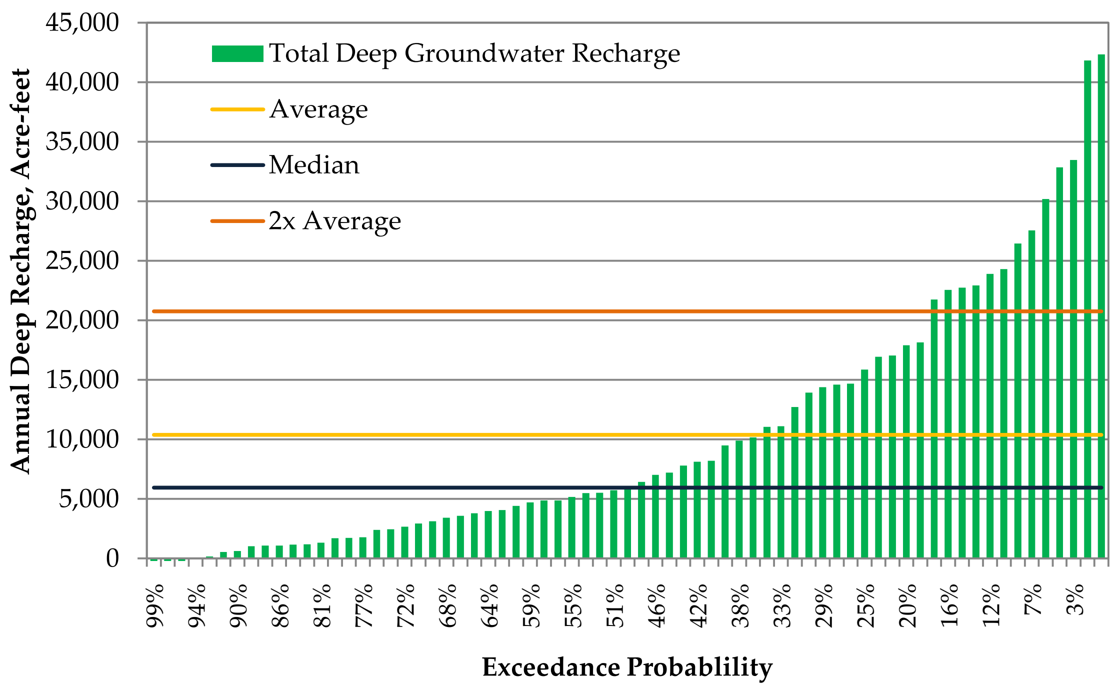


Figure 33: Exceedance Probability Distribution of Annual Deep Groundwater Recharge - 1942 to 2010

The 19 to 36% probability of having a single year shortfall made up the following year supports basing drought curtailment criteria on multi-year periods of below average recharge rather than single-year events. Only cumulative multi-year shortfalls exceeding 10,500 acre-feet, where there is less than 19% probability of making up the shortfall, should be considered for Stage 2 drought curtailments. The suggested criterion for Stage 3 drought curtailment is a shortfall exceeding 21,000 acre-feet, which has a less than 5% probability of being made up the following year.

4.3.3 Rainfall Criteria Development

Although the PRMS model could be updated annually to dynamically estimate the deep groundwater recharge shortfall, drought criteria based on rainfall will be easier for the District to implement. Therefore, the results of the PRMS model were evaluated to identify multi-year rainfall amounts that signal deep recharge shortfalls exceeding 10,500 and 21,000 acre-feet.

The District would like to use winter rainfall data that allows them to declare drought curtailments for peak usage months, such as between May and October of a dry year. To implement a drought curtailment in May, the District would need to declare a drought curtailment no later than April. Therefore, the curtailment decision needs to be made on incomplete data for the water year. Correlations of full water year deep recharge estimated by the PRMS model with rainfall through February, rainfall through March, and full water year rainfall were evaluated (Figure 34). The correlation coefficient between the total rainfall for the year and the amount of deep recharge for the year is 0.9176. The correlation coefficient between rainfall measured through March and the amount of deep recharge measured at the end of the year is only slightly less, 0.9045. The correlation coefficient between rainfall measured through February and the amount of deep recharge measured at the end of the year drops off to a value of 0.739. These correlations show that rainfall through March predicts full water year recharge better than rainfall through February, and approaches the reliability of using full water year rainfall. We recommend that drought curtailments be based on rainfall through March.

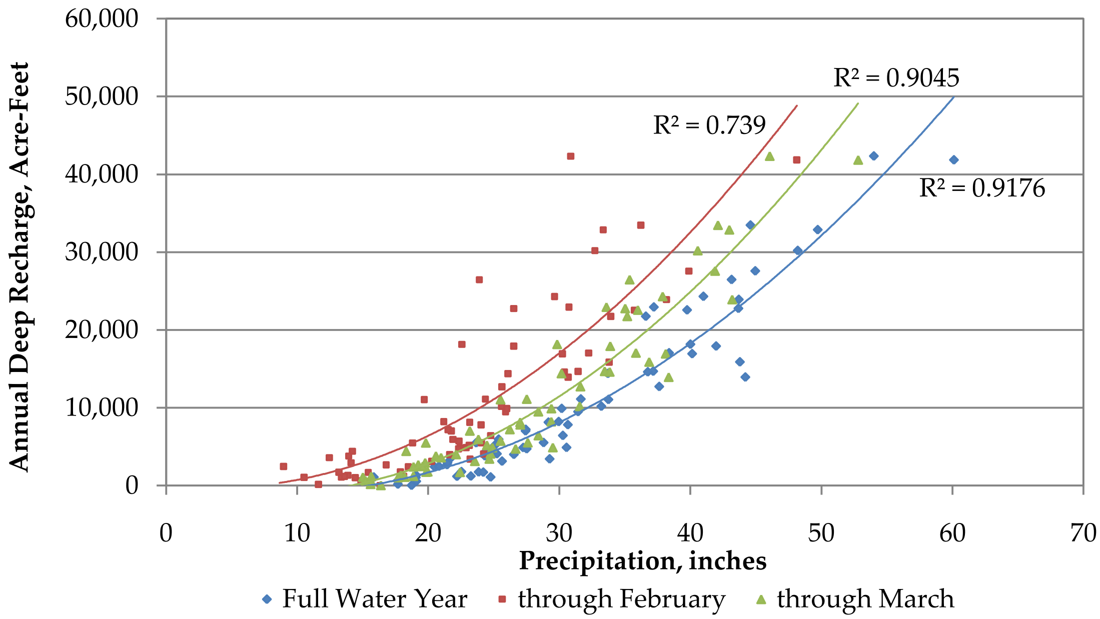


Figure 34: Estimated Annual Deep Recharge vs. Precipitation for the Santa Cruz Cooperative Station

Correlation between rainfall and deep groundwater recharge shows that rainfall records from the Santa Cruz cooperative precipitation station provide more reliable predictions than data from the District's Longridge and Mancarti stations (Figure 35). We recommend that rainfall criteria for drought curtailments are based on Santa Cruz station data.

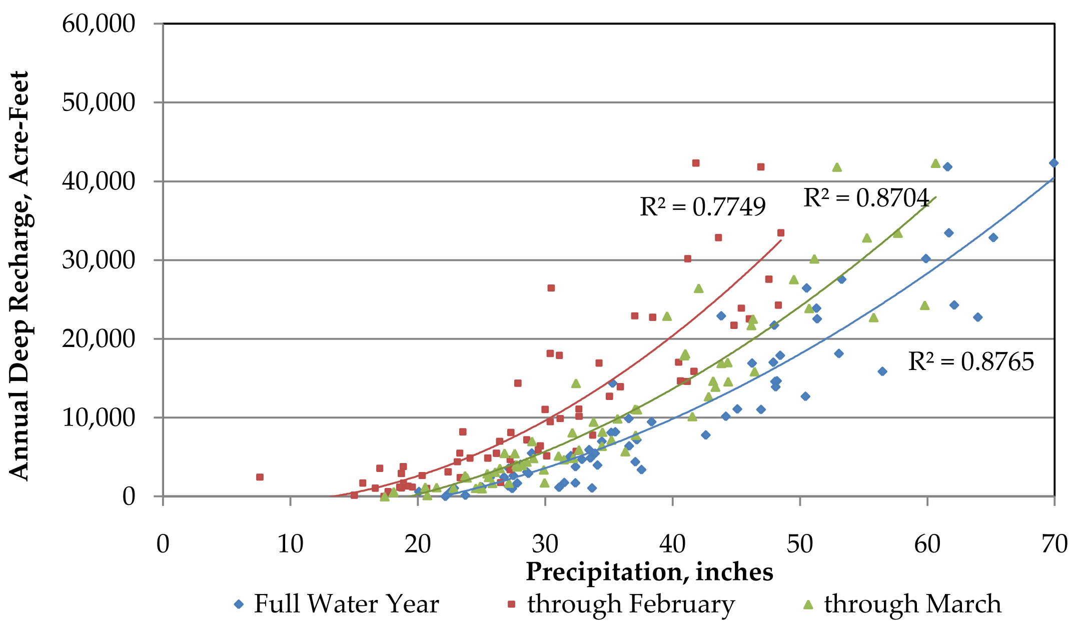


Figure 35: Estimated Annual Deep Recharge vs. Average Precipitation for the Longridge and Mancarti Stations

The PRMS model results were evaluated to identify multi-year deep recharge shortfalls exceeding the drought curtailment criteria of 10,500 and 21,000 acre-feet, and to estimate the multi-year rainfall amounts corresponding to those shortfalls. The multi-year rainfall comprises Santa Cruz cooperative station rainfall from October of the first water year of the period through March of the last year of the period. Appropriate rainfall criteria are rainfall amounts that identify a high percentage of the periods with recharge shortfalls great enough to declare a drought curtailment, and also result in a low percentage of "false positives" where the rainfall would suggest a drought curtailment when the recharge shortfall was not that great.

Rainfall criteria were estimated by first summing the PRMS calculated cumulative deep recharge for every 2-year, 3-year, 4-year, and 5-year period in the extended model. These deep recharge values were graphed against cumulative rainfall through March, as shown in Figure 36 through Figure 42.

We will use Figure 37 as an example to show how rainfall criteria were estimated from these graphs. This figure graphs the cumulative deep recharge for every three-year period against cumulative rainfall through March of the third year. A Stage 2 shortfall is indicated by the yellow line, and is equivalent to a cumulative three-year recharge of less than 21,000 acre feet (10,500 acre-feet less than the 31,500 acre-feet that is the average rainfall for a three year period). Our goal is to use rainfall to identify all years that fall below the yellow line. We selected 80 inches of rainfall as the criterion to identify these years. This is shown with the dashed line. Based on this rainfall criterion, points to the left of the dashed line are considered drought periods, and points to the right of the dashed line are considered non-drought periods. The results on Figure 37 show that using 80 inches as our rainfall criterion correctly identifies 85% of the modeled three-year drought periods (green diamonds); and 15% of the modeled three-year drought periods are not identified (violet triangle). This criterion also results in two false positives (orange squares).

A similar analysis was conducted for two-year periods,four-year, and five-year periods, as well as Stage 3 and Stage 4 drought criteria. Stage 4 criteria are based on four-year and five-year periods with extreme recharge shorfalls. The two periods identified ended in 1991 and 1992 (Figure 41 and Figure 42). Table 8 summarizes the resulting rainfall criteria for drought curtailments.

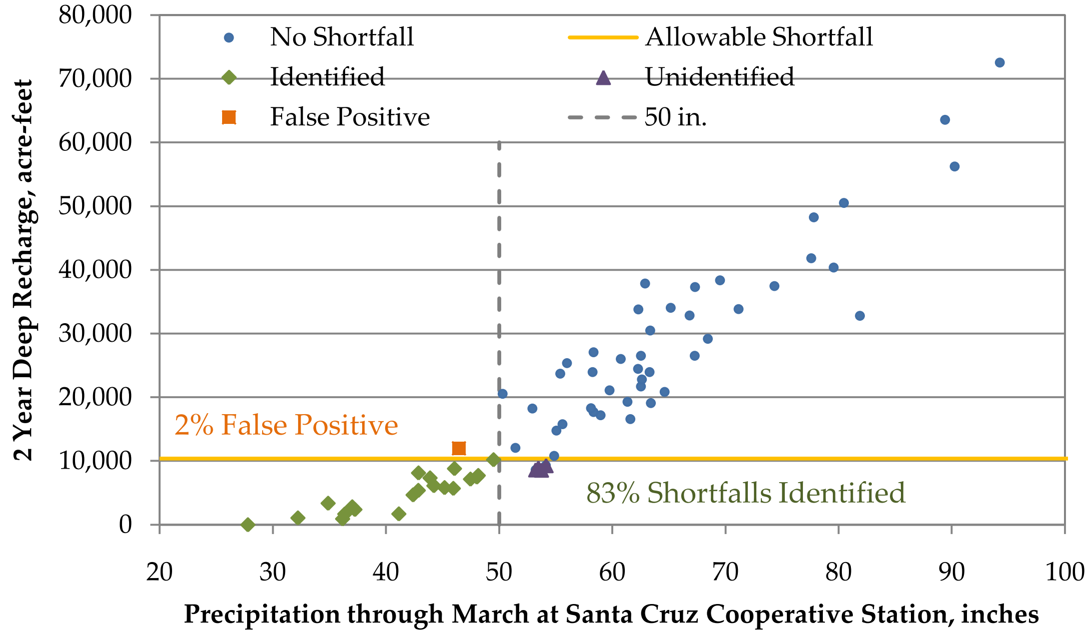


Figure 36: Identifying Two Year Deep Recharge Shortfalls for Stage 2 Drought Curtailment

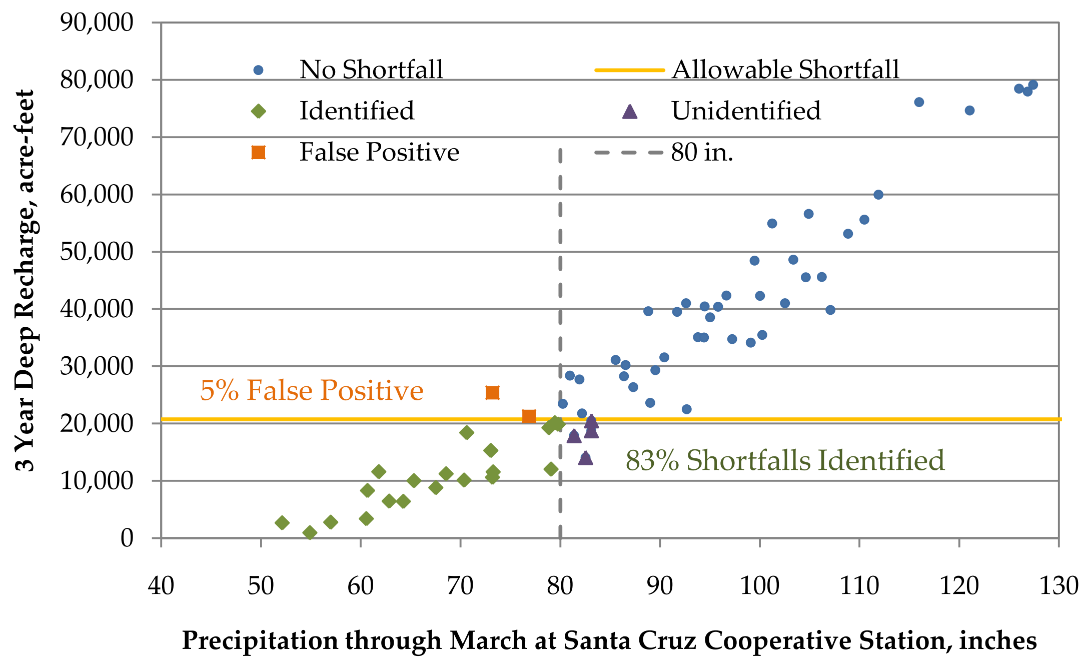


Figure 37: Identifying Three Year Deep Recharge Shortfalls for Stage 2 Drought Curtailment

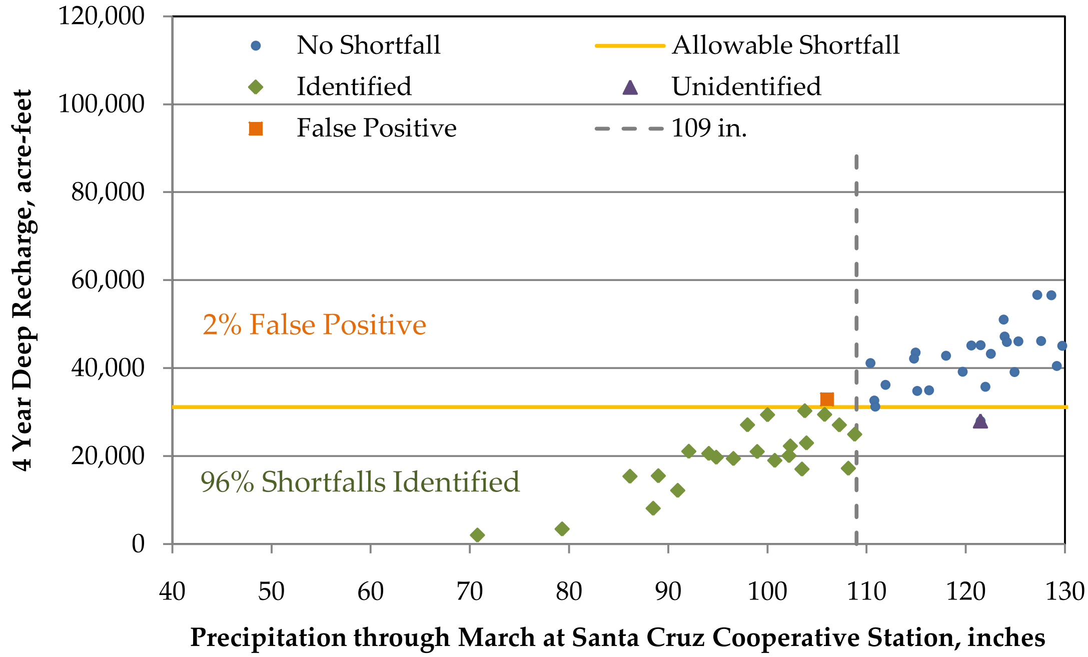


Figure 38: Identifying Four Year Deep Recharge Shortfalls for Stage 2 Drought Curtailment

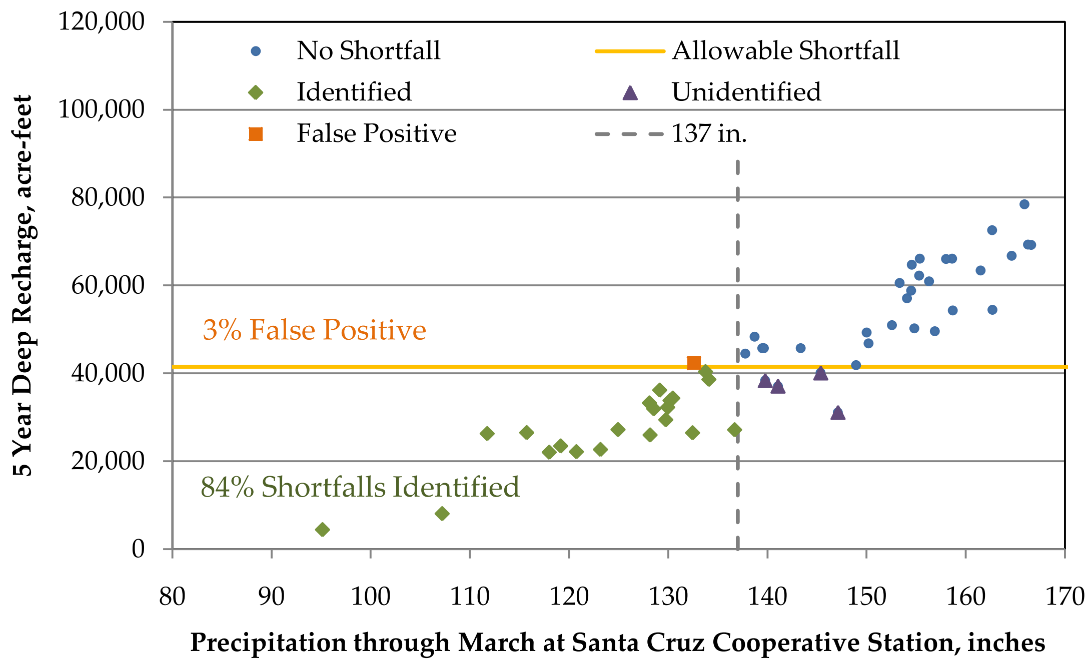


Figure 39: Identifying Five Year Deep Recharge Shortfalls for Stage 2 Drought Curtailment

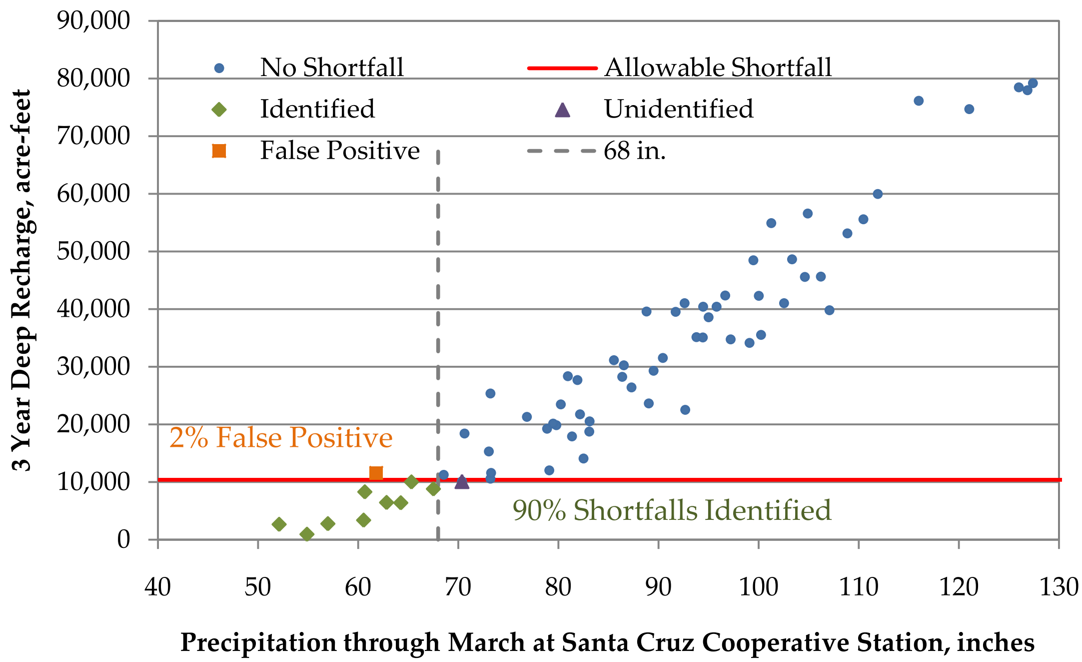


Figure 40: Identifying Three Year Deep Recharge Shortfalls for Stage 3 Drought Curtailment

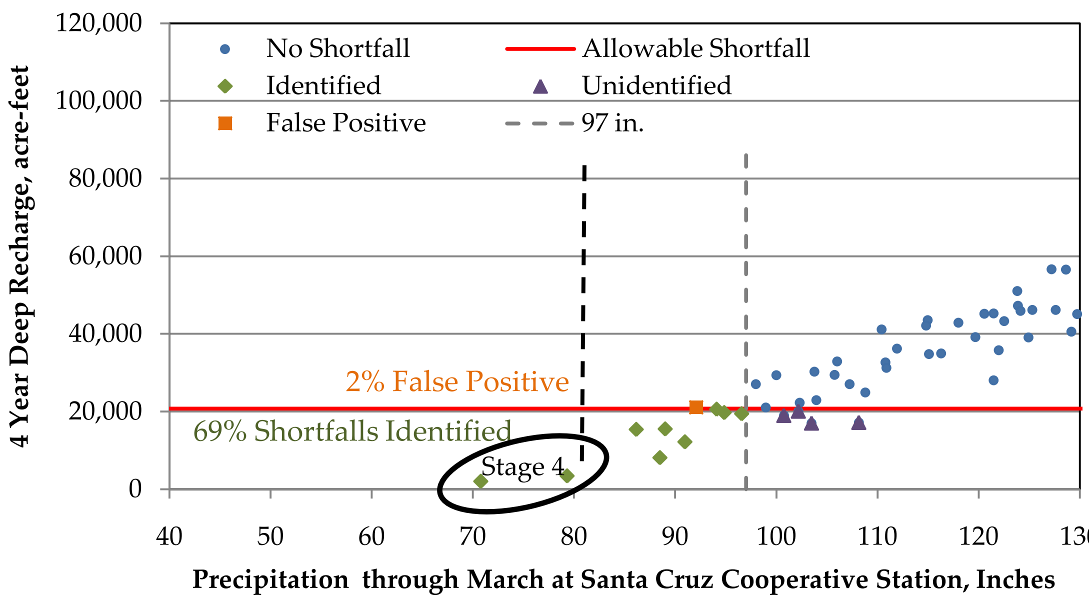


Figure 41: Identifying Four Year Deep Recharge Shortfalls for Stage 3 Drought Curtailment

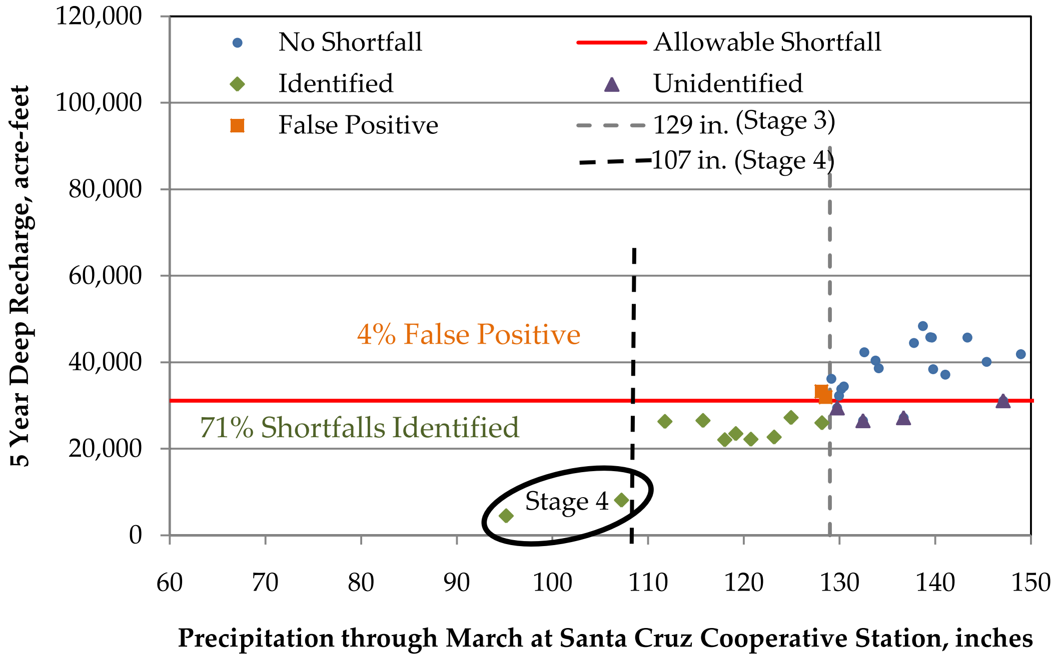


Figure 42: Identifying Five Year Deep Recharge Shortfalls for Stage 3 Drought Curtailment

Table 8: Drought Curtailment Multi-Year Rainfall Criteria

Number of Years	Stage 1	Stage 2	Stage 3	Stage 4
	Rainfall through March (inches)			
1	< long-term median	-	-	-
2	-	< 50	-	-
3	-	< 80	< 68	-
4	-	< 109	< 97	< 80
5	-	< 137	< 129	< 107

4.3.4 Rainfall Criteria Application

To assure public acceptance of the drought curtailment criteria, we suggest that curtailment only be declared in years when rainfall at the Santa Cruz cooperative station through March is below the median rainfall of 26 inches, regardless of the cumulative rainfall amount over the previous year(s). In years with below median rainfall, a drought curtailment would be declared if multi-year rainfall meets any one of the criteria in Table 8.

Applying these criteria to the rainfall record at the Santa Cruz cooperative station from Water Year 1942 to 2010 would result in the curtailment decisions displayed on Figure 43. Stage 1 curtailment would have been declared in 10 of 68 years (15%), Stage 2 curtailment would have been declared in 13 of 68 years (19%), Stage 3 would have been declared in 9 of 68 years (13%), and Stage 3 would have been declared in 2 of 68 years (3%). Based on 68 years of data, Table 9 summarizes the probability of each stage occurring in any given year.

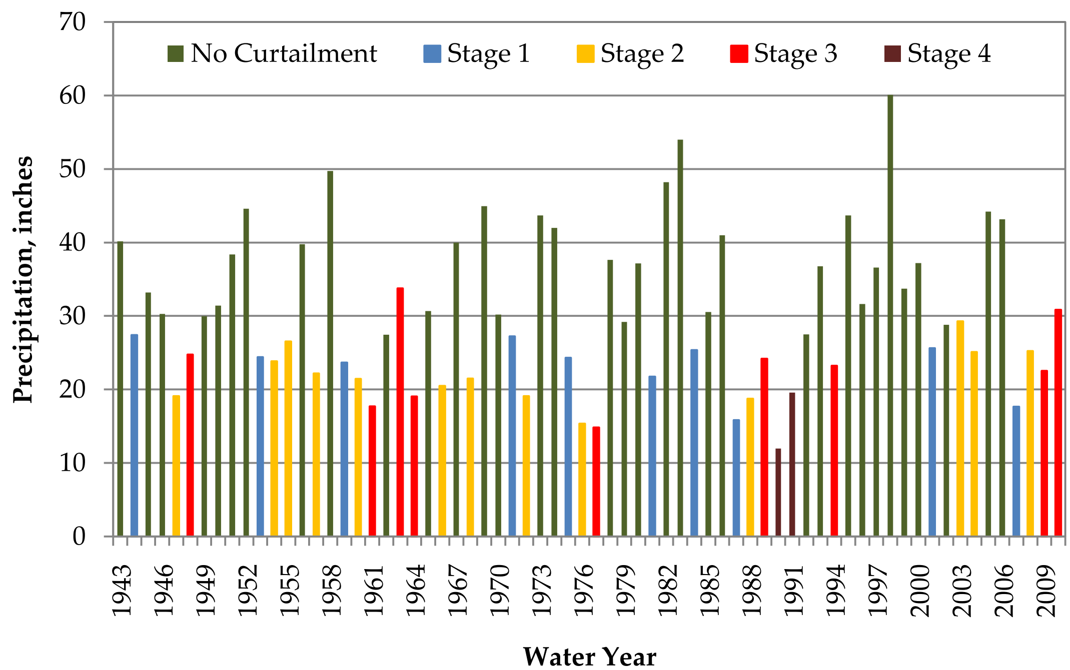


Figure 43: Application of Rainfall Drought Curtailment Criteria for Water Years 1942-2010

Table 9: Probability of Stage Occurring in Any Given Year

No Curtailment	Stage 1	Stage 2	Stage 3	Stage 4
50%	15%	19%	13%	3%

4.3.5 EXTENDING AND UPDATING THE PRMS MODEL

An optional approach to establishing rainfall criteria for drought curtailment would be to extend the PRMS model to include climate data through March and assume climate data for the rest of the water year. The predicted deep groundwater recharge shortfall resulting from extending the model would be compared to 10,500 acre-feet and 21,000 acre-feet to declare Stage 1 and Stage 2 drought curtailments, respectively. This optional approach could also be used in conjunction with rainfall criteria.

The model should also be updated periodically because the deep groundwater recharge shortfall and rainfall criteria for curtailment are based on model results. The update would include extending the model to include up-to-date data and recalibration, if necessary. A good time for these updates would be in years with above average rainfall, as there will be available time before drought curtailment needs to be evaluated again.

4.4 OTHER FUTURE USES

The PRMS model can be used to evaluate a number of different environmental conditions that would assist basin managers in long-term planning:

1. Changes in groundwater recharge and runoff in response to predicted climate change projections. Projections would be obtained from global climate models and emission scenarios.
2. Changes in groundwater recharge and runoff in response to increased urbanization or land use change such as deforestation.

Furthermore, PRMS can be updated annually as discussed in the previous section to estimate deep groundwater recharge for the concluding water year. This would provide water managers with a "running total" of groundwater recharge on an annual basis and assist in declaring drought curtailment.

PRMS is the surface water component of GSFLOW, which is the USGS's coupled groundwater and surface water flow model. In GSFLOW, PRMS and MODFLOW are essentially integrated into one hydrologic model that gives equal weight to each water resource. GSFLOW would result in a comprehensive modeling tool for management of water resources in the Soquel-Aptos area.

4.5 MODEL LIMITATIONS

PRMS is primarily a surface water runoff simulator. The routing of water to the groundwater reservoir is not as sophisticated as some other available methods. For a more accurate estimator of the fate of recharged groundwater, a groundwater model would need to be linked to the surface water model. GSFLOW is the tool used by the USGS to couple the groundwater and surface water models by integrating PRMS and MODFLOW.

Currently PRMS does not allow for changing land use during the modeled period. The USGS is currently working on methods to incorporate such temporal changes in PRMS (personal communication, Hay 2010).

Because the model does not take into account groundwater pumping, return flow, or losses from water and sewer systems, it cannot be used to determine the complete water budget. Additional modules would need to be added to take these inputs into account.

Due to the model's daily time step limitation, it cannot be used to evaluate changes in recharge due to changes in storm intensity. An hourly time step would be needed, which is not supported by the current PRMS software (PRMS-2010).

No formal uncertainty analysis was performed. However, during the calibration process it was possible to get an idea of what parameters were sensitive to changes in other parameters. Models such as PRMS can be equally well calibrated using various parameter combinations. Each set of equally valid parameters will inherently result in a range of outputs. Precipitation is the model input for which we had the most data, and therefore its parameters were fixed. The component with no direct data is actual ET which was calculated by the model primarily from PET, but also canopy cover and soil properties. Modeled PET was calibrated to data from a National Weather Service dataset that was averaged for the study area. The other attributes mentioned above and which were used to calculate actual ET are more difficult to model and so there is some inherent margin of error.

We found that actual ET is a sensitive parameter that impacts deep groundwater recharge values the most. This combined with changes in canopy density can result in estimates of deep groundwater recharge that fluctuates by hundreds of acre-feet per year, which equates to around 5% of the total recharge. We decided not to calibrate canopy density but to honor the values from USGS's 2001 canopy density dataset. We have confidence that because we were able to calibrate PET well, we have minimized a source of ET uncertainty.

SECTION 5
CONCLUSIONS

A PRMS model of the Soquel-Aptos area was developed and calibrated to ten streamflow gages. The model was used to successfully determine the rainfall-recharge relationship of the model area. One of the main observations from the modeled hydrologic response was that as rainfall increases, recharge increases proportionally faster.

Deep groundwater recharge from the calibrated model for the District's hydrogeologic system area compares favorably to a previous recharge study by Johnson and other (2004). A comparison of results is shown in the table below.

Hydrogeologic System Area Average Annual Water Budget Summary

Method	Aquifer Outcrop	Precipitation	Streamflow	Evapo-transpiration	Deep Groundwater Recharge
		Acre-Feet per Water Year			
Johnson et al. (2004)	Purisima	93,500	24,700	61,800	7,000 (6,100)
	Aromas	18,900	1,800	14,200	2,900
	Total	**112,400**	**26,500**	**76,000**	**9,900 (9,000)**
PRMS	Purisima	91,300	24,500	60,500	6,600
	Aromas	19,200	2,100	12,200	4,200
	Total	**110,500**	**26,500**	**72,700**	**10,800**

Apart from estimating the water budget, the calibrated PRMS can be used for a number of other purposes:

1. To provide a defendable rational for drought curtailment in the Soquel-Aptos area.
2. To evaluate changes in groundwater recharge and runoff in response to predicted climate change.
3. To evaluate changes in groundwater recharge and runoff in response to increased urbanization or land use change such as deforestation.
4. To provide input to a groundwater flow model.

As part of this study, an extended version of the PRMS model was used to establish the long-term rainfall-recharge relationship in the Soquel-Aptos area. This extended model was used to develop potential drought curtailment criteria for the District. Evaluating changes in climate and land use were not part of this study.

For the District to implement a drought curtailment in May, we recommend using rainfall data from October through March from the Santa Cruz cooperative station. The rainfall criteria are based on model predictions of when multi-year recharge shortages are likely to be greater than 10,500 acre-feet for declaring a Stage 1 curtailment, and greater than 21,000 acre-feet per year for declaring a Stage 2 curtailment. The table below shows an example of rainfall criteria for declaring Stages 1 and 2 curtailments.

Drought Curtailment Multi-Year Rainfall Criteria

Number of Years	Stage 1 Rainfall through March (inches)	Stage 2 Rainfall through March (inches)
2	< 50	None
3	< 80	< 68
4	< 106	< 97

An optional approach to establishing rainfall criteria for drought curtailment would be to extend the PRMS model to include climate data through March and assume climate data for the rest of the water year. The predicted deep groundwater recharge shortfall resulting from extending the model would be compared to 10,500 acre-feet and 21,000 acre-feet to declare Stage 1 and Stage 2 drought curtailments, respectively.

The PRMS model developed for the Soquel-Aptos area can be integrated with the groundwater model, MODFLOW, using GSFLOW. This process would result in a comprehensive modeling tool for management of water resources in the Soquel-Aptos area.

SECTION 6
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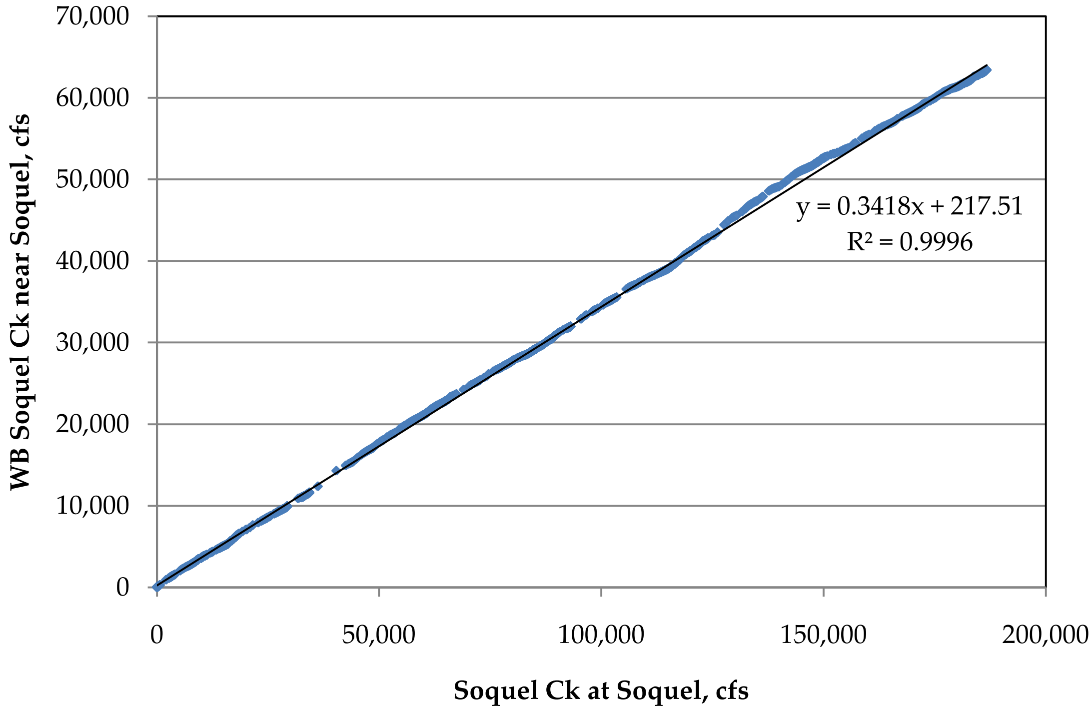
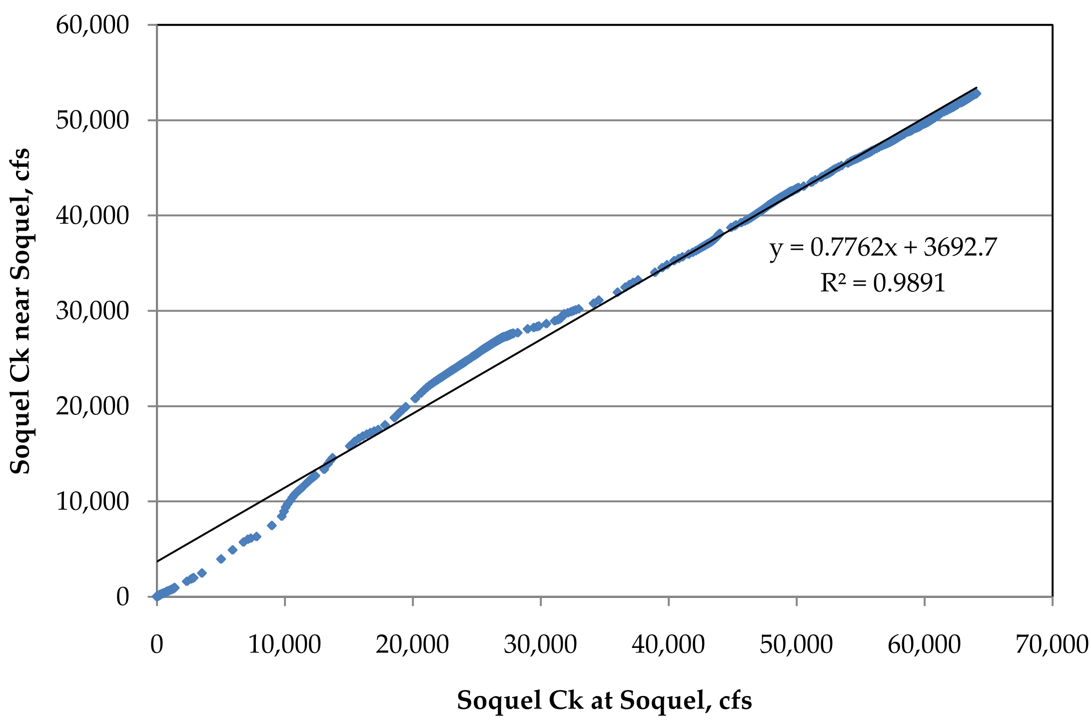
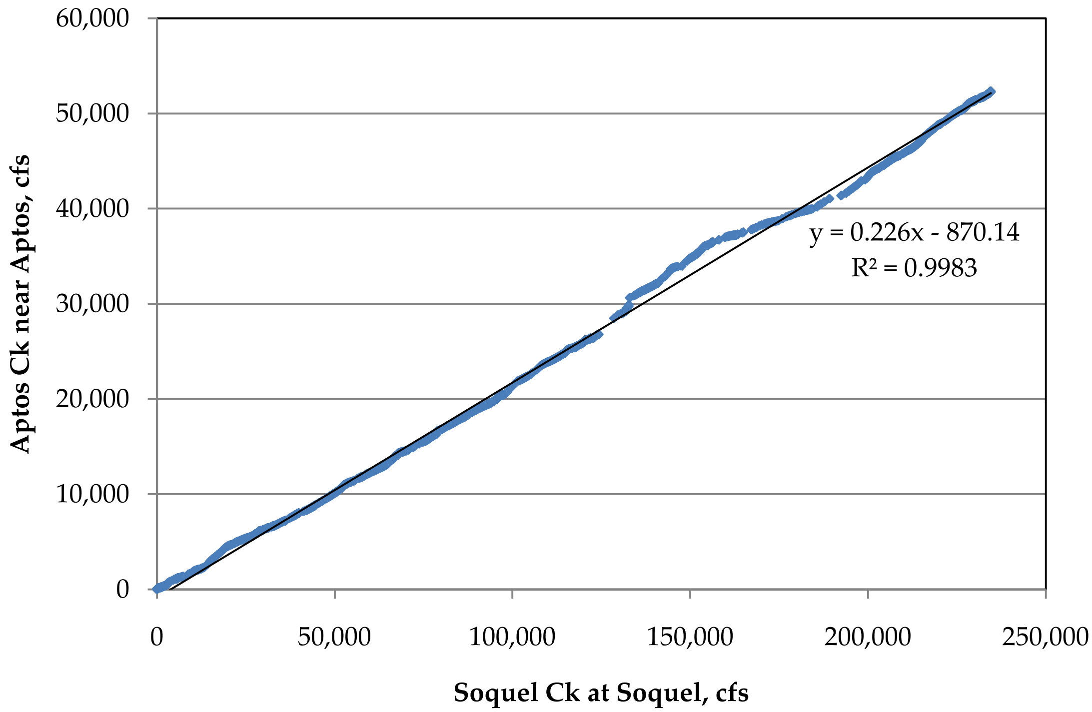
APPENDIX A: STREAMFLOW DOUBLE-MASS CURVES



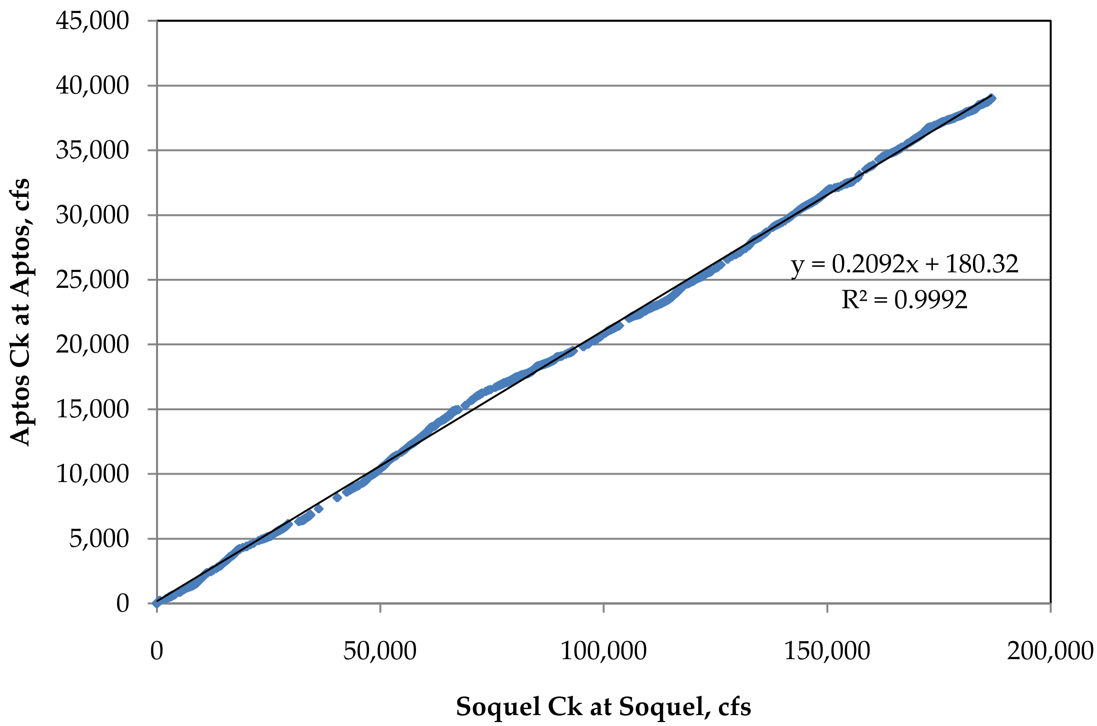
Soquel Creek at Soquel (Gage 5) vs. West Branch Soquel Creek near Soquel (Gage 3)



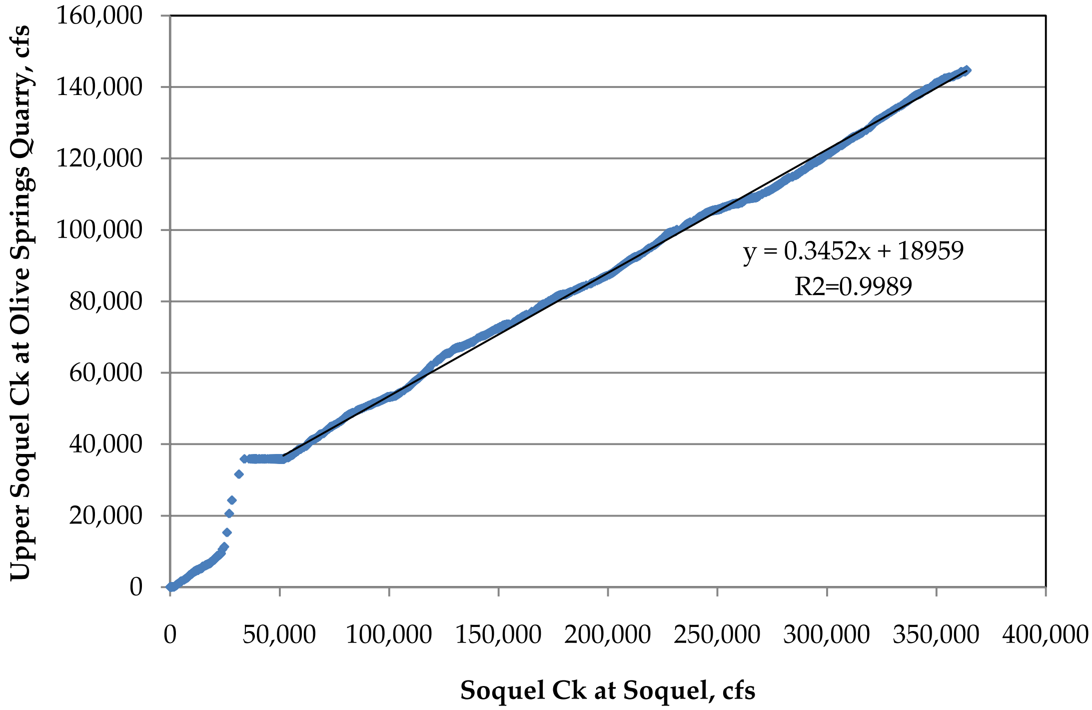
Soquel Creek at Soquel (Gage 5) vs. Soquel Creek near Soquel Creek (Gage 4)



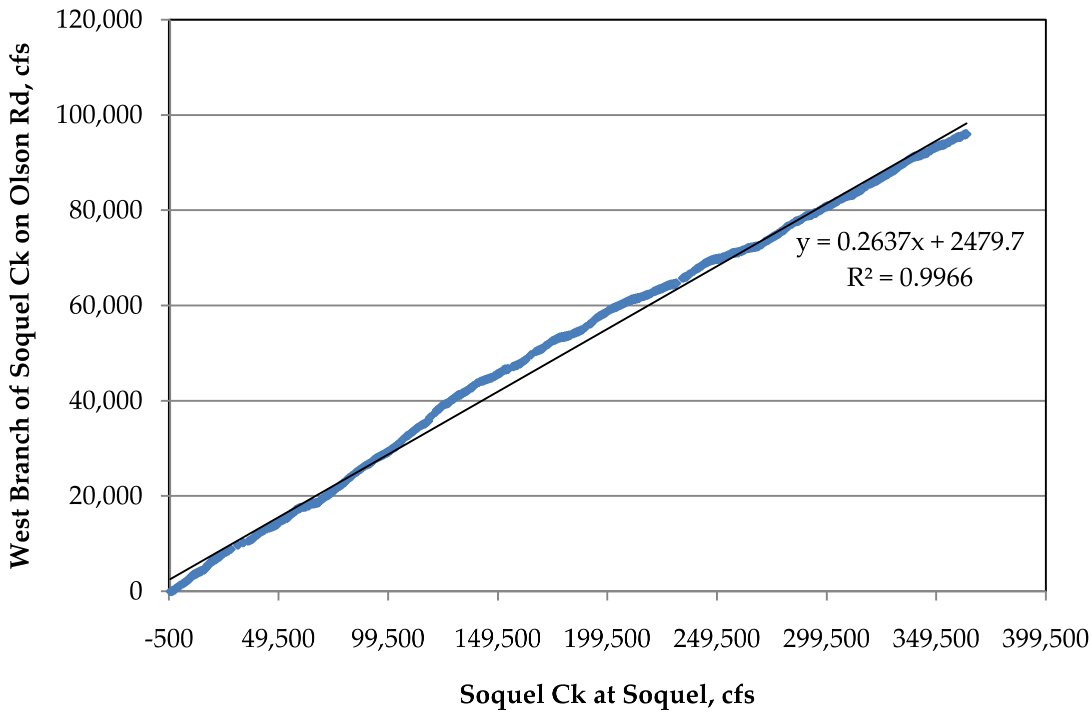
Soquel Creek at Soquel (Gage 5) vs. Aptos Creek near Aptos (Gage 6)



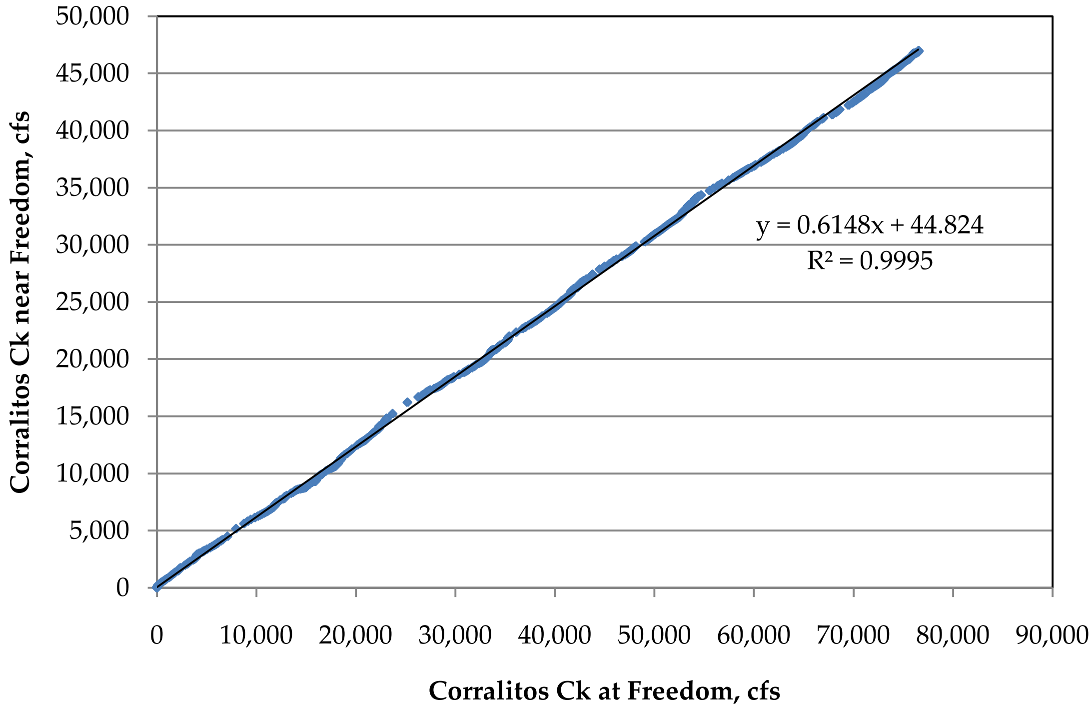
Soquel Creek at Soquel (Gage 5) vs. Aptos Creek at Aptos (Gage 9)



Soquel Creek at Soquel (Gage 5) vs. Upper Soquel - District (Gage 2)



Soquel Creek at Soquel (Gage 5) vs. vs. West Branch Soquel - District (Gage 1)



Corralitos Creek at Freedom (Gage 8) vs. Corralitos Creek near Corralitos (Gage 7)

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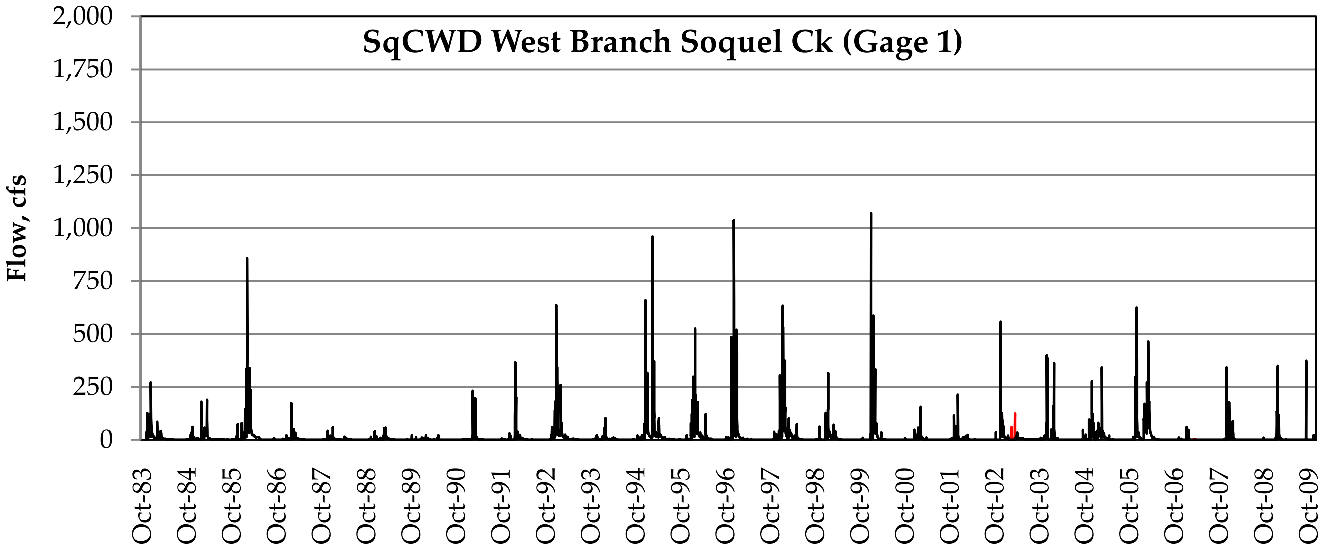
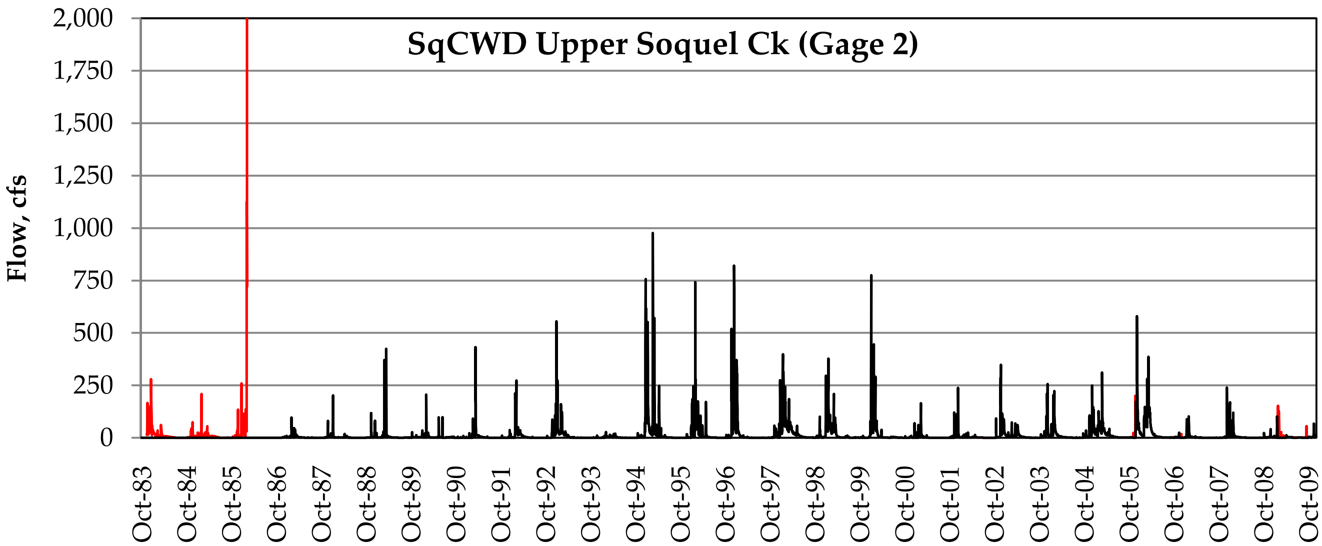
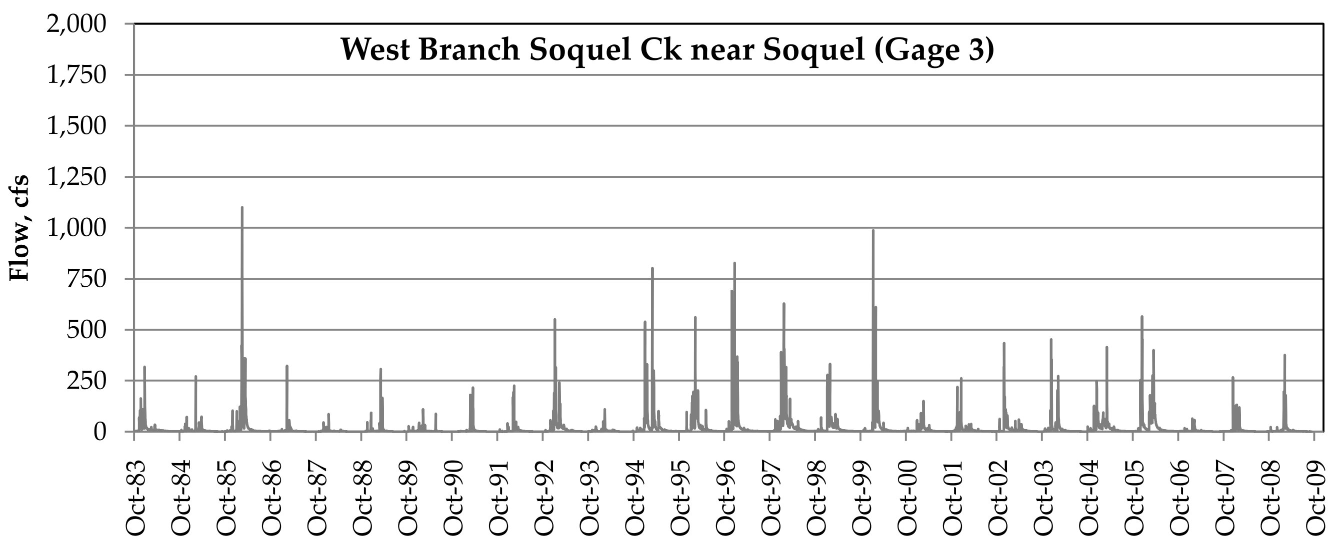
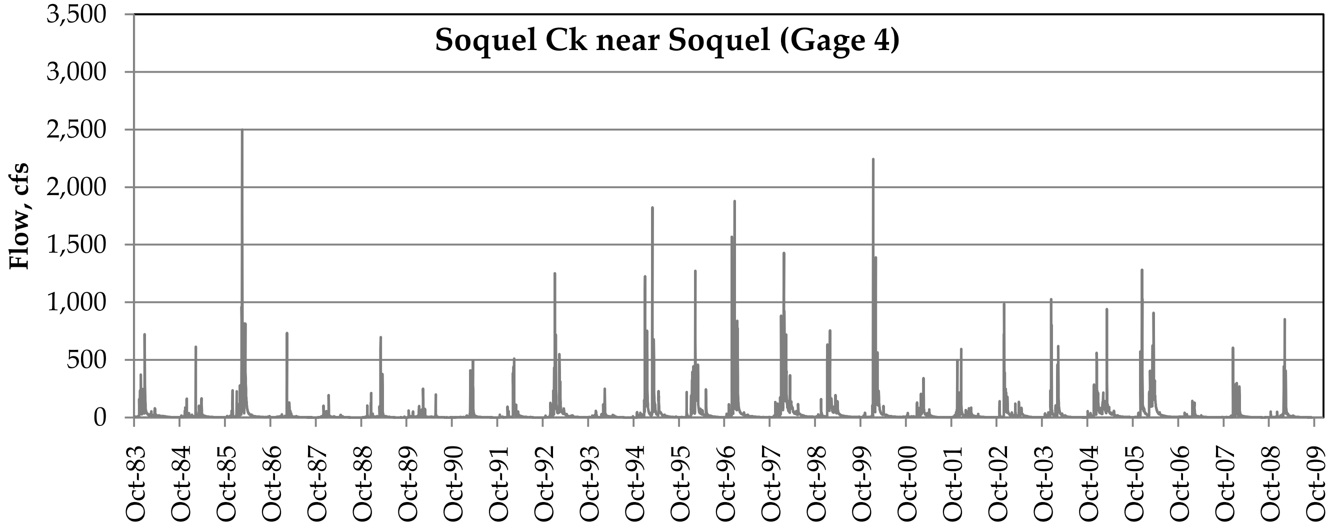
APPENDIX B: STREAMFLOW DATA – SYNTHESIZED AND MEASURED

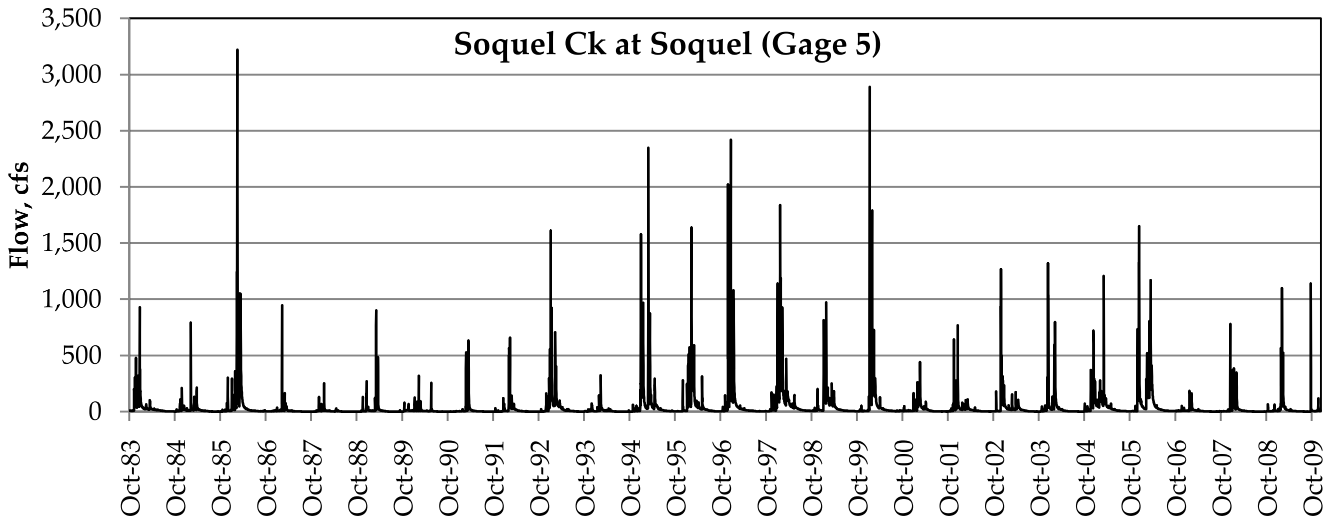


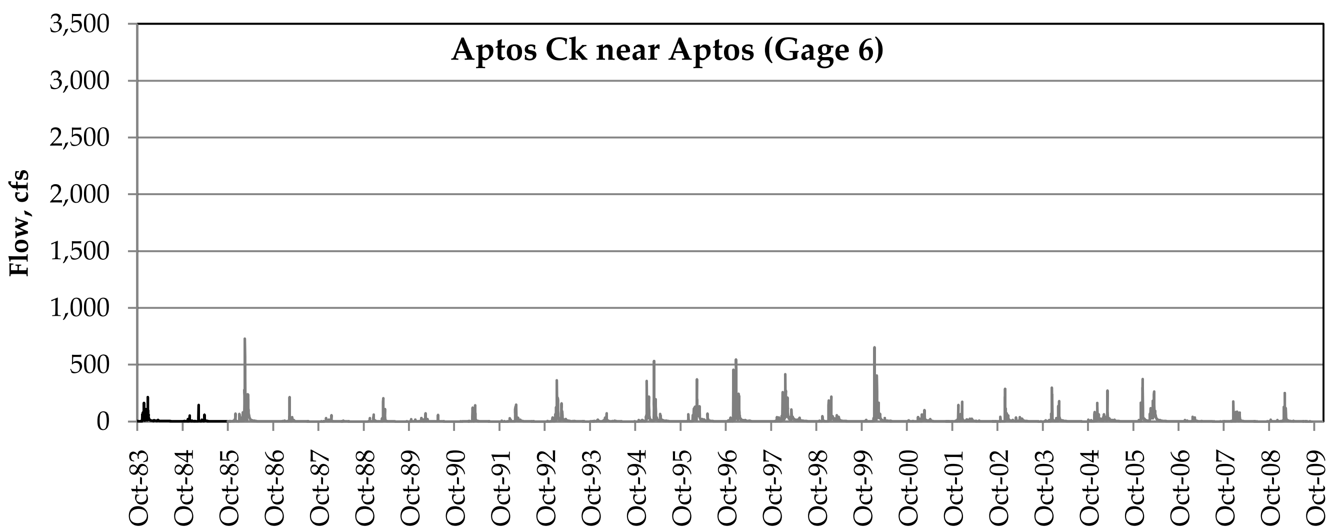




Grey = synthesized, black = measured, red = Kaeger estimated







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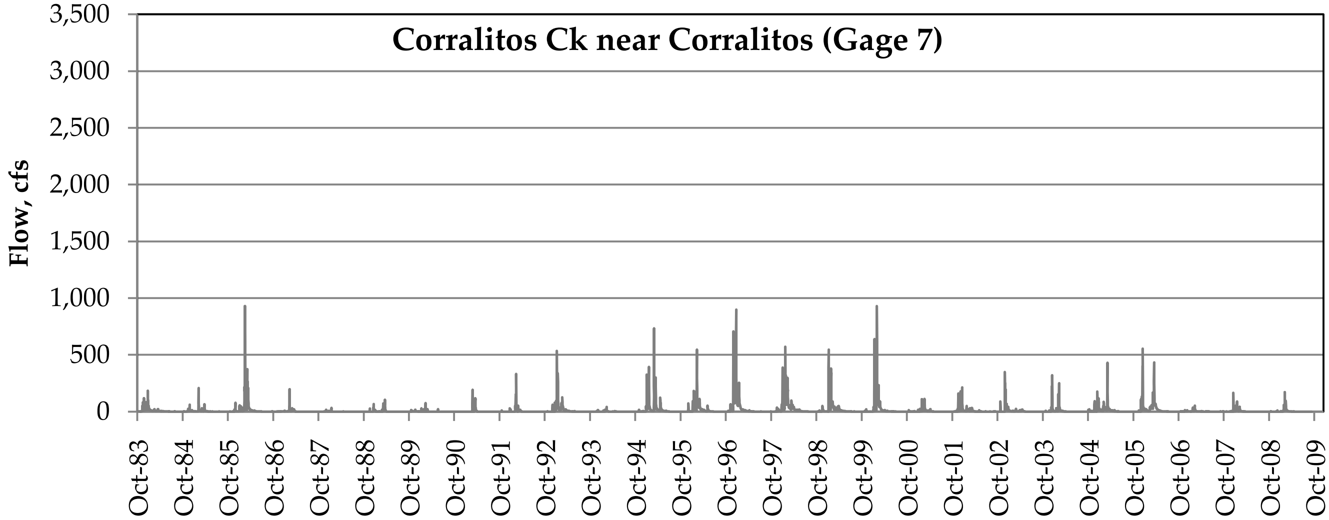

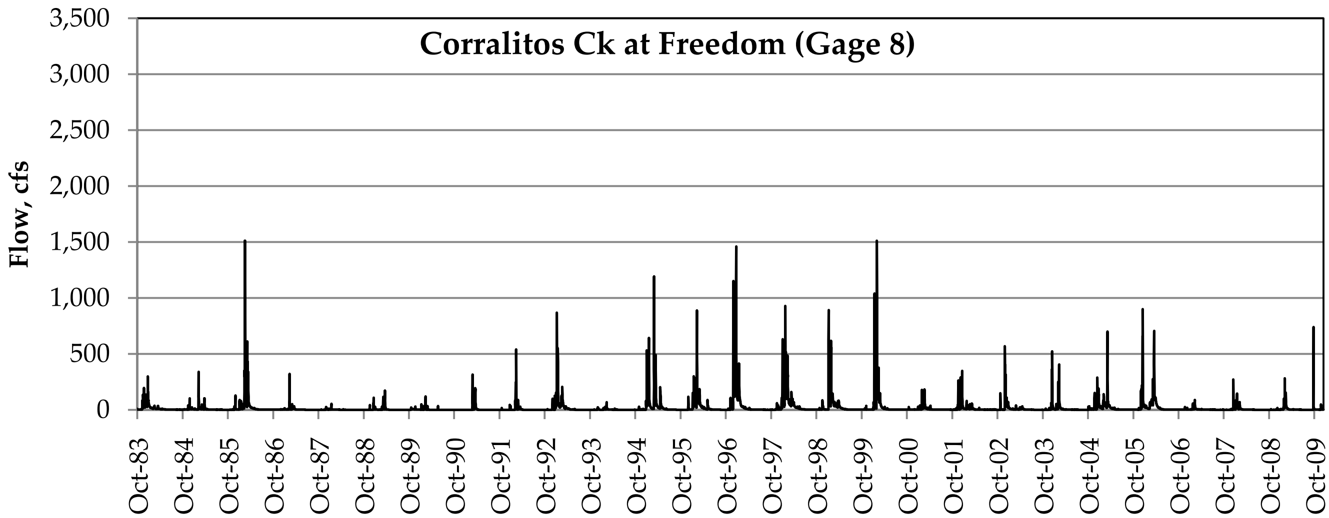

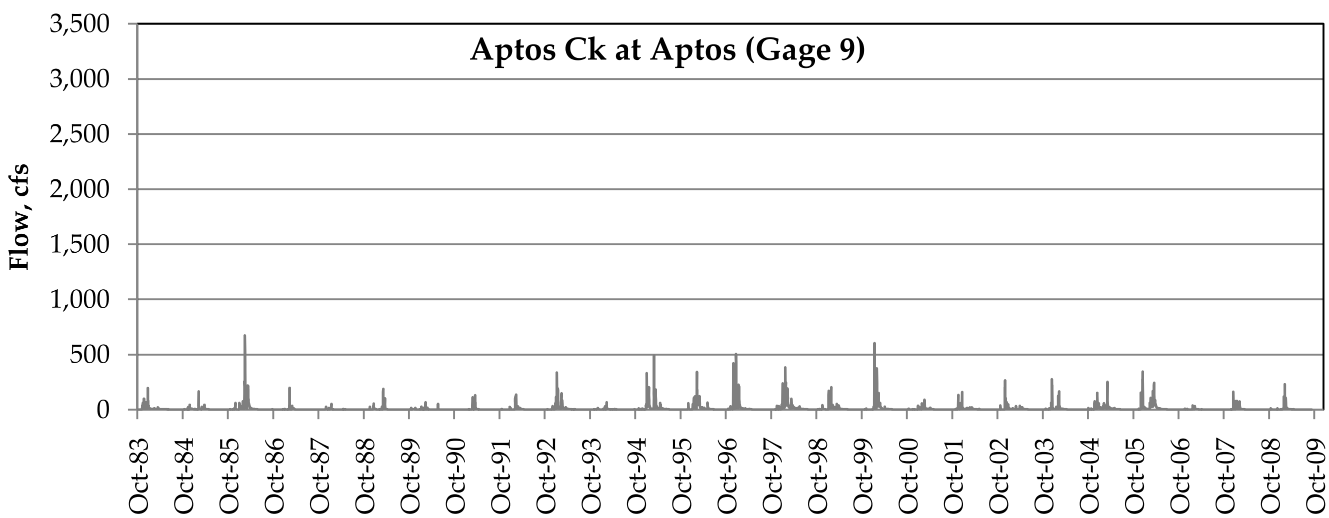

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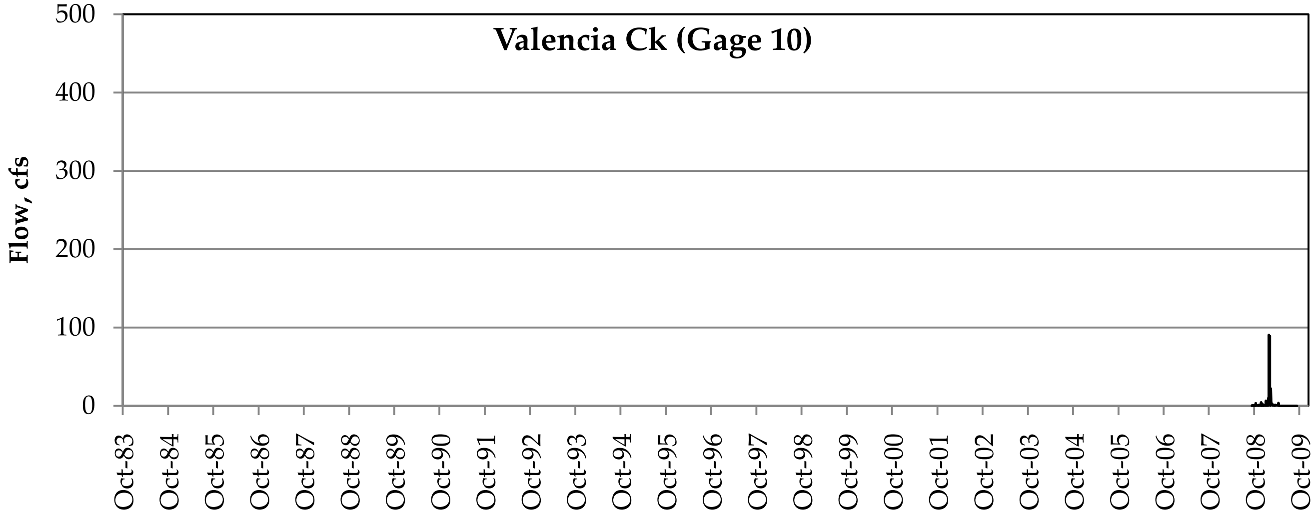

black = measured