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ABBREVIATIONS

ET	evapotranspiration
CIMIS	California Irrigation Management Information System
GIS	geographical information system
HRU	hydrologic response unit
NHD	National Hydrography Dataset
PET	potential evapotranspiration
PRMS	Precipitation-Runoff Modeling System
SqCWD	Soquel Creek Water District
USGS	United States Geological Survey

1814 Franklin St, Suite 501
Oakland, CA 94612

DRAFT TECHNICAL MEMORANDUM

To:	Ron Duncan
From:	Justin Huntington, Huntington Hydrologic
	Georgina King and Cameron Tana, HydroMetrics WRI
Date:	August 19, 2016
Subject:	Santa Cruz Mid-County Basin Groundwater Flow Model: Precipitation-Runoff Modeling System Setup (Task 2)

1. INTRODUCTION

This technical memorandum documents the completed and ongoing activities to develop a model of the surface watershed for the integrated surface water-groundwater flow model of the Santa Cruz Mid-County Basin (Basin). Scoping meetings for development of a groundwater model for the basin directed use of the U.S. Geological Survey (USGS) model code GSFLOW (Markstrom et al., 2008) that is a fully integrated watershed-groundwater model. GSFLOW is being used because simulating surface water-groundwater interaction is a top priority use of the model. GSFLOW integrates the Precipitation-Runoff Modeling System (PRMS) watershed model code with the MODFLOW groundwater model code. This technical memorandum documents the setup of PRMS for the Santa Cruz Mid-County model.

HydroMetrics WRI (2011) previously developed a PRMS watershed model of the Basin to provide recharge estimates for Soquel Creek Water District's preliminary planning of long-term water supply, as well as provide input to Central Water District's groundwater model (HydroMetrics WRI and Kennedy/Jenks, 2014). For development of a GSFLOW model, the USGS recommended during the scoping process that the PRMS watershed model be based on a rectangular grid, rather than the sub-watershed discretization used by the previous PRMS model. Therefore, we have developed a grid based PRMS model, although we have leveraged the previous work by using data sets input into the previous PRMS model.

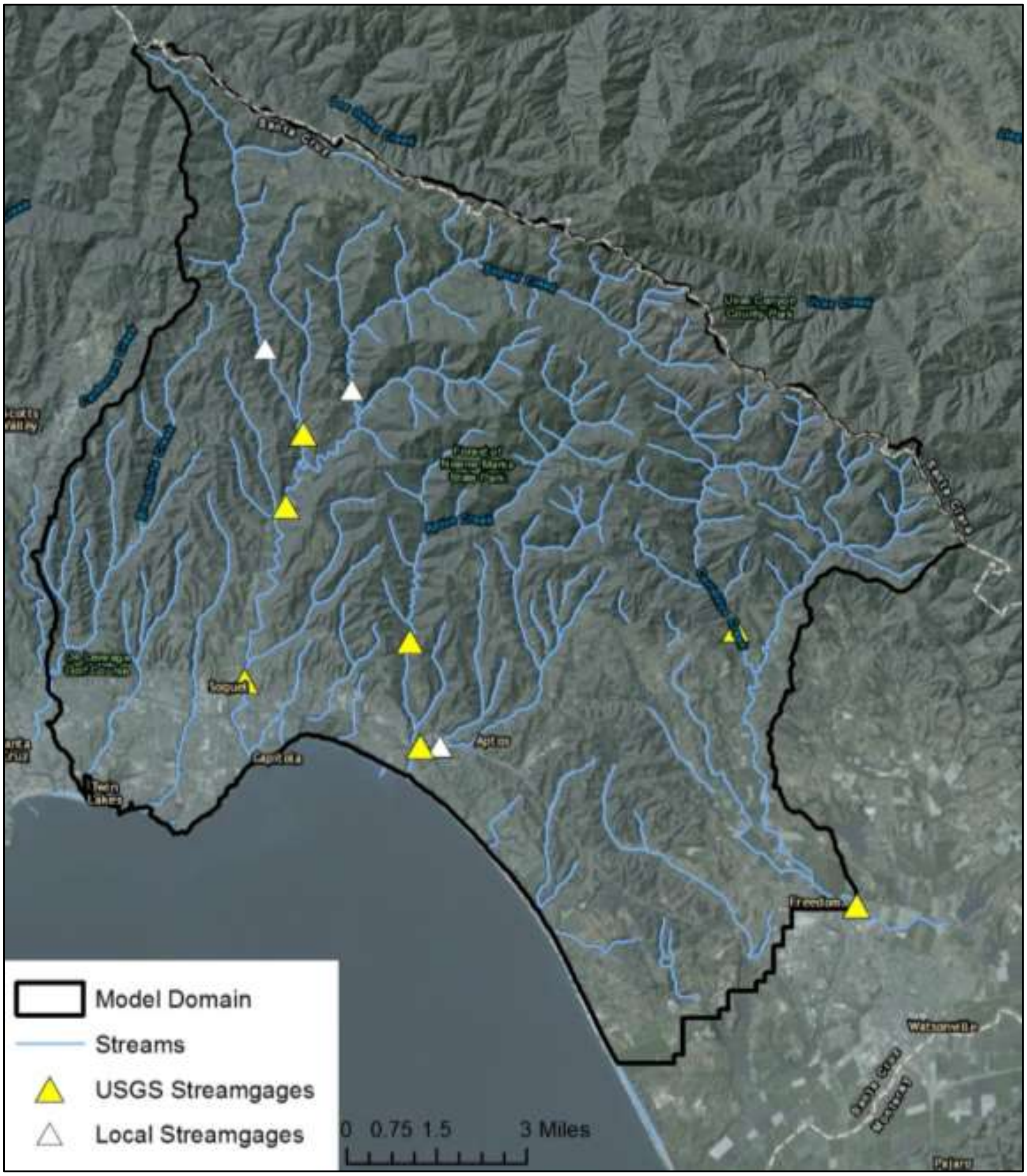

Figure 1. Model Domain, Streams, and Stream Gauges of the Santa Cruz Mid-County Basin

2. MODELING APPROACH

The model used to simulate hydrologic inflows and outflows in the model domain is the USGS's Precipitation-Runoff Modeling System (PRMS). PRMS is a modular deterministic, distributed- parameter, physical-process watershed model used to simulate precipitation, climate, and land use on watershed response (Leavesley et al., 1983; Markstrom et al., 2015). The model was first developed in 1983 (Leavesley, et al., 1983), and has undergone numerous improvements, both conceptually and programmatically. The PRMS-IV version was used for the Santa Cruz Mid-County Basin groundwater model.

PRMS simulates rain-generated and snowmelt runoff in a fully distributed sense, where runoff can cascade among four neighboring surface grid cells, reinfiltrate, or flow to a stream. The soil zone is represented by coupled continuity equations with storages that represent different components of soil porosity conceptualized in PRMS as the preferential, gravity, and capillary reservoirs (Figure 2).

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.

In GSFLOW mode, PRMS provides all surface fluxes and states for needed boundary conditions, and flow beneath the base of the soil zone is simulated by a three-dimensional groundwater model MODFLOW. This includes vertical unsaturated flow and saturated groundwater flow such as simulation of groundwater flow to and from streams and lakes, groundwater recharge, groundwater evapotranspiration, and many other hydrologic processes. In GSFLOW mode, vertical unsaturated flow is simulated by MODFLOW using the Unsaturated-Zone Flow (UZF1) Package (Niswonger et al., 2006). Stream exchanges with the subsurface are simulated by MODFLOW using the Streamflow Routing (SFR2) package (Niswonger et al., 2005; Markstrom et al., 2008). Development of the PRMS/MODFLOW/GSFLOW model grid that accurately represents the topography, climate, vegetation, and hydrologic features and their connections (i.e. stream locations, connections, lakes) of the study area is a critical first step in building a GSFLOW model. The following sections describe the approach and data used for developing the model grid and PRMS surface water model for the Santa Cruz Mid-County Basin.

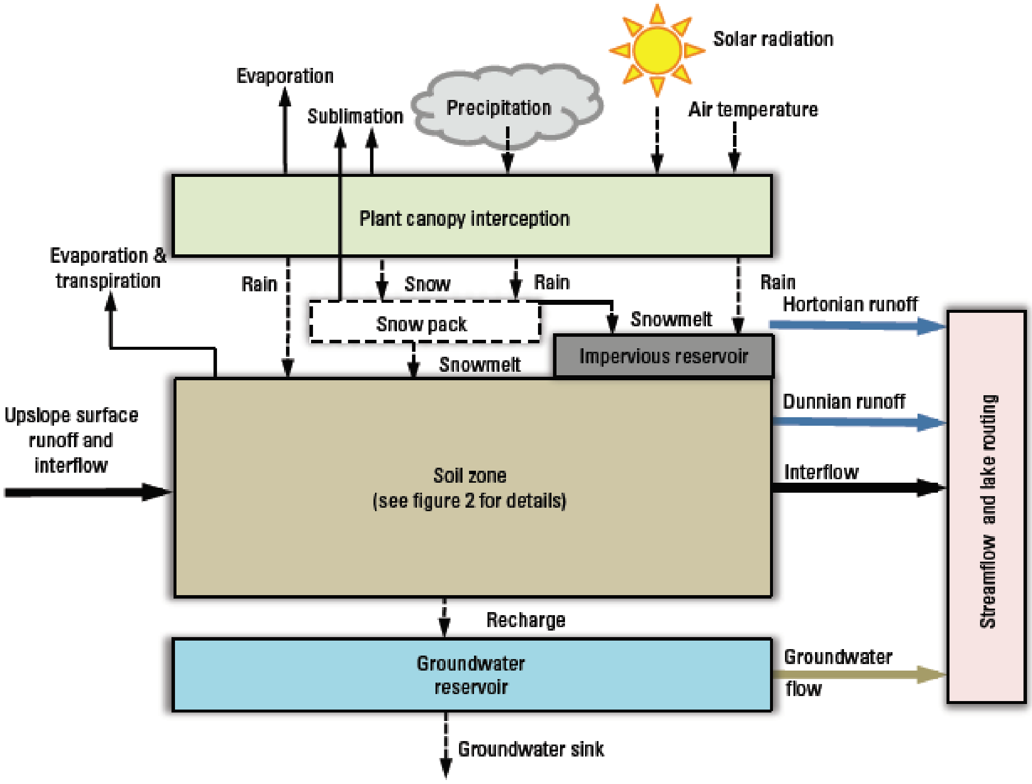

Figure 2. Overview of the Precipitation-Runoff Modeling System Model Components and Conceptualization of Hydrologic Response Unit (modified from Markstrom et al., 2015 and HydroMetrics WRI, 2011)

3. MODEL DISCRETIZATION

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.

As introduced above, the USGS recommended that the PRMS watershed model be based on a rectangular grid for use with GSFLOW. The rectangular grid is identical for both PRMS watershed processes and MODFLOW groundwater model. Having identical grid PRMS and MODFLOW grids greatly simplifies mapping parameters and fluxes between the two models and maintains efficiency.

Selection of the cell size to best represent HRUs was based on identifying the largest grid cell size that best preserved finer scale elevation distributions across the study area. The objective was to represent finer scale elevation distributions while minimizing the number of grid cells to maintain computational efficiency. This was accomplished by computing the mean elevation of each model cell for varying cell sizes ranging from 100 to 1,000 feet. Figure 3 illustrates the distribution of elevation for different grid cell sizes, where it is evident that a cell size of 800 feet represents the distribution of finer scale elevations fairly well. An additional benefit of the 800 foot cell size is that the coarser grid significantly decreases computation time without compromising elevational representation of the system.

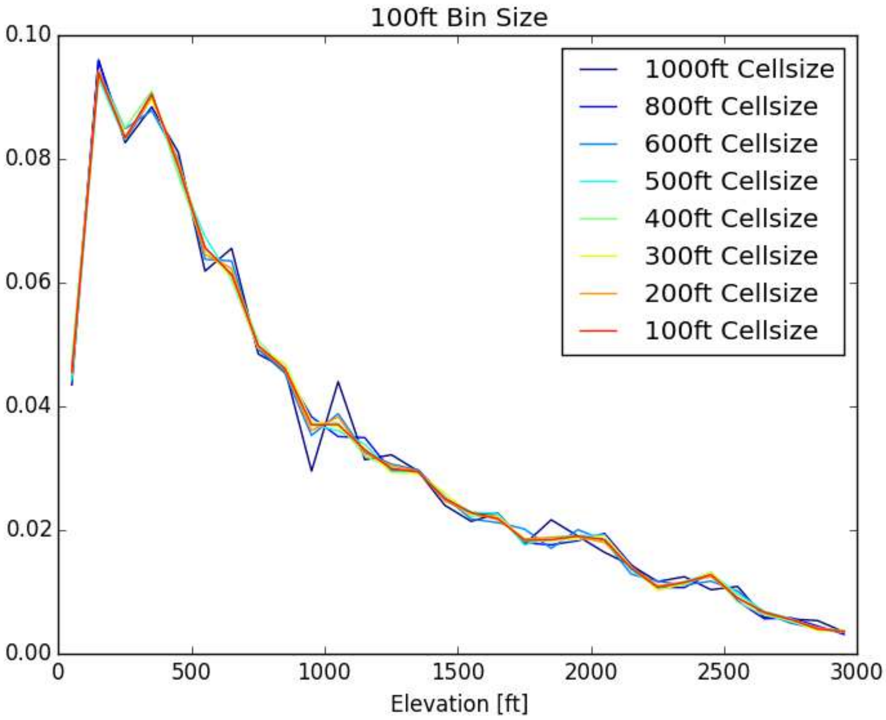

Figure 3. Probability Density Function (PDF) Graph of Grid Elevation for Various Grid Resolutions

Based on this result, a discretization of 800 feet for horizontal grids for both PRMS and MODFLOW was selected (Figure 4). Grid cells represent both PRMS HRUs and MODFLOW cells. Spatial datasets of climate, geology, vegetation, soils, and land use were mapped to the 800 foot model HRUs for PRMS, MODFLOW, and GSFLOW parameterization. PRMS development and GIS parameterization is discussed in Section 5.3.

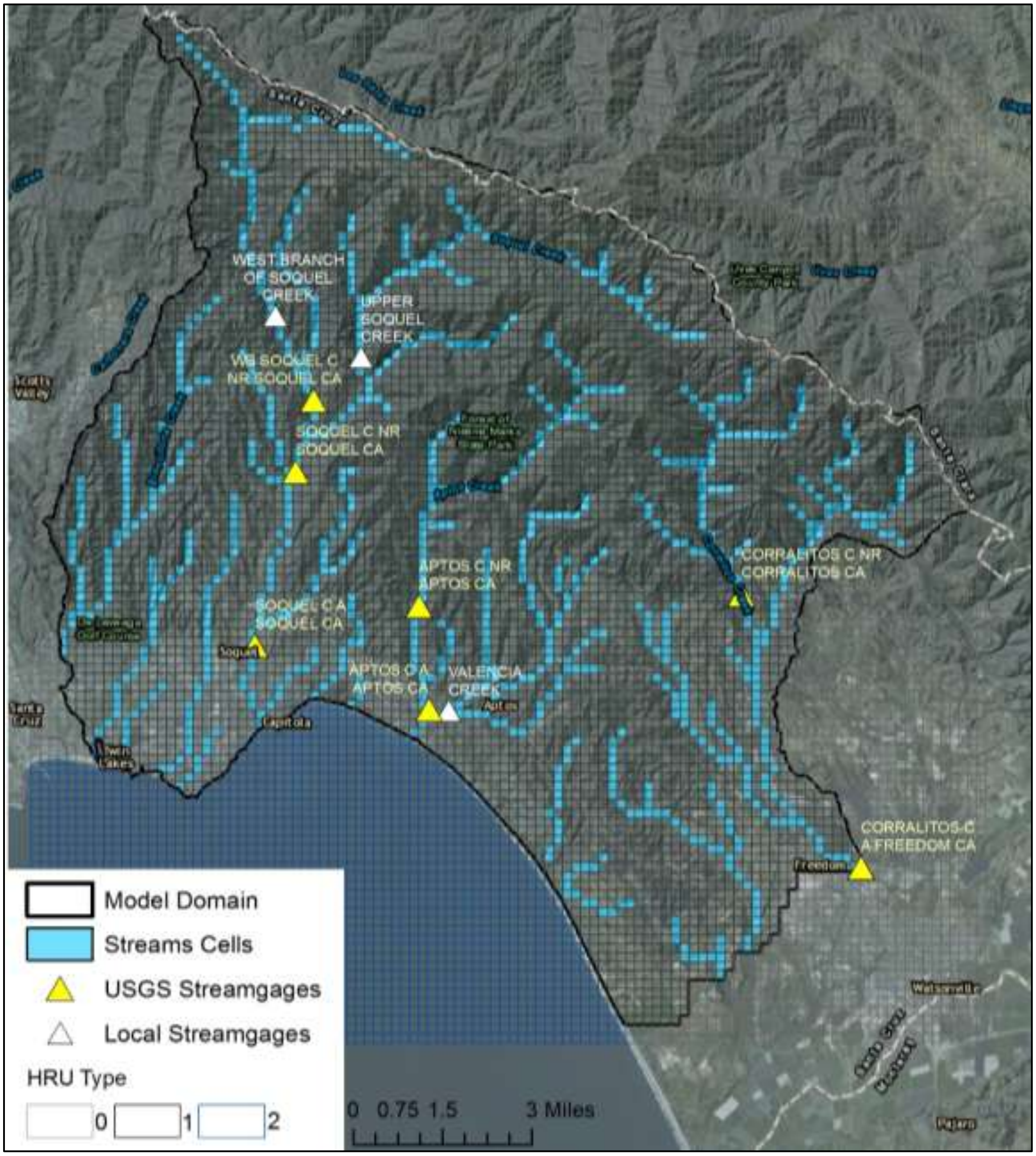

Figure 4. Model Domain and 800 Foot Model Grid showing Inactive (HRU Type = 0), Active (HRU Type = 1), Water (HRU Type = 2), and Stream Cells

4. PRMS MODULES

PRMS uses different modules to simulate various water and energy processes. Each module requires specific input to execute, and computes outputs which can be used as input to other modules. The modules selected for the Santa Cruz Mid-

County Basin PRMS were based on the availability of data and appropriateness for local conditions. Modules used are summarized in Table 1.

Table 1: Modules used in Santa Cruz Mid-County Basin PRMS

Module Name	**Module Description**
basin	Defines shared watershed-wide and HRU physical parameters and variables
cascade	Determines computational order of the HRUs and groundwater reservoirs for routing flow downslope
soltab	Computes potential solar radiation and sunlight hours for each HRU for each day of the year
obs	Reads and stores observed data from all specified measurement stations
temp_laps	Distributes maximum and minimum temperatures to each HRU using temperature data measured at least two temperature stations at different elevations, based on an estimated lapse rate between pairs of stations
precip_1sta	Determines the form of precipitation and distributes it to each HRU using on the basis of a measured value of precipitation and parameters used to account for elevation, spatial variation, topography, gage location, and deficiencies in gage catch
ddsolrad	Distributes solar radiation to each HRU and estimates missing solar radiation data using a maximum temperature per degree-day relation
transp_tindex	Computes transpiration using a temperature index that is the cumulative sum of daily maximum temperature for each HRU after the model reaches the transpiration starting month. The period of transpiration for each HRU ends when the simulation reaches the month specified
potet_jh	Determines whether current time period is one of active transpiration, and computes the potential evapotranspiration using the Jensen-Haise formulation (Jensen and Haise, 1963) Plan replacement with PRMS modules potet_pt or potet_pm under development using the Priestly-Taylor formulation (Priestly and Taylor, 1972) and Penman-Monteith formulation (Monteith, 1965), respectively, to better simulate climate change scearios.
intcp	Computes volume of intercepted precipitation, evaporation from intercepted precipitation, and throughfall that reaches the soil or snowpack

Module Name	Module Description
srunoff_smidx	Computes surface runoff and infiltration for each HRU using a non-linear variable-source-area method allowing for cascading flow
soilzone	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
gwflow	Simulates storage and inflows to and outflows from the groundwater reservoir (GWR). The GWR has infinite capacity and is the source of simulated baseflow. Will not be used when running GSFLOW in integrated mode.
strmflow	Computes daily streamflow as the sum of surface runoff, shallow-subsurface flow, detention reservoir flow, and groundwater flow Will not be used when running GSFLOW in integrated mode.
water_use_read	Module under development planned for implementation to add irrigation return flow at watershed surface (Regan and LaFontaine, 2016).

5. INPUT DATA

Data required for PRMS can be separated falls 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 model domain such as elevation, slope, aspect, geology, soil type, land use, and vegetation type and density. These spatial data are represented in PRMS as model parameters that are assigned to HRUs.

5.1. Climate Distribution

Precipitation was spatially distributed across the PRMS model using the precip_1sta module, where a combination of spatial and temporal data is used from DAYMET mean monthly precipitation distributions (Thornton et al., 1997; Thornton et al., 2014) and daily precipitation measurements from the National Weather Service (NWS) Santa Cruz COOP station, respectively. Figure 5 illustrates the spatial distribution of DAYMET mean annual precipitation across the study area, and highlights that the majority of the precipitation falls at high altitudes near the northern and western edge of the model domain. Mean monthly

DAYMET precipitation (1981-2010 climatology) distributions were mapped to model cells, and the ratio of mean monthly DAYMET precipitation to mean monthly Santa Cruz COOP precipitation was computed for each model cell to develop spatial scaling factors (parameters termed rain_adj and snow_adj within PRMS). Daily precipitation was simulated at each HRU using the precip_1sta module by multiplying daily precipitation measurements from the NWS Santa Cruz COOP station by respective HRU precipitation scaling factors.

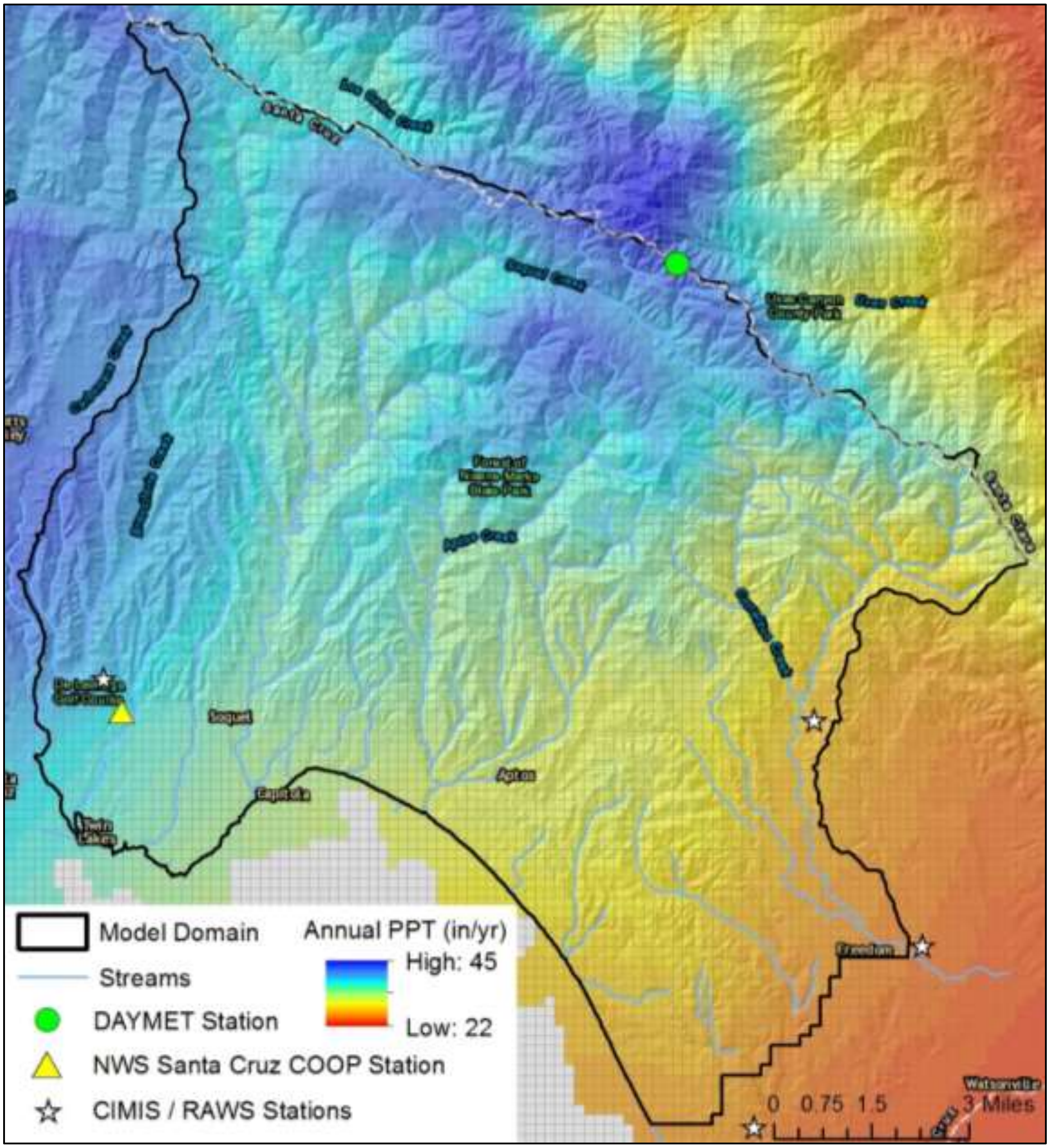

Figure 5. Spatial Distribution of DAYMET Mean Annual (1981 – 2010) Precipitation Mapped to Model Cells

Daily maximum and minimum air temperature (Tmax and Tmin) was simulated at each HRU using the temp_laps module, where daily temperature lapse rates were computed based on base station and lapse station temperature data. Daily Tmax and Tmin was simulated at each HRU based on daily NWS Santa Cruz COOP station measurements of Tmax and Tmin, respective lapse rates, and HRU cell elevations relative to base and lapse station elevations. Because no climate station exists at high altitudes within the model domain, DAYMET data was chosen to as a proxy for Tmax and Tmin measurements (i.e. lapse station) that is along the northern model boundary / mountain ridgeline (Figure 5). Potential evapotranspiration (PET) was simulated using the Jensen and Haise module (Jensen and Haise, 1963) which is a function of Tmax and Tmin, and solar radiation. Future simulations of PET will be based on more physically based Priestley-Taylor or Penman-Monteith formulations as those modules have just been incorporated into PRMS.

5.2. Streamflow Data

There are a number of USGS streamflow gages in the model domain. However, most of the gages are now inactive, with only two being currently operational (Table 2 and Figure 4). The District operates two local streamflow gages within the Soquel Creek watershed (Table 2 and Figure 4).

Table 2: Summary of Santa Cruz Mid-County Basin PRMS Streamflow Gages

Station Name	USGS Station Number	Gage Type	Data Record	DataFile ID	PRMS Sub-Basin ID
Corralitos Creek at Freedom	11159200	USGS	10/1/1956 - present	7	2
Soquel Creek at Soquel	11160000	USGS	5/1/1951 – present	8	10
Soquel Creek near Soquel	11159940	USGS	10/1/1968 – 9/30/1972 Estimated for model period*	16	11
West Branch Soquel Creek near Soquel	11159800	USGS	10/1/1958 – 10/6/1972 Estimated for model period*	9	12
Upper Soquel Creek	NA	Local	10/1/1983 - 1/30/1986 11/21/1986 - present	10	13
West Branch	NA	Local	11/11/1983 - present	11	14
Valencia Creek (County)	NA	Local	10/1/2008 - 12/31/2009	12	15
Aptos Creek at Aptos	11159700	USGS	10/1/1958 – 10/6/1972 Estimated for model period*	13	16
Corralitos Creek near Corralitos	11159150	USGS	10/1/1957 – 10/11/1972 Estimated for model period*	14	17

Station Name	**USGS Station Number**	**Gage Type**	**Data Record**	**DataFile ID**	**PRMS Sub-Basin ID**
Aptos Creek near Aptos	11159690	USGS	10/1/1971 – 9/30/1985 Estimated for model period*	15	18
Branciforte Creek at Santa Cruz	11161500	USGS	Estimated for model period*	17	NA

Notes: **bold** denotes gage used for preliminary PRMS calibration
* Estimated based on linear regressions from double-mass curves generated between gages with incomplete records and one of the two gages with complete records for overlapped data periods

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. Linear regression equations were developed for each of the double-mass curves. The double-mass curves were extrapolated to the entire model calibration period based on the linear regression equation. Additional detail on this approach can be found in HydroMetrics WRI (2011)

5.3. Model Parameters

PRMS uses over 240 model parameters to define various hydrologic processes. Parameters are assigned to each HRU, groundwater reservoir, stream segment, and cascade. For this model, parameter values remain fixed throughout the PRMS simulation. 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 are assigned default values.

The parameterization of the Santa Cruz Mid-County Basin PRMS was accomplished using multiple GIS datasets including:

- DAYMET mean monthly precipitation and temperature distributions (Thornton et al., 1997; Thornton et al., 2014),

- 10 meter resolution digital elevation model (DEM), with derived slope and aspect (National Elevation Dataset, 2015),
- USGS National Hydrography Dataset (NHD),
- LANDFIRE vegetation type and density distributions (LANDFIRE, 2010), and
- SSURGO soils data of percent sand, silt, clay, and available water holding capacity (USDA, 2012).

Custom Python scripts were developed to map GIS datasets to PRMS HRUs and compute PRMS parameters. Topographic, vegetation, and soil parameters were computed following recommended equations and remap classification tables found in Viger and Leavesly (2007).

HRU-to-HRU connections and PRMS cascade parameters were computed using the Cascade Routing Tool (CRT) (Henson et al., 2013). CRT was used to condition the upscaled 800 foot resolution DEM of the study area to fill unintended swales, create continuous down-sloping HRUs, and ultimately simulate stream locations. The upscaled and conditioned DEM was adjusted and CRT was iteratively executed to optimize stream locations and connections relative to NHD streamlines. Sub-watersheds were delineated according to stream gage locations and primary tributary confluences (Figure 6) such that simulated streamflow could be easily compared to measured streamflow for model calibration. Custom scripts were written and executed to attribute model stream cells with stream segment and reach identifiers needed for routing sub-basin generated flows to respective stream segments and reaches within PRMS and MODFLOW's Stream Flow Routing Package (Figure 6).

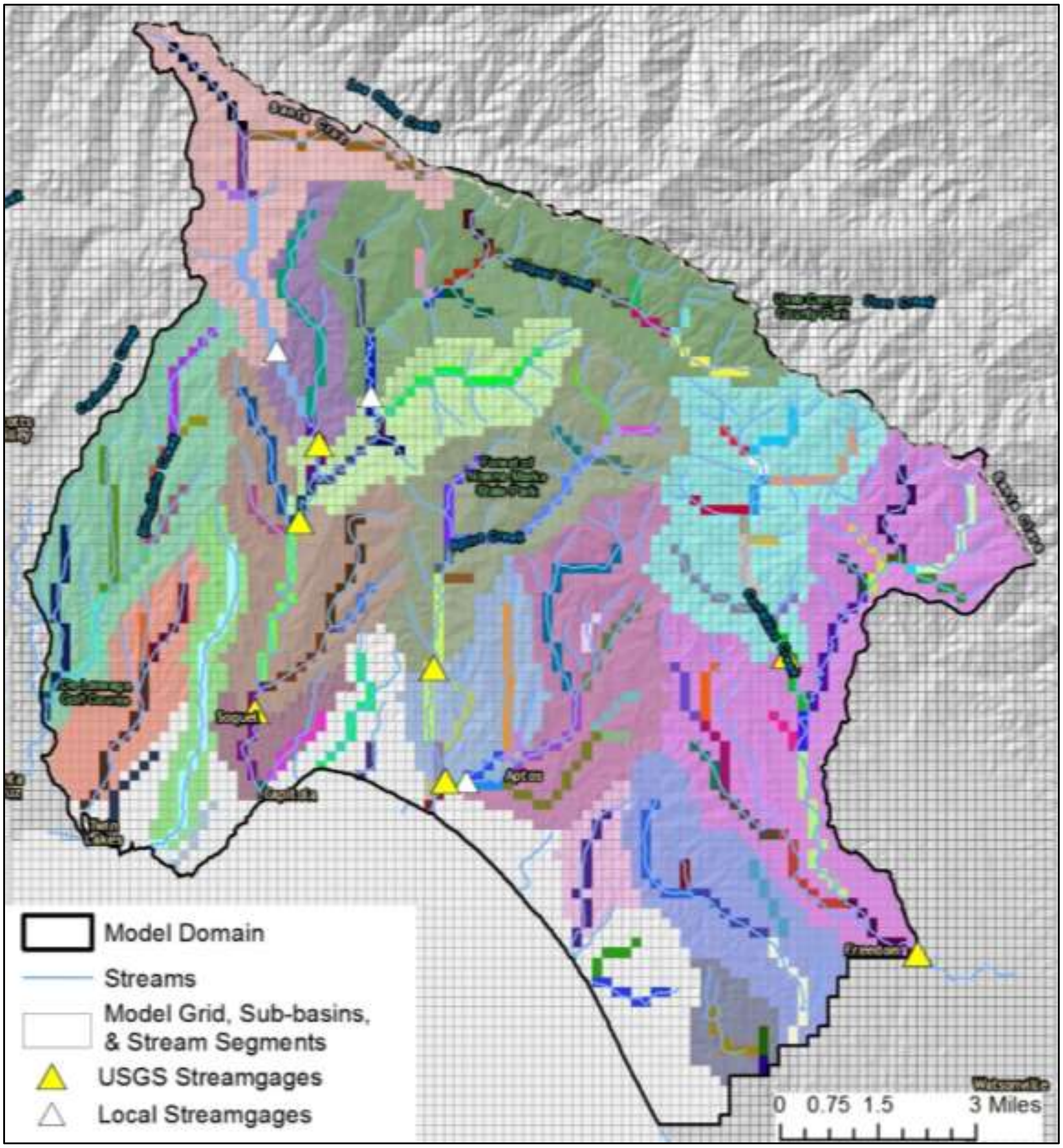

Figure 6. Spatial Distribution of Model Sub-basins and Stream Segments - Sub-basin and Stream Cell Colors Represent Unique Sub-basins and Stream Segments

6. CALIBRATION

For the current PRMS model calibration, a step-wise approach was used to calibrate and evaluate the PRMS model at annual, monthly, and daily timesteps using observed daily average streamflow. PRMS solar radiation and PET parameters were first calibrated to measured solar radiation and calculated PET at CIMIS and RAWS stations within or near the study area (Figure 5). Solar radiation and PET were initially calibrated to accurately estimate the atmospheric demand and actual evapotranspiration (ET) from the study area. PRMS soil parameters of soil_moist_max, sat_threshold, and preferential flow parameters were then adjusted such that measured streamflows were reasonably simulated at the two active stream gages (Table 2).

Measured streamflow provides the integrated hydrologic information to evaluate the annual, monthly, and daily water budget and simulated fluxes of precipitation, ET, and streamflow. Goodness of fit between the simulated and observed streamflow was only assessed at annual time steps for initial model simulations, and will be further assessed at monthly and daily time steps using the Nash-Sutcliffe statistic (Nash and Sutcliffe, 1970). The calculation of the Nash-Sutcliffe statistic is described in HydroMetrics WRI (2011).

6.1. Potential Evapotranspiration

Mean monthly simulated and observed PET is shown in Figure 7. In general, the preliminary calibration of potential ET is acceptable, however, during the spring months PRMS is slightly over simulating PET. Further calibration of Jensen and Haise PET coefficients, or re-calibration will be required when changing PET algorithms to Priestley-Taylor or Penman-Monteith based formulations.

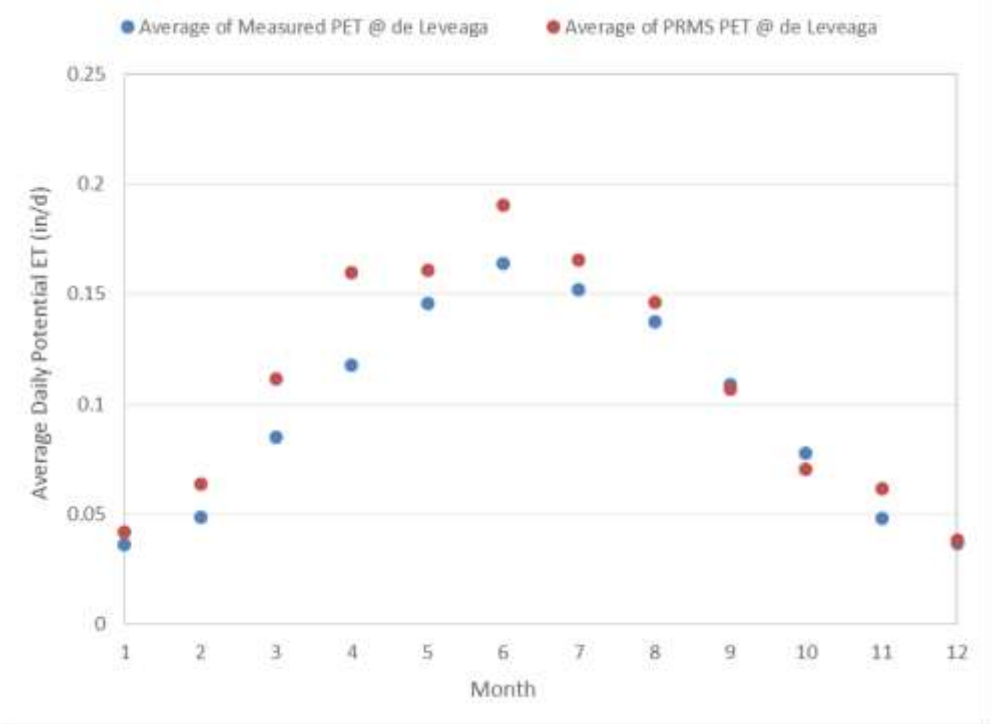

Figure 7. Preliminary Calibration of PRMS Simulated Potential Evapotranspiration (PET) using measured PET at the de Levaga CIMIS Station

6.2. Streamflow

Historical PRMS streamflow simulations are shown and compared to measured streamflow at an annual timescale in Figure 8 and

Figure 9 for the Soquel Creek at Soquel and the Corralitos Creek at Freedom gages, respectively.

A second phase of calibration will be to use Parameter Estimation (PEST) software to optimize PRMS parameters to achieve the best match between measured and simulated streamflow with the PRMS model and integrated GSFLOW model. It is anticipated that soil-zone parameters will be the parameters primarily adjusted.

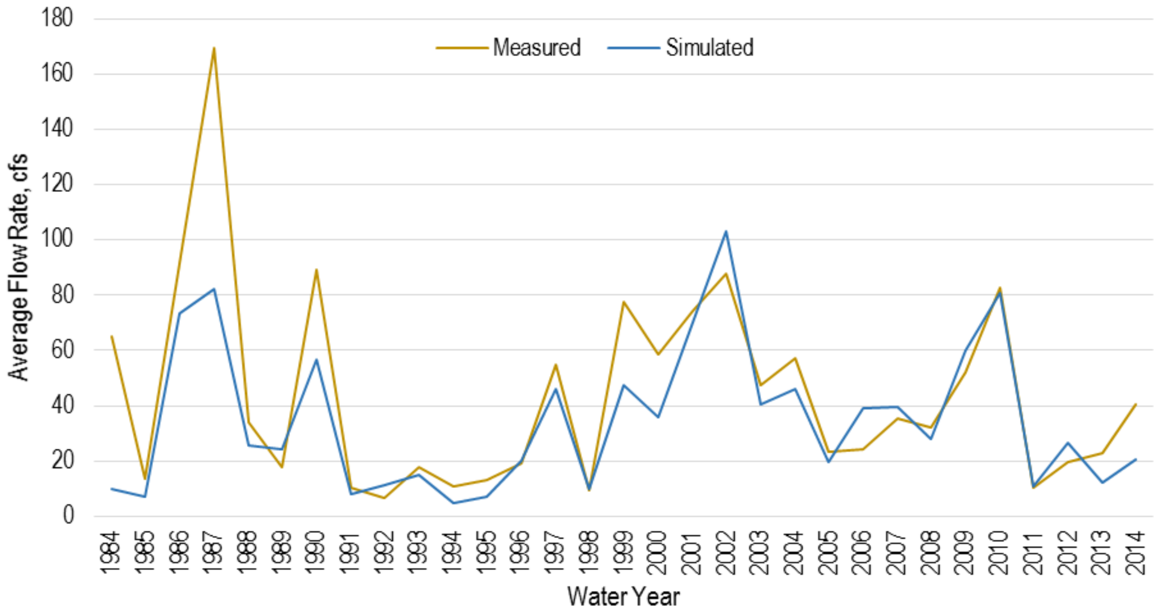

Figure 8. Annual Comparison of Measured and Simulated Stream Flow at the Soquel Creek at Soquel Gage

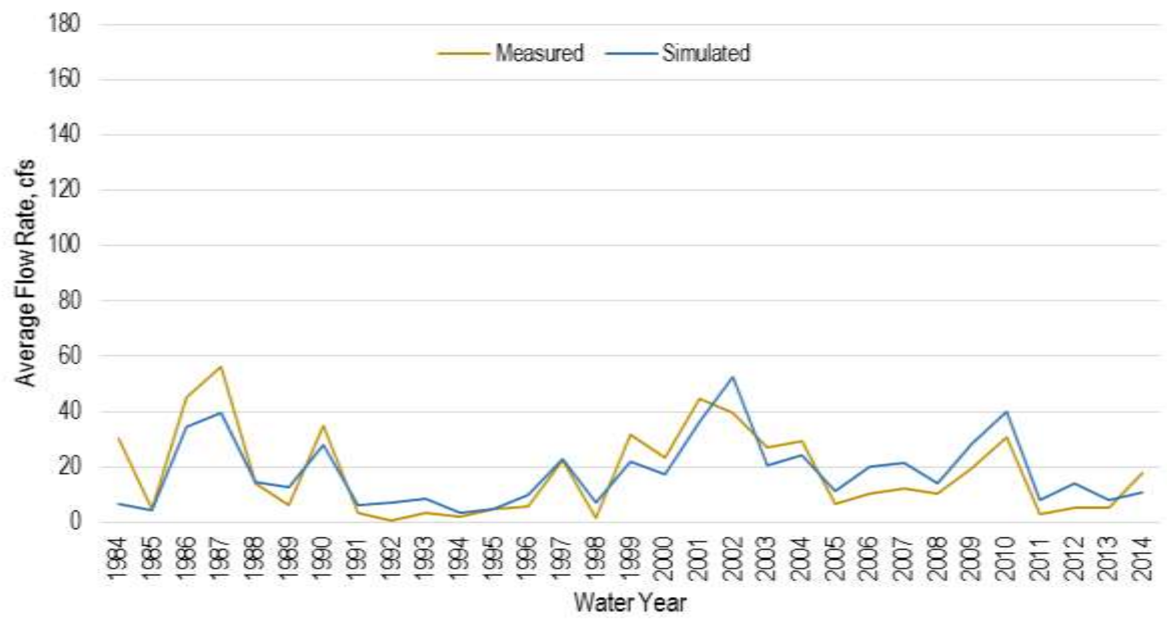

Figure 9. Annual Comparison of Measured and Simulated Stream Flow at the Corralitos Creek at Freedom Gage

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