# INTRODUCTION

Ensuring sustainability of the Carmel River basin’s surface and groundwater supply in the face of changing environmental and water management factors is crucial for protecting ecosystem services of the Carmel River. Understanding the relationships between seasonal and annual rainfall and groundwater recharge, discharge, streamflow, and surface and groundwater interactions that occur is fundamental to managing the basin effectively. Justifying pumping curtailments and planning for impacts related to future land use change are examples of management decisions that could benefit from an improved understanding of surface and groundwater processes and interactions under current and future climate, landuse, and water management.

# PREVIOUS WORK

Previous water resource investigations have primarily focused on flood, water accounting, and groundwater water resource studies.

Durbin groundwater model (and other?)

Kapple et al., 1984 ground water flow model

Camp Dresser & McKee, et al., 1994 water resource evaluation study

Staal, Gardner and Dunne, Inc Hydrogeologic Simulation of Carmel groundwater

Right on Q (2011) Fractured Rock Wells Letter Report

Right on Q Hydrogeology (2011). Monterey Peninsula Water Management District Fractured Rock Wells Letter Report, 61 p.

Right on Q Hydrogeology (2013). Assessment of Previous Models, Data Inventory, and Development of a Conceptual Model for Simulating Flow in the Carmel River and its Alluvial Aquifer: Support Services for MPWMD’s IRWMP Project 8, 157 p.

Oliver, J (1995) groundwater model

Kondolf et al., (1987) J of H paper

Jonathan Frame – An integrated Surface Water-Groundwater Interaction Model for the Carmel River (2010)

Bedrock fracture study (others?)

Carmel Valley Sim model

Phreatophyte ET study

# OBJECTIVE

The objective of this report is to summarize the background, modeling approach, and development of a Precipitation Runoff Modeling System (PRMS, Markstrom *et al*., 2015) surface water model and steady state MODFLOW groundwater model for the Carmel River basin (Figure 1). The ultimate goal is to use the calibrated PRMS and MODFLOW models for the development and execution of an integrated surface and groundwater model, GSFLOW (Markstrom *et al.*, 2008) of the Carmel River basin. This report focuses on documenting the construction and calibration of the PRMS model, and conceptual model development and construction of the steady state MODFLOW model.

# MODELING APPROACH

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). PRMS simulates snowmelt- and rain-generated 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). 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, including 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. Vertical unsaturated flow is simulated by MODFLOW using the Unsaturated-Zone Flow (UZF1) Package (Niswonger *et al.*, 2006). Stream and lake exchanges with the subsurface are simulated by MODFLOW using Streamflow Routing (SFR2) and Lake (LAK7) packages (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 layers used for developing the PRMS and MODFLOW model grid and components for the Carmel River basin.

# METHODS

## Model Discretization

Discretization of the model grid was based on identifying the largest grid cell size that best preserved finer scale elevation distributions across the study area, and that was fine enough to resolve topographic features that control surface and groundwater interactions where they are known to occur (i.e. the narrows). 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 60-200 m. Figure 3 illustrates the distribution of elevation for different grid cell sizes, where it is evident that a cell size of 100 m represents the distribution of 60 m elevations fairly well. Based on this result, a discretization of 100 m for horizontal grids for PRMS and MODFLOW was chosen (Figure 4a & 4b). Grid cells represent both PRMS Hydrologic Response Units (HRUs) and MODFLOW cells. Having identical grid PRMS and MODFLOW grids greatly simplifies mapping computed parameters and fluxes between the two models. Spatial datasets of climate, geology, vegetation, soils, and land use were mapped to the 100 m model grid for PRMS, MODFLOW, and GSFLOW parameterization (PRMS and MODFLOW development and GIS parameterization discussed below).

## Climate Distribution

The distribution of climate is simulated within PRMS, and is based on point station measurements of precipitation and temperature, along with information about the relationships between point station data and spatiotemporal distributions of temperature and precipitation. The simulation length of the model is ultimately constrained to the period of record available for observed or estimated daily precipitation and temperature. For this report, the period of record considered is from 10/1/1959 to 12/31/2012.

### Precipitation

Simulated precipitation is distributed across the PRMS model using the precip\_1sta module, where a combination of spatial and temporal data are used, including Parameter-elevation Regression on Independent Slopes Model (PRISM) mean monthly spatial precipitation distributions (Daly et al., 1994) (400 m spatial resolution) and daily time series of National Weather Service (NWS) San Clemente COOP station (Figure 5). Missing daily precipitation data within the San Clemete station record were filled with station coincident grid cell estimates from Maurer et al. (2002) data (12 km spatial resolution) from 1959-1979, and station coincident DAYMET grid cell estimates (Thornton et al., 1997; Thornton et al., 2014) (1 km spatial resolution) from 1980-2012 (DAYMET period of record is from 1980 to pres.). In total, 131 missing days were filled with Maurer et al. (2002) and DAYMET precipitation data. Prior to filling missing station data with grid cell estimates from Maurer et al. (2002) and DAYMET, bias correction of estimated precipitation and temperature data was completed following the commonly used quantile-quantile cumulative distribution function (CDF) mapping technique (Panofsky and Brier 1968; Wood et al., 2004; Mejia et al., 2012) (Figure 6). Bias correction was required since Maurer et al. (2002) and DAYMET precipitation estimates were representative of average precipitation (and elevation) over 12 km and 1 km grid cells, respectively, coincident with the San Clemente NWS COOP station, and therefore not representative of relatively lower elevation of the station (i.e. located at the San Clemente dam site in the river valley).

Figure 5 illustrates the spatial distribution of PRISM mean annual precipitation across the study area, and highlights that the majority of the precipitation falls at high altitudes near the southern of the watershed boundary. Mean monthly PRISM precipitation (1981-2010 climatology) distributions were mapped to model cells, and the ratio of mean monthly PRISM precipitation to mean monthly San Clemente 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 PRMS HRU within the precip\_1sta module by multiplying daily precipitation measurements (and estimates for missing periods) at the NWS San Clemente COOP station by respective HRU precipitation scaling factors.

### Temperature and Potential Evapotranspiration

Daily maximum and minimum air temperature (Tmax and Tmin) was simulated at each HRU using the temp\_1sta module, where daily temperature data is distributed according to station measurements of daily Tmax and Tmin, specified lapse rates, and HRU cell elevations. Two climate stations were used to simulate daily Tmax and Tmin, where each station was assigned HRUs in which respective Tmax and Tmin was simulated. The NWS Carmel Valley COOP weather station was assigned to model cells within the valley area, while the Hastings Remote Automated Weather Station (RAWS) was assigned to model cells within the upland areas (Figure 7). Assignments of stations to respective HRUs was necessary to account for temperature inversions that commonly occur and were recorded by the Carmel Valley COOP weather station.

Missing temperature data for the Carmel Valley COOP station record were filled with with bias corrected Maurer et al. (2002) grid cell estimates from 1/1/1959 – 6/30/1978 (totaling 45 days), from 7/1/1978 – 12/31/1979 (totally 184 days), and with bias corrected DAYMET grid cell estimates from 1/1/1980 – 2/1/2002 (totaling 15 days). DAYMET grid cell estimates of daily Tmax and Tmin from 1/1/1980 to 12/31/2012 were used to represent measured Tmax and Tmin at the Hastings RAWS since the station had a limited data record (1997-pres.). No bias correction of the Hastings RAWS DAYMET data was performed due the minimal bias between the two temperature datasets due to similar elevation between the station and the DAYMET grid cell. Potential evapotranspiration (PET) was simulated using the Jensen and Haise module (potet\_jh) (Jensen and Haise, 1963) which is a function of Tmax and Tmin, solar radiation, and elevation. Solar radiation was simulated using the degree-day solar radiation module (ddsolrad), which is a function of daily Tmax, estimated clear sky solar radiation, and monthly degree-day coefficients.

## PRMS Parameterization and Calibration

PRMS relies on numerous spatial and temporal parameters to define various hydrologic processes. The parameterization of PRMS was primarily accomplished using multiple geographic information system (GIS) datasets including PRISM 400 m spatial resolution mean monthly precipitation and temperature distributions (Daly et al., 1994), 10 m digital elevation model (DEM) and slope and aspect (derived from USGS National Elevation Dataset), 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 HRU grid cells and compute respective PRMS parameters. Topographic, vegetation, and soil parameters were computed following recommended equations and remap classification tables found in Viger and Leavesly (2007). Cell-to-cell connections and PRMS cascade parameters were computed using the Cascade Routing Tool (CRT) (Henson et al., 2013). CRT was used to condition upscaled 100 m HRU elevations to fill swales, create continuous down-sloping HRUs, and ultimately simulate stream locations. Upscaled and conditioned HRU elevations along stream and river areas were adjusted manually and CRT was iteratively executed to optimize stream and river locations and connections relative to National Hydrography Dataset (NHD) streamlines. Watersheds were delineated for 17 separate sub-basins according to stream gage locations and primary tributary confluences (Figure 8) such that simulated streamflow could be easily compared to measured streamflow for model calibration and summary statistics (Table x). Custom scripts were written and executed to attribute model stream cells with unique stream segments (n=2437) and reach identifiers needed for routing sub-basin generated flows to respective stream segments and reaches within PRMS, and MODFLOW modules UZF1 and SFR2 (Figure 8).

For PRMS model calibration, a step-wise approach was used to calibrate and evaluate PRMS model simulations at annual, monthly, and daily timesteps. PRMS solar radiation and PET parameters were first calibrated by comparing simulations to measurements of solar radiation and calculated PET at the Hastings RAWS stations, and by adjusting mean monthly PRMS solar radiation (dday\_intcp and dday\_slope) and PET parameters (jh\_coef) to best match the observations. PET was computed using Hastings RAWS station measurements of daily Tmax, Tmin, relative humidity and solar radiation following the American Society of Civil Engineers Penman-Monteith equation for reference evapotranspiration (ETo) (ASCE-EWRI, 2005). Solar radiation and PET was first calibrated to accurately estimate the atmospheric demand (i.e. ETo) and subsequent actual evapotranspiration (ET) estimates from the study area. PRMS soil parameters that control overland flow, interflow, baseflow, and water available for ET were then calibrated such that measured and estimated unimpaired streamflow was well simulated at primary calibration stream gages (Table x) at annual, monthly, and daily timesteps. Comparing simulated streamflow at the basin outlet (i.e. USGS Near Carmel gage) allowed for evaluation of the mean annual water budget by comparing simulations of basin area-weighted precipitation, ET, and streamflow depths with measured area-weighted streamflow depths. Unimpared streamflow at the USGS Near Carmel was estimated using data from the Carmel Valley Simulation Model (CVSIM). Goodness of fit assessment between simulated and observed streamflow using the Nash-Sutcliffe statistic (Nash and Sutcliffe, 1970) was only performed at annual, monthly, and weekly time steps for the xxx gage, for initial model simulations and calibration, but will be assessed at other subbasins/gages within the model once the calibration of the GSFLOW model occurs.

## MODFLOW Parameterization and Calibration

MODFLOW-NWT (Niswonger *et al.*, 2011) was constructed and initially calibrated independent of PRMS using a steady-state stress period, including representation of stream flow (SFR2), Lakes (LAK7), and unsaturated-zone flow (UZF1). Unlike traditional groundwater models that are typically limited in extent to alluvial valley or primary aquifer areas, the model constructed in this study extends to mountain block watershed divides and simulates groundwater flow over the entire watershed. The primary advantage to this approach is maintaining hydrologic connectivity between upland mountain block watershed and valley fill aquifers, and surface and groundwater flows. Accordingly, the conversion of precipitation to recharge and other water budget components is simulated by the model as opposed to calculating recharge external to the model and applying recharge as a constant or time-dependent boundary condition. This approach is preferred because it provides a mechanism for simulating feedbacks between climate, recharge, and groundwater storage, which is necessary, for example, to simulate the linkages between climate warming and saturation excess runoff. Once run in GSFLOW mode, model updating is also very convenient with this approach since all that is required are updates to the climate data file(s).

The Hydrogeologic Framework Model (HFM) developed in this study formed the basis for determining total number of layers, vertical layer discretization, and assignment of hydraulic properties in the MODFLOW model. The HFM was developed using a hybrid conceptual and data driven approach. The data-driven component of the HFM consisted of a lithologic database of units derived from well logs within the watershed, surficial geologic map (Ludington et al., 2007), and digital depth to bedrock distribution based from a previous study (Logan, 1983a), and HRU model cell land surface elevations. Alluvium areas primarily consists of Pliocene to Holocene terraces, and Quaternary stream deposits and outwash. Mountain block areas primarily consist of early to late Cretaceous granodiorite, early Proterozoic to Cretaceous schist, and smaller amounts of Paleocene to Oligocene sandstone and mudstone (Figure 9)x. A well log and generalized lithologic database was developed based on a combination of datasets from different studies and databases (Curry, 1997; Logan, 1983a; Right on Q, 2011, 2013; MPWMD monitoring well database). The spatial distribution wells within the database primarily consisted of located in the alluvium and valley floor areas, and mountain block wells where accurate location information and depth to groundwater information existed (Figure 10x). This database served as the basis for the data-driven approach for delineating hydrogeologic units and hydraulic properties in alluvial fill and mountain block areas. In mountain block areas where hydrogeological information is generally lacking, the inclusion of a conceptual component to the HFM was necessary. This conceptual component involved integrating surficial geologic information and specifying shallow alluvium areas along streams within the mountain block, while honoring observed transitions of increased alluvial thickness from the mountain block to valley floor areas (Logan, 1983a) (Figure 11x) and follows previous GSFLOW conceptual model developments (Huntington and Niswonger, 2012).

The combination of lithologic and conceptual information was used in combination to identify four general hydrogeologic units: shallow and deep alluvium, weathered bedrock, and unweathered bedrock. Each hydrogeoloic unit corresponds to a designated MODFLOW layer, with layers 1 and 2 consisting of shallow and deep alluvium, and layers 3 and 4 consisting of weathered and unweathered bedrock, respectively. Alluvium layers are discontinuous over mountain block layers where the spatial distribution of active model cells within layers 1 and 2 of the mountain block honors observed locations of streams and alluvium around streams. Total alluvial thickness begins at 4 m in the highest elevation mountain block stream areas and linearly increases towards the valley. Valley floor alluvial thicknesses honor the interpolated thickness from the lithologic database and depth to bedrock contours from previous studies (Figure 11 x). Alluvium within the stream areas of the mountain block were assigned to layer 1. Layers 1 and 2 have zero thickness outside stream alluvial areas within the mountain block. Layers 3 and 4 represent the mountain block where all cells are active within the model domain, and represent weathered and unweathered bedrock, respectively. Based on well logs that were located in the mountain block, the bedrock at the surface was considered a weathered zone with enhanced permeability and assigned to be 150 m thick (i.e. layer 3 thickness), and the unweathered bedrock and was assigned to have 300 m thickness (i.e. layer 4 thickness). Initial hydraulic conductivity values were assumed to be uniform within each layer, and were derived from previously reported estimates and summaries (Logan, 1983a,b; Kapple et al, 1984; Right on Q, 2011; 2013) and later adjusted according to during the steady state calibration processes (described below) (Table x).

Custom Python scripts were executed to map and compute SFR2 parameters such as unique segment and reach IDs, flow direction, slope, reach length, and contributing HRU cell IDs. Manning’s roughness was estimated based on a range of values (~ 0.03 to 0.04) representing natural cobble channels that are clean and straight, and with deep pools, respectively. For the mainstem of the Carmel River, high resolution channel survey data (FEMA, 2009) was used to define average channel width and depth for each stream segment (Figure 12 x). Streamflow depth and were then generated using tabulated values relating stream depth to width to flow for each segment. These tabulated values were used as input to SFR2 Data Set 4b using the ICALC = 4 option. Stream depth and width estimates for upland streams (non-mainstem stream cells) were derived and input to SFR2 (ICALC = 1 assuming rectangular channel) based on exponential relationships between model cell flow accumulation and stream channel width and depth estimated from field measurements and high resolution imagery estimates and assumed values. Initial distributions of UZF1 and SFR2 parameters, including vertical saturated hydraulic conductivity, soil water content properties (saturation, initial, and extinction water contents), and groundwater ET extinction depths were assumed and assigned to model cells based on typical and previously reported values for alluvium, mountain block, and phreatophyte areas (Huntington and Niswonger, 2012) (Table x). Phreatophyte distributions were assumed to follow streams and mapped wooded and non-wooded phreatophyte delineations along the Carmel River flood plain according to Christensen and Geisler (2010). Groundwater extinction depths were assumed to range from 2 to 4 m for stream and mainstem Carmel River floodplain phreatophyte areas, respectively.

Mean annual PRISM precipitation was scaled to represent the mean annual streamflow (i.e., sum of recharge, interflow, and overland runoff), and utilized as net infiltration for UZF1 and MODFLOW-NWT. Calibration of UZF1 and MODFLOW-NWT was performed by adjusting the precipitation scaling factor and layer specific homogeneous aquifer hydraulic conductivity values until there was a good visual correspondence between the simulated and observed steady-state flows in streams, lake and reservoir stages and outflows, groundwater heads, and the locations of major discharge and wetland areas. Wetland areas were used to calibrate the model by assuming groundwater heads were equal to land surface elevations in wetland areas and comparing surface elevations to simulated head. Steady-state lake and reservoir stages were simulated by simulating surface and groundwater inflows, while specifying mean annual outflows based on gage records.

## GSFLOW Parameterization and Calibration

# RESULTS

## PRMS Calibration and Historical Simulations

Mean mean monthly simulated and observed potential ET 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. Historical PRMS streamflow simulations are shown and compared to measured streamflow at annual and monthly timescale in Figures xx and xx, respectively. As a criterion for calibration, greater than 0.xx Nash Sutcliffe Efficiency (NSE) was desired and obtained at the annual timestep, and greater than 0.xx at the monthly timestep for most gauges. Calibration statistics are shown for each gauge in Table x.