RMP

REGIONAL MONITORING PROGRAM FOR WATER QUALITY IN SAN FRANCISCO BAY

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San Francisco Bay Regional Watershed Modeling Progress Report, Phase 1

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Preface

The San Francisco Bay total maximum daily loads (TMDLs) call for a 50% reduction in mercury (Hg) loads by 2028 and a 90% reduction in PCBs loads by 2030. In support of these TMDLs, the Municipal Regional Permit for Stormwater (MRP) (SFBRWQCB, 2009, SFBRWQCB, 2015) called for the implementation of control measures to reduce PCBs and Hg loads from urbanized tributaries. In addition, the MRP has identified additional information needs associated with improving understanding of sources, pathways, loads, trends, and management opportunities of pollutants of concern (POCs). In response to the MRP requirements and information needs, the Small Tributary Loading Strategy (STLS) was developed, which outlined a set of management questions (MQs) that have been used as the guiding principles for the region's stormwater-related activities. In recognition of the need to evaluate the loads or concentrations of POCs from small tributaries changing on a decadal scale, the updated 2018 STLS Trends Strategy (Wu et al., 2018) prioritized the development of a new dynamic regional watershed model for POCs (PCBs and Hg focused) loads and trends and developed a multi-year plan to obtain initial answers by 2022. This regional modeling effort will provide updated estimates of POC concentrations and loads for all watersheds in the region. The regional model will also provide a mechanism for evaluating management actions and management impact on future trends of POC loads or concentrations.

The regional model will also be developed to include other pollutants, such as contaminants of emerging concern (CEC), sediment, and nutrients. This dynamic model is likely to benefit other Regional Monitoring Program (RMP) workgroups that have similar management questions. For example, the new dynamic regional model could be utilized in the future to estimate stormwater CEC loads from small tributaries to the Bay.

An integrated modeling strategy will help to address RMP questions in a more efficient manner. The development of this regional watershed model provides the potential linkages of other models (food web, Bay single box, Bay dynamic, etc.), which is a step forward to a more integrated modeling framework. As this model is developed, flexibility to link with other models will be one of the considerations.

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Executive Summary

A new dynamic regional watershed model for Bay Area hydrology, sediment, and pollutant loads and trends is being developed by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP). The watershed of this new model is the area that drains to San Francisco Bay from the nine adjacent counties around the Bay (excluding the Sacramento and San Joaquin drainages). The Loading Simulation Program in C++ (LSPC) modeling framework was selected because of its capacity to simulate large complex regions with mixed land use types, a wide range of pollutants, including upland erosion and sediment transport, and in-stream water quality processes (e.g., bank erosion, settling, and resuspension). This is the first progress report to document the model development and hydrologic calibration effort. The report includes six sections: 1) background and proposed timeline for the regional watershed model project and the hydrologic simulation results; 2) modeling framework and general modeling approaches with LSPC; 3) modeling development effort on data collection and preparation, as well as the hydrologic model structure and setup; 4) hydrologic model calibration; 5) proposed sediment and POC model structure; and 6) key elements of the next phases of model development. The goal of this report is to facilitate discussions that lead to consensus among stakeholders on future model developments. This report serves as phase 1 of what is anticipated to be a three-phase development effort (sediment in phase 2 and pollutants in phase 3) but there may also be subsequent application phases.

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Abbreviations and Acronyms

ACCWP	Alameda Countywide Clean Water Program
BAHM	Bay Area Hydrologic Model
BASMAA	Bay Area Stormwater Management Agencies Association
CDWR	California Department of Water Resources
CCCWP	Contra Costa Countywide Clean Water Program
CECs	contaminant of emerging concern
CONUS	The contiguous United States
CSO	combined sewer overflow
CSS	combined sewer system
CWA	Clean Water Act
DCIA	Directly Connected Impervious Area
DEM	digital elevation model
EBMUD	East Bay Municipal Utility District
ECWG	Emerging Contaminants Workgroup
EIA	effective impervious area
EMC	event mean concentration
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
GGB	Golden Gate Bridge
GIS	geographical information system
GSI	green stormwater infrastructure
HRU	hydrologic response unit
HSPF	Hydrologic Simulation Program – FORTRAN
HUC	Hydrologic Unit
LSPC	Loading Simulation Program in C++
MAE	mean absolute error

MQs	management questions
MRP	Municipal Regional Permit
MS4	municipal separate storm sewer system
MTC	Metropolitan Transport Commission
NCDC	National Climatic Data Center
NLDAS	North American Land Data Assimilation System
NLCD	National Land Cover Dataset
NMS	Nutrient Management Strategy
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRMSE	normalized root mean squared error
NSE	Nash-Sutcliffe Efficiency
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PET	potential evapotranspiration
POCs	Pollutants of concern
PRISM	Parameter Elevation Regression on Independent Slope Model
RAA	Reasonable Assurance Analysis
RE	relative error
RMP	Regional Monitoring Program for Water Quality in San Francisco Bay
RMSE	root mean squared error
RWSM	Regional Watershed Spreadsheet Model
SCVWD	Santa Clara Valley Water District
SFEI	San Francisco Estuary Institute
SFPUC	San Francisco Public Utilities Commission
SFBRWQCB	San Francisco Bay Regional Water Quality Control Board
SPLWG	Sources, Pathways, and Loadings Workgroup
STLS	Small Tributary Loading Strategy

SedWG	Sediment Work Group
SWS	subwatershed
swTELR	Stormwater Tool to Estimate Load Reductions
SWMM	Stormwater Management Model
POCs	pollutants of concern
TAC	Technical Advisory Committee
TIA	total impervious area
TMDL	total maximum daily load
USDA	U.S. Department of Agriculture
USGS	U.S. Geologic Survey
WBD	Watershed Boundaries Datasets

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1. Introduction

1.1 Background

The San Francisco Bay TMDLs call for a 50% reduction in Hg loads by 2028 and a 90% reduction in PCBs loads by 2030. In support of these TMDLs, the Municipal Regional Permit for Stormwater (MRP) (SFBRWQCB, 2009, SFBRWQCB, 2015) called for the implementation of control measures to reduce PCBs and Hg loads from urbanized tributaries. In addition, the MRP has identified additional information needs associated with improving understanding of sources, pathways, loads, trends, and management opportunities of Pollutants of Concern (POCs). In response to the MRP requirements and information needs, the Small Tributary Loading Strategy (STLS) was developed and outlined a set of management questions (MQs) that guide the stormwater-related activities conducted by the Sources, Pathways, and Loading Workgroup (Table 1, SFEI, 2009; Wu et al., 2018). The objective of this study is to complete a regional watershed model to serve as the basis for sediment and POCs modeling and as the first phase of regional model development to support trends evaluation. Example applications of the model for water and sediment loads (Table 1) will later be extended to POCs in those environmental matrices.

Table 1. Management questions used by the Sources, Pathways, and Loadings Workgroup (SPLWG) to prioritize studies, as well as example application of the regional watershed model to these questions.

Management Question	Example Information Application
Q1: What are the loads or concentrations of Pollutants of Concern (POCs) from small tributaries to the Bay?	The model will produce an estimate of flow, sediment, and POC concentrations and loads for each individual watershed.
Q2: Which are the high-leverage small tributaries that contribute or potentially contribute most to Bay impairment by POCs?	Estimates of concentration, load, or yield produced by the regional model at each watershed can be compared to explore relative loading rates and their relationship to specific priority margin areas (Yee et al., 2019), operational landscape units (Beagle et al., 2019), or Bay segments.
Q3: How are loads or concentrations of POCs from small tributaries changing on a decadal scale?	Time series of flow, sediment, and POC loads for 1999-2018 can be used to assess trends for individual watersheds and the region. The model could be extended in the future to include additional water years.
Q4: Which sources or watershed source areas provide the greatest opportunities for reductions of POCs in urban stormwater runoff?	Model outputs of flow, sediment, and POCs will help identify high-yield areas within watersheds that can be targeted for management actions.
Q5: What are the measured and projected impacts of management action(s) on loads or concentrations of POCs from small tributaries, and what management action(s) should be implemented in the region to have the greatest impact?	Management actions, both existing and planned or anticipated, could be evaluated in the model through scenario runs to predict future loads based on land-use management scenarios and climate changes.

Over the past decade, considerable effort, including both field monitoring and modeling, has been made by the RMP and countywide municipal stormwater programs to address these management questions. These efforts have mostly focused on addressing Q1, Q2, and Q4. Questions remain as to how loads at the regional scale have and will change as a result of decadal long management actions in relation to TMDL goals (Q3). In recognition of the need to answer Q3, the updated 2018 STLS Trends Strategy (Wu et al., 2018) prioritized the development of a new dynamic regional watershed model for POC (PCBs and Hg focused) loads and trends and developed a multi-year plan to obtain initial answers by 2022.

In addition to addressing Q3, this regional modeling effort will also directly support Q1, Q2, and Q4 by providing updated estimates of POC concentrations and loads for all watersheds in the region. The regional model could also provide a mechanism to evaluate current or planned management impact on trends of POC loads or concentrations in support of Q5. The study will provide information essential to understanding spatial and temporal characteristics of hydrology and sediment loads, at the scales of individual watersheds and the whole region to address the SPLWG high-level management questions.

The regional model will be developed to include other pollutants, such as contaminants of emerging concern (CECs) and nutrients. Beyond POC questions, this new dynamic model is likely to benefit other RMP workgroups that have similar management questions. The phase one of the model development is focusing on the hydrology of the watersheds. Erosion and suspended sediment transport modeling will be developed in phase two. Sediment has emerged as a constituent targeted for research and management actions to inform sea level rise adaptation (Schoellhamer et al., 2018) and light-limited primary productivity in the Estuary (SFEI, 2014). The Sediment Workgroup (SedWG) has identified estimating sediment loads from Bay Area watersheds as a research need, and the Nutrient Management Strategy (NMS) is using estimates and trends of sediment loads to help support their modeling efforts to estimate future algal biomass and bloom occurrence in the Bay. In addition, the Emerging Contaminants Workgroup (ECWG) has developed a Contaminants of Emerging Concern (CECs) Strategy that identifies stormwater as a significant pathway for many CECs and calls for a combined modeling and monitoring approach to estimate their loads (Lin et al., 2018). A new dynamic regional model could be utilized in the future to estimate stormwater CEC loads from small tributaries to the Bay.

To support this direction, a new project was funded by the RMP in 2021 to develop an integrated watershed modeling and monitoring implementation strategy for sediment, nutrients, and CECs. The strategy will document the decision rationale for the suite of contaminants or contaminant classes for consideration under new future monitoring and modeling efforts, evaluate data requirements for loads estimation for each contaminant/class, use conceptual models to identify model data requirements and data gaps, and develop and determine the priority and timing of a series of recommended studies.

In addition, there is interest by some RMP stakeholders for a more integrated modeling strategy. Currently, this model, along with other modeling efforts (Bay dynamic simulation models, food web models, and mass balance conceptual box models of the Bay and Bay margins), are minimally or not integrated, but rather are used as stand-alone tools to answer project-specific questions. In the absence of a long-term programmatic integrative strategy to develop a suite of linked and co-developed modeling tools that are inclusive of needs across all the working groups of the RMP, there will likely be missed opportunities for co-development that will create inefficiencies later in adapting or retrofitting models to receive or accept linkages from one another. As this model is developed, flexibility to link with other models will be one consideration. To help address this interest, a Supplementary Environmental Project (SEP) has been proposed to develop a strategy for model integration, as well as a case study to demonstrate proof of concept.

1.2 Previous Work and Model Selection

A dynamic watershed model is essentially a series of algorithms applied to watershed characteristics and meteorological data to simulate land-based processes including rainfall-runoff, interflow, groundwater flow, flow routing, and pollutant loadings over an extended period. A well-calibrated watershed model can be used to characterize loadings from the upland watersheds of the Bay, ensuring that all major watershed sources and pathways are represented.

There have been four regional modeling efforts to quantify the sources, pathways, and loadings of sediment and contaminants draining to the Bay from the nine adjacent counties (Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, and the small area of San Francisco that is not serviced by a combined sewer system). These regional efforts varied in sophistication from an uncalibrated simple model (Davis et al., 2000); a combination of a flow-based statistical extrapolation and a land use-based method (Lewicki and McKee, 2010; McKee et al., 2013); a calibrated annual average Regional Watershed Spreadsheet Model (RWSM; Wu et al., 2017; SFEI, 2018); and a calibrated dynamic Bay Area Hydrologic Model (BAHM; Clear Creek Solutions, 2017). These are described below.

In 2000, stormwater flows and sediment and pollutant loads were estimated using a simple rainfall/runoff model (Davis et al., 2000). The simple model is a deterministic model that uses a linear relation between actual total stormwater volume, annual rainfall amount, and land use, as well as a linear relation between load and stormwater volume using an average concentration for each distinct land use type. In the simple model, areas upstream from reservoirs with catchment areas in excess of 20 mi^2 were removed from the analysis on the basis that significant retention of particles likely occurs, a simplification that is likely reasonable for pollutants that are dominantly in the particulate phase but concerning for dissolved phase pollutants, such as nitrogen and some pesticides. The 1995 ABAG land use dataset was used for the classifications in this study (ABAG, 1995). At 200-meter resolution, there were approximately 160 land use classes, which were generalized into six categories: agricultural, commercial, industrial, open, residential, and water.

Building from that work, Lewicki and McKee (2010) evaluated hydrologic, physical, and land use characteristics of the San Francisco Bay watersheds to predict relationships between watershed sediment loads and geomorphic processes, and, ultimately, to provide an updated estimate of regional suspended sediment loads from small tributaries. For watersheds dominated by non-urban land use, they used a combination of statistical relationships between peak flows and measured suspended sediment loads for three unique climatic provinces to estimate annual and average loads. In watershed areas dominated by urban land uses, they used a deterministic model of similar class to that of Davis et al. (2000), but this time based on a USLE-like and sediment delivery ratio combined relationship (Donigian and Love, 2003). They modified the load estimates by a delivery ratio to simulate edge-of-channel loads from the surrounding watershed area (NRCS, 1983), whereby the amount of sediment delivery to the channel decreases as watershed size increases. Using the combination of these two methods, the yields in Bay Area watersheds were estimated to range from 30 to 1,100 metric tonnes/km^2/year, not dissimilar to the range reported by McKee et al. (2003): 27-1,639 t/km^2/year. Annual average loads were estimated to be 1.3 M metric tonnes, 4-fold greater than estimated by Davis et al. (2000) and 1.67-fold greater than estimated by McKee et al. (2003).

The Regional Watershed Spreadsheet Model (RWSM) was developed to estimate average annual regional- and sub-regional-scale loads for the San Francisco Bay Area (Wu et al., 2017; SFEI, 2018). As with Davis et al. (2000) and Lewicki and McKee (2010), they also used a deterministic empirical model based on the volume-concentration method that was modernized to include automated calibration procedures (Box, 1965) and Monte Carlo-style error simulation as a component of the outputs (SFEI, 2018). It is a useful tool for providing regional (Bay-wide) and sub-regional (e.g., individual county, Bay segment, or priority margin unit) estimates of pollutant loads; for testing hypotheses about which watersheds may be exporting relatively higher or lower loads to the Bay relative to watershed area; and for estimating regionally averaged, land use-specific event mean concentrations (e.g., ng/L in runoff) and yields (e.g., g/km^2/yr for a given area). The RWSM model is designed to estimate long-term average loadings at the regional scale and is currently calibrated using flow from 19 watersheds for the annual average rainfall from 1981-2010, split into three provinces (cf. Lewicki and McKee, 2010), and PCBs and Hg loads from eight watersheds. No sediment calibration was achieved, although there was considerable trial effort during development (Wu et al., 2017).

The Bay Area Hydrologic Model (BAHM) was originally developed by AQUA TERRA Consultants for the Brake Pad Partnership (BPP) to estimate the copper from brake pad wear debris released to the Bay (Donigian et al., 2007). The BAHM 2013 is a tool used by land development projects to analyze the hydromodification effects and sizing solutions to mitigate the increased runoff from these projects. The model is built on HSPF, a continuous simulation model capable of estimating flow and pollutant loads for mixed land-use watersheds. The model delineated the Bay Area into 22 watersheds and simulated flow, sediment, and copper loads from 1980 to 2005. In 2017, using some seed money provided by the Nutrient Management Strategy (NMS), SFEI updated and recalibrated this model. The areas directly draining into the Bay were delineated into finer resolution. There are now 47 total sub-basins in the updated model. The 1992 National Land Cover Dataset (NLCD, Vogelmann et al., 2001) was used in the original model, and grouped into six land use categories: Forest, Shrub/Wooded, Grass/Wetland, Developed Landscape, Impervious, and Agriculture. The land use data were updated to 2013 NLCD, classified in the same categories. The modeling period was modernized to the period 1999-2017.

In addition to the four models SFEI developed and updated, local municipalities are required to develop Reasonable Assurance Analysis (RAA) models to demonstrate that the implementation of future management actions can provide attainment of TMDL wasteload allocations (ACCWP, 2018; CCCWP, 2018; SCVURPPP, 2020; SMCWPPP, 2020; Solano Permittees, 2020). Various models were used by the different countywide stormwater programs, including SWMM (Huber, 2005), LSPC (Tetra Tech, 2009), SUSTAIN (Lai, 2007), and swTELR (Beck et al., 2017). For regional loading and trend estimation, ideally a consistent method should be applied to the whole Bay Area.

The primary consideration for model selection is to represent the variety of pollutants and pathways in the watersheds draining to the Bay. The selected model should be a scientifically sound representation of the watershed loading and transport system and should be a useful management tool. Some of the required modeling capabilities include:

- Simulate variations of hydrologic responses due to spatially and temporally variations in weather patterns and the related transient soil moisture condition of the surface/subsurface;
- Simulate time-variable chemical loadings from various sources in the watershed and estimate the relative pollutant contributions over time;
- Develop scenarios to evaluate changes in loadings for water-quality control/management design with different spatial scales, and link management (control measure) changes in the watersheds to changes in loading and instream concentrations of contaminants.

The HSPF and LSPC models were the two primary watershed models considered for the regional watershed model. LSPC is built from the same underlying algorithms as HSPF, and HSPF parameters can be readily transferred to an LSPC input format. Both HSPF and LSPC models have the capacity to simulate large complex regions with mixed land use types, a wide range of pollutants, including upland erosion and sediment transport, and in-stream water-quality processes (e.g., bank erosion, settling, resuspension), which suits the requirements of a regional and multi-purpose watershed model. The models include hydrologic, chemical, and sediment-loading simulation to predict chemical fate and transport on a watershed scale. They can generate either hourly results or daily average results to predict and compare the modeled outcome with observational data and/or to further use the results for advanced management decision support. LSPC model is selected because of its data structure allows for including large number of watersheds and complex model runs within one modeling file. The LSPC model has also been used as a platform for two (San Mateo (SMCWPPP, 2020) and Santa Clara (SCVURPPP, 2020)) of the five RAA models in the Bay Area, providing an opportunity for cross validation of modeling results at different spatial scales.

1.3 Timeline of Regional Model Development

The 2018 STLS Trends Strategy lays out a multi-year plan that outlines the need to assess decadal-scale trends in regional POC loads using a combination of dynamic modeling and monitoring (Wu et al., 2018). The multi-year plan also specifies a timeline, deliverables, and budget for the regional dynamic model development over 4 years. The first step of this plan, completed in 2019, was to develop a Modeling Implementation Plan (MIP) to guide model development, which included model platform and development procedures and a timeline (Wu and McKee, 2019). The general timeline and major deliverables of the regional modeling work are listed in Table 2. The MIP was reviewed by the STLS in April 2019 and the SPLWG in May 2019 and approved later in 2019. Thus, the major task for year 2020 was hydrologic modeling of the Bay Area; the tasks of model data collection and model setup have been completed. For 2021, the multi-year tasks include completing calibration and validation of the regional model for hydrology and suspended sediment. The hydrology and sediment model will be used as the basis for POC modeling. The PCBs and Hg model setup and calibration will be completed in 2022. The hydrology and sediment model platform can also be the basis for modeling other POCs.

This report documents the progress of data collection and preparation for model development, as well progress on the hydrologic model structure and setup. It outlines the overarching modeling strategy, key elements, and steps of regional model development. It also presents a proposed sediment and POC model structure to facilitate discussions that lead to consensus among stakeholders on key elements of the future phases of model development. It serves as a phase 1 report of the regional dynamic model development efforts and as the documentation of the basis for the general regional watershed model.

Table 2. Timeline and Deliverables for Bay Regional Watershed Model Development.

Year	Deliverable
2015-2018	Loads and trends strategy conception; Develop conceptual model; Statistical analysis of PCBs trends in Guadalupe River; Completion of Small Tributaries Loading Strategy: Modeling and trends Strategy.
2019	Modeling Implementation Plan
2020 (Phase 1)	Complete hydrology calibration
2021 (Phase 2)	Review and incorporation of new land-use data
	Complete sediment model setup
	Complete sediment model calibration and documentation; PCBs and Hg model data collation and general POCs model planning started.
2022 (Phase 3)	Complete PCBs and Hg model setup
	Complete PCBs and Hg model calibration and documentation
	Review CEC monitoring and conceptual modeling, identify data needs and gaps for CECs dynamic modeling, provide the next steps for CECs monitoring and modeling recommendations.
2023 (Possible future phases)	Model application runs for answering RMP questions. Options may include: ● Model refinements for better representation of spatial variability ● Model refinements for assessing trends associated control measure implementation and land use change ● Characterization of sedimentation process in flood control channels ● Assessment of future scenarios loading estimates ● Model development for other contaminants ● Linking and doing model runs to support models of physical and biological processes on the Bay margins or in the Bay
	Model application runs for answering RMP questions. Modeling plan for other POCs (e.g., CECs).

2. Overview of Modeling Framework and Approach

2.1 Study Area

The San Francisco Bay landward of the Golden Gate Bridge (GGB) receives discharge, sediment, and contaminant loads from an area of 162,145 km^2. The Sacramento and San Joaquin Rivers together form a large inverted delta at the northeastern extremity of the river-dominated northern estuary and together drain 154,000 km^2 of California's Central Valley. These are not part of the model domain being developed and described here. The remainder of the area upstream of the GGB, 8,145 km^2 (5% of the total GGB watershed), is associated with the “small tributaries” of the nine urbanized counties that directly fringe the Bay (Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco). The geology of these small tributaries is dominated by erodible marine sedimentary and meta-sedimentary rocks (see geologic map of California: CGS, 2006). Topography varies from sea level around the Bay to 1,173 m on Mount Diablo in the Contra Costa County. The Coast Range Mountains that ring the Bay are subject to periodic and often destructive wildfires that lead to temporary but large increases in the erodible sediment pool (Moody and Martin, 2009). Land use in the small tributaries of the Bay Area is approximately 50% urbanized, housing a total population of 7.151 million (Census, 2010). Rainfall varies with topography and distance from the Pacific coast, from about 300 mm in the interior of the Livermore Valley to the east to over 1500 mm at the heads of the Napa and Sonoma watersheds to the north. In these and the other small tributary watersheds, clear seasonal patterns exist: mean peak discharge occurs in February each year, and a mean of 93% of total annual discharge occurs from October to April almost completely in relation to rainfall.

2.2 Overarching Modeling Framework

LSPC is a comprehensive watershed model that can serve as a dynamic hydrologic and water quality tool. It provides a dynamic, continuous simulation of hydrology and water-quality processes. During the past several years, LSPC has been extensively used to develop hundreds of EPA-approved TMDLs (Carter et al., 2005; Craig et al., 2007; Flynn et al., 2007; Yusuf and Zhang, 2019; Parker et al., 2003). The model is based on the Stanford Watershed Model (Crawford and Linsley, 1966) and modularized HSPF framework. The model includes these major modules:

- PERLND/IMPLND: modules of hydrologic processes on pervious/impervious land
- SEDMNT/SOLIDS: modules of sediment production and removal from pervious/impervious land
- PQUAL/IQUAL: modules of pollutant production/removal from pervious/impervious land
- RCHRES: module of in-stream flow and water quality processes
- SEDTRN: module of sediment transport, deposition, and scour in streams
- GQUAL: module of pollutant fate and transport in streams

All these modules include various submodules and options for both simplified and complex process representations.

Similar to the RAA models of San Mateo (SMCWPPP, 2020), Santa Clara (SCVURPPP, 2020), Alameda (ACCWP, 2018), and Contra Costa (CCCWP, 2018), a Hydrologic Response Unit (HRU) is the basic modeling land unit of LSPC (Figure 1). Each subwatershed (SWS) consists of a combination of different HRUs. The hydrologic, sediment transport, and water-quality accumulation and wash-off processes are simulated at the HRU level. Each HRU type represents a land type with similar physical characteristics, such as land cover, land use, soil type, slope, and imperviousness. The hydrologic and water-quality responses are considered similar for land units with the same HRU type. The different parameter sets assigned for different HRU types can be used to distinguish and quantify the differences in hydrologic, sediment, and contaminant-related processes across different land features. The HRU responses are then aggregated at the subwatershed scale.

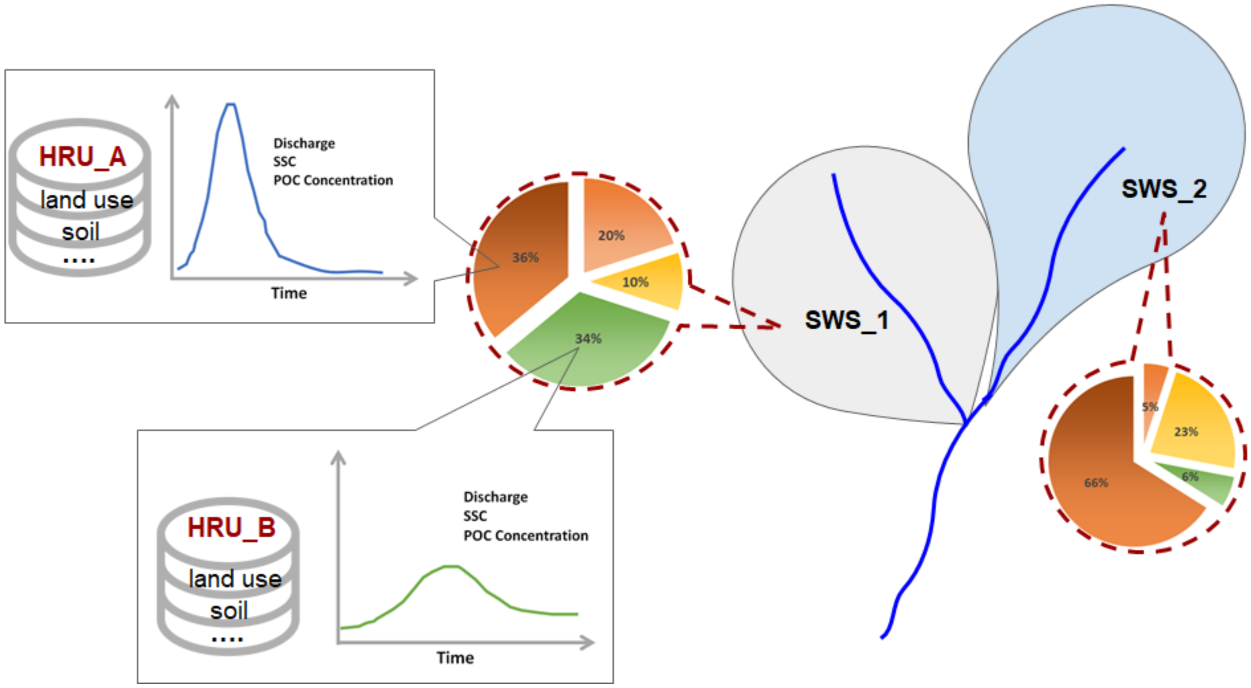

Figure 1. Hydrologic response unit (HRU) and subwatershed (SWS) structure in LSPC. The curves in the plot represent different shapes of hydrograph (sedigraph, pollutograph) generated from different HRUs.

2.2.1 Upland Hydrologic Processes Representation

Figure 2 provides a graphical representation of the fluxes and pools of hydrologic processes in the LSPC model. Hydrologic components included are precipitation, interception (CEPSC), evapotranspiration, overland flow, infiltration, interflow (IRC), subsurface storage (upper zone storage is UZSN, lower zone storage is LZSN), groundwater flow (AGWRC), and groundwater loss (DEEPFR).

Precipitation (rainfall and snowfall) first undergoes interception storage (CEPSC). If interception storage is filled, all remaining precipitation proceeds to the land surface and infiltrates (INFILT) into soil at different rates (using the Philip infiltration algorithm) based on varied soil types. Precipitation that reaches the ground is divided into surface and subsurface portions. Any water that does not infiltrate is divided between upper zone storage (UZSN), interflow (INTFW), and overland flow. Water in upper zone storage evaporates or moves deeper into the soil profile. Infiltrated water first fills the capacity of lower zone storage (LZSN) and moves downwards via percolation. Evaporation and plant matter exert a demand on available water from base flow outflow (BASETP), interception storage (CEPSC), upper zone storage (UZSN), groundwater storage (AGWETP), and lower zone storage (LZSN).

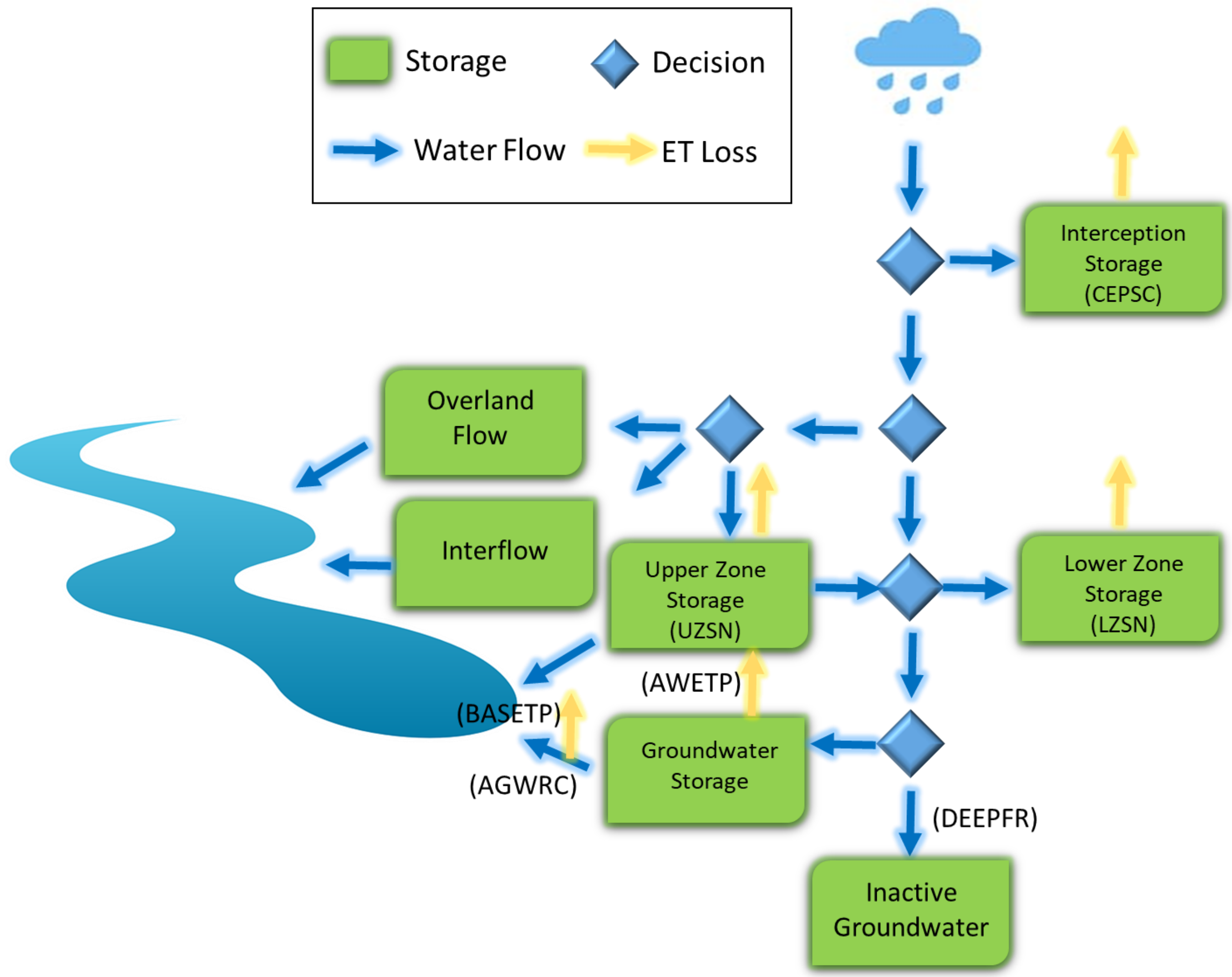

Figure 2. Hydrologic process representations of LSPC.

The LSPC model contains three major pathways of outflow: surface, interflow, and groundwater. Overland flow is routed to the stream directly and timing is based on a specified slope (SLSUR), surface roughness (NSUR), and distance (LSUR) values of the overland flow plane. Interflow travels to the stream through the soil matrix, and the timing depends on the interflow recession constant (IRC). Active groundwater storage is released to the stream through a groundwater recession constant (AGWRC). The remaining water is considered as inactive groundwater (water without the capacity to become streamflow), which is supplied by a value for DEEPFR.

All parameters are allowed to vary by HRU category. The HSPF Version 12 User's Manual presents a detailed description of relevant hydrologic algorithms (Bicknell et al., 2001).

2.2.2 Upland Sediment Processes Representation

Figure 3 shows the upland sediment scheme of the LSPC model. The soil erosion processes on pervious and impervious land are simulated with different modules.

Soil Erosion from Pervious Land

LSPC simulates sediment yield from pervious land surface to streams in two stages. First, rainfall detachment rate (in tons/acre) is calculated as:

$$DET = P^{JRER} \cdot (1 - COVER) \cdot SMPF \cdot KRER, \qquad \text{Equation 1}$$

where DET is the detachment rate (tons/acre), COVER is the dimensionless factor accounting for the effects of land cover on the detachment of soil particles, SMPF is the dimensionless management practice factor, KRER is the coefficient in the soil detachment equation, JRER is the exponent in the soil detachment equation, and P is precipitation depth in inches over the simulation time interval. KRER and JRER are two main calibration parameters to adjust the erosion potentials across different vegetation and soil types, land surface roughness, and geologic types, among other factors.

Second, the detached soil particles are transported to streams by overland flow. The detached soil particles are stored in detached sediment storage. Actual detached sediment storage available for transport (DETS) is a function of the reincorporation rate (AFFIX) and accumulation/removal over time (NVSI).

Transport capacity is the upper limit of sediment that the overland flow can carry. The transport capacity for detached sediment from the land surface (STCAP) is represented as a function of overland flow:

$$STCAP = KSER \cdot (SURS + SURO)^{JSER}, \qquad \text{Equation 2}$$

where KSER is the coefficient for transport of detached sediment, SURS is surface water storage (inches), SURO is surface outflow of water (in/hr), and JSER is the exponent for transport of detached sediment.

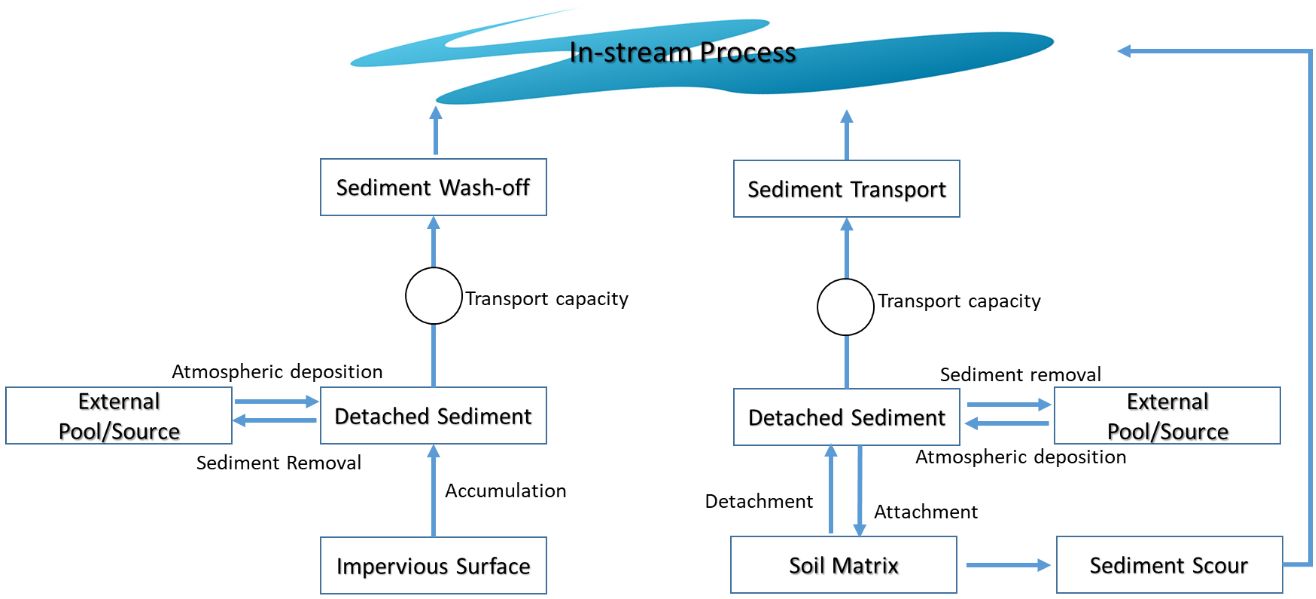

Figure 3. Soil erosion and sediment transport schemes on pervious and impervious land.

Sediment Simulation from Impervious Land

LSPC simulates sediment yield from impervious land surface with a buildup and wash-off method. The detached sediment is accumulated in the surface storage (SLDS) on those days when precipitation did not occur during the previous day, using the equation:

$$\mathrm{SLDS} = \mathrm{ACCSDP} + \mathrm{SLDSS}\cdot(1.0 - \mathrm{REMSDP}), \qquad \text{Equation 3}$$

where ACCSDP is accumulation rate of the solids storage, SLDSS is solids in storage at start of day, REMSDP is unit removal rate of solids in storage and removal of solids by runoff and other means from the impervious land segment. The solids outflow may be used to simulate quality constituents associated with particulates.

Wash-off of solids is limited by transport capacity of overland flow. The transport capacity is calculated by the equation:

$$\mathrm{STCAP} = \mathrm{DELT60}\cdot\mathrm{KEIM}\cdot(SURS + SURO)^{\mathrm{JEIM}}, \qquad \text{Equation 4}$$

where STCAP is capacity for removing solids, KEIM and JEIM are coefficient and exponent for transport of solids, SURS is surface water storage and SURO is surface outflow of water.

The transport capacity is estimated and compared to the amount of solids available. When STCAP is greater than the amount of solids in storage, wash-off is calculated by:

$$\text{SOSLD} = \frac{\text{SLDS} \cdot \text{SURO}}{\text{SURS} + \text{SURO}}, \qquad \text{Equation 5}$$

If the storage is sufficient to fulfill the transport capacity, then the following relationship is used:

$$\text{SOSLD} = \frac{\text{STCAP} \cdot \text{SURO}}{\text{SURS} + \text{SURO}}, \qquad \text{Equation 6}$$

where SOSLD is wash-off of solids and SLDS is solids storage.

2.2.3 Upland POC Processes Representation

The LSPC model provides a general and flexible framework for simulating pollutants. POC constituents are tracked in the model as dissolved and particulate mass in subsurface flow pathways. Similar to the simulation of sediment, two major components are estimated to assess particulate constituents from the land surface: accumulation and availability of contaminant mass on the land surface and wash-off of contaminants to the stream. The model can also use buildup/washoff for dissolved constituents - QUALOF. In addition, adsorbed constituents can be modeled as a concentration (a.k.a. “potency factor”) in the sediment load – QUALSD. The subsurface contributions of dissolved constituents are estimated with an Event Mean Concentration (EMC) method, which can be applied to surface runoff, interflow and groundwater for different land units (HRU).

PQUAL modules (simulation of pollutants for pervious land segments) and IQUAL modules (simulation of pollutants for impervious land segments) are used to represent the loading processes for pollutants in LSPC for each land unit (HRU). Accumulation rates are assigned to HRUs to simulate buildup of pollutants on the land surface. Particulate pollutants can be simulated either as sediment-associated or with a buildup/wash-off method.

If pollutant loading is simulated via a sediment-associated approach, the transport of contaminants from the land surface to water bodies is directly related to the sediment yield. Similarly, if loading is specified via a water concentration in runoff, then it is a direct function of the hydrologic simulation. For the buildup/wash-off formulation, the mass removed by wash-off is a function of the depth of flow and the stored mass.

2.2.4 Instream Fate and Transport

Reaches are paired with subwatersheds in the LSPC model for instream hydrologic and POC fate and transport processes simulation. Model reaches are defined as the representative stream of each subwatershed and typically represent the main channel. A single stream reach is associated with one subwatershed. Reach connectivity from headwaters to the pour points of the receiving water body is defined. The stream network links the surface runoff and subsurface flow from each of the land segments of subwatersheds and routes them through the water bodies. The stream model includes precipitation and evaporation from the water surfaces as well as flow contributions from the watershed, upstream stream reaches, point sources, and withdrawals (such as irrigation).

A well-mixed, one-dimensional reach with a trapezoidal cross section is used to represent stream channels in LSPC. The channel geometry is described in Figure 4.

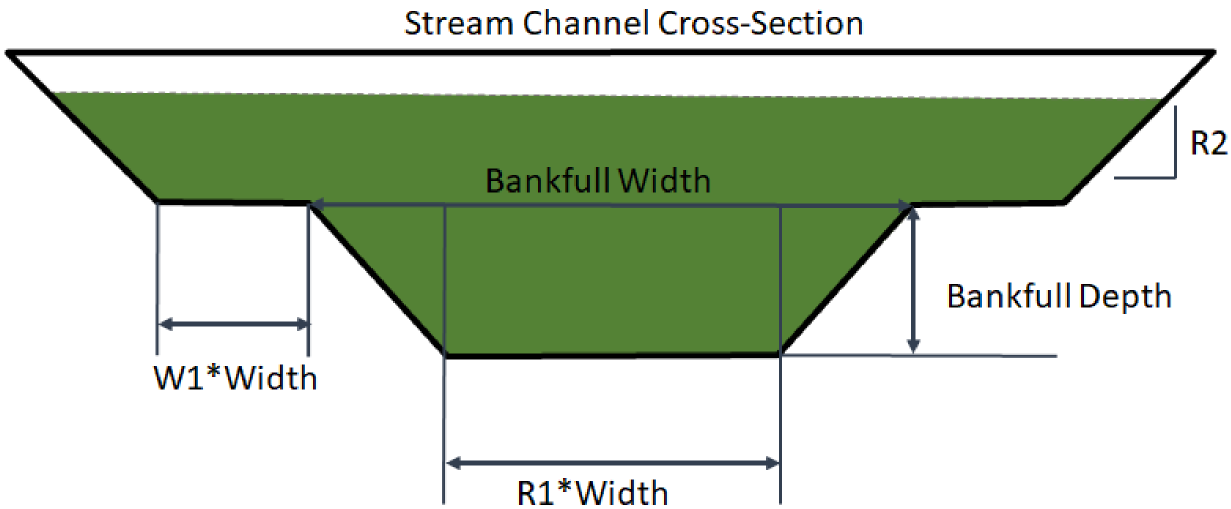

Figure 4. Stream channel representation in the LSPC model.

Input parameters for the reaches include initial depth, length, bankfull depth, width, slope, and Manning's roughness coefficient. The depth and width of the channel can either be input by the user or estimated by drainage area with the empirical relationship developed by Leopold and Maddock (1953). For the channels with different shapes, a stage-volume-discharge function table can be used to model hydraulics. The function table (F-Table) defines the functional relationship between water depth, surface area, water volume, and outflow of the stream segment. Users can define a F-Table for each stream segment or LSPC can generate the F-Table based on the geometry of the segment. The kinematic wave method is used as the routing technique.

LSPC representation of instream sediment and POC transport is described in Bicknell et al. (2001). LSPC uses a single sediment bed layer. LSPC continuously updates the bed composition in each reach based on relative amounts of scour or deposition of the three defined sediment size classes (sand, silt, and clay). LSPC can simulate bank erosion as a potential source of sediment independent of storage in the channel bed. The LSPC RCHRES component represents various instream processes, including advection, dispersion, sorption to sediment, volatilization, and decay. For low solubility non-polar organics such as PCBs, the model representation includes sorption to solids in the water column and bed sediment, exchanges between the water column and bed sediment, and general first-order decay. The PCBs can be grouped into different congeners or aroclors in the simulation to reflect the different decay rates of different species.

In general, multiple HRUs are used to account for the heterogeneity of hydrologic, sediment, and POC fate and transport processes across the Bay Area. Imperviousness, soil types, land cover and land use, and slopes all are factors that are considered in the HRU classification. Both upland and instream processes are simulated in the LSPC model to capture the hydrology and contaminants dynamics at the subwatershed scale. Hydrology, sediment transport, and water-quality calibration and validation will be conducted in sequence. The hydrology model serves as the basis of the sediment and water-quality models. This phase 1 report focuses on introducing the basic structure of the hydrologic model. The modeling plans and proposed approaches for sediment and POCs are discussed in the last section.

3. Regional Watershed Model Setup

The LSPC model uses empirical relationships to mimic certain hydrologic and water quality processes at HRUs or subwatersheds level. The watershed area is divided into numerous (in this case 237) subwatersheds that each consists of numerous HRUs to reflect the spatial heterogeneity of the hydrological and water quality processes. Hydrologic processes are simulated for each HRU, then are aggregated based on area to develop the local loads of subwatersheds to the stream reach. Finding the right balance in the size and numbers of HRUs and subwatersheds, and spatial and temporal resolution of meteorological data is a fundamental step for model development. This model setup section summarizes watershed segmentation, stream network development, HRU development, and meteorological data preparation.

3.1 Watershed Segmentation

Watershed segmentation refers to the subdivision of the entire modeling extent into smaller, discrete subwatersheds and reaches for modeling and analysis. The Watershed Boundary Dataset (WBD) is used to define the spatial extent. Four Hydrologic Unit Codes 8-digit (HUC8) watersheds, which spatially cover all the small tributary subwatersheds to the Bay, were used to define the modeling spatial domain. The size of subwatersheds with one-hour time of concentration were estimated using Kirpich's formula (Kirpich, 1940):

$$\mathrm{t_c} = \frac{0.06628\mathrm{L}^{0.77}}{\mathrm{S}^{0.385}}, \qquad \text{Equation 7}$$

where t_c is time of concentration in hours, L is the flow length from outlet to divide in kilometers, and S is the slope in meter per meter. The time of concentration is defined as the time needed for water to flow from the most remote point in a watershed to the watershed outlet. A simplified estimation of time of concentrations with the average slope of 5% and the travel length of 5 kilometers and 10 kilometers are 43 minutes and 74 minutes. Kirpich's formula is a simplified estimation that does not distinguish sheet flow and concentrated flow. It may not give an accurate estimation of the watershed response time (McKee et al., 2003), nonetheless it could be used to size the watersheds to have similar response time at the subdaily scale. Based on the rough estimation, most delineated subwatersheds range in size from approximately 25-50 km^2 (10 – 20 miles^2), with smaller watersheds at low slope urban regions and larger watersheds in mountainous regions.

This watershed delineation was based primarily on existing hydrologic boundaries (Federal standards and procedures for the National Watershed Boundary Dataset (WBD), 2013), watersheds delineated with stormwater network information (BAARI stream and stormwater network, watersheds delineated for RWSM model), watershed layers from local sources (e.g., Valley Water), and elevation models, including LiDAR and topo-bathy derivations. Other sources used to determine watershed delineations included the locations of flow and water-quality monitoring stations and dams and large reservoirs. Watersheds were split at locations of long-term flow and water-quality monitoring sites, as well as at pour points and at dams on large reservoirs.

Diked and filled baylands, flood management infrastructure, and other modifications are prevalent around the lower edges of Bay watersheds. The LSPC model uses a one-dimensional channel network to simulate in-stream process, thus it cannot represent the complicated hydrologic or sediment and water-quality transport dynamics in tidally impacted channels as they pass into the Bay. As such, the regional watershed model does not include tidal process-dominated areas such as tidal marshes. Interpretation of the lower edge of watersheds near where they meet the Bay is based on current land use and land cover, elevation, historical baylands extent (SFEI, 1998), and Operational Landscape Units of the Bay shore (SFEI Adaptation Atlas). Examples of low elevation areas that affect the mapping decisions are:

- Diked, often subsided lands, in Marin, Sonoma, Napa, and Solano Counties;
- Bay fill areas in and adjacent to the urbanized Central and South Bay;
- Restored and unrestored salt ponds around the Bay.

The final watershed segmentations are shown in Figure 5. The model has 237 subwatersheds, 138 of which have an area between 10 and 20 square miles (Figure 6). The mean and maximum subwatershed size are 13.3 and 29.8 square miles, respectively.

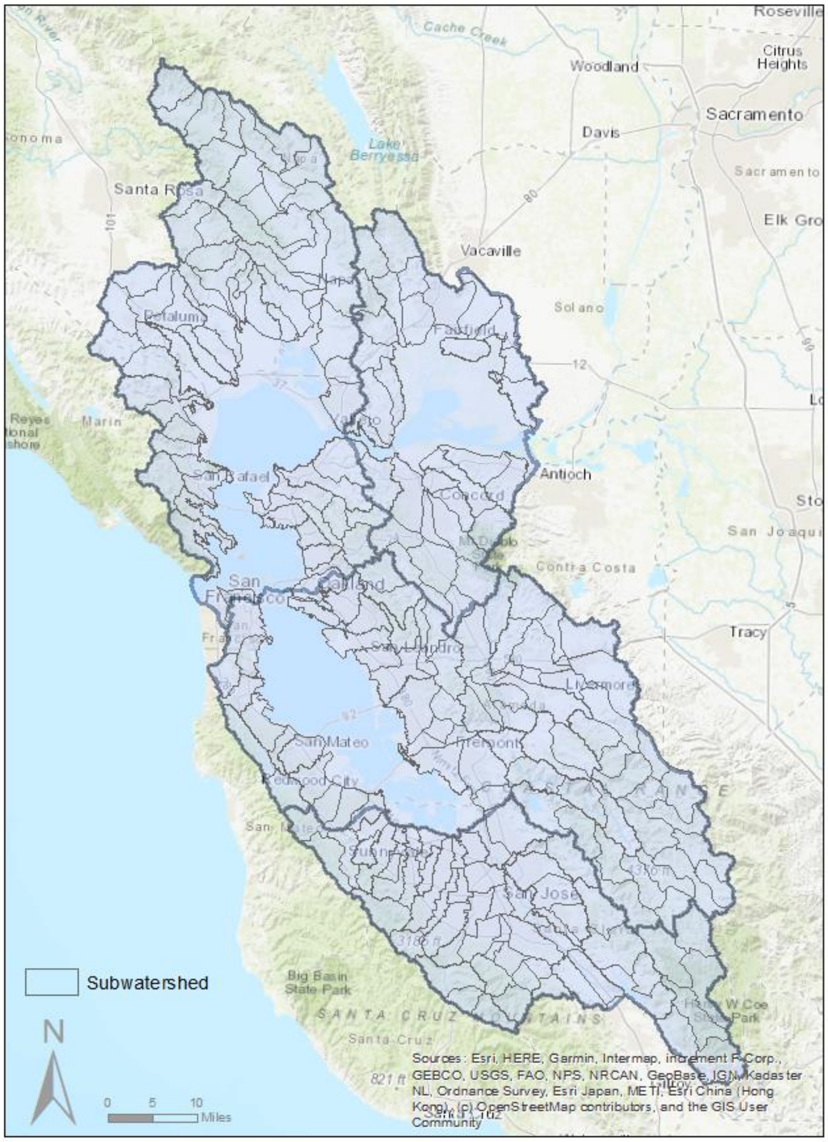

Figure 5. Watershed delineation; the dark blue lines identify the boundaries of the four HUC8 watersheds for the spatial domain of the regional watershed model.

Only the area that drains to the Bay was included in the modeling domain. Several subwatersheds were delineated within the combined sewer system region of the city of San Francisco. The flow and load from combined sewer systems can be post-processed after model runs. The flow and contaminant loads from combined sewers can be added as point sources.

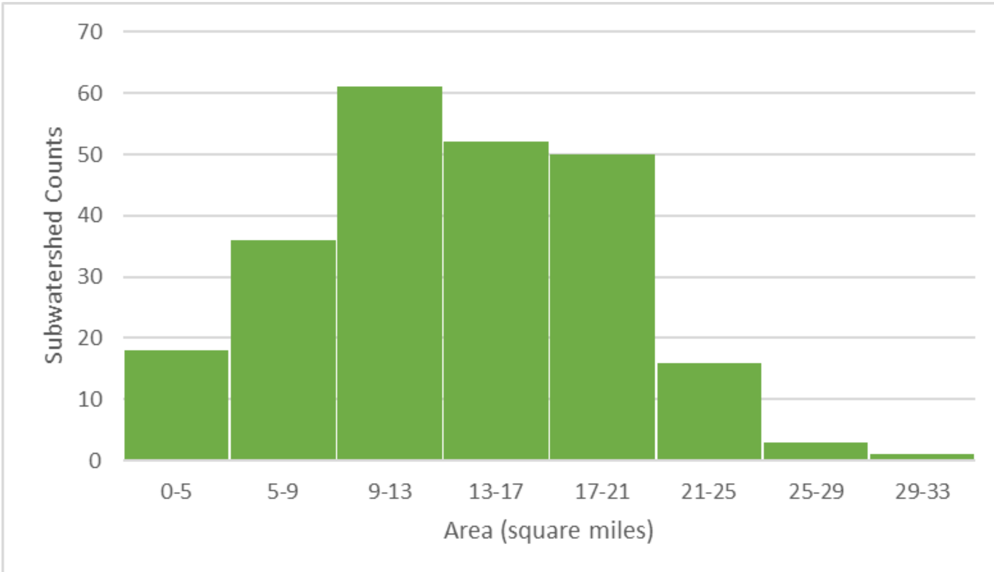

Figure 6. Histogram of subwatershed size.

3.2 Reach Characteristics and Network Development

The stream network is constructed to represent the major tributary streams and portions of stream reaches where significant changes in water quality occur. Each subwatershed is assigned one stream segment. Reaches and stream network development rely on several data sources, including the detailed BAARI Stream Network (SFEI, 2017), NHD & WBD, and Operational Landscape Units near the Bay shore (SFEI Adaptation Atlas). Most higher order streams (Strahler ≥ 4 in BAARI Streams) were included. Strahler ≥ 3 or Strahler ≥ 2 channels from BAARI Streams are added if the delineated subwatershed does not contain streams of higher orders. Only one stream segment can be assigned to a subwatershed in the LSPC model, thus the detailed stream network from BAARI is simplified. Simplifications are conducted with respect to a comprehensive planimetric map of the local drainage network. Simplification occurs where:

- tributary creeks having low elevation confluences with major rivers are simplified by modeling them draining to the Bay (e.g., Carneros Creek was routed to the Bay and the tidal portion of the lower Napa River is omitted);
- distributary and flood diversion channels (e.g., the connecting channel between the main channel of Alameda and the Old Alameda Creek watershed) are omitted;
- the main tributary is kept and other are omitted if multiple tributaries within one subwatershed all fed into a reservoir;
- two or three pour points/gauges are located close to each other were grouped into one.

Where delineated subwatersheds contain neither a digitized stream nor storm pipes, hypothetical drainage lines are developed based on the drainage area, DEM elevation, and slope data to determine likely flow paths. The channel is not included in the stream network, but the drainage area is retained and runoff from the drainage area is routed to the adjacent stream.

Figure 7 shows the simplified stream network of the Bay Area. Length and slope data for natural reaches are estimated using the USGS National Elevation Dataset DEMs (10 m) and digitized reach lengths. Artificial channels with cross-section and other design data (channels in Zone 7 water district, the city of Sunnyvale) are input into the LSPC model directly. Four different parameter sets are used to distinguish the different types of reach segments (natural fluvial, unnatural fluvial, natural tidal, unnatural tidal).

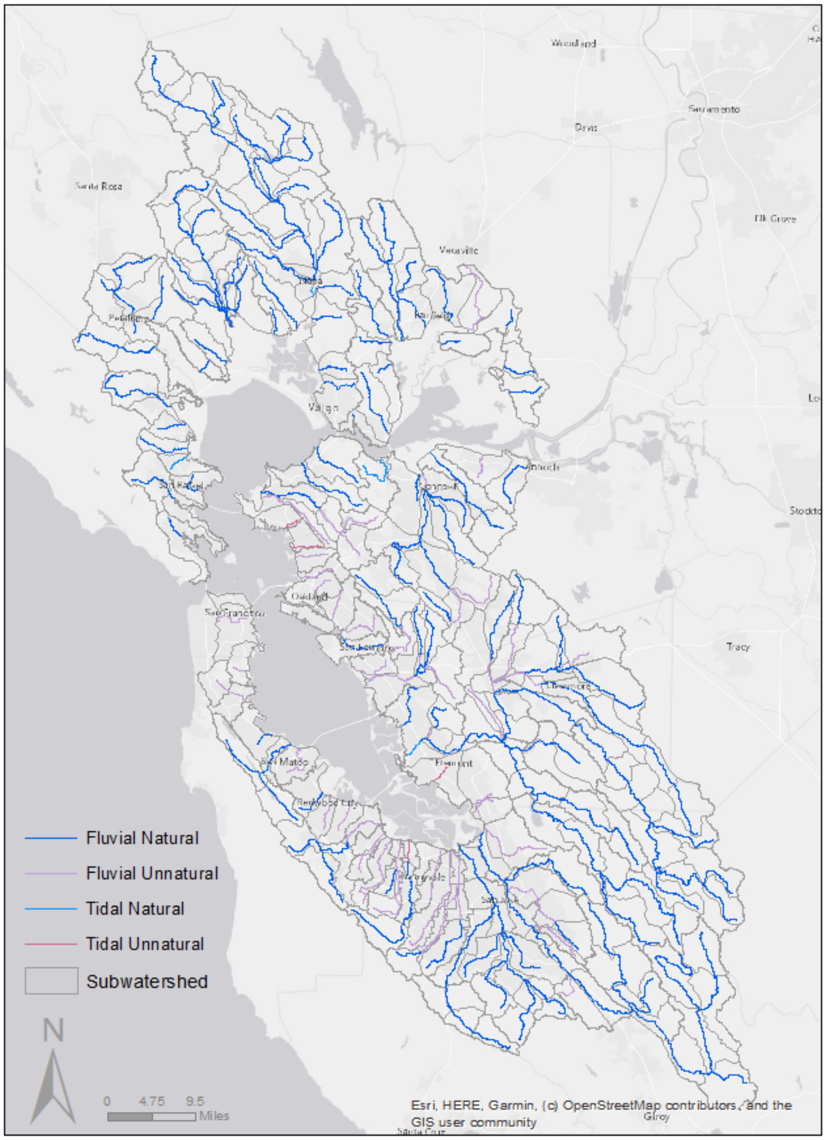

Figure 7. Stream network represented in the model.

3.3 HRU Development

The HRU is the basic modeling land unit, which combines land use/cover, soil type, slope, imperviousness, and other characteristics. Each HRU is a generalized representation of a specific type of source area within the sub-basin. The HRU approach allows incorporation of a high degree of detail into the model while also allowing for efficient simulation and relatively short model run times. The HRUs developed in the Bay regional watershed model account for land use/cover, soil type, imperviousness, slope, and geology.

3.3.1 Land Use and Land Cover

Land use and land cover are important input data for watershed models as they represent key characteristics of a watershed. Due to the rapid urbanization process in the Bay Area, land use and land cover has evolved and continue to evolve. One of the goals of the Bay Area regional watershed model is to estimate the loadings changes on a temporal scale. Year 2002 is considered as a baseline year for the PCBs and Hg TMDLs. Two sources of land use data are available for the region around the baseline year—the USGS National Land Cover Database (NLCD, Vogelmann et al., 2001) and ABAG (2005). NLCD includes land use and percent impervious surface, is in 30-meter resolution, and is updated every five years. In contrast, the ABAG land use layer was developed in 2005 (from 2-4-year-old data) and has not been updated since. While NLCD has a distinct advantage of continuous updates to land use over time, it does not have the urban land use classification that is important to simulate legacy PCBs and Hg, both closely associated with industrial land use. A hybrid approach was used to develop the land use and land-cover layer—ABAG for urban land using reclassification and grouping, and NLCD for open and rural area land cover and imperviousness. ABAG 2005 and NLCD 2006 (Xian et al., 2009) datasets were used to develop the HRU classification to reflect the land use and land cover around 2002. The transportation land use in the ABAG dataset includes multiple transportation related land-use types, such as roads, railways, airports, and harbors. The 'Old' (breaking at 1968 for Industrial and 1974 for the other three LUs) and 'New' urban land uses were initially developed by SFEI's previous RWSM work for the PCBs model. It was based on the overlay of a historic urban layer developed by USGS with ABAG urban classes. Details can be found in the project report of PCBs in caulk (BASMAA, 2017; Klosterhaus et al., 2011). The pollutant-loading characteristics and control measures applied to major roads are different for other transportation and uses. NLCD included an imperviousness descriptor layer (Homer et al., 2020; Dewitz, 2019) that was used to identify primary and secondary roads of the Bay Area. The impervious descriptor layer defines which impervious layer pixels are roads. The impervious descriptor information is generated from NAVSTREETS™-derived roads, urban areas, and energy production sites. The primary and secondary roads identified using NLCD developed imperviousness descriptor layer were subtracted from the transportation land use of the ABAG (2005) layer. The remaining transportation land use was classified as 'Other Transportation' in the model. Land-use and land-cover descriptions of the regional watershed model were compiled as shown in Table 3. The land use and land-cover classes can be further refined for future POC modeling.

Table 3. Land-use and land-cover class description and data sources.

LULC	Major Source	Comments
New Commercial	ABAG 2005	Urban land use class from ABAG
New Industrial	ABAG 2005	Urban land use class from ABAG
New Residential	ABAG 2005	Urban land use class from ABAG
Old Commercial	ABAG 2005	Urban land use class from ABAG
Old Industrial	ABAG 2005	Urban land use class from ABAG
Old Residential	ABAG 2005	Urban land use class from ABAG
Other Transportation	ABAG 2005	Parking lots, airports, railways, tertiary and thinned roads
Major Roads	NLCD IMP Descriptor	Primary and secondary roads
Water	NLCD 2006	
Agriculture	NLCD 2006	
Mixed Urban	NLCD 2006	Developed area that are not identified as ABAG urban land use
Barren	NLCD 2006	
Forest	NLCD 2006	
Grass	NLCD 2006	
Wetland	NLCD 2006	

Years 2000 to 2006 were used for the hydrologic calibration. Knowing there were issues with 2005 ABAG land use data (e.g., land use description does not match the exact land use in some regions), it might be possible to substitute improved data from the local stormwater programs where it is available. In addition, a 2018 data set is currently under development by ABAG/Bay Area MTC with additional funding and staff support from the RMP. More recent land use data, once developed, could be used to update the regional model with the same HRU classification.

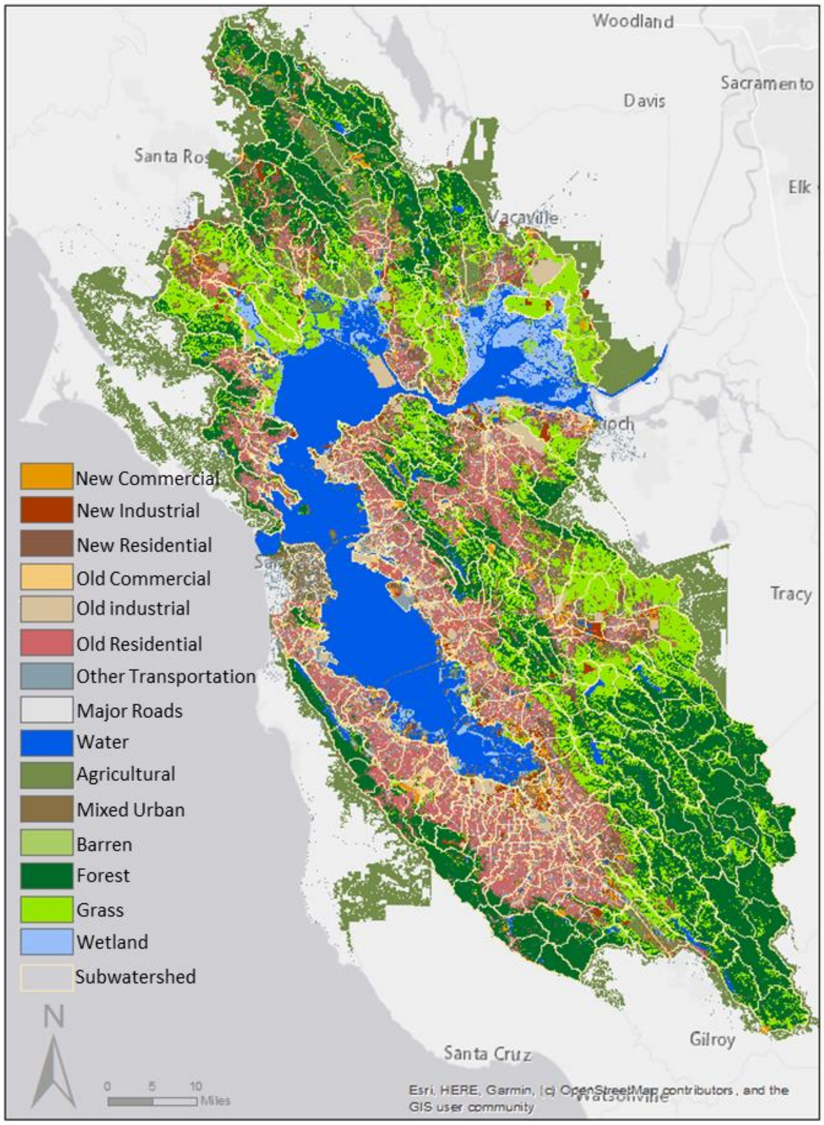

Figure 8. Land use and land cover in the Bay Area.

3.3.2 Soil Types

Different soil types have very different hydrologic and sediment-yield responses. In the regional watershed model, hydrologic soil groups (HSG) are used to characterize varied soil properties. Soil hydrologic groups of the Bay Area were obtained from the Soil Survey Geographic Database (SSURGO) and the State Soil Geographic Database (STATSGO). Soils were mainly grouped into four types of HSGs (A, B, C, D). Type A soil has the highest infiltration rate, whereas type D soil is more prone to generate surface runoff. Soil groups A/D, B/D, and C/D were grouped into D, given the shallow groundwater table in a large area of the modeling domain. Figure 9 shows the spatial distribution of different soil types of the Bay Area. Areas without SSURGO data were filled with the STATSGO soil classification. The area of type A soil is less than 1% of the Bay Area. In the regional watershed model, type A and type B soil are combined into one group, which brackets the range of infiltration rates for both A and B soils. Different types of soil can be assigned different erodibility rates, particle-size distributions, detachment coefficients and exponents, and other parameters related to soil erosion processes. The soil map spans both pervious and impervious surfaces. The imperviousness layer was overlain to estimate impervious surfaces (details in section 3.3.4).

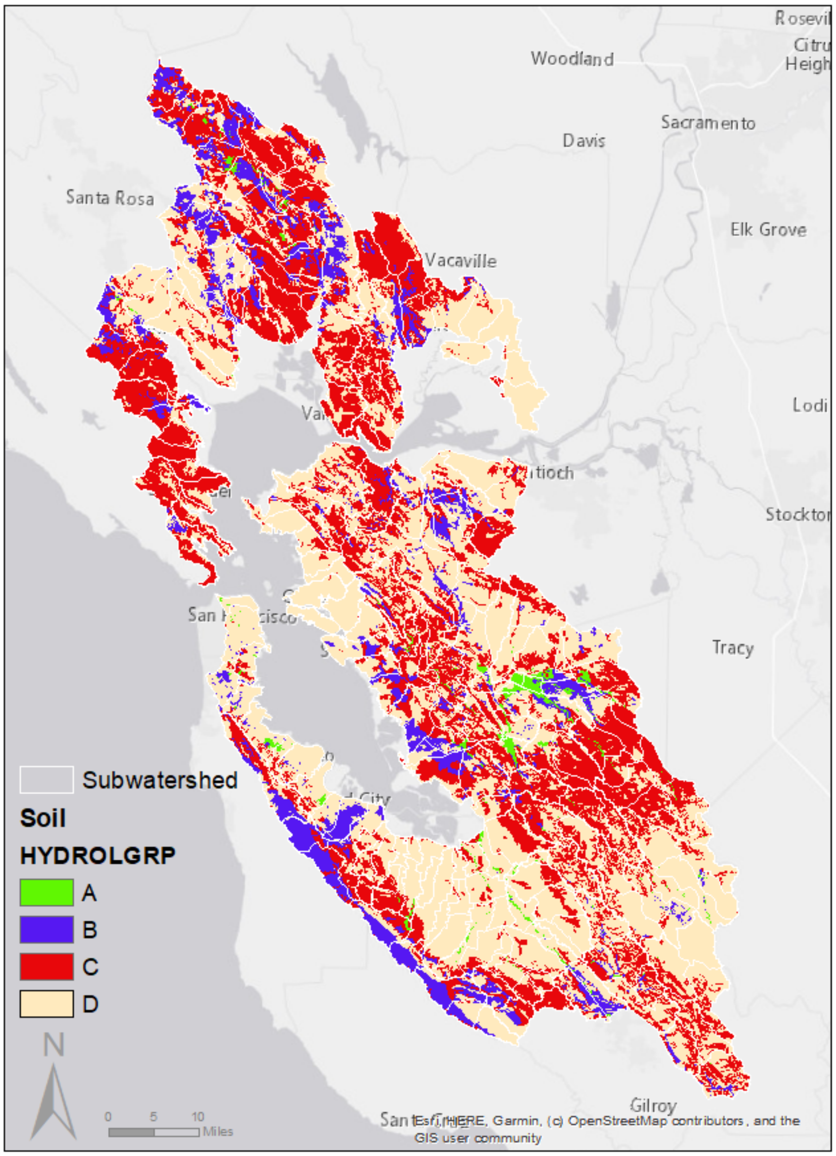

Figure 9. Spatial distribution of hydrologic soil groups.

3.3.3 Slope Class

Slope is also an important factor for HRU development. Slope influences runoff and moisture storage processes, as well as the soil erosion processes (erosion potential, slope stability, etc.). Percent slope was calculated from the 10-meter DEM from NED, and the slope values were classified as Low (< 5 percent), Medium (5-15 percent), and High (> 15 percent) based on the histogram of slopes for all 237 watersheds (5 percent slope is equivalent to 37 percentile, 15 percent slope is equivalent to 64 percentile). Figure 10 shows the spatial distribution of the three slope classes. The portions of area in Low, Medium, and High slope classes are 37%, 27%, and 36%, respectively.

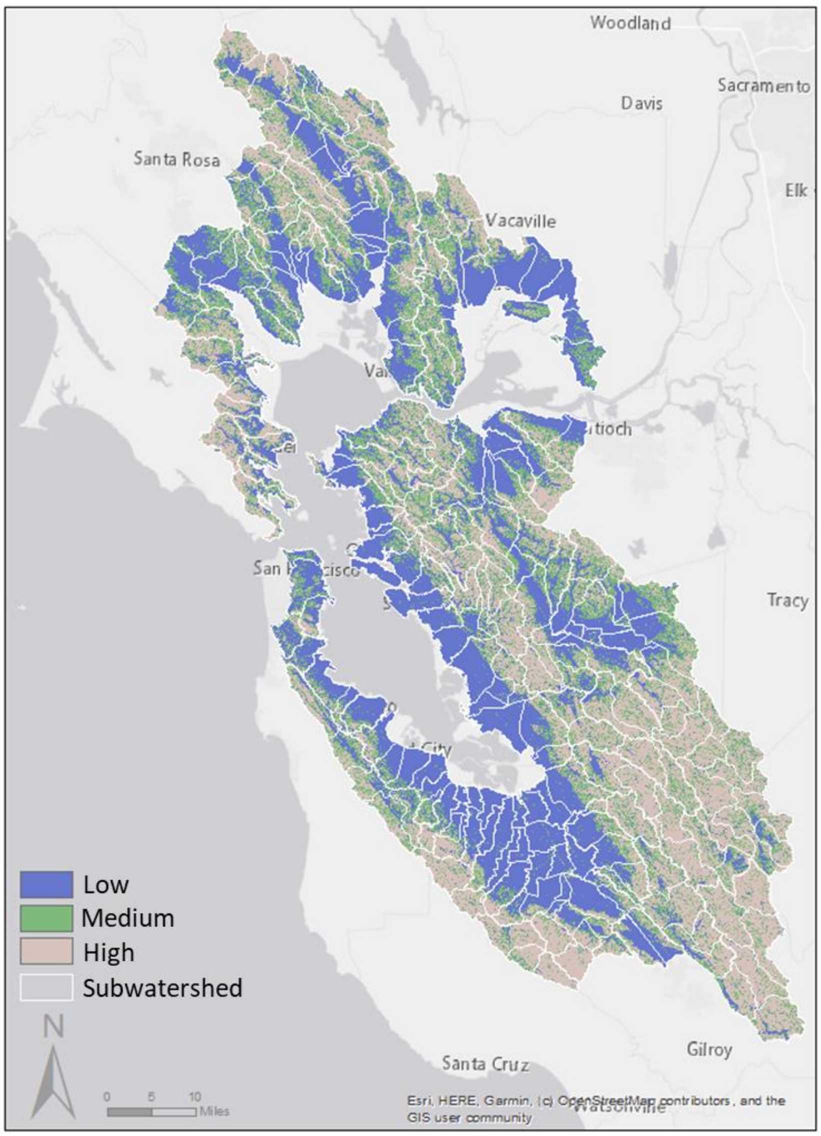

Figure 10. Slope classes of the Bay Area.

3.3.4 Impervious Area

The hydrologic processes on impervious and pervious surfaces are different. The rainfall-runoff, sediment and pollutant accumulation, and wash-off processes in the LSPC model are simulated in different modules for pervious and impervious surfaces. The NLCD provides 30-meter grid cells of percent impervious cover. The NLCD imperviousness percentage and area of land categories were multiplied to derive the total impervious area (TIA). Not all impervious surfaces are directly connected to streams. In less developed areas, runoff generated from impervious areas is usually routed to the surrounding pervious surface first before entering the stream. LSPC does not simulate the routing of runoff from different land areas within each subwatershed, thus the runoff generated on different land surfaces are lumped at the outfall of subwatershed and delivered to the stream. An estimate of effective impervious area (EIA), defined as the subset of the total impervious area (TIA) often hydrologically connected to stream networks via stormwater infrastructure, is required to better model the runoff volume and timing in the patches with high percentage of impervious surface (e.g., urban areas). Accurate estimation of EIA requires detailed local flow and impervious area measurements. Sultana (2020) derived a regional relationship between EIA and TIA for semi-arid regions of southern California based on flow data. However, the relationship between EIA and TIA derived from rainfall and flow data are regional specific and subject to change in different climate regions. Due to lack of detailed data support, the estimation of Directly Connected Impervious Area (DCIA) is considered as a surrogate for EIA. Sutherland's method (1995) is used to estimate DCIA:

$$DCIA = a * TIA^b \,, \qquad \text{Equation 8}$$

where a and b are parameters for varied land use and land cover.

Table **4** shows the different parameters used in this project. The area of DCIA calculated with Equation 8 is subtracted from the land category to represent the impervious portion of each specific land use. The remaining land-use portion represents the pervious portion.

Table 4. Parameters of Sutherland equation on different land use.

Land Use	a	b
Commercial	0.1	1.5
Industrial	0.1	1.5
Residential	0.4	1.2
Transportation	0.1	1.5
Mixed Urban	0.4	1.2
Agriculture	0.01	2
Forest	0.01	2
Grass	0.01	2

3.3.5 Geology

Geologic features can have a large impact on hydrologic and sediment accumulation transport processes. Different geologic landscapes of the Bay Area produce different amounts of sediment. In general, there are five main geologic types in the Bay Area: Franciscan Formation, Mesozoic-Tertiary sedimentary, Great Valley, Sonoma Volcanics and Quaternary deposits. The Sonoma Volcanics and Quaternary deposits have the lowest erosion potential and therefore were grouped together. The subwatersheds in the Bay Area contain four major geologic types (Figure 11). The geologic type with the maximum area within a subwatershed boundary was assigned to that subwatershed. Most of the subwatersheds have one dominant geologic type. A geologic type is considered as a dominant geologic type if the area of that geologic type within a subwatershed is larger than 50% of the total area. Approximately 80% subwatersheds have a dominant geologic type occupying larger than 50% of its area. The varied geologic features were represented as four different parameter groups in the regional watershed model. Each geologic type has its own specific parameter group. All HRUs were subject to geologic types and can be calibrated differently to account for the geology controls across the landscapes.

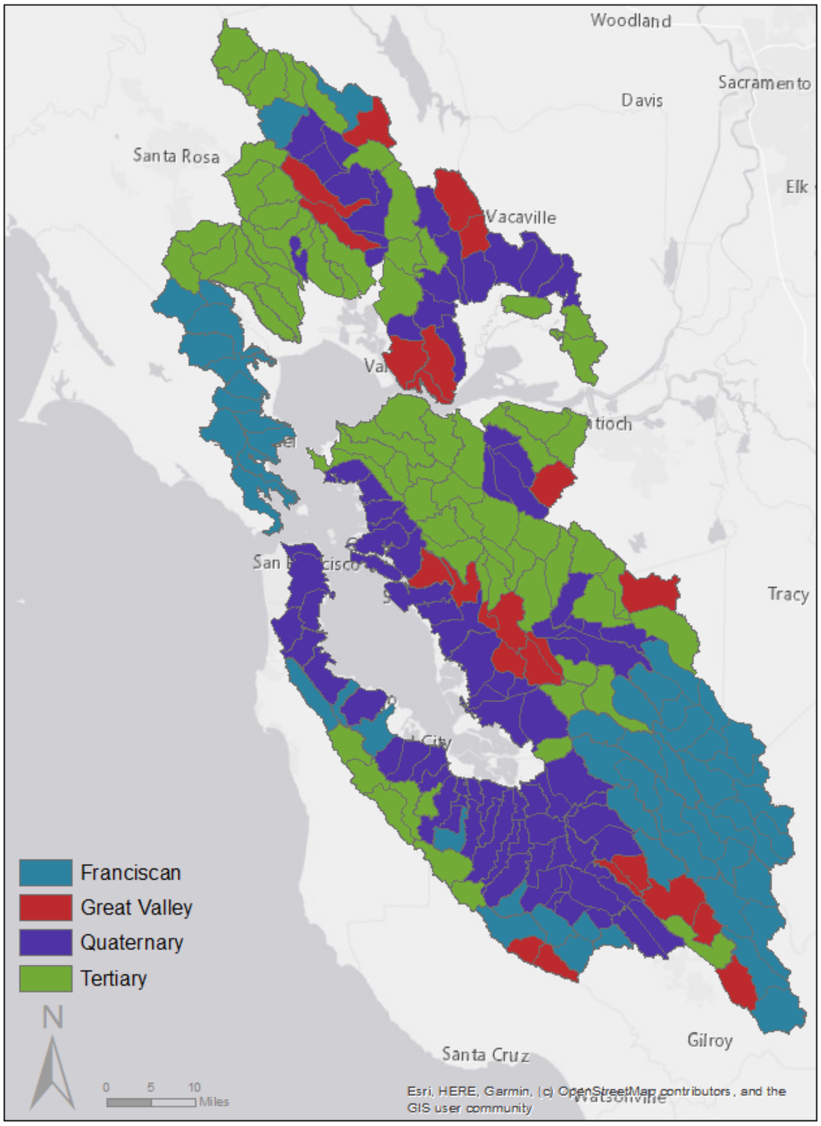

Figure 11. Major geologic features of each subwatershed.

3.3.6 Model HRUs

Land use, land cover, soil, and slope layers were overlain to generate HRU categories. The DCIA was calculated for each HRU category and then used to divide HRU categories into pervious and impervious portions. To reduce model complexity, some small HRUs (less than 0.1% of the total area) were consolidated with other HRUs. For instance, barren land use was lumped into grass land use and wetland was lumped into water. After consolidation, a total of 54 HRUs were developed to represent the landscape of the Bay Area. For different geologic types, the HRU category remains the same but specific parameters could be adjusted based on the geologic characteristics.

Final model HRUs are shown in Table 5, along with general groupings used for mapping and summary purposes. Some HRU placeholders (e.g., construction sites, GSI treated area, control measures) were also created to leave some flexibility for future modeling tasks.

Table 5. HRUs descriptions of the regional watershed model.

HRU ID	HRU Names	Land Use	HSG	Slope	Imperviousness	Area (ac)	Area %
1	Agri_AB	Agriculture	A/B	Low	Pervious	18,636	0.9%
2	Agri_C	Agriculture	C	Low	Pervious	28,456	1.4%
3	Agri_D	Agriculture	D	Low	Pervious	15,391	0.8%
4	GrassBarren_AB	Grass, Barren	A/B	Medium	Pervious	25,964	1.3%
5	H_Forest_AB	Forest	A/B	High	Pervious	40,541	2.0%
6	H_Forest_C	Forest	C	High	Pervious	236,796	11.7%
7	H_Forest_D	Forest	D	High	Pervious	214,338	10.6%
8	H_GrassBarren_C	Grass, Barren	C	High	Pervious	66,367	3.3%
9	H_GrassBarren_D	Grass, Barren	D	High	Pervious	66,526	3.3%
10	L_Forest_AB	Forest	A/B	Low	Pervious	4,874	0.2%
11	L_Forest_C	Forest	C	Low	Pervious	9,330	0.5%
12	L_Forest_D	Forest	D	Low	Pervious	10,392	0.5%
13	L_GrassBarren_C	Grass, Barren	C	Low	Pervious	34,008	1.7%
14	L_GrassBarren_D	Grass, Barren	D	Low	Pervious	65,541	3.2%
15	M_Forest_AB	Forest	A/B	Medium	Pervious	19,125	0.9%
16	M_Forest_C	Forest	C	Medium	Pervious	79,324	3.9%
17	M_Forest_D	Forest	D	Medium	Pervious	73,455	3.6%
18	M_GrassBarren_C	Grass, Barren	C	Medium	Pervious	85,423	4.2%
19	M_GrassBarren_D	Grass, Barren	D	Medium	Pervious	103,846	5.1%
20	MajorRoads	Major Roads	-	Low	Pervious	37,891	1.9%
21	MixedUrban_AB	Mixed Urban	A/B	Low	Pervious	18,940	0.9%
22	MixedUrban_C	Mixed Urban	C	Low	Pervious	39,382	1.9%
23	MixedUrban_D	Mixed Urban	D	Low	Pervious	63,825	3.2%
24	NewCommercial_AB	New Commercial	A/B	Low	Pervious	4,090	0.2%
25	NewCommercial_C	New Commercial	C	Low	Pervious	8,680	0.4%
26	NewCommercial_D	New Commercial	D	Low	Pervious	14,801	0.7%
27	NewIndustrial_AB	New Industrial	A/B	Low	Pervious	4,843	0.2%
28	NewIndustrial_C	New Industrial	C	Low	Pervious	6,981	0.3%
29	NewIndustrial_D	New Industrial	D	Low	Pervious	19,012	0.9%
30	NewResidential_AB	New Residential	A/B	Low	Pervious	18,274	0.9%
31	NewResidential_C	New Residential	C	Low	Pervious	35,076	1.7%
32	NewResidential_D	New Residential	D	Low	Pervious	46,595	2.3%
33	OldCommercial_AB	Old Commercial	A/B	Low	Pervious	7,408	0.4%
34	OldCommercial_C	Old Commercial	C	Low	Pervious	11,526	0.6%
35	OldCommercial_D	Old Commercial	D	Low	Pervious	41,131	2.0%

HRU ID	HRU Names	Land Use	HSG	Slope	Imperviousness	Area (ac)	Area %
36	OldIndustrial_AB	Old Industrial	A/B	Low	Pervious	2,974	0.1%
37	OldIndustrial_C	Old Industrial	C	Low	Pervious	8,568	0.4%
38	OldIndustrial_D	Old Industrial	D	Low	Pervious	38,474	1.9%
39	OldResidential_AB	Old Residential	A/B	Low	Pervious	29,643	1.5%
40	OldResidential_C	Old Residential	C	Low	Pervious	50,474	2.5%
41	OldResidential_D	Old Residential	D	Low	Pervious	127,461	6.3%
42	OtherTransportation_AB	Other Transportation	A/B	Low	Pervious	10,555	0.5%
43	OtherTransportation_C	Other Transportation	C	Low	Pervious	22,767	1.1%
44	OtherTransportation_D	Other Transportation	D	Low	Pervious	65,031	3.2%
45	Water	Water, Wetland	-	-	-	26,664	1.3%
46	MajorRoads_IMP	Major Roads	-	Low	Impervious	2,048	0.1%
47	MixedUrban_IMP	Mixed Urban	-	Low	Impervious	10,802	0.5%
48	NewCommercial_IMP	New Commercial	-	Low	Impervious	820	0.0%
49	NewIndustrial_IMP	New Industrial	-	Low	Impervious	1,074	0.1%
50	NewResidential_IMP	New Residential	-	Low	Impervious	7,289	0.4%
51	OldCommercial_IMP	Old Commercial	-	Low	Impervious	2,890	0.1%
52	OldIndustrial_IMP	Old Industrial	-	Low	Impervious	2,348	0.1%
53	OldResidential_IMP	Old Residential	-	Low	Impervious	32,378	1.6%
54	OtherTransportation_IMP	Other Transportation	-	Low	Impervious	3,658	0.2%

3.4 Meteorological Data

Meteorological data are a critical input that drive both simulated hydrology and the water-quality responses. Models require appropriate representation of weather data constituents such as precipitation, potential evapotranspiration (PET), temperature, dew point temperature, wind speed, cloud cover, and solar radiation. The preparation of meteorological time series was an important part of model development.

3.4.1 Precipitation

Precipitation is the most important meteorological forcing data for hydrologic simulation. In general, hourly precipitation (or finer resolution) data are recommended and preferred for hydrologic modeling because the lengths of local storm events are mostly less than a day. The Bay Area has large spatial variation in annual precipitation totals, ranging from 313 mm/year at the East and South Bay to more than 1700 mm/year in the coastal mountainous region and the heads of Sonoma and Napa Valleys (Figure 12). Due to the spatial variation of rainfall, increasing the spatial representation of rainfall time series in the model can help with better representing overall precipitation totals and timing.

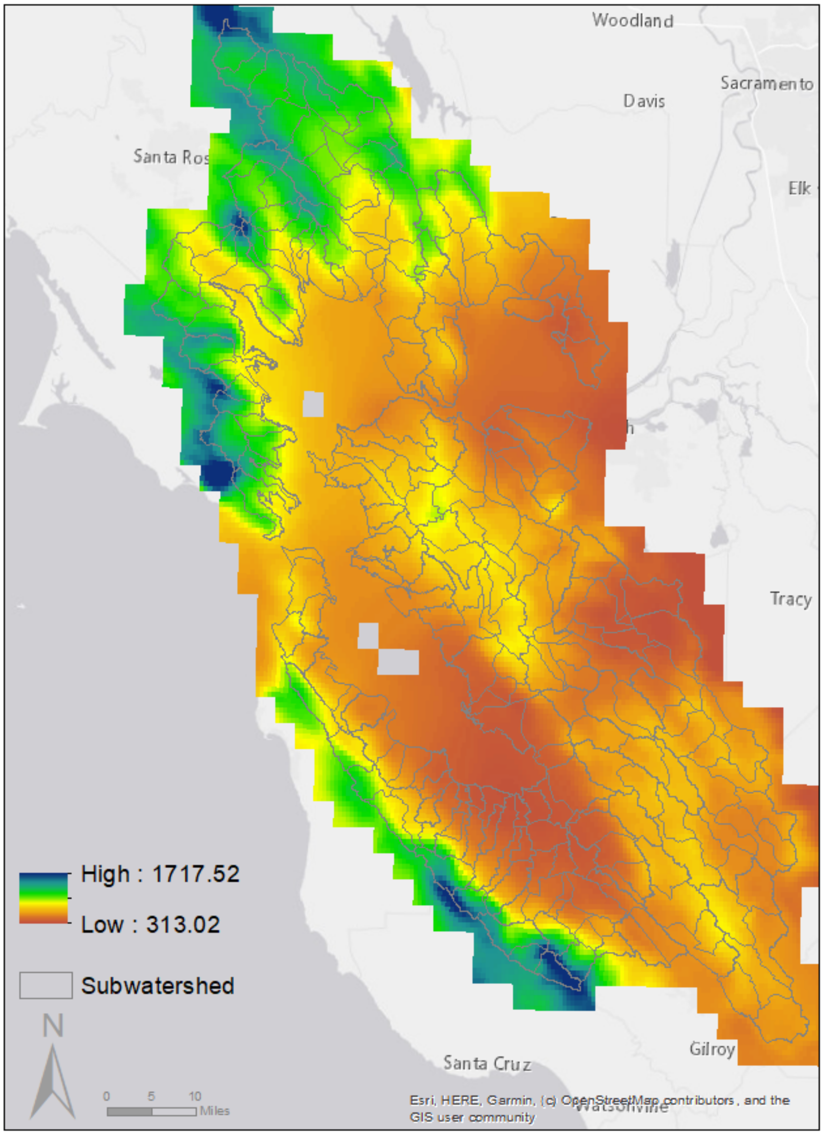

Figure 12. Thirty years (1981-2010) of average annual rainfall (mm) map (data source: PRISM 800-meter rainfall map).

Types of rainfall data sources commonly used to drive hydrologic models include gridded- and point-based data from rain gauges (Figure 13). An inventory of the precipitation data sources available in the Bay Area is presented in Table 6. Rainfall data from national and local monitoring networks were gathered. National Climatic Data Center (NCDC) sources include the daily Global Historical Climate Network (GHCND), hourly precipitation data (HPD), and integrated surface data (ISD). Local rainfall monitoring systems include California Irrigation Management Information System (CIMIS) and Santa Clara Valley Water District (SCVWD) alert system. Gridded weather data sources include PRISM (Parameter-elevation Relationships on Independent Slopes Model) climate data, Daymet version 3 daily data, and North American Land Data Assimilation System Version 2 (NLDAS-2) forcing data.

Point-based precipitation time-series data were processed for the rain gauges that are located within the modeling domain. One drawback of the rain gauge data is that even relatively good quality data contains missing records. Figure 14 shows the missing record percentage of rainfall data from 1999 to 2019 from 79 rain gauges in our region. Only 43 rain gauges have less than 20% missing data. In general, GHCND data have the smallest data gaps; however, rainfall was recorded daily. Rain gauges with higher frequency data have larger data gaps. The average percentage of missing data is 36% for rain gauges with hourly or finer temporal resolution records. Large amounts of missing data result in coarse spatial resolution of point-based rainfall time series and increasing uncertainties of the accuracy of rainfall brought about by filling of data gaps.

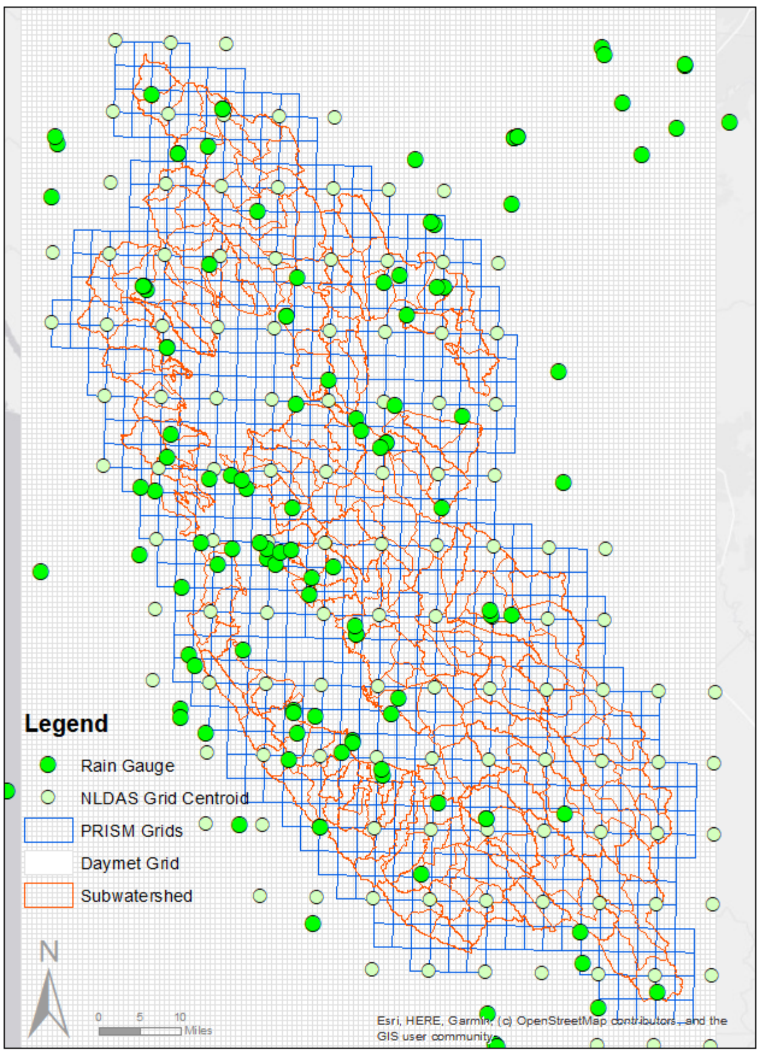

Figure 13. Locations and footprints of different rainfall data sources.

Table 6. The inventory of precipitation data sources of the Bay Area.

Rainfall Data	Data Type	Data Portal	Frequency	Spatial Resolution	Reference
HPD	Point	https://www.ncdc.noaa.gov/IPS/hpd/hpd.html	15 min	Point	(Hammer and Steurer, 1998)
ISD	Point	https://www.ncdc.noaa.gov/isd	Hourly	Point	(Smith et al., 2011)
CIMIS	Point	https://cimis.water.ca.gov/	Hourly	Point	(Craddock, 1990)
SCVWD	Point	https://www.valleywater.org/your-water/alert-system-real-time-data	Hourly	Point	-
GHCND	Point	https://www.ncdc.noaa.gov/ghcnd-data-access	Daily	Point	(Vose et al., 1992)
NLDAS-2	Gridded	https://ldas.gsfc.nasa.gov/nldas/nldas-2-forcing-data	Hourly	~12.5km*12.5 km	(Xia et al., 2012)
PRISM	Gridded	http://www.prism.oregonstate.edu/	Daily	4km*4km	(Daly and Bryant, 2013)
Daymet-v3	Gridded	https://daymet.ornl.gov/	Daily	1km*1km	(Thornton et al., 2016)
NEXRAD QPE/MRMS	Gridded	https://www.nssl.noaa.gov/projects/mrms/	Hourly	1km*1km	(Zhang et al., 2016)

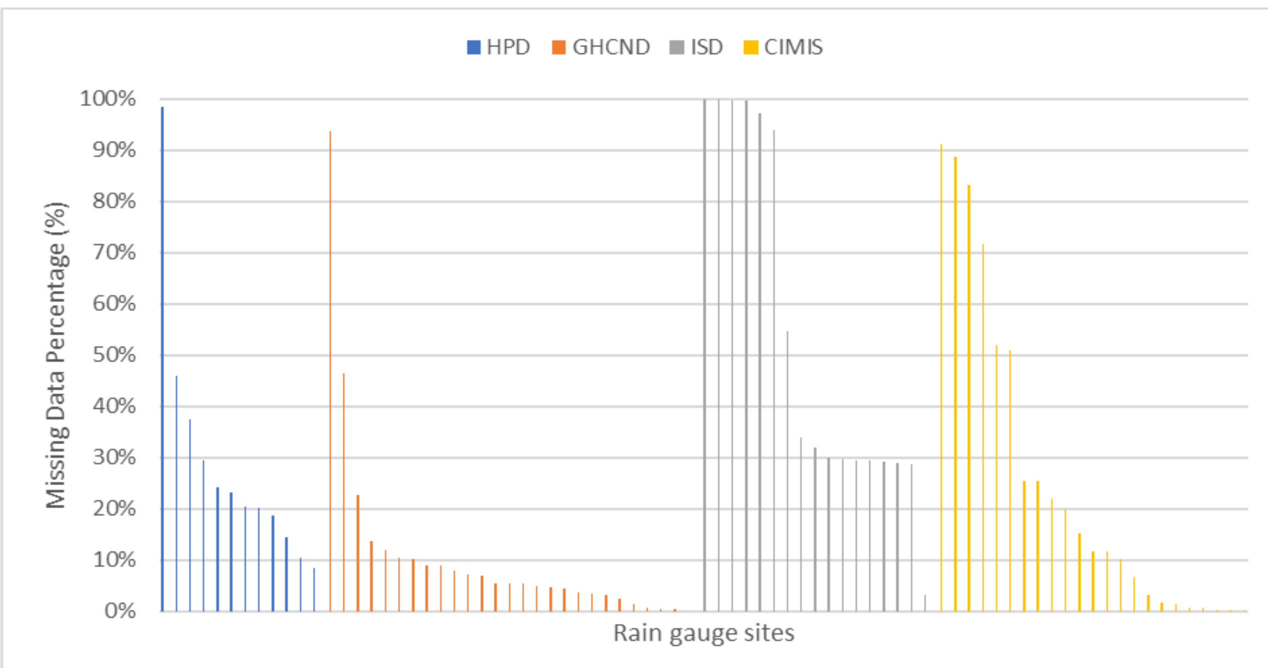

Figure 14. Amount of missing data from 79 rain gauges (1999-2019). Sites without missing data were included.

Gridded weather products can be used to provide high spatial resolution and continuous rainfall time series. In this project, three different types of gridded rainfall data were used with different purposes.

Daymet version 3 data provides daily precipitation of the continental United States (CONUS) starting from 1980 with a 1 km x 1 km spatial resolution. Its interpolation algorithm is based on the spatial convolution of a truncated Gaussian filter and a set of location stations (Thornton et al., 1997). In the Daymet algorithm, spatially and temporally explicit empirical analyses of the relationships of temperature and precipitation to elevation are performed. In addition, a daily precipitation occurrence algorithm is introduced as a precursor to the prediction of daily precipitation amount.

PRISM climate data is another source of gridded daily rainfall. PRISM provides daily rainfall for 1981 to 2019 with a 4 km x 4 km spatial resolution. It applies a climate-elevation regression function and station-based precipitation data for the interpolation of rainfall at each grid cell. Though the spatial resolution is coarser than Daymet, it has shown a better spatial precipitation representation than other gridded based rainfall data due to a denser station data set (approximate 13,000 stations are included), especially in mountainous and coastal areas of the western United States, characterized by large elevation gradients, rain shadows, and coastal effects (Daly et al., 2008). PRISM climate group also provides an 800-meter resolution 30-year average annual rainfall data for the CONUS (Figure 12).

A third gridded product is the North American Land Data Assimilation System (NLDAS-2) meteorological time series. NLDAS-2 provides continuous hourly data from 1979 to present on a 1/8-degree grid (~12.5 km x 12.5 km). The hourly precipitation data in NLDAS-2 are disaggregated from daily gauge and PRISM precipitation with Doppler radar and satellite precipitation products. NLDAS-2 also provides hourly temperature, humidity, wind speed, solar radiation, air pressure, and potential evapotranspiration.

Quantitative precipitation estimate (QPE) product derived from weather radar are also available as another gridded source. The most recent version of the radar based precipitation product is Multi-Radar/Multi-Sensor System (MRMS) which provides hourly precipitation estimate at 1 km x 1 km spatial resolution. However, the earliest QPE data starts in early 2000 (after 2002), which cannot cover the temporal range of this modeling analysis.

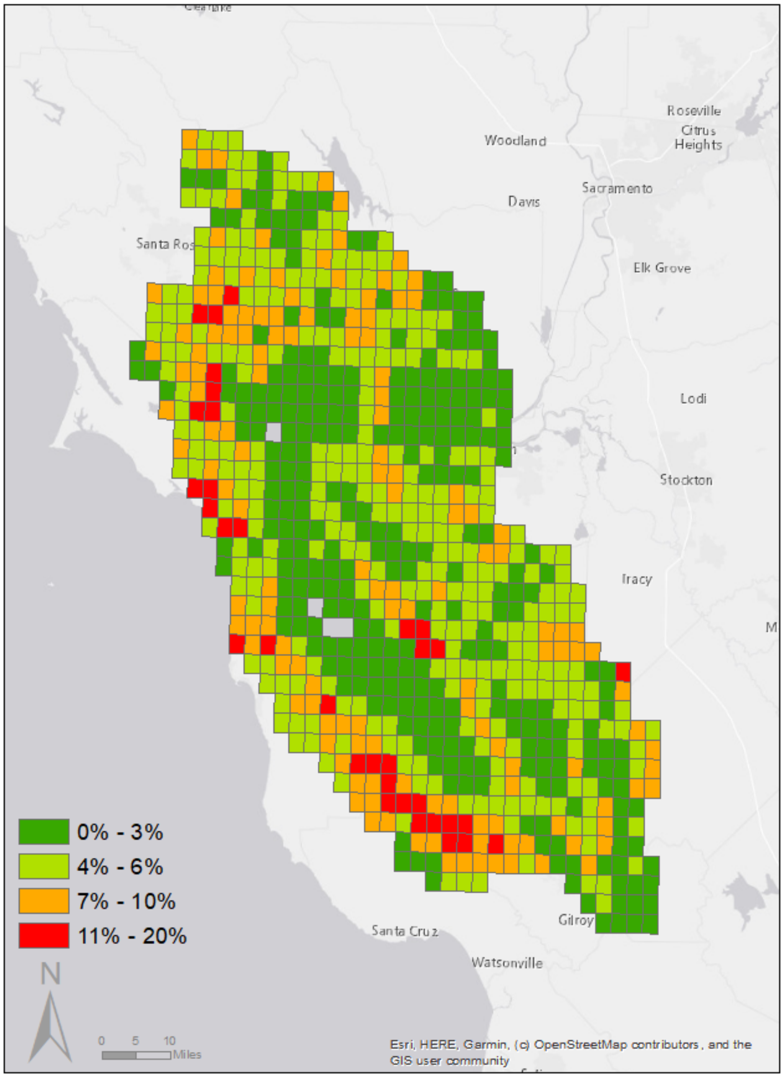

Figure 15. The coefficient of variation of PRISM 800-meter resolution 30 year (1981-2010) annual average data at each 4 km x 4 km grid cell.

All three grid-based precipitation data products rely on the weather station data collected by the NCDC. Local rainfall monitoring networks (e.g., CIMIS, SCVWD) were not used as reference data for any of the three grid-based data products. The PRISM 4-km daily rainfall product is considered the gridded rainfall product with high spatial resolution and best rainfall spatial distribution. To investigate the rainfall spatial variation within the 4 km x 4 km grid, the PRISM 800-meter resolution, 30-year average annual rainfall (1981-2010) was compared to the PRISM 4-km daily data. The 30-year average annual rainfall was calculated at each 4-km grid for 1981 to 2010 from daily rainfall time series. The coefficient of variation of the 30 year average rainfall from 25 PRISM 800-m grids within each 4-km x 4-km grid was calculated (Figure 15). In the mountainous region, a coefficient of variation larger than 10% within a single 4-km x 4-km grid is common. The absolute differences in annual rainfall between rainfall data sources with different spatial resolution are shown in Figure 16. The 30-year average rainfall was summarized from PRISM 800-meter grids to the 4-km grids and compared to the 30-year average rainfall value calculated from daily time series of corresponding 4-km grids. The differences of the 30-year average annual rainfall indicate the 4-km resolution rainfall data have lower annual rainfall values in the northwest and west coastal regions of the Bay relative to the average rainfall value derived from 800-meter grids, while there are higher annual rainfall values in the south and southeast regions of the Bay. The differences of annual rainfall can be as large as 129 mm for a single 4-km grid between data with different spatial resolutions.

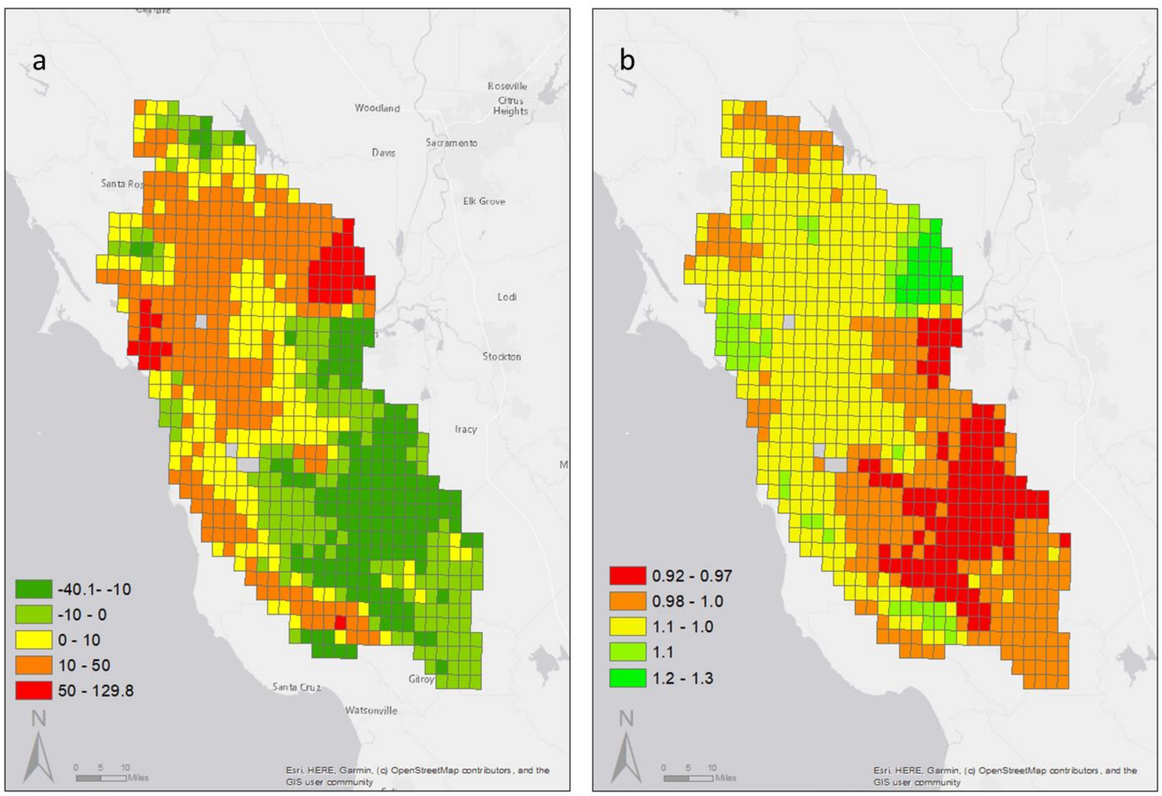

Figure 16. (a) The difference (PRISM 4 km - PRISM 800 m) and (b) the ratio between PRISM 4 km and PRISM 800 m data in mean annual rainfall of 1981-2020 (mm).

The spatial distribution of annual average rainfall (1999-2019) from different data sources were also compared at the subwatershed scale (Figure 17). The average annual rainfall at each subwatershed was calculated by averaging the rainfall amounts of all grids within the subwatershed for gridded based data sources (PRISM 4 km x 4 km, Daymet). The annual average rainfall from rain gauges were interpolated with an inverse distance weighting (IDW) method and then summarized at the subwatershed scale. The accuracy of average annual rainfall derived from rain gauge data depends on the density of rain gauges and the spatial variation of rainfall. As shown in Figure 17a, because there are few rain-gauge data available, the spatial interpolation based on only rain-gauge data is prone to large errors. Similarly, the Daymet data sources are mainly from the ground based Global Historical Climatology Network (GHCN)-

Daily dataset. The differences of average annual rainfall are larger in regions with less rain-gauge data available (Figure 17b). PRISM data is derived from national and multiple local rain-gauge networks, as well as the Radar stage 2 and 4 grids. The uncertainty of the precipitation spatial patterns can be reduced by merging multiple data sources. Previous research indicates that PRISM outperforms Daymet for the mountainous and coastal areas of the western United States (Daly et al., 2008).

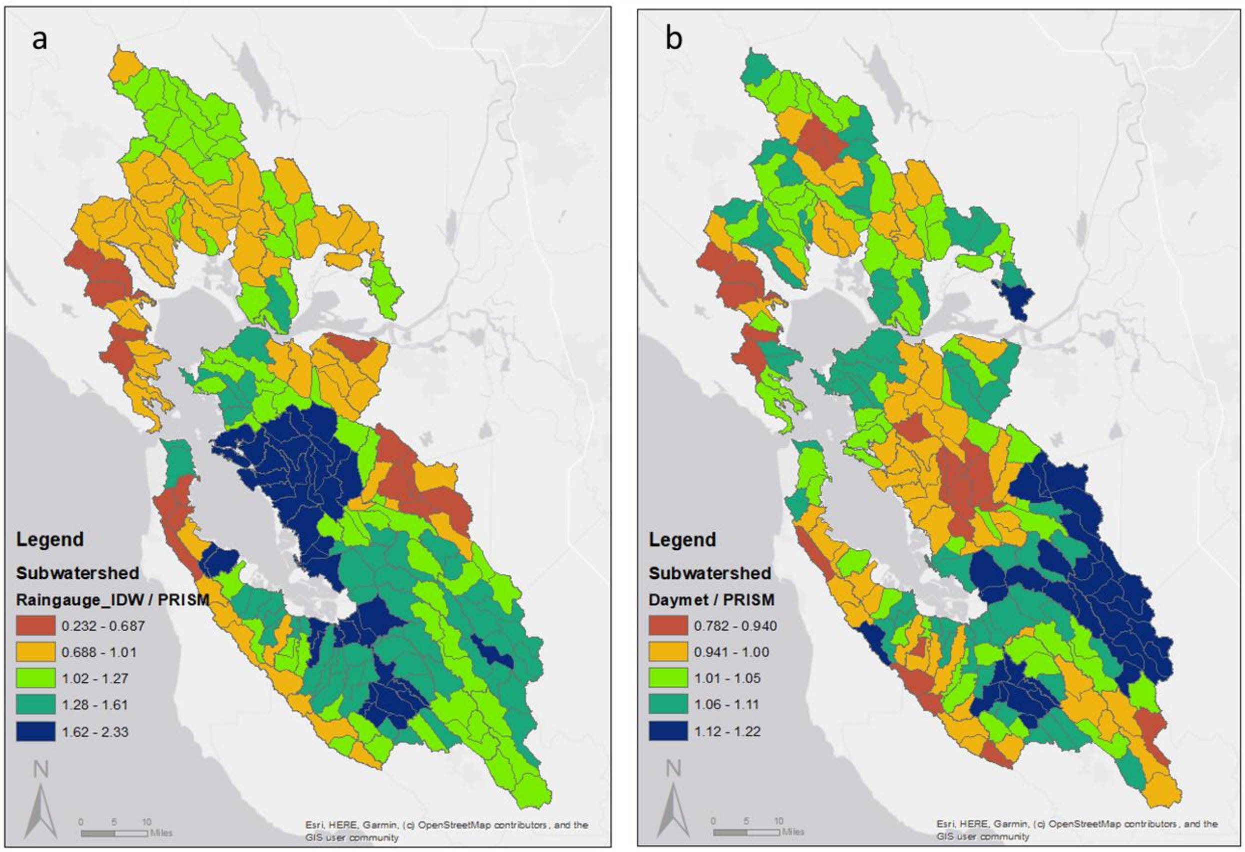

Figure 17. The ratio of average annual rainfall between (a) IDW interpolated rain gauge data and PRISM; (b) Daymet and PRISM.

To make the best use of all the available rainfall data, and to preserve the most detail of rainfall spatial variance, a mixed set of point-based and grid-based rainfall data is used to develop the rainfall forcing data to drive the LSPC model. In this project, PRISM data are used as the gridded rainfall data source and point-based rainfall data from national and local rain-gauge networks and NLDAS-2 rainfall data are used to bias-correct the PRISM rainfall data. Two major steps of rainfall data processing are shown in Figure 18. The first step is to conduct statistical bias correction of spatial daily rainfall data. A weighted IDW interpolation is used for the bias correction. From 1999 to 2019, 760 PRISM 4-km x 4-km grid rainfall time series within the modeling domain were downloaded and processed as the basis for bias correction. Daily precipitation time series from the same period were downloaded and summarized for rain gauges of different data sources that have less than 20% missing data and 117 NLDAS-2 12.5 km x

12.5 km grids. The daily rainfall time series from rain gauges and NLDAS are used to produce bias correction information.

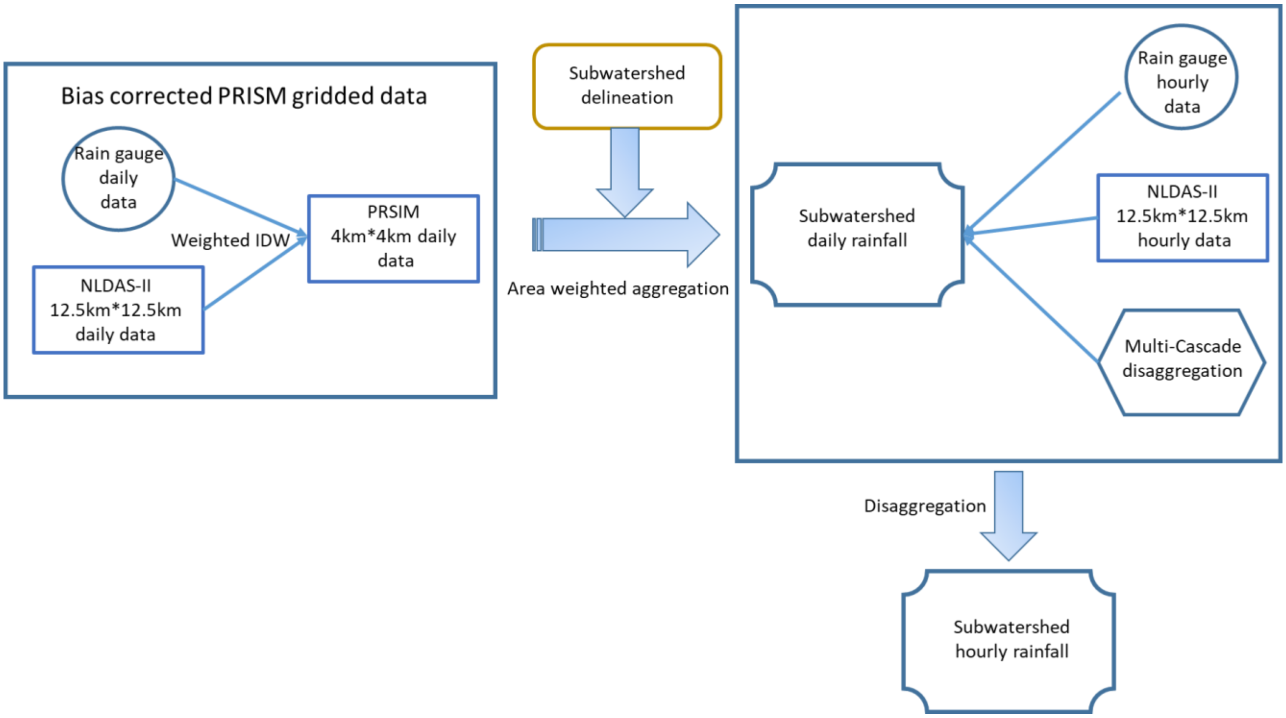

Figure 18. Rainfall data processing scheme.

For each PRISM grid, the six nearest reference points (rain gauges, NLDAS-2 grid centroids) are assigned as reference rainfall time series. The search radius is set to 10 miles to avoid over-correcting the PRISM data with rain records that are far from the location. The second order inverse distance weighting (IDW) method is applied to calculate the weight of each bias corrected value (Equation 9):

$$w_i(x) = \frac{1}{d(x,x_i)^2}, \qquad \text{Equation 9}$$

where w_i is the weight of ith bias corrected rainfall value, d is the distance between the centroid of Daymet grid (x) to the reference point (x_i).

The biased corrected value is then calculated as the weighted mean of the five values:

$$P_c(x) = \frac{\sum P_{ci}(x) * w_i}{\sum w_i}. \qquad \text{Equation 10}$$

Only reference points with positive rainfall values are used in the bias correction for each rainy day of PRISM data. After all daily rainfall time series of 760 PRISM grids are bias-corrected, the daily rainfall time series for 237 subwatersheds are generated based on the mean of PRISM grid data within subwatershed boundaries. Figure 19 shows the spatial distribution of correction ratio of each PRISM grid. The correction ratio is defined as the difference between the bias-corrected PRISM and the raw PRISM annual rainfall divided by the raw PRISM average annual rainfall. The PRISM grids near rain gauges have large correction ratios because of the heavier weights assigned to the rain-gauge data. This method can provide a more accurate rainfall estimate at locations near rain gauges and conserve the general spatial pattern of the PRISM dataset.

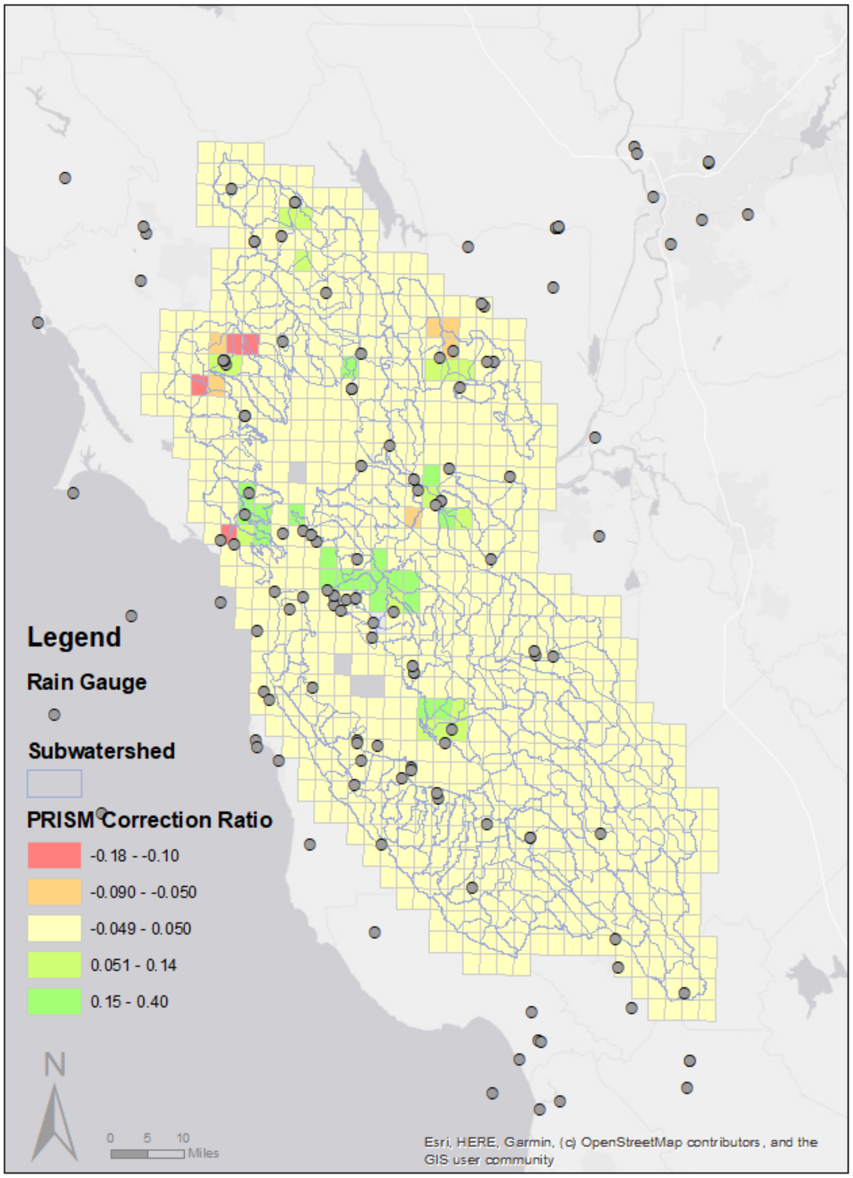

Figure 19. The spatial distribution of annual rainfall correction ratio of each PRISM grid (4 km x 4 km).

Daily precipitation records for each subwatershed are then disaggregated to an hourly time step. The hourly rainfall records from rain gauges and the rainfall records of 117 NLDAS-2 grids are used to disaggregate the daily rainfall. Similar to the daily bias correction step, a spatial analysis is completed to assign six nearest hourly precipitation time series from rain gauges and NLDAS grids to each subwatershed. For each rainy day of subwatershed rainfall data, sub-daily rainfall distributions are generated from the rain gauge or NLDAS-2 hourly data and the subwatershed rainfall daily data are disaggregated to an hourly time step according to the sub-daily precipitation patterns of the hourly data:

$$P_h(t) = P_d * \frac{P_{Rh}(t)}{P_{Rd}}, \qquad \text{Equation 11}$$

where P_h is the disaggregated hourly rainfall data at hour t, P_d is the daily rainfall of subwatershed, $P_{Rh}\, and\ P_{Rd}$ are hourly and daily rainfall of reference points. A threshold of 0.1 inch for daily rainfall is applied to the random cascade model. If daily rainfall is less than 0.1 inch, the daily rainfall is not disaggregated into hourly rainfall and the daily rainfall is assigned to the first hour of the day.

If there are hourly rainfall records of rain-gauge data, the nearest rai- gauge data is used for disaggregation. Otherwise, NLDAS-2 hourly data is used. If no hourly rainfall data are available from the six reference points, a multi-cascade rainfall disaggregation method proposed by Olsson (1998) is used to generate hourly rainfall records. The multi-cascade method is a probability-based disaggregation method. The disaggregation assumes a doubling of temporal resolution for each step. For each step, the time series of cascade level i is disaggregated to level i + 1 with twice the frequency. The procedure is applied successively until the desired temporal resolution is reached. It preserves mass, so that the precipitation total of the disaggregated time series is equal to the respective value of the original time series. The splitting weights are calculated based on the probabilities calculated with the nearest hourly data records of reference point:

$$W_1, W_2 = \begin{cases} 0\ and\ 1\ with\ probability\ P(0/1) \\ 1\ and\ 0\ with\ probability\ P(1/0) \\ x\ and\ 1-x\ with\ probability\ P\left(\frac{x}{1-x}\right);\ 0 < x < 1 \end{cases}, \qquad \text{Equation 12}$$

The disaggregation of daily data is applied for the following steps: 24h → 12h → 6h → 3h → 1.5h → 0.75h. The time series with a 45-minute time step are evenly distributed to the time series with a 15-minute time step and then aggregated to hourly data. A python library 'Melodist' is used to do the multi-cascade disaggregation (Förster et al., 2016). Based on these steps, hourly rainfall forcing data to drive the LSPC model was generated on 760 grids (4 km x 4 km) and summarized for all 237 subwatersheds for October 1999 to September 2019 (20 water years).

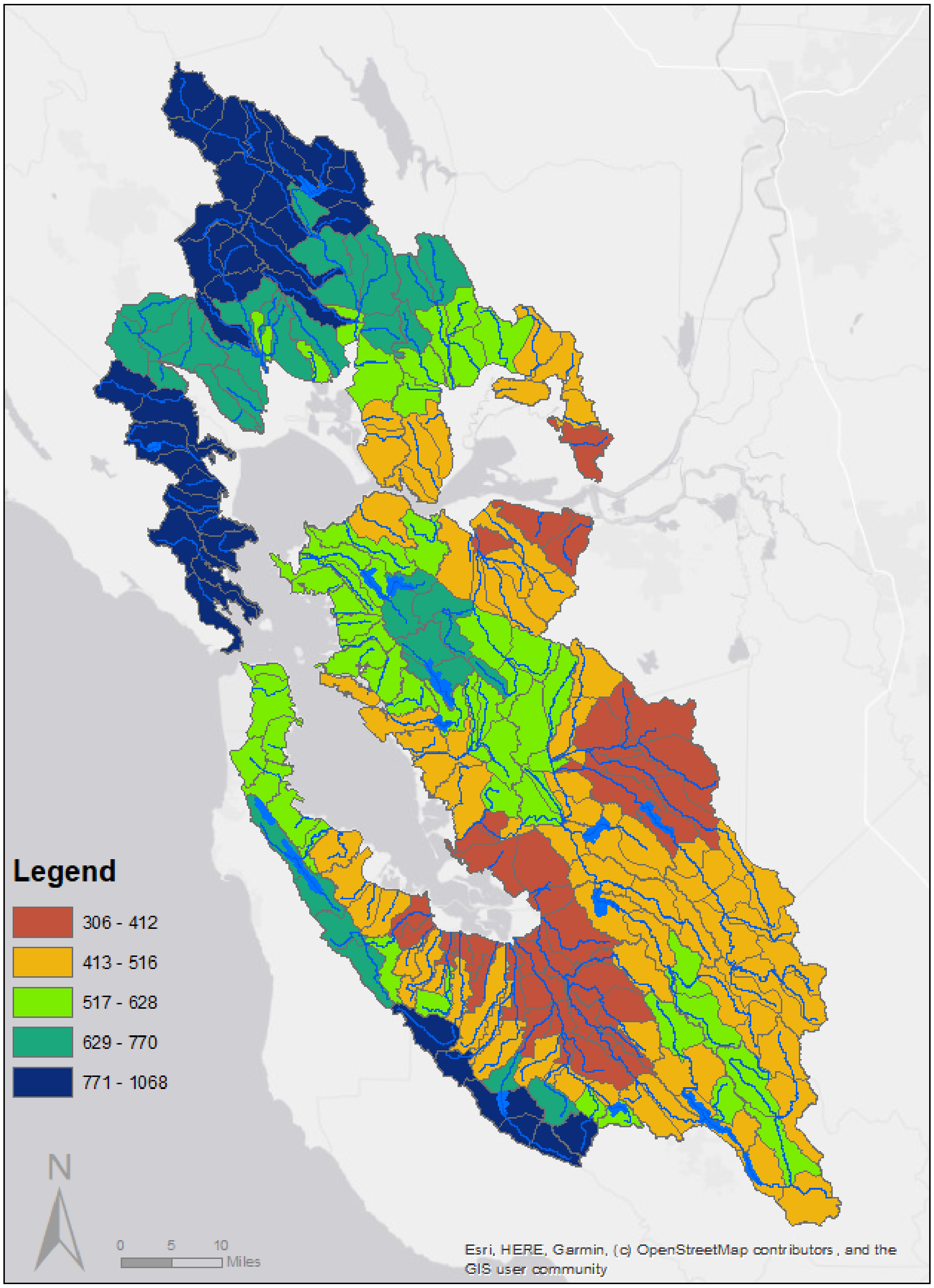

Figure 20. The annual average watershed rainfall (mm) map derived from corrected PRISM data (4 km x 4 km).

3.4.2 Other Meteorological Data

For hydrologic simulation, meteorological variables are required for heat transfer, energy, and evapotranspiration calculations. NLDAS-2 gridded data are used to generate the time series for these meteorological variables. Data from 117 NLDAS-2 grid cells that align with the modeled area are downloaded and processed for LSPC model inputs.

Air Temperature

NLDAS-2 temperatures are converted from Kelvin to degrees Fahrenheit as required by the LSPC model.

Wind Travel

Wind travel (miles/hour) is derived from NLDAS-2 directional hourly wind speeds (UGRD and VGRD in m/s):

$$W_t = \left(\frac{z}{z_a}\right)^r \times \frac{3600}{1609} * \sqrt{U^2 + V^2}\ , 0\ \leq z \leq z_a. \qquad \text{Equation 13}$$

Where $\frac{z}{z_a}$ is an elevation ratio (0.2 in this case), r is a surface roughness exponent (0.143 for agricultural land with some houses, shrubs, and plants). NLDAS-2 provides estimation of directional hourly wind speeds (m/s) at 10 meters above land surface. A power law relation is applied to scale the 10 meter wind speed to 2 meter wind speed to fit the LSPC model input requirement.

Solar Radiation

The hourly shortwave solar radiation (W/m^2) from NLDAS-2 is converted to the LSPC required unit, Langleys.

Cloud Cover

Cloud cover is not a meteorological variable that has observation records. Cloud cover fraction is back calculated using the method by Davis (1996). The ratio between solar radiation and cloudless sky solar radiation is used to derive the cloud cover with a unit of one tenth:

$$C = \left(1.484 * \left(1 - \frac{E}{E_s}\right)\right)^{\frac{1}{2.854}}, \qquad \text{Equation 14}$$

where E and E_s are solar radiation and cloudless solar radiation.

Cloudless sky solar radiation can be estimated as a function of latitude and time. The E_s is calculated and disaggregated for each NLDAS-2 grid using the method that BASINS provides (https://github.com/respec/BASINS/blob/4356aa9481eb7217cb2cbc5131a0b80a932907bf/atcMetCmp/modMetCompute.vb).

Dew Point Temperature

Dew point temperature is calculated using the temperature, atmospheric pressure, and specific humidity data from NLDAS-2. First, the relative humidity is calculated using Equation 15:

$$rh = 0.263pq \left(\exp\left(\frac{17.67(T - T_0)}{T - 29.65}\right)\right)^{-1}), \qquad \text{Equation 15}$$

where rh is relative humidity, p is atmospheric pressure, q is specific humidity, T is temperature, T_0 is reference temperature (273.16 K).

Then the relationship proposed by Lawrence (2005) is used to calculate dew point temperature:

$$T_d = T - \frac{100 - rh}{5},$$ Equation 16

Potential evapotranspiration

Hourly potential evapotranspiration (PET) estimates are included in the NLDAS-2 dataset, generated using a modified Penman scheme (Mahrt and Ek, 1984). It is derived from temperature and humidity data.

All meteorological variables mentioned above and required by the LSPC model are derived for each NLDAS-2 grid cell. Then the spatial analysis was done to assign each subwatershed with the value from the NLDAS-2 grid cell with the maximum area within the subwatershed boundary.

3.5 Other Hydrologic Settings

For urban watersheds, irrigation can greatly influence the model during dry periods. The water used for irrigation is estimated by calculating irrigation demands in the LSPC as the difference between accumulated rainfall and the accumulative evapotranspiration for a certain period of time defined by user. The actual evapotranspiration is estimated by multiplying the potential evapotranspiration by the evapotranspiration coefficient. The evapotranspiration coefficient varies at different HRUs and different times of year. Monthly varied evapotranspiration coefficients are assigned to agricultural and urban pervious HRUs for the irrigation demand calculation. Irrigation demands are calculated during dry season (May to October). Irrigation demands are calculated for agricultural land and pervious urban land. Antecedent 7 days are used as a threshold for comparing the deficit of precipitation and evaporation for the irrigation demand calculation. The calculated irrigation demand is filled by withdrawing water from the reach within corresponding subwatershed and applying to vegetation canopy.

Several reservoirs are located within the modeling domain. Reservoir representation is introduced in section 4.4.

Rating tables collected from USGS flow sites and local Water Districts are assigned to the corresponding reaches of the LSPC model. The F-tables are created for reaches with rating tables for the hydraulic simulation.

4. LSPC Hydrology Calibration

Calibration for watershed modeling follows the sequence of hydrology, then sediment, and finally water quality. Considering the rapid urbanization process and land-use changes, the hydrology calibration will be performed for 7 years (2000-2006). The selected period is centered on the period when the land use data were collected (ABAG 2005, NLCD 2006) and the TMDL reference year 2002. The initial hydrologic parameters are referenced from the BAHM HSPF model. Parameters are adjusted iteratively to improve the general water budget, high and low flows, and hydrographs. Model parameter adjustment follows the guidance and ranges in BASINS Technical Note 6 (USEPA, 2000). A new land use layer (data reflecting land uses near 2018) will be created by MTC in near future. A dynamic land use input is expected for the later phases of model development. The model will be calibrated and validated at a longer period (2000-2018) with the dynamic land use inputs to verify the impacts caused by land use changes. Three calibration sites with large drainage areas are used for model validation with the 2018 and 2019 monitoring data. Large subwatersheds are not very sensitive to the land use changes, thus are more appropriate to verify the model performance than small subwatersheds.

For a complete hydrologic calibration, three characteristics of watershed hydrology must be examined successively: 1) monthly, seasonal, and annual flow volumes; 2) baseflow volumes and recessions; and 3) peak and timing of storm events. At each calibration station, simulated and observed flows for each characteristic are examined and key hydrologic parameters are adjusted to attain acceptable criteria. Comparisons are performed for daily, monthly, and annual flows. The major purpose of the model development is to estimate the stormwater contaminants loadings from watersheds to the Bay, thus the hydrologic calibration process gives heavier weights on flow volume and wet season flow calibration than the baseflow during dry periods.

4.1 Hydrology Calibration Sites

Hydrology calibration is done at stream gauges where historic flow records are available. Seventeen USGS flow gauges are selected for hydrology calibration (Table 7, Figure 21). Stream gauges are selected based on the following criteria:

- flow records are available during the calibration period;
- spatial distribution which spreads over the whole region;
- within or near headwater watershed (minimize in-stream process impact) for HRU parameterization; or near the pour point to the Bay (represent a large drainage area).

As shown in Figure 21, stream gauges are grouped into two sets, HRU calibration and DA sites. The stream gauges near headwaters are selected for HRU parameterization (HRU calibration sites). Stream gauges near pour points and with large drainage areas are selected for verify HRU calibration and channel parameterization (DA sites).

The hydrologic calibration process follows a three-step approach. First, the stream gauges selected for HRU parameterization are used for hydrology calibration to represent reasonable hydrologic process representations for varied HRUs. Land-based hydrologic parameters are adjusted at this step. This step focuses on calibrating hydrologic related parameters of each HRU. The nine selected HRU calibration subwatersheds are grouped together. Each of the subwatershed is a combination of different HRUs. The HRU specific parameters are adjusted during the calibration process to improve the model simulation of this whole group. This calibration step is aimed to represent the hydrologic processes of different HRU correctly, thus to have a good summarized model performance at subwatershed scale. The HRU-based calibration method can 1) avoid overfitting the model parameters with site-specific information/errors, and 2) reduce the uncertainty of hydrologic simulation at regions with less monitoring data by representing the hydrologic processes at the HRU level. For instance, Contra Costa County has little stream-flow monitoring data for model calibration purposes. By calibrating the hydrologic processes of HRU types, which exist in both Contra Costa County and other counties, at locations with monitoring data, the hydrologic simulations at Contra Costa County can be improved.

Then the LSPC model is calibrated against stream gauges with large drainage areas to improve the accuracy of flow simulation at the regional scale. This step is both a verification of HRU calibration results at a larger spatial scale (multiple subwatersheds) and a calibration process focusing on reach parameters.

At last, the hydrographs of subwatersheds with upstream reservoirs are visually inspected and the model are calibrated to fit the reservoir operations.

Table 7. Stream gauges selected for hydrology calibration (2000-2006).

Subwatershed ID	Site ID	Station Name	Lat	Long	DA (mi^2)	Elev (m)	Data Period	Data Availability
4205	11167800	GUADALUPE R AB ALMADEN EXPRESSWAY A SAN JOSE CA	37.281	-121.88	61.8	145	10/1/2003-10/5/2011	96%
4202	11169025	GUADALUPE R ABV HWY 101 A SAN JOSE CA	37.374	-121.933	160	17.57	5/23/2002-12/31/2019	100%
4802	11166000	MATADERO C A PALO ALTO CA	37.422	-122.136	7.26	17.01	1/1/1999-11/6/2017	100%
4006	11169800	COYOTE C NR GILROY CA	37.078	-121.494	109	790	1/1/1999-12/31/2019	73%
1304	11458500	SONOMA C A AGUA CALIENTE CA	38.323	-122.494	58.4	94.28	1/1/1999-12/31/2019	87%
1406	11456000	NAPA R NR ST HELENA CA	38.511	-122.456	78.8	191.37	1/1/1999-12/31/2019	93%
4302	11169500	SARATOGA C A SARATOGA CA	37.254	-122.039	9.22	0	1/1/1999-12/31/2019	100%
4902	11164500	SAN FRANCISQUITO C A STANFORD UNIVERSITY CA	37.423	-122.189	37.4	115.75	1/1/1999-12/31/2019	100%
4000	11172175	COYOTE C AB HWY 237 A MILPITAS CA	37.422	-121.927	319	10	1/1/1999-12/31/2019	100%
3712	11180500	DRY C A UNION CITY CA	37.606	-122.024	9.39	85.12	1/1/1999-12/31/2019	100%
3703	11179000	ALAMEDA CREEK NILES	37.587	-121.961	633	85.65	1/1/1999-12/31/2019	100%
3506	11180825	SAN LORENZO C AB DON CASTRO RES NR CASTRO V CA	37.695	-122.045	18	260	1/1/1999-12/31/2019	100%
3507	11180960	CULL C AB CULL C RES NR CASTRO VALLEY CA	37.718	-122.054	5.79	0	1/1/1999-12/31/2019	100%
3500	11181040	SAN LORENZO C A SAN LORENZO CA	37.684	-122.14	44.6	6.13	1/1/1999-12/31/2019	100%
3109	11182500	SAN RAMON C A SAN RAMON CA	37.773	-121.995	5.89	530	1/1/1999-12/31/2019	100%

Subwatershed ID	Site ID	Station Name	Lat	Long	DA (mi^2)	Elev (m)	Data Period	Data Availability
1403	11458000	NAPA R NR NAPA CA	38.368	-122.303	218	24.74	1/1/1999-12/31/2019	100%
1066	11459500	NOVATO C A NOVATO CA	38.108	-122.58	17.6	14.76	1/1/1999-12/31/2019	100%

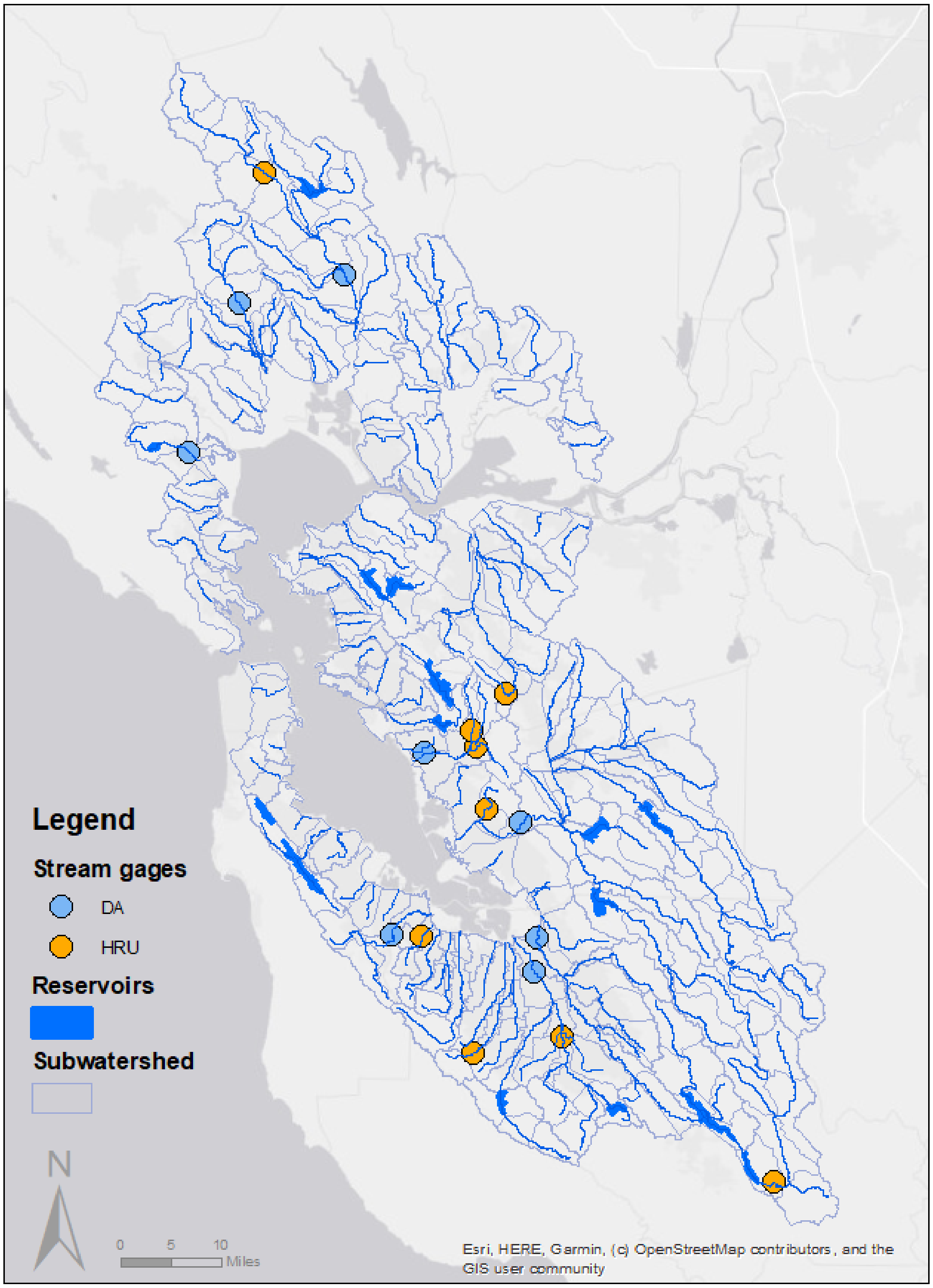

Figure 21. Stream gauges selected for hydrology calibration. HRU calibration sites are selected for HRU parameterization, DA sites are selected for calibration of a large drainage area.

4.2 Acceptance Criteria for Hydrology Calibration

To evaluate model performance from the three aforementioned aspects (flow volumes, baseflow volumes, and recessions and peak and timing of storm events), three indices are selected to quantify the model results. Error indices are commonly used in model evaluation, including percent bias (PBIAS), mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE). These indices are valuable in assisting analysis of the results. PBIAS, RMSE, MAE, and MSE value of 0 indicate a perfect fit. Percent of bias (PBIAS) is selected to evaluate the water budget simulation. The ratio between RMSE and standard deviation (RSR) standardizes the RMSE using the standard deviation of monitoring data. RSR is an index that incorporates the error information with a scaling factor, thus the RSR value can be compared to different components (e.g., sites with different flow rates and variances). The optimal value of RSR is 0, which indicates zero RMSE or residual variation and perfect model simulation. The lower RSR, the lower the RMSE, and the better the model simulation performance. The Nash-Sutcliffe efficiency (NSE) is a widely used and reliable statistic for assessing the goodness of fit of hydrology calibration (Nash and Sutcliffe, 1970). NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance and reflects the overall fit of a hydrograph. Values may vary from $-\infty$ to 1.0. A value of NSE = 1.0 indicates a perfect fit between modeled and observed data, whereas values less than 0 indicate that model predictions of temporal variability in observed flows are worse than using the average of observed data.

Given the approximate nature of models and inherent uncertainty and errors associated with input and observed data, it is recommended that acceptable ranges, rather than absolute criteria, should be used as general targets or goals for model calibration and validation. Table 8 lists general calibration/validation acceptable ranges that are reported in the literature for three key statistics (Donigian, 2002; Moriasi, et al., 2007; Duda, et al. 2012). The PBIAS are checked for total flow, highest flows (flows larger than 90th percentile) and wet season flows.

Table 8. General acceptable targets for LSPC hydrology calibration

Statistic	Very good	Good	Fair	Poor
PBIAS	< 10	10 -15	15-25	> 25
NSE	> 0.75	0.65-0.75	0.5-0.65	< 0.5
RSR	< 0.5	0.5 - 0.6	0.6-0.7	> 0.7

In addition to the three quantitative indices, visual comparison between simulated and modeled time series of the stream flow are also done during the calibration process. The daily hydrographs are plotted for each calibration site (Appendix A) to verify the timing and magnitude of stream flow after storm events and the log-hydrographs are plotted to verify whether the model results match the event recession patterns. The log-hydrographs are used to check and calibrate AGWRC and other groundwater parameters. The exceedance probability curves of daily flow and scatter plots on monthly flow are plotted to check the agreements of modeled and monitored water budget and stream flow distributions (Appendix A). The ranges of model parameters and their reference values are listed in the Appendix B.

4.3 HRU Calibration (Headwater Subwatersheds)

The rainfall-runoff process on upland in the LSPC model is HRU based. The HRU calibration step is focusing on correctly representing and distinguishing the hydrologic processes of different HRU types. Nine of the 17 calibration sites are located at or near the headwater subwatersheds. The hydrographs generated from these subwatersheds are mainly controlled by the rainfall-runoff processes on different HRUs and are affected less by other factors such as channel processes, artificial controls, etc. These nine subwatersheds are selected for the HRU calibration (Table 9). Table 10–12 summarize the distribution of different land uses, soil types, and geologic characteristics for the HRU calibration subwatersheds. The nine selected subwatersheds cover all the land surface features for hydrologic calibration.

Table 9. Selected subwatersheds for HRU calibration.

Subwatershed ID	Site ID	Station Name	Drainage Area (mi^2)	Elevation (m)
4205	11167800	GUADALUPE R AB ALMADEN EXPRESSWAY A SAN JOSE CA	61.8	145
4802	11166000	MATADERO C A PALO ALTO CA	7.26	17.01
4302	11169500	SARATOGA C A SARATOGA CA	9.22	0
3712	11180500	DRY C A UNION CITY CA	9.39	85.12
3506	11180825	SAN LORENZO C AB DON CASTRO RES NR CASTRO V CA	18	260
3507	11180960	CULL C AB CULL C RES NR CASTRO VALLEY CA	5.79	0
3109	11182500	SAN RAMON C A SAN RAMON CA	5.89	530
1406	11456000	NAPA R NR ST HELENA CA	78.8	191.37
4006	11169800	COYOTE C NR GILROY CA	109	790

Table 10. Land use, in percent area, for the HRU calibration subwatersheds.

	1406	3109	3506	3507	3712	4006	4205	4302	4802
Agriculture	8.9%	0.0%	0.0%	0.0%	0.1%	0.5%	0.5%	0.2%	0.0%
Commercial	0.8%	11.7%	0.1%	5.5%	1.0%	0.4%	3.8%	1.0%	15.3%
Forest	68.0%	40.6%	42.1%	48.1%	36.5%	84.7%	57.7%	85.2%	6.3%
Grass	8.0%	38.0%	37.9%	36.2%	54.5%	12.2%	8.9%	1.6%	13.3%
Industrial	0.8%	0.6%	0.0%	0.0%	0.0%	0.0%	1.6%	0.0%	2.4%
Other Urban	4.0%	3.7%	3.4%	4.0%	3.0%	1.2%	5.8%	4.3%	7.7%
Residential	7.0%	2.6%	12.6%	4.6%	3.4%	0.0%	15.2%	5.8%	43.7%
Transportation	1.8%	2.2%	3.7%	0.9%	1.4%	0.1%	4.7%	1.7%	11.2%
Water	0.5%	0.5%	0.1%	0.5%	0.1%	1.0%	1.9%	0.2%	0.1%

Table 11. Hydrologic soil groups and imperviousness, in percent, for the HRU calibration subwatersheds.

	1406	3109	3506	3507	3712	4006	4205	4302	4802
A/B	30.1%	6.6%	7.1%	0.7%	12.8%	1.6%	11.2%	61.5%	0.0%
C	51.9%	56.4%	60.2%	70.6%	51.2%	32.6%	46.9%	16.7%	38.1%
D	17.2%	36.1%	32.1%	28.0%	35.4%	64.8%	37.6%	21.5%	59.5%
IMP*	0.4%	0.4%	0.5%	0.2%	0.6%	0.0%	2.4%	0.1%	2.4%
Water	0.5%	0.5%	0.1%	0.5%	0.1%	1.0%	1.9%	0.2%	0.1%

* 'IMP' is the directly connected impervious area.

Table 12. Geologic characteristics, in percent, for the HRU calibration subwatersheds.

	1406	3109	3506	3507	3712	4006	4205	4302	4802
Franciscan	25%	0%	0%	0%	0%	86%	68%	0%	0%
Tertiary	75%	100%	0%	100%	0%	0%	0%	100%	100%
Quaternary	0%	0%	0%	0%	0%	0%	32%	0%	0%
Great Valley	0%	0%	100%	0%	100%	14%	0%	0%	0%

The hydrograph and log-hydrograph are plotted for each subwatershed at each calibration round to check the model performance on the timing and magnitude of peak flows, the falling limbs of hydrographs, and the groundwater recession at low-flow periods (Figure 22).

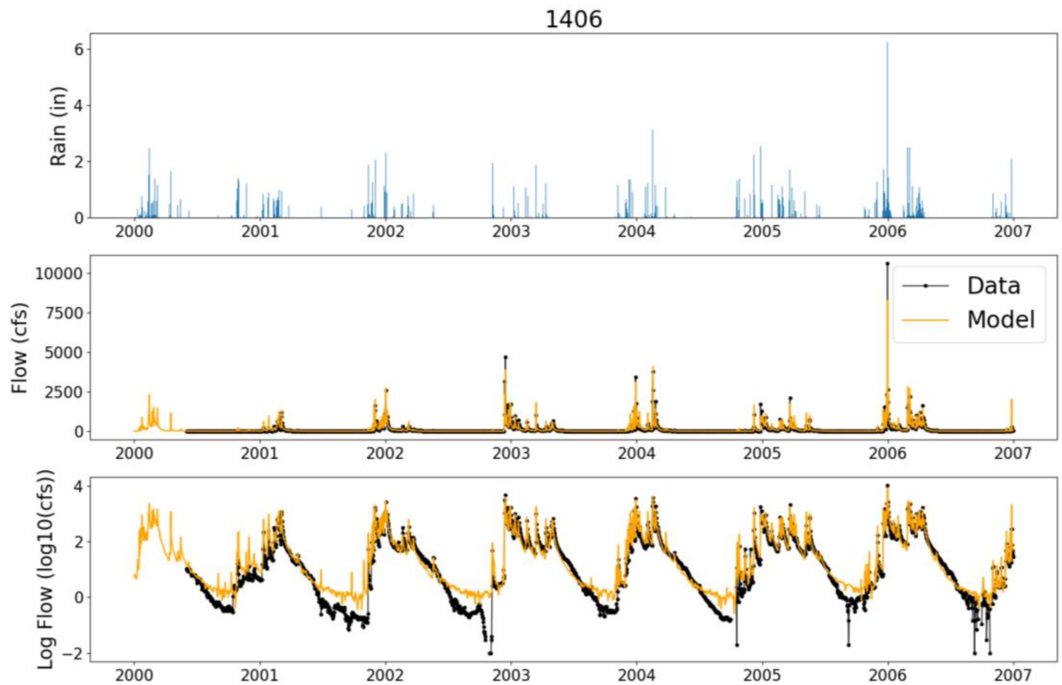

Figure 22. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 1406 (USGS gauge name: NAPA R NR ST HELENA CA, USGS gauge ID: 11456000).

The exceedance curve of daily flow is plotted for each subwatershed to check if there are extreme biases for the probability distribution of flow rates (Figure 23). The monthly scatter plot of stream flow volume is also plotted to check the monthly water budget for each subwatershed (Figure 23). Figure 22 and Figure 23 are examples from subwatershed 1406. The above-mentioned three types of plots for all calibration subwatersheds can be found in Appendix A. In visually evaluating the three types of plots for each subwatershed, the model appears to represent the rainfall runoff dynamics and the groundwater recessions reasonably well. The correlation coefficient (R^2) between monitored and modeled monthly flow volume are calculated. The values of R^2 exceed 0.75 for all HRU calibration subwatersheds.

The NSE and RSR are evaluated for each calibration subwatershed. PBIAS are calculated for total flow volume, highest 10% of flows, and wet-season (November to April) flows to quantify the model performance on the water budget simulation and the seasonality representation. Table 13 summarizes the model performance at the HRU calibration subwatersheds. The model captures the flow dynamics very well. The values of NSE, RSR, and total PBIAS are at a 'Very Good' level for all subwatersheds. Only one subwatersheds has the PBIAS of wet season flow slightly larger than 10% and all other subwatersheds have 'Very Good' wet season flow results. Six out of nine subwatersheds have 'Very Good' PBIAS results of the highest 10% flow. Two others are only slightly larger (-13% and -11%) and are at the 'Good' level. One subwatershed has -20% PBIAS of the highest 10% flow, which is at 'Fair' level. In general, the model has very good performance on flow volumes and peaks (timing and quantity) at the regional scale. The solid model performance in estimating wet season flows sets up a good foundation for estimating sediment and contaminant stormwater load.

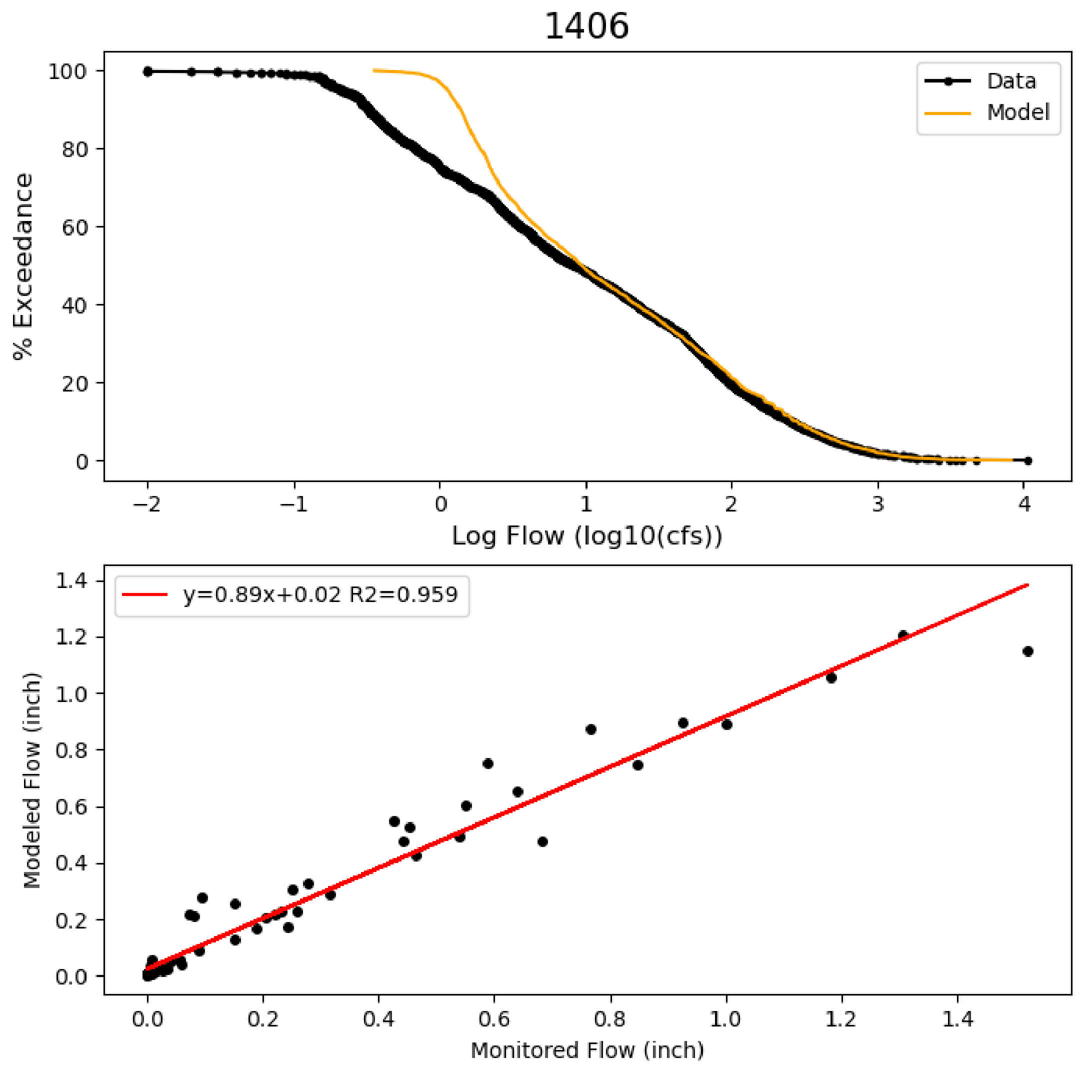

Figure 23. Top: Stream flow exceedance curve for subwatershed 1406 (USGS gauge name: NAPA R NR ST HELENA CA, USGS gauge ID: 11456000). Bottom: Monthly modeled versus monitored flow scatter plot.

Table 13. The model performance matrix (2000-2006) at HRU calibration subwatersheds*.

Subwatershed ID	Flow Gauge Name	Nash-Sutcliffe efficiency (NSE)	RSR	Percent Bias (PBIAS)	High Flow (> 90th percentile) PBIAS	Wet Season (May to October) Flow PBIAS
4802	MATADERO C A PALO ALTO CA	0.91	0.31	-3%	8%	5%
4302	SARATOGA C A SARATOGA CA	0.87	0.36	4%	6%	10%
4205	GUADALUPE R AB ALMADEN EXPRESSWAY A SAN JOSE CA	0.91	0.30	-7%	6%	1%
4006	COYOTE C NR GILROY CA	0.92	0.28	-5%	-13%	-7%
3712	DRY C A UNION CITY CA	0.87	0.36	-8%	-20%	-9%
3506	SAN LORENZO C AB DON CASTRO RES NR CASTRO V CA	0.88	0.35	4%	-7%	8%
3507	CULL C AB CULL C RES NR CASTRO VALLEY CA	0.82	0.42	5%	-7%	7%
3109	SAN RAMON C A SAN RAMON CA	0.79	0.46	-9%	-11%	-4%
1406	NAPA R NR ST HELENA CA	0.95	0.21	4%	-5%	4%

* Color code: Green -> Very Good, Yellow -> Good, Grey -> Fair.

4.4 Reservoir Representation

Subwatersheds with urban features are subject to human impacts such as land-surface development, artificial channels, diversions, and dams. HRU classification addresses the differences in hydrologic processes on natural and developed land surfaces. To represent human impacts within stream channels, stream channels are separated into natural and artificial groups. Stream-channel roughness, slope, and bank slope are adjusted for different stream-channel types. Stream channels with rating curves available from the USGS are set up in the model. Stream channels without available rating curves use the model-generated rating curves based on the geometry of the channels. Stream channels without known depths and widths are extrapolated from upstream and downstream channels or derived from the accumulated drainage area of that stream segment.

Reservoirs are commonly used in the SF Bay region for water supply, flood control, and other purposes. These artificial controls have large impacts on both timing and magnitude of stream-flow patterns. Fifteen major reservoirs (Table 14) within the area of interest are set up in the regional watershed model to better quantify the discharge from the dams. Reservoir design, outflow rates, stages, and withdrawal data are collected from USGS, CDWR, SFPUC, EBMUD, and SCVWD. The reservoirs in the model are set up as storage units with specific hydraulic function tables (F-Table).

Table 14. Reservoirs represented in the model.

Reservoir ID	Reservoir	Reservoir Surface Area (ac)	Vol(ac-ft)	Depth
91066	Stafford Lake	222	9474	134
91454	Lake Hennessey	706	31,000	1378
91806	Lake Curry	272	12129	140
93252	San Pablo Reservoir	854	43193	170
93254	Briones Reservoir	735	67520	273
93452	Lake Chabot	340	10281	142
93454	Upper San Leandro Reservoir	622	37960	191
93764	Del Valle Reservoir	805	77100	222
93786	San Antonio Reservoir	768	50500	193
93793	Calaveras Reservoir	1807	100000	210
94005	Anderson Lake	1221	89278	240
94006	Coyote Lake	616	22541	138
94215	Lexington Reservoir	412	19044	195
94259	Calero Reservoir	333	9738	98
95352	Lower Crystal Springs Reservoir	1323	57910	140

Reservoir operations such as water withdrawal and downstream releases are driven by multiple factors besides hydrologic factors. It is also common for water across a group of reservoirs to be reallocated via diversion channels. The operation decision process is dynamic and is not based on fixed control rules between reservoir storage (stage) and water withdrawal/release. To accurately model reservoir operations is beyond the scope of this study. In this study, the major calibration target is to sufficiently quantify water balances and releases from reservoirs to downstream stream channels to support the model calibration effort. Water withdrawal data are summarized from records gathered from Water Districts and CDWR. The time series of water withdrawal are converted to average daily water withdrawal amount and are applied to the corresponding reservoirs. The low-flow release and spillway overflow are estimated by hydrograph separation from adjacent downstream stream gauges. The reservoir stage-discharge relation tables (F-Tables) are derived and calibrated to fit the low-flow releases and spillway overflows and to mimic the downstream hydrographs. Figure 24 is an example of monitored and modeled hydrographs immediately downstream of Stafford Lake. All the hydrographs downstream of reservoirs show obvious artifacts. The model, though unable to fully represent the complex reservoir operations, presents a close approximation of reservoir water release after adjusting the F-Tables against monitoring flow data. The F-Tables of reservoirs without immediate downstream flow records are extrapolated from F-Tables from calibrated reservoirs and are calibrated based on the records from stream gauges located further downstream.

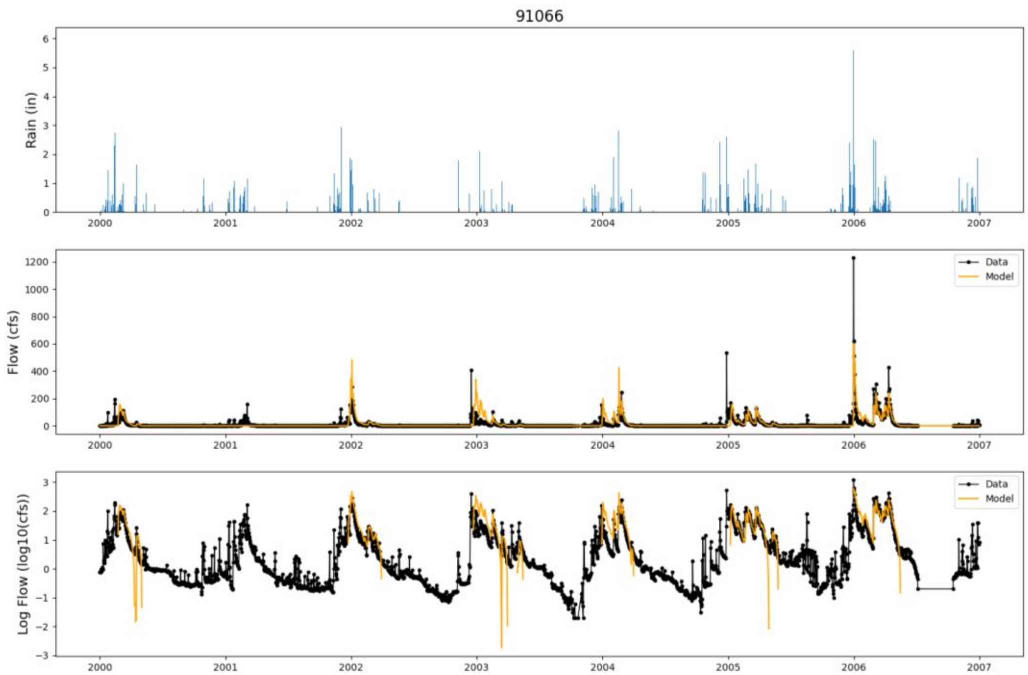

Figure 24. Rainfall, daily hydrograph, and log-hydrograph for the subwatershed downstream of Stafford Lake.

Five calibration subwatersheds have reservoirs upstream. Model performance at these subwatersheds with reservoirs at upstream are evaluated. Table 15 summarizes the evaluation index for these subwatersheds. The model has very good estimation of total flow volume at all five subwatersheds. Wet-season flow volume for the five subwatersheds are equal to or better than the 'Good' level. Only one subwatershed has the flow that are larger than 90th percentile of flow overestimated by more than 25%. The NSE and RSR values are all above the 'Fair' level, which indicates the model represents the hydrographs reasonably well given artificial impacts exist in these subwatersheds.

Figure 25 -27 show the modeled and monitored hydrographs of three major tributaries in the Bay Area (Guadalupe River, Coyote Creek, and Alameda Creek). The impact of artificial control on hydrographs can be identified from the log-hydrographs during low-flow periods. The upstream boundary conditions (discharge releases from reservoirs) impact the shape of hydrographs. By calibrating the reservoir operations to support the water balance estimation, the model captures the timing and peaks of storm events reasonably well.

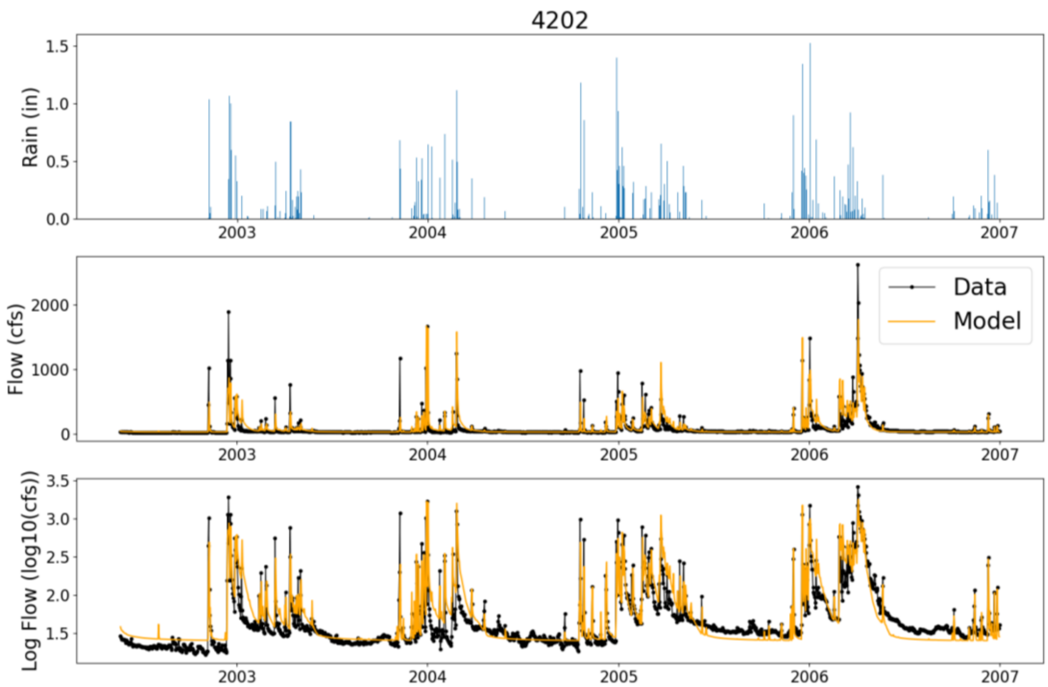

Figure 25. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4202 (USGS gauge name: GUADALUPE R ABV HWY 101 A SAN JOSE CA, USGS gauge ID: 11169025).

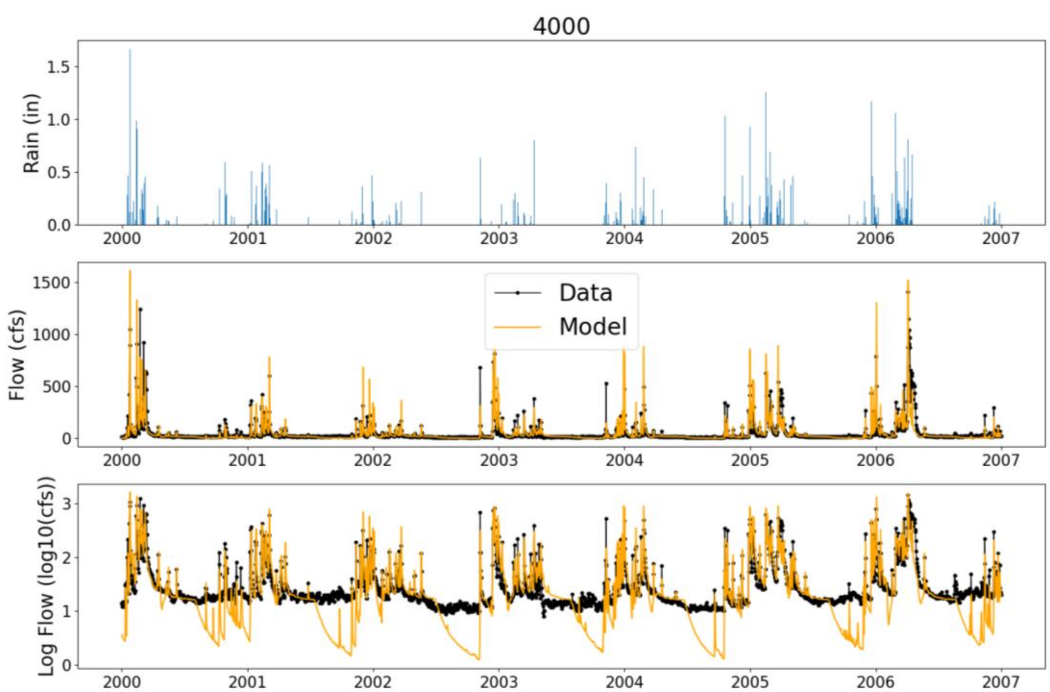

Figure 26. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4000 (USGS gauge name: COYOTE C AB HWY 237 A MILPITAS CA, USGS gauge ID: 11172175).

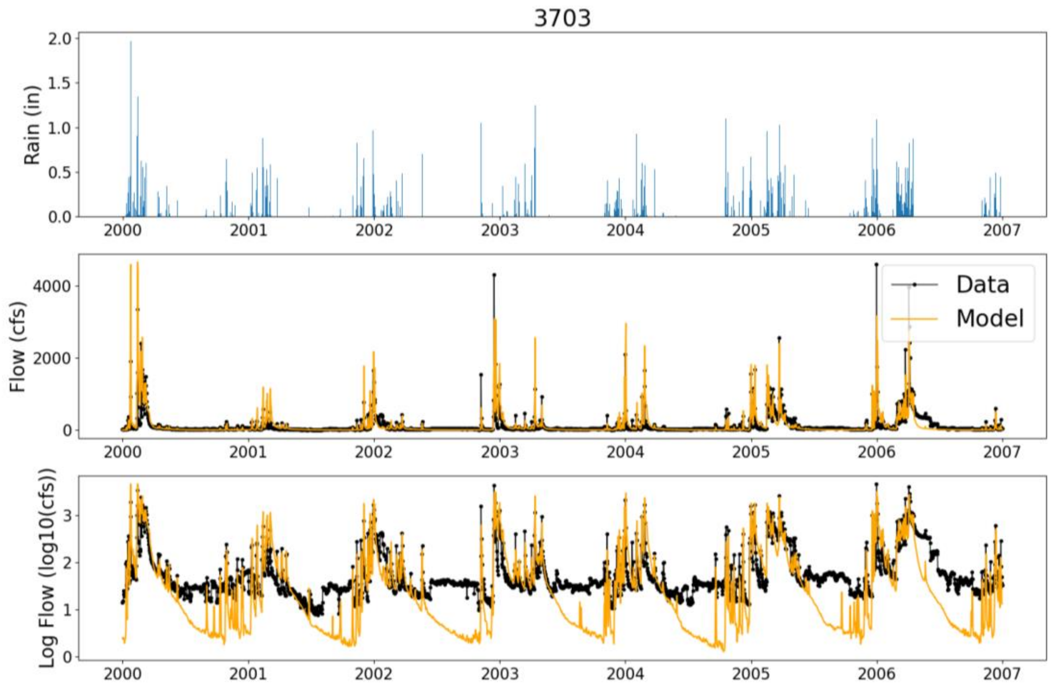

Figure 27. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3703 (USGS gauge name: ALAMEDA CREEK NILES, USGS gauge ID: 11179000).

Table 15. The model performance matrix (2000-2006) at calibration subwatersheds with upstream reservoirs*.

Subwatershed ID	Flow Gauge Name	Nash-Sutcliffe efficiency (NSE)	RSR	Percent Bias (PBIAS)	High Flow (> 90th percentile) PBIAS	Wet Season (May to October) Flow PBIAS
4202	GUADALUPE R ABV HWY 101 A SAN JOSE CA	**0.83**	**0.41**	**4%**	**7%**	**9%**
4000	COYOTE C AB HWY 237 A MILPITAS CA	**0.72**	**0.53**	**-7%**	**-8%**	**-2%**
3703	ALAMEDA CREEK NILES	**0.61**	**0.62**	**1%**	**14%**	19%
1403	NAPA R NR NAPA CA	**0.96**	**0.19**	**4%**	**-8%**	**-4%**
1066	NOVATO C A NOVATO CA	**0.50**	**0.70**	**6%**	**30%**	**9%**

* Color code: Green -> Very Good, Yellow -> Good, Grey -> Fair, Pink -> Poor.

The hydrographs, exceedance curves, and scatter plots for these five subwatersheds can be found in Appendix A. In general, the model is capable of good estimations of flow volumes and hydrographs of subwatersheds under the impacts of dynamic artificial controls with simplified reservoir operation representation. The reservoir operations are highly dynamic and not subject to a fixed rule, thus it is suggested to have the reservoir F-Tables recalibrated against monitoring data to achieve a better estimate of downstream hydrographs for the years outside the calibration period.

4.5 Validation with subwatersheds with large drainage area

Subwatersheds with large drainage areas are integrations of hydrologic processes occurring on multiple upstream subwatersheds, stream channels, water bodies, and artificial controls (dams, reservoirs, etc.). Reservoir operations vary temporally and need recalibration to better fit hydrographs outside of calibration periods. Headwater watersheds have small drainage areas and thus are more sensitive to land use changes than downstream subwatersheds. The land use data for hydrologic calibration are derived from ABAG 2005 and NLCD 2006, which are suitable for the calibration period (2000-2006). Data from years 2018 and 2019 are used for model validation. The urbanization processes occurring during the last two decades have changed the land surface features and therefore also the hydrologic processes in the SF Bay region. Subwatersheds with large drainage areas can buffer the impact of the urbanization process on hydrologic processes because of the smaller area of changed land uses relative to the entire drainage area. Three calibration subwatersheds with large drainage areas and without reservoirs upstream. These three subwatersheds are suitable to validate the model hydrologic processes representations with old land use data (ABAG 2005 and NLCD 2006). New land use data will be gathered and incorporated into the model for the future simulations outside the calibration period.

Figure 28 to Figure 30 show the hydrographs and log-hydrographs of these three subwatersheds during the calibration period (2000-2006). Figure 31 to Figure 33 show the hydrographs and log-hydrographs during the validation period (2018-2019). The comparison between monitored and modeled time series at calibration and validation periods shows consistency in model performance. The model does not show drastic changes in performance for years that are not calibrated. Possible reasons for existing biases include: the model does not have a good estimate on the groundwater level changes, which impacts the surface water-groundwater interaction; and the land use layer data was collected before 2005 which may not reflect the land use changes in 21 years (1999-2019).

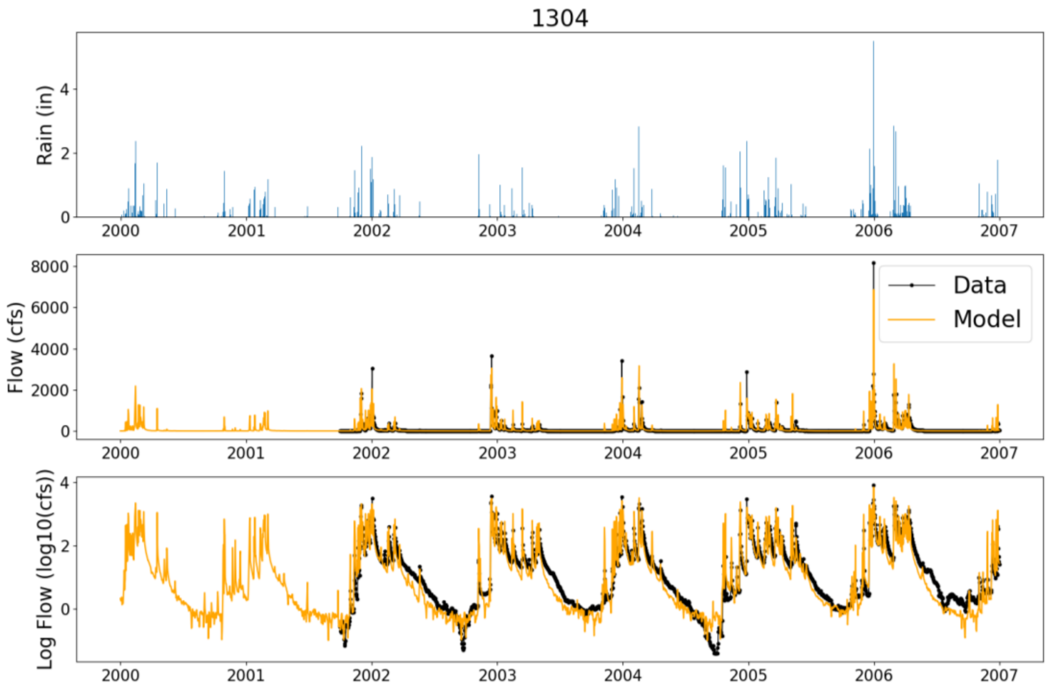

Figure 28. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 1304 (USGS gauge name: SONOMA C A AGUA CALIENTE CA, USGS gauge ID: 11458500) during the calibration period (2000-2006).

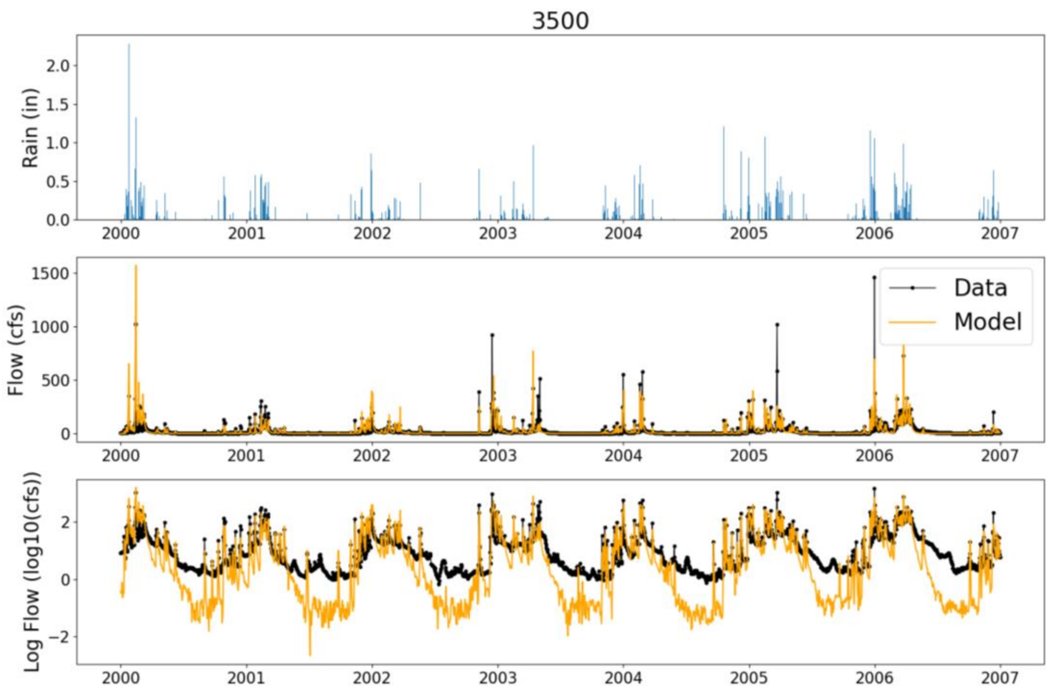

Figure 29. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3500 (USGS gauge name: SAN LORENZO C A SAN LORENZO CA, USGS gauge ID: 11181040) during the calibration period (2000-2006).

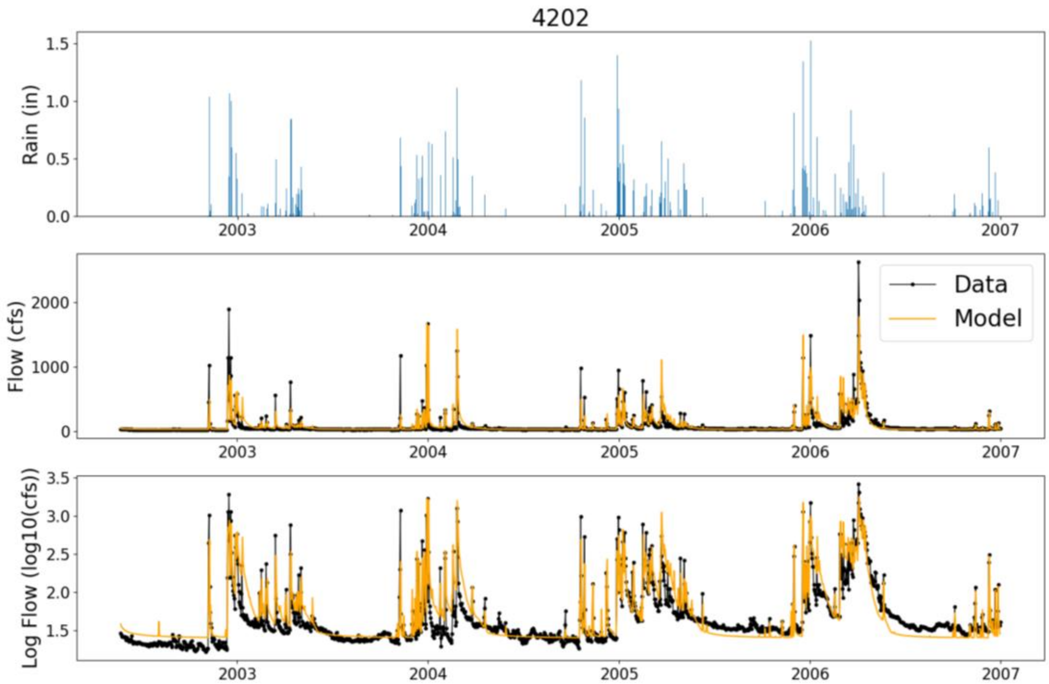

Figure 30. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4902 (USGS gauge name: SAN FRANCISQUITO C A STANFORD UNIVERSITY CA, USGS gauge ID: 11164500) during the calibration period (2000-2006).

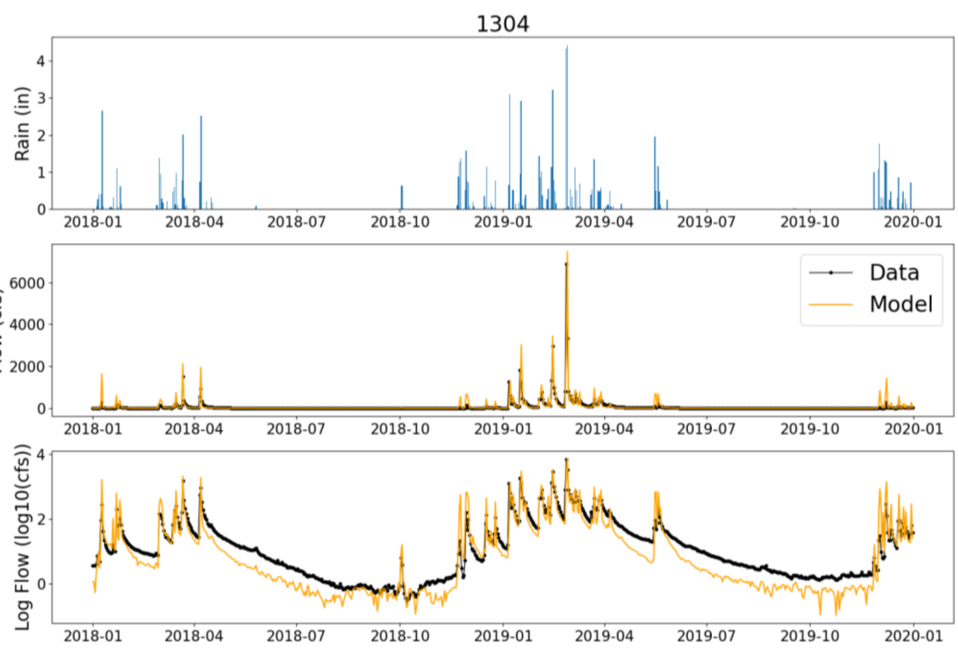

Figure 31. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 1304 (USGS gauge name: SONOMA C A AGUA CALIENTE CA, USGS gauge ID: 11458500) during the validation period (2018-2019).

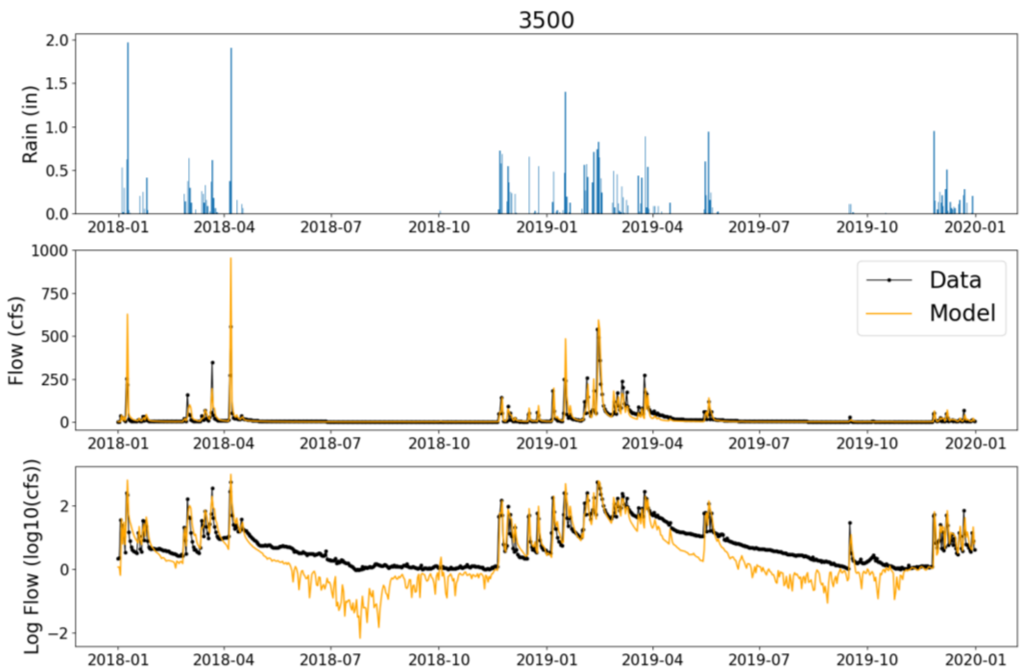

Figure 32. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3500 (USGS gauge name: SAN LORENZO C A SAN LORENZO CA, USGS gauge ID: 11181040) during the validation period (2018-2019).

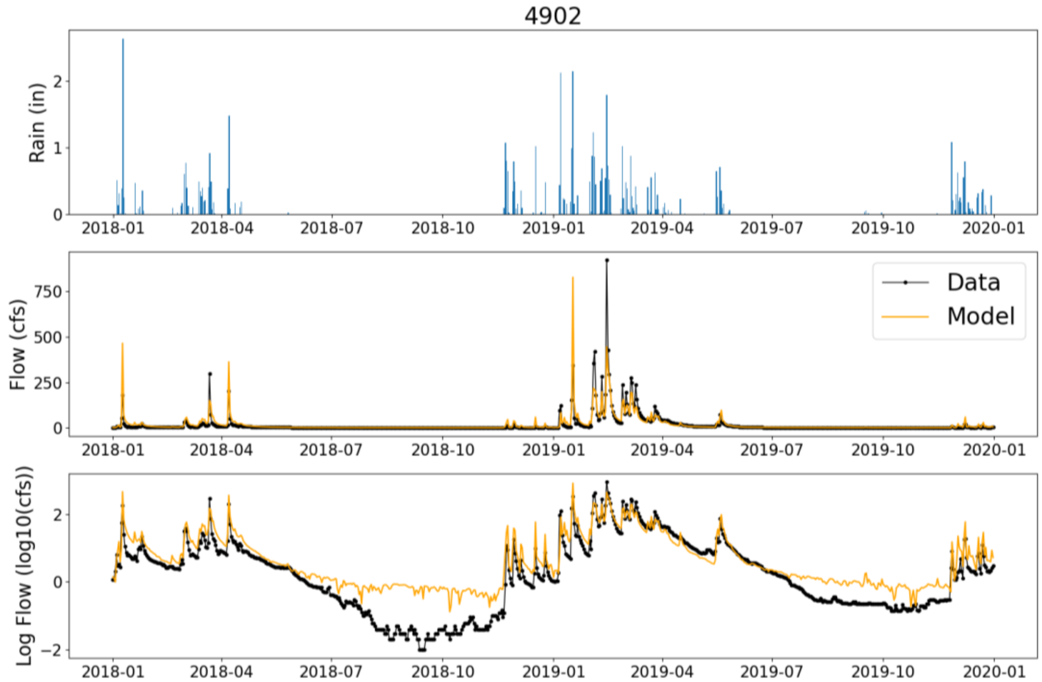

Figure 33. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4902 (USGS gauge name: SAN FRANCISQUITO C A STANFORD UNIVERSITY CA, USGS gauge ID: 11164500) during the validation period (2018-2019).

Table 16 summarizes the model performance of these three subwatersheds during calibration and validation periods. The model has 'Good' and better performance for all the indices at the three sites. The PBIAS of the volume of total flow and the wet season flow are 13% ('Good' level) for Sonoma Creek at validation period and the PBIAS for the highest 10% flow is 11% ('Good' level) at the stream gauge near Stanford University (a heavily urbanized subwatershed) during validation periods. The model has 'Very Good' performance for all other evaluation criteria at other sites for both calibration and validation period. The model performance is expected to be improved when new land-use data are gathered and incorporated into the model and longer periods have been used for model calibration and validation.

Table 16. Model performance at three subwatersheds with large drainage area during calibration and validation periods.

	Calibration (2000-2006)			Validation (2018-2019)		
Subwatershed ID	4902	3500	1304	4902	3500	1304
Flow Gauge Name	SAN FRANCISQUITO C A STANFORD UNIVERSITY CA	SAN LORENZO C A SAN LORENZO CA	SONOMA C A AGUA CALIENTE CA	SAN FRANCISQUITO C A STANFORD UNIVERSITY CA	SAN LORENZO C A SAN LORENZO CA	SONOMA C A AGUA CALIENTE CA
NSE	0.91	0.76	0.95	0.90	0.93	0.95
RSR	0.31	0.49	0.22	0.32	0.26	0.21
PBIAS	8%	-3%	5%	7%	-7%	13%
Highest 10% PBIAS	-1%	5%	-3%	-11%	-8%	-2%
Wet Season flow PBIAS	7%	6%	-5%	6%	-3%	13%

* Color code: Green-> Very Good, Yellow-> Good.

In summary, the current hydrologic model has a solid simulation performance on the HRU-based hydrologic processes. A simplified reservoir setting is set up in the model and is able to incorporate the impacts of artificial controls into the hydrologic simulation to some extent and improve the hydrographs downstream from reservoirs. The model has good performance at downstream subwatersheds with and without upstream reservoirs during the calibration period. The model shows consistently good performance at downstream subwatersheds during both calibration and validation periods.

5. Sediment and POC (PCBs) Modeling Plan

5.1 Sediment Calibration

LSPC simulates sediment dynamics with two processes: 1) overland processes of sediment erosion and transport to produce sediment loadings; and 2) channel processes of deposition, scour, and transport. Similar to hydrologic modeling, upland sediment modeling is HRU based. A USLE-based soil detachment method and a transport-capacity-based sediment transport method are used for soil erosion simulation on the pervious land surface. A buildup-wash-off-based method is used for solid accumulation and delivery on impervious land surfaces. Sediment calibration follows the hydrologic calibration and is an essential step before calibration for sediment-associated pollutants (e.g., PCBs). Sediment calibration involves two steps: first, adjusting sediment erosion parameters to match sediment loading to stream channels; and second, adjusting in-stream parameters to align simulated sediment concentrations with observed data. The goal is to represent the overall sediment behavior of the watershed that is consistent with conceptual models and observed concentration and loading data.

Sediment calibration is generally much more uncertain than hydrologic calibration because it is difficult to simulate varied and localized sediment processes, and because there is a lack of sufficient sediment data to accurately calibrate the model. Currently, sediment data in the Bay Area are scarce. There are only 14 USGS stations that measure suspended sediment concentration and flow. In addition, two stations operated and maintained by Balance Hydrologics provide concentrations of suspended sediment during various periods (Table 17). In addition, the RMP has monitored suspended-sediment concentrations and loads at Zone 4 Line A for four wet seasons; at, Marsh Creek, North Richmond Pump Station, and Sunnyvale East Channel for three wet seasons; and at Pulgas Creek Pump Station South for two wet seasons. The RMP and the San Mateo and Santa Clara County stormwater programs have sampled single-storm composite sediment concentration data at > 140 locations since 2011.

The single-storm composite data will be used to parameterize HRU-based soil erosion variables. Then the in-stream sediment process will be calibrated at the sediment gauges that have data records during the hydrologic calibration period. By the time we are ready for sediment calibration, a new land use layer from ABAG may be developed. Based on the 2005/2006 land use data and the most recent land use data, a time series of land use will be generated for the regional watershed model to account for the land use change in recent years. The sediment model with varying HRU and geology inputs will then be validated at sediment gauges with recent data records.

Table 17. Daily sediment sites for model calibration.

Station ID	**Station Name**	**Area (mi^2)**	**Sediment Records**
11179000	Alameda Ck. At Niles	633	2000-2018
11177000	Arroyo De La Laguna Near Pleasanton	405	2000-2003
11176900	Arroyo De La Laguna At Verona	403	2007-2018
11172175	Coyote Ck. Above Highway 237 At Milpitas	826	2004-2007 2009-2013
11458000	Napa R. Near Napa	565	2018
11169025	Guadalupe R. Above Highway 101 At San Jose	565	2003-2018
11173575	Alameda Ck. Below Welch Ck. Near Sunol	414	2000-2003 2007-2013
11167800	Guadalupe R. Above Almaden Expressway At San Jose	145	2008-2011
11458500	Sonoma Ck. At Agua Caliente	151	2018
11181040	San Lorenzo Ck. At San Lorenzo	61.8	2009-2018
11174600	Alamo Canal Near Pleasanton	58.3	2017
11460000	Corte Madera Ck. Near Ross	44.8	2010-2013
11180900	Crow Creek Near Hayward	39.4	2000-2003
11172365	Zone 6 Line B At Warm Springs Boulevard At Fremont	18.1	2000-2002
Balance Hydrologics	Wildcat Ck. At Vale Road At Richmond	10.4	2006-2015
Balance Hydrologics	Codornices Ck. At Cornell Ave	0.77	2005-2018

Sediment calibration will also be evaluated using graphical and statistical assessments. For graphical assessment, time series and scatter plots will be used to compare observed and simulated sediment concentrations or loads, and for statistical assessment, correlation coefficient, and error indices such as percent error between observed and simulated values will be used. For sediment, at monthly or annual time steps, an error or < 20% is thought to indicate a very good calibration, 20-30% a good calibration, and 30-45% a fair calibration (Duda et al., 2012).

5.2 Pollutants of Concern (POC) Calibration

For pollutants for which sediment is the main transport vector, the POC calibration will be the last step of model calibration and validation, following the completion of sediment calibration. The goal of POC calibration is to obtain agreement of simulated and observed concentrations within acceptance criteria with physically realistic parameters. The POC loading from different land uses should be consistent with the expected ranges based on the literature, conceptual models, and field observations.

For sediment-associated pollutants such as PCBs, buildup/wash-off (with atmospheric deposition or other distributed emissions) is used for impervious land segment simulation of pollutant generation. For pervious land, a combination approach of sediment potency and specification of concentrations in subsurface flow pathways is applied. The potency factors for PCBs and Hg can be estimated based on particle ratios calculated from field observations (e.g., Gilbreath et al., 2020).

Over the past decade, there has been considerable effort to collect POC load and concentration data in the Bay Area by the RMP and BASMAA member agencies. During WY 2003-2014, loads were intensively monitored out at nine small tributary watersheds for PCBs and at eight for Hg where samples were collected from two and eight winter seasons at each site (McKee et al., 2015). In addition, the RMP conducted screening-level (single composite samples from one storm) POC monitoring in WY 2011 and continuing from WY 2015 onward at sites around the Bay Area. This effort is focused on small watersheds and Municipal Separate Storm Sewer System (MS4) catchments that have a disproportionately large area with potential PCBs sources (i.e., old industrial land uses) (Gilbreath et al., 2020). The stormwater programs for Santa Clara and San Mateo counties have also completed screening-level monitoring (primarily in small MS4 catchments) using the same sampling methodology. These data have recently been compiled for > 140 sites and were mainly collected in Santa Clara, Alameda, and San Mateo counties with fewer sites in Contra Costa and Solano counties, and will be used in POC calibration. The emerging contaminants monitoring for the last 2 years and planned (2022-2023) monitoring for the future can be used for CEC model calibration and validation.

Similar to the sediment calibration process, POC calibration will begin with screening-level composite samples to calibrate HRU-based parameters such as buildup/wash-off rates and potency factors. The land-based parameters will be modified iteratively to verify that unit area loading rates for different HRUs are reasonable relative to literature values or local land use loading information. After ensuring reasonable upland loading rates, calibration to instream observations will be done to refine the simulation. Most POC sampling data were collected including and after water year 2010, thus the dynamic HRU input will be used for POC simulation.

POC calibration will be assessed similarly to sediment because of a lack of sufficient monitoring data. Time-series and scatter plots will be used to compare observed and simulated POC concentrations and loads, and correlation coefficient and percent error will be used for statistical assessment. For water quality, calibration is considered very good when the percent error at monthly and annual timescales is < 15%, good at 15-25%, and fair at 25-35%.

6. Summary and Future Enhancements

The regional watershed LSPC model is a work in progress. The data used and assumptions and categorizations described in this document are subject to change as new data are obtained and calibration efforts required. The current hydrologic model setup and calibration serves as a solid foundation for future model developments on sediment and pollutant simulations. LSPC is also a flexible and powerful tool that will be a useful platform for synthesizing our understanding of regional hydrologic, sediment, and pollutant-loading processes. For the following phases and future model development, the regional watershed model could be enhanced in several ways in future.

The watershed delineation of this regional watershed model is mainly based on NHD and previous SFEI projects. Other local resources such as the Oakland Museum subwatershed boundaries may provide better accuracy and resolution than NHD.

Land use data are crucial for hydrologic, sediment, and contaminants simulation. Knowing the MTC is working on producing a new land use layer with recent acquired data, this study uses NLCD 2006 and ABAG 2005 as major land use sources and expects to use the latest land use data once available. The expected new land use layer generated by MTC can be a source to verify some questionable high PCBs load area that are raised by local RAA modeling effort, such as the large buffer areas surrounding San Francisco International Airport(SFO). In phase two of the model development, more land use data will be gathered and processed to create time series of land use to reflect land use changes in the recent 20 years at the Bay area. Other sources of land use data such as NWALT (https://pubs.er.usgs.gov/publication/ds948) and the changes in imperviousness for U.S. urban areas layer (https://www.sciencebase.gov/catalog/item/5acbeb40e4b0e2c2dd13d4da). The approaches to estimate the total impervious area (TIA) and directly connected impervious area (DCIA) could have considerable impacts on urban hydrology and contaminants loads simulation. The original Sutherland method results a relatively low DCIA area value comparing to other methods used by local RAA models (e.g., San Mateo and Santa Clara). Different EIA and DCIA estimation methods can be investigated in next phase of model development to check if there can be any potential improvement.

Due to lack of potential evaporation site records within the modeling domain, it is difficult to verify the potential and actual evapotranspiration (ET) results from the model. As an import water budget term, other data sources could be considered to verify the accuracy of ET in future model activities, such as MODIS evapotranspiration products. This study is focused on estimating stormwater contaminants loads, thus the baseflow accuracy is not a major concern. However, to make the watershed model more applicable to other situations, baseflow simulation can be improved by incorporating groundwater-surface water interactions in future. The MODFLOW based groundwater level study by USGS (Befus et al., 2020) could serve as groundwater data and model resources for future model improvement on groundwater and surface water interactions.

The depth of width of channel cross sections are mainly estimated by empirical relationships developed by Leopold and Maddock (1953). There are several local and more recent studies available to derive the relationships between drainage area and channel geometries, such as Marin-Sonoma regional curves (https://www.sfestuary.org/wp-content/uploads/2014/05/Stream-Design-Curve-Marin-Sonoma-2013.pdf). Using a locally-derived relationship is preferred in the next phase of model development as the sediment transport process can be largely impacted by channel hydraulics, which is subject to channel geometries.

In general, this report serves as a reference documentation of the first phase of the regional watershed model development. The model setup and hydrologic calibration details are documented for audiences who are interested in using the regional watershed model in future. Future model enhancement directions are also listed in this document as a guidance for the future phases of model development.

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Appendix A. Performance of Calibration Sites

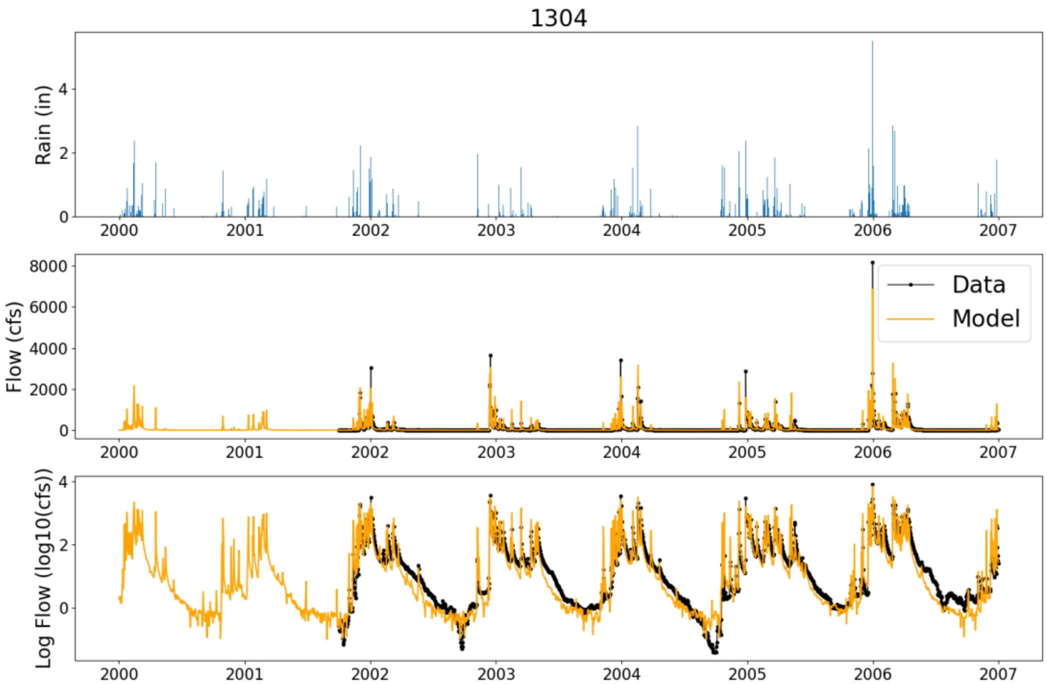

Fig 1a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 1304 (USGS gauge name: SONOMA C A AGUA CALIENTE CA, USGS gauge ID: 11458500)

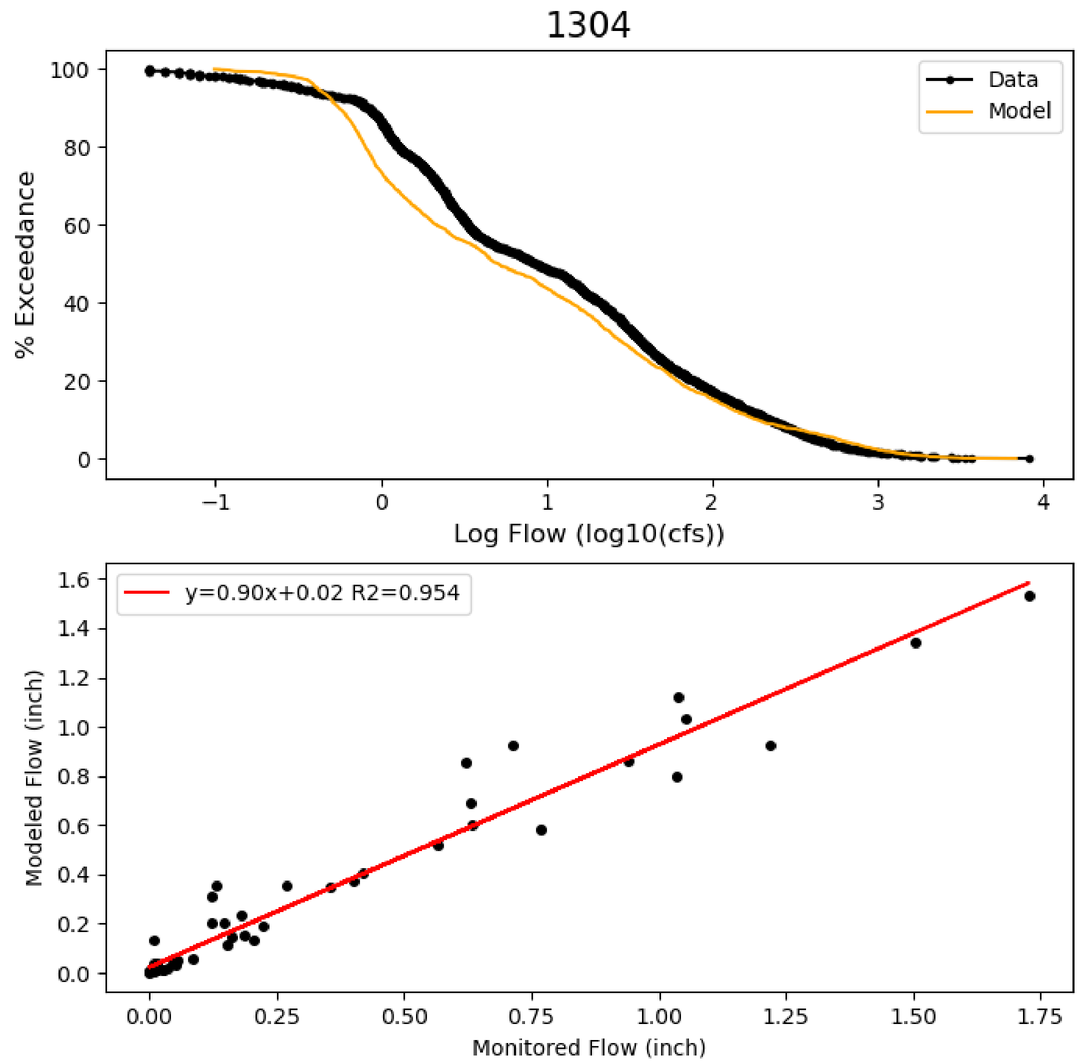

Fig 1b. Top: Stream flow exceedance curve for subwatershed 1304 (USGS gauge name: SONOMA C A AGUA CALIENTE CA, USGS gauge ID: 11458500). Bottom: Monthly modeled versus monitored flow scatter plot Rainfall, daily hydrograph, and log-hydrograph

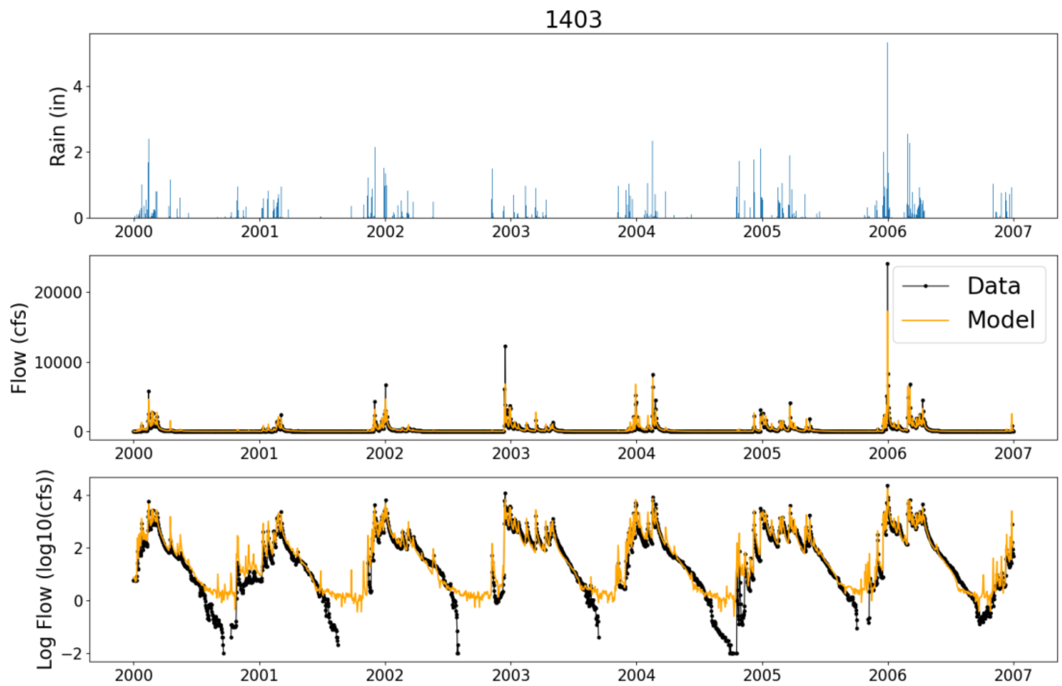

Fig 2a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 1403 (USGS gauge name: NAPA R NR NAPA CA, USGS gauge ID: 11458000)

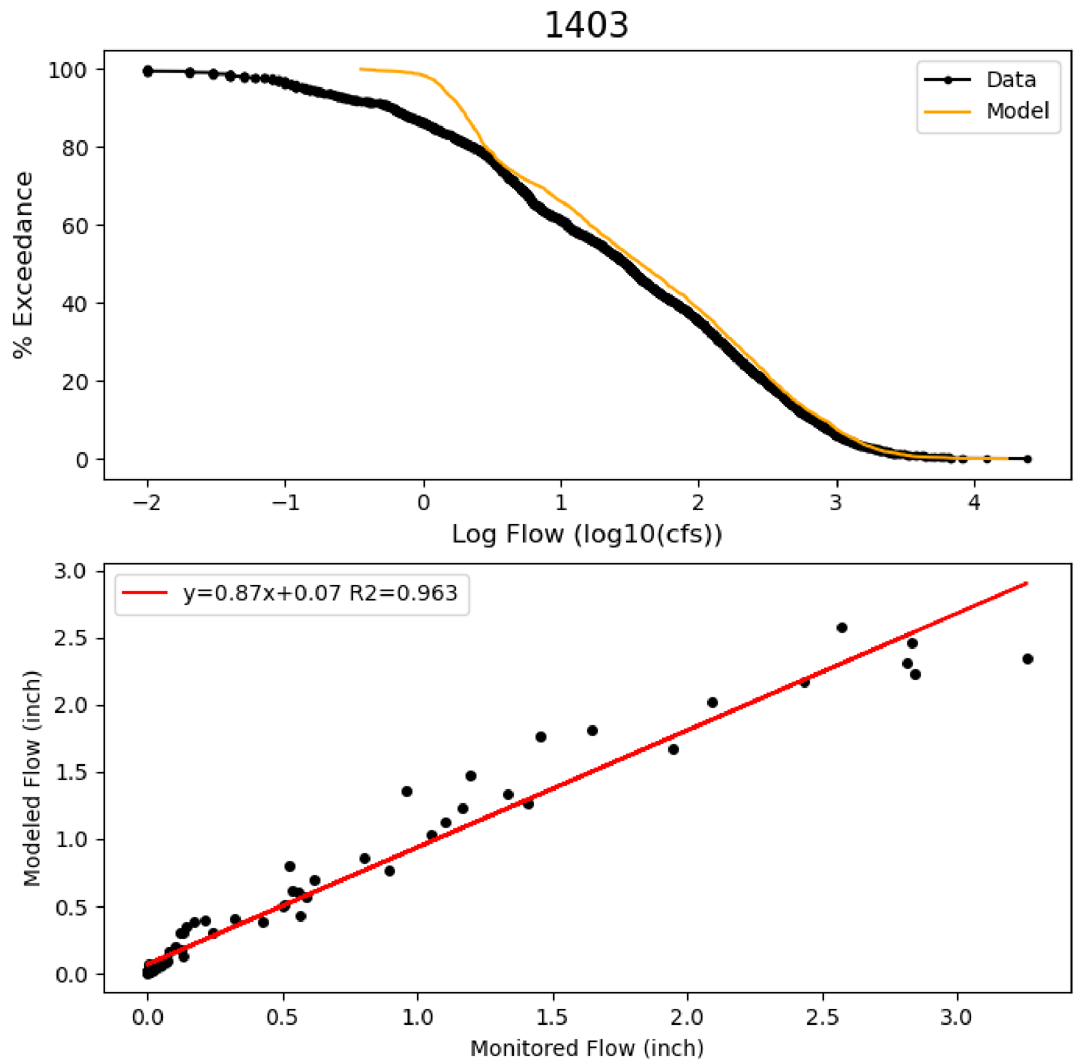

Fig2b. Top: Stream flow exceedance curve for subwatershed 1403 (USGS gauge name: NAPA R NR NAPA CA, USGS gauge ID: 11458000). Bottom: Monthly modeled versus monitored flow scatter plot Rainfall, daily hydrograph, and log-hydrograph

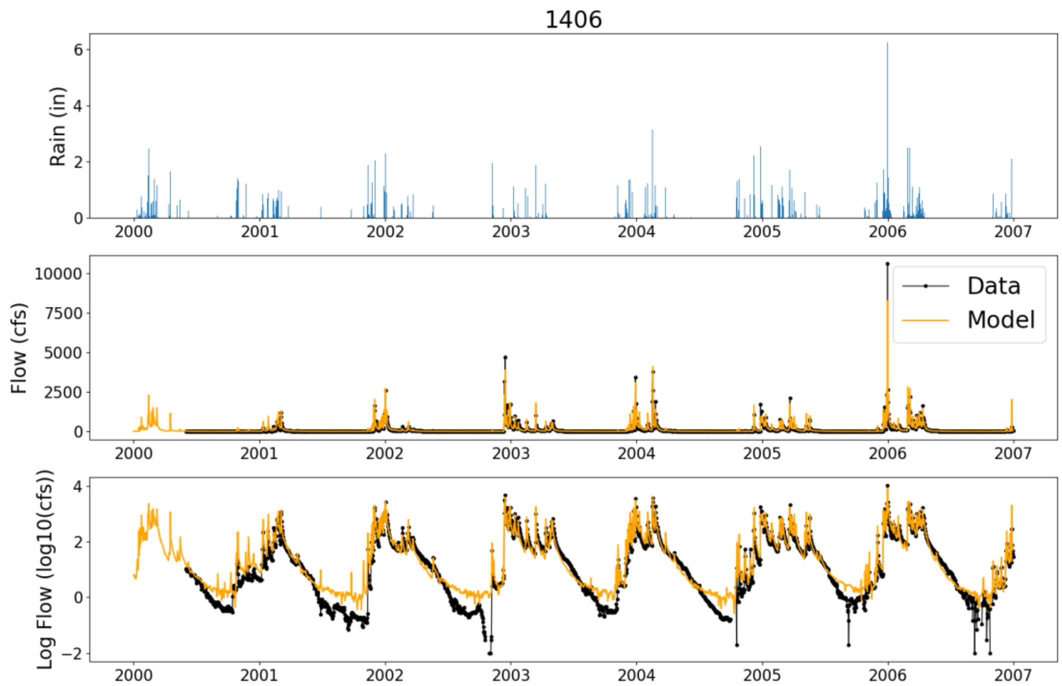

Fig 3a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 1406 (USGS gauge name: NAPA R NR ST HELENA CA, USGS gauge ID: 11456000)

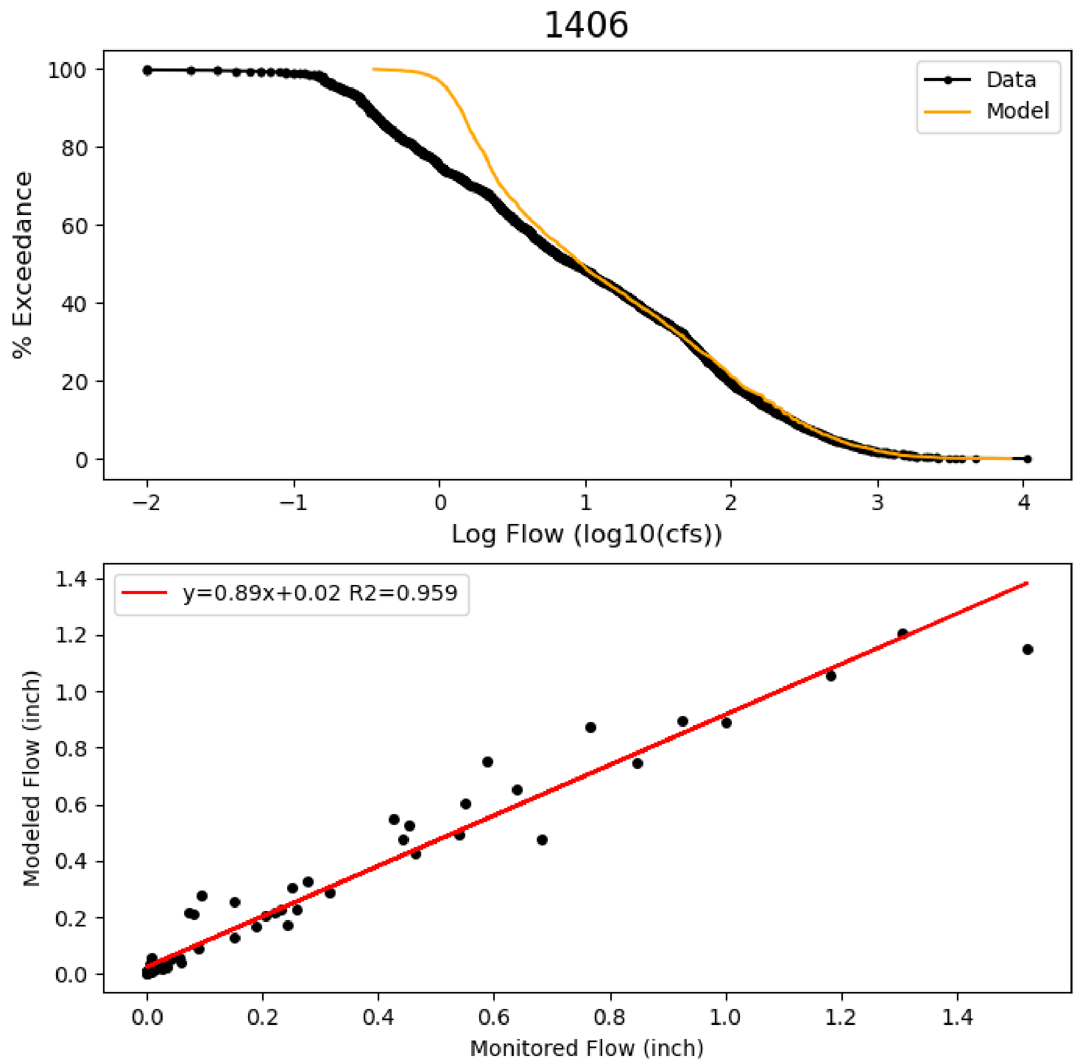

Fig3b. Top: Stream flow exceedance curve for subwatershed1406 (USGS gauge name: NAPA R NR ST HELENA CA, USGS gauge ID: 11456000). Bottom: Monthly modeled versus monitored flow scatter plot

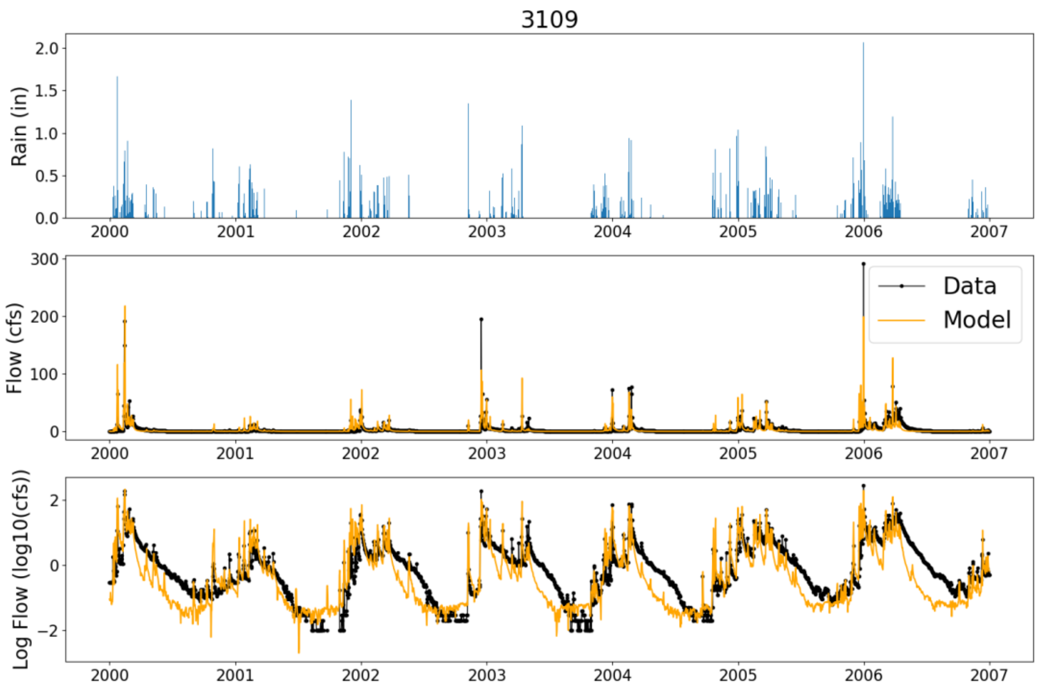

Fig 4a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3109 (USGS gauge name: SAN RAMON C A SAN RAMON CA, USGS gauge ID: 11182500)

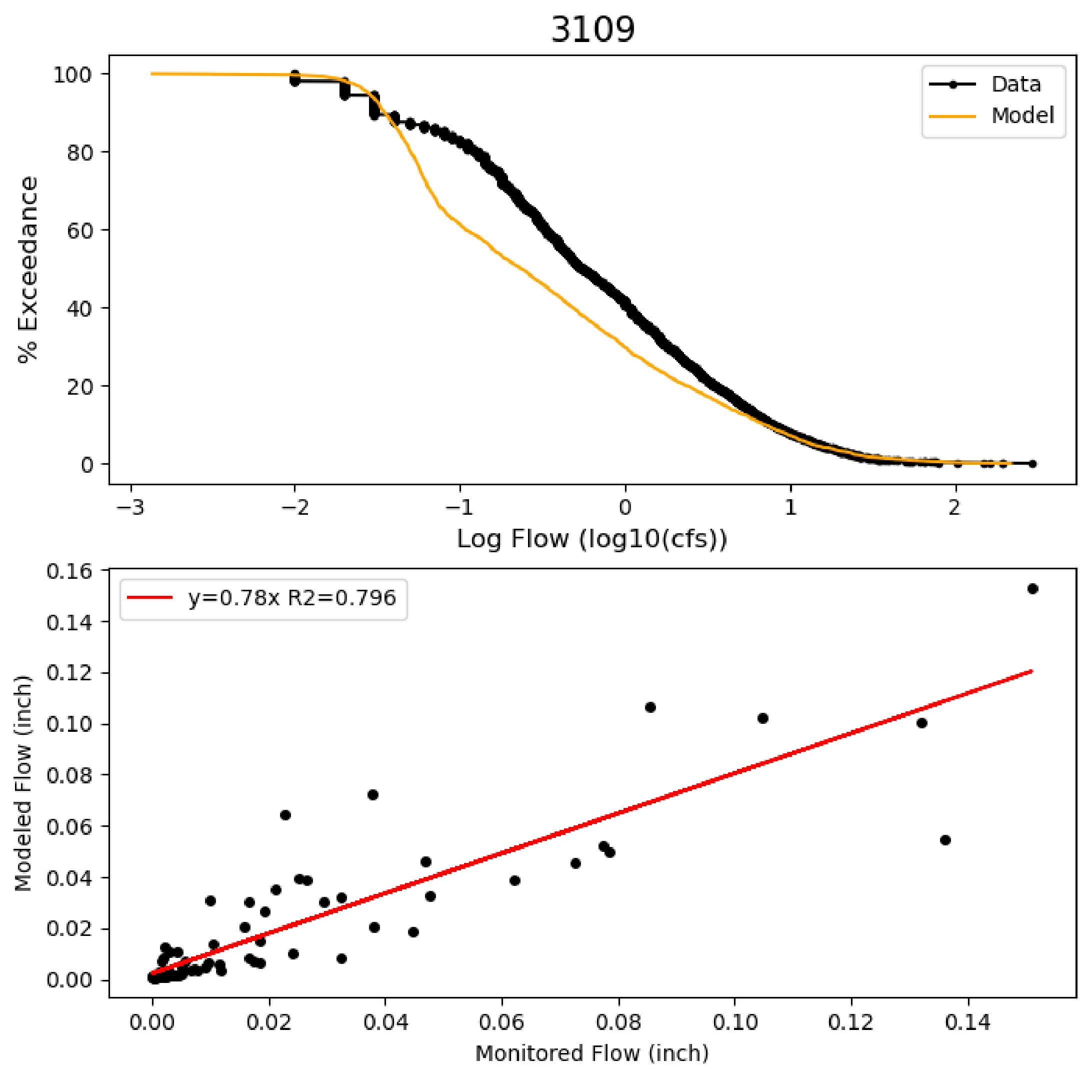

Fig 4b. Top: Stream flow exceedance curve for subwatershed 3109 (USGS gauge name: SAN RAMON C A SAN RAMON CA, USGS gauge ID: 11182500). Bottom: Monthly modeled versus monitored flow scatter plot

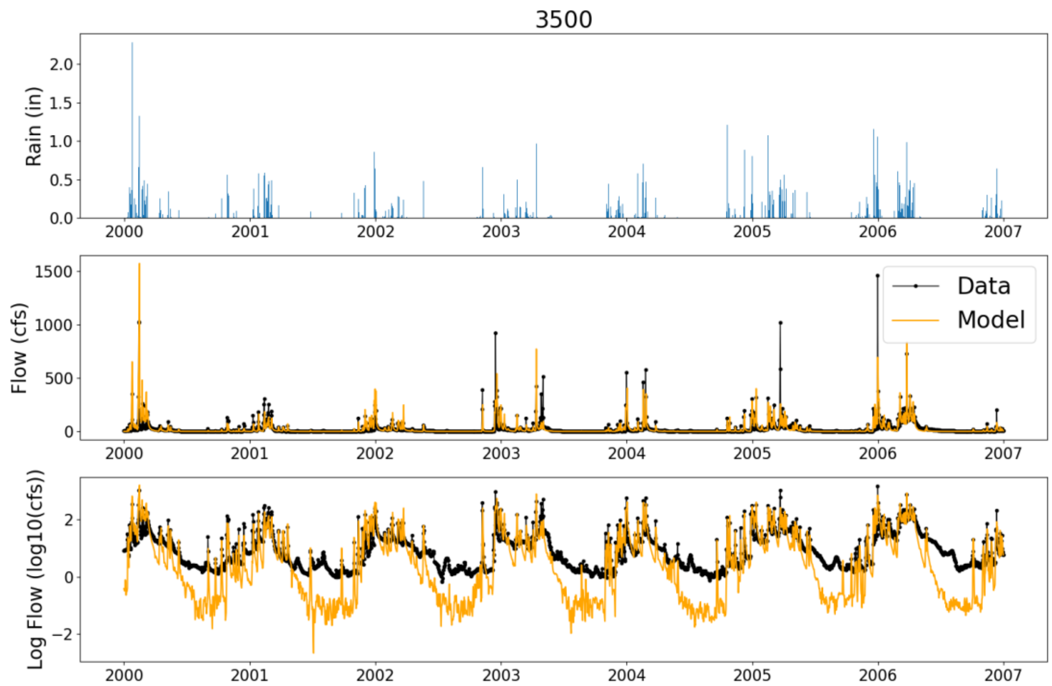

Fig 5a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3500 (USGS gauge name: SAN LORENZO C A SAN LORENZO CA, USGS gauge ID: 11181040)

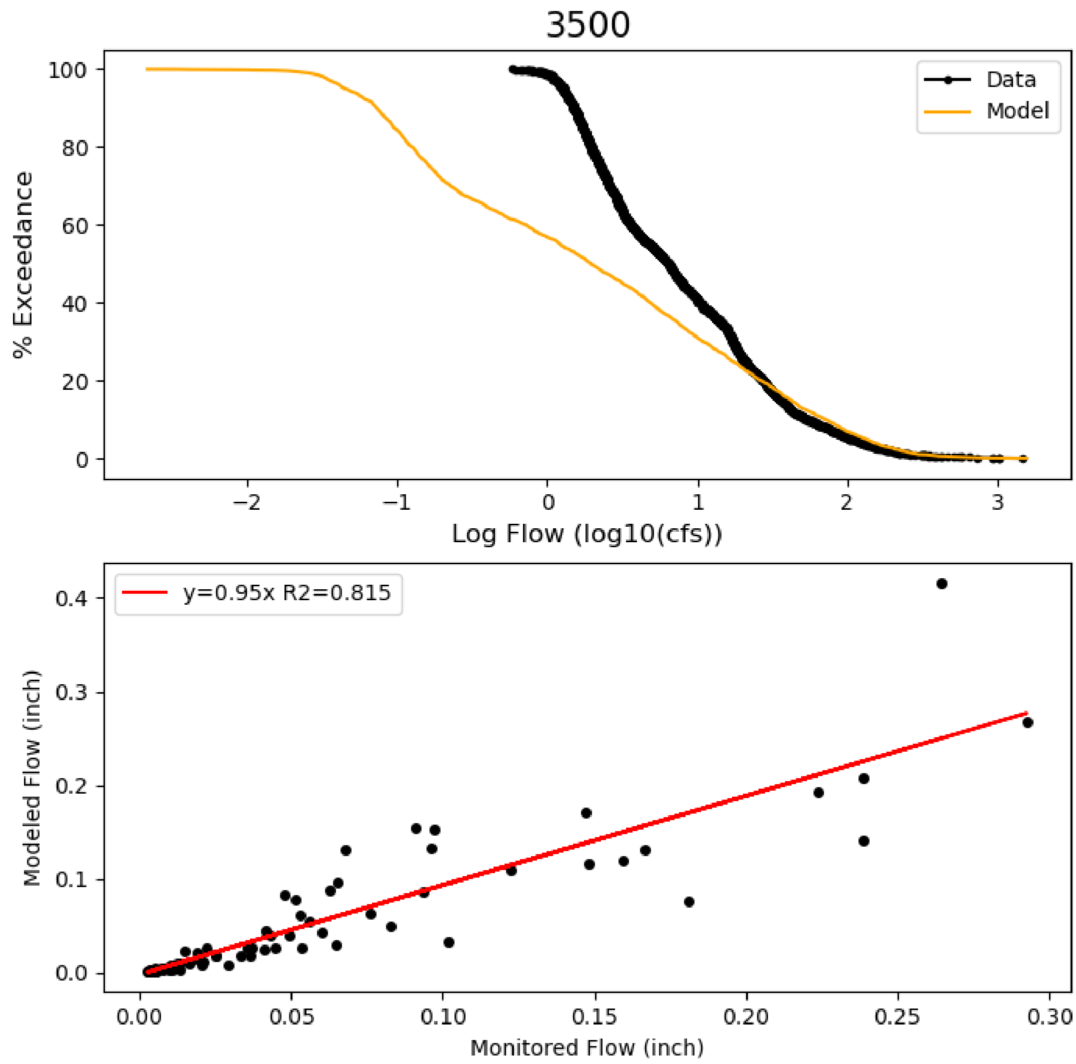

Fig 5b. Top: Stream flow exceedance curve for subwatershed 3500 (USGS gauge name: SAN LORENZO C A SAN LORENZO CA, USGS gauge ID: 11181040). Bottom: Monthly modeled versus monitored flow scatter plot

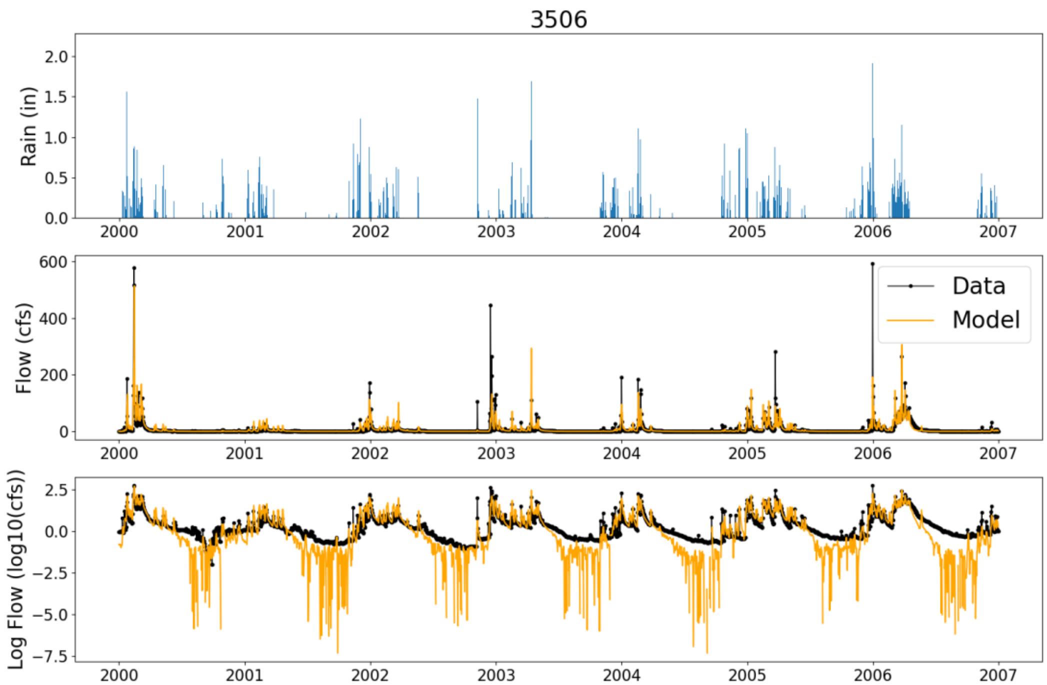

Fig 6a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3506 (USGS gauge name: SAN LORENZO C AB DON CASTRO RES NR CASTRO V CA, USGS gauge ID: 11180825)

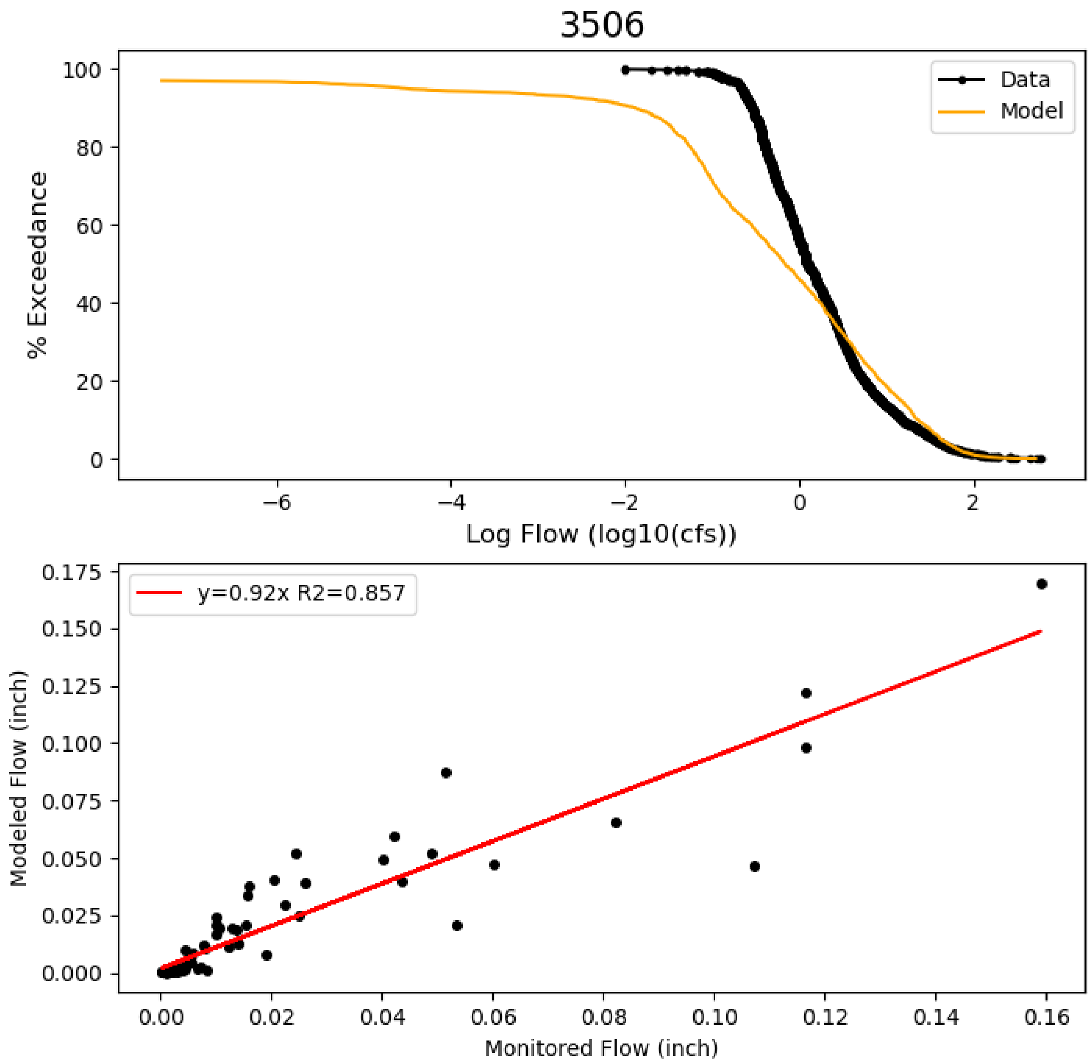

Fig 6b. Top: Stream flow exceedance curve for subwatershed 3506 (USGS gauge name: SAN LORENZO C AB DON CASTRO RES NR CASTRO V CA, USGS gauge ID: 11180825). Bottom: Monthly modeled versus monitored flow scatter plot

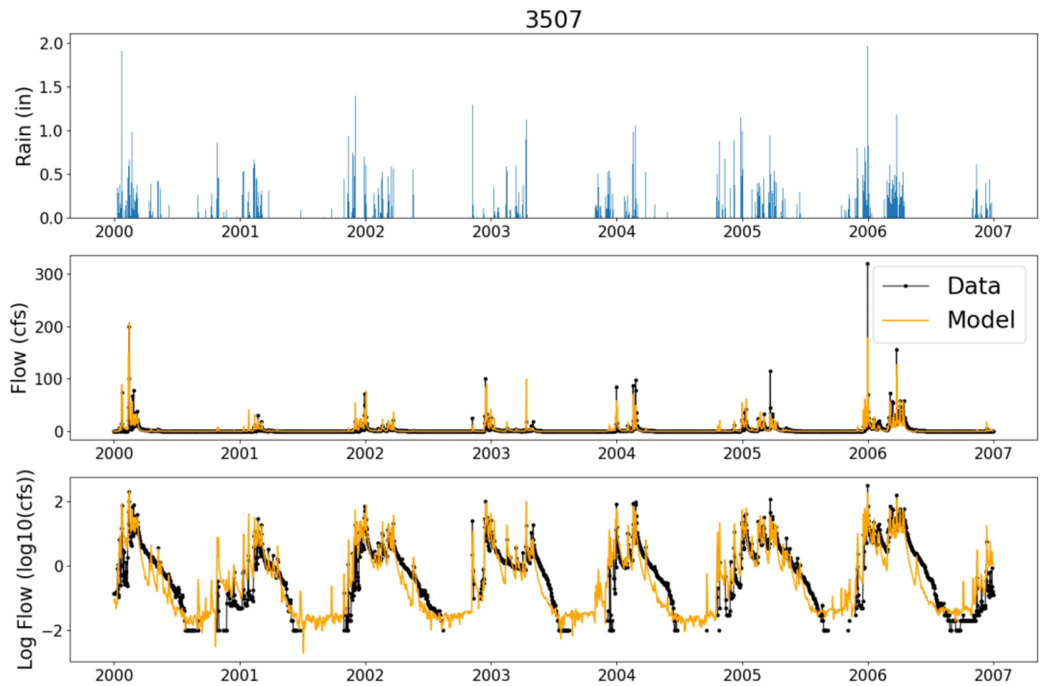

Fig 7a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3507 (USGS gauge name: CULL C AB CULL C RES NR CASTRO VALLEY CA, USGS gauge ID: 11180960)

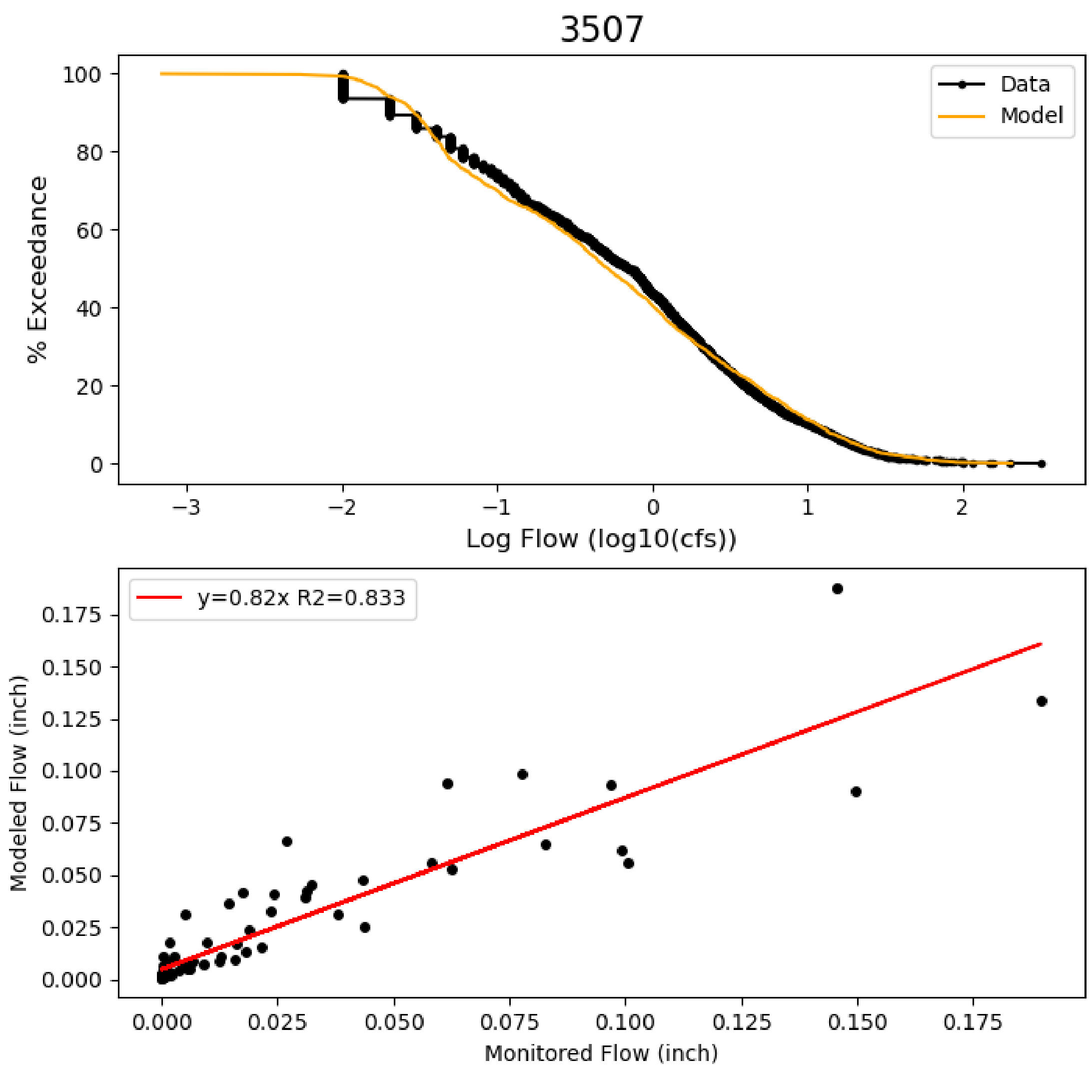

Fig 7b. Top: Stream flow exceedance curve for subwatershed 3507 (USGS gauge name: CULL C AB CULL C RES NR CASTRO VALLEY CA, USGS gauge ID: 11180960). Bottom: Monthly modeled versus monitored flow scatter plot

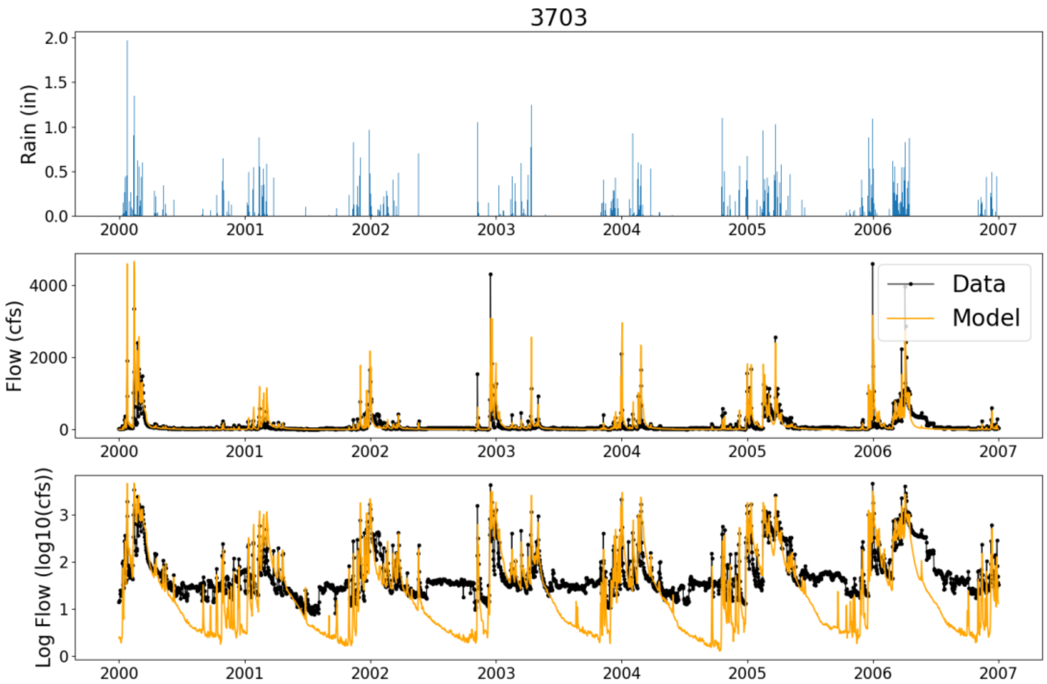

Fig 8a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3703 (USGS gauge name: ALAMEDA CREEK NILES, USGS gauge ID: 11179000)

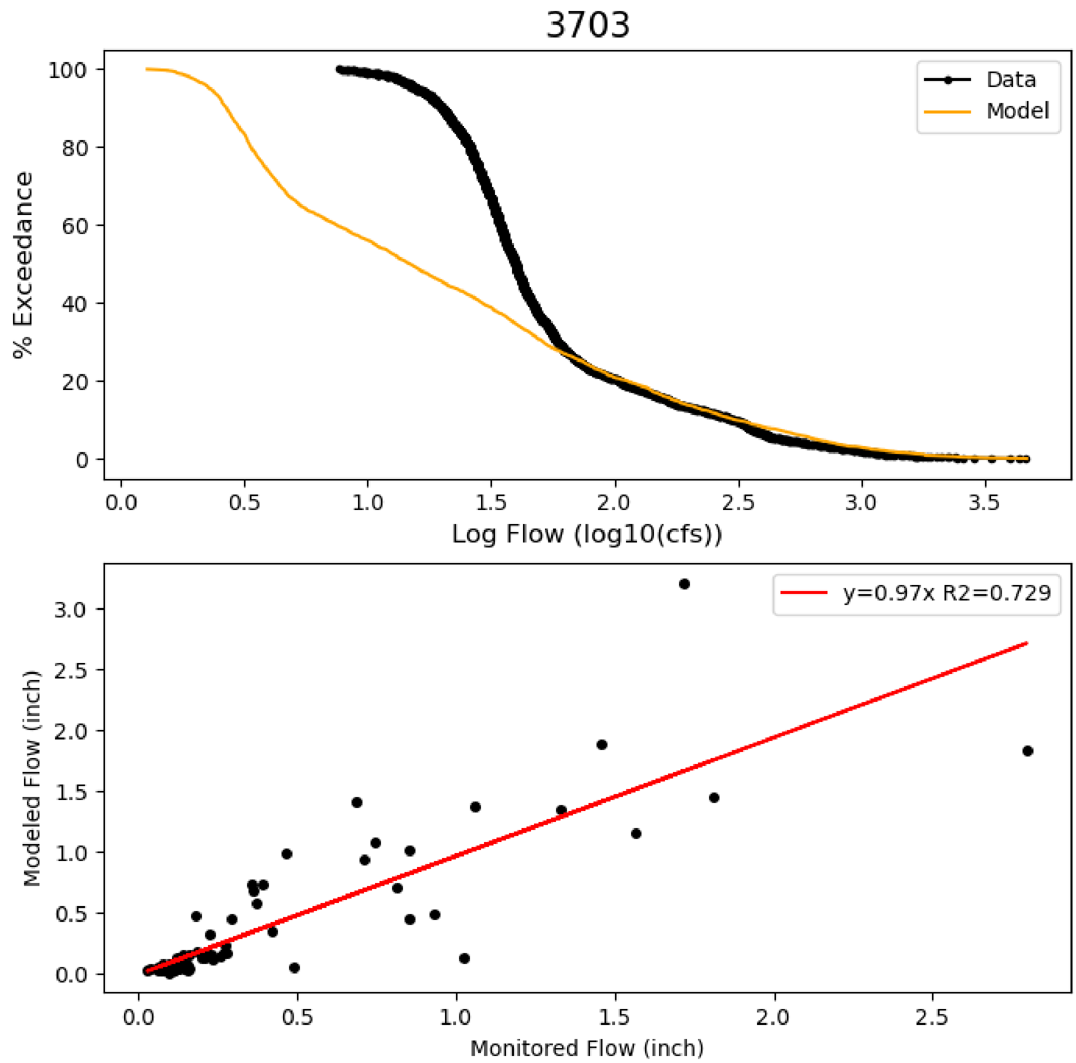

Fig 8b. Top: Stream flow exceedance curve for subwatershed 3703 (USGS gauge name: ALAMEDA CREEK NILES, USGS gauge ID: 11179000). Bottom: Monthly modeled versus monitored flow scatter plot

Fig 9a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 3712 (USGS gauge name: DRY C A UNION CITY CA, USGS gauge ID: 11180500)

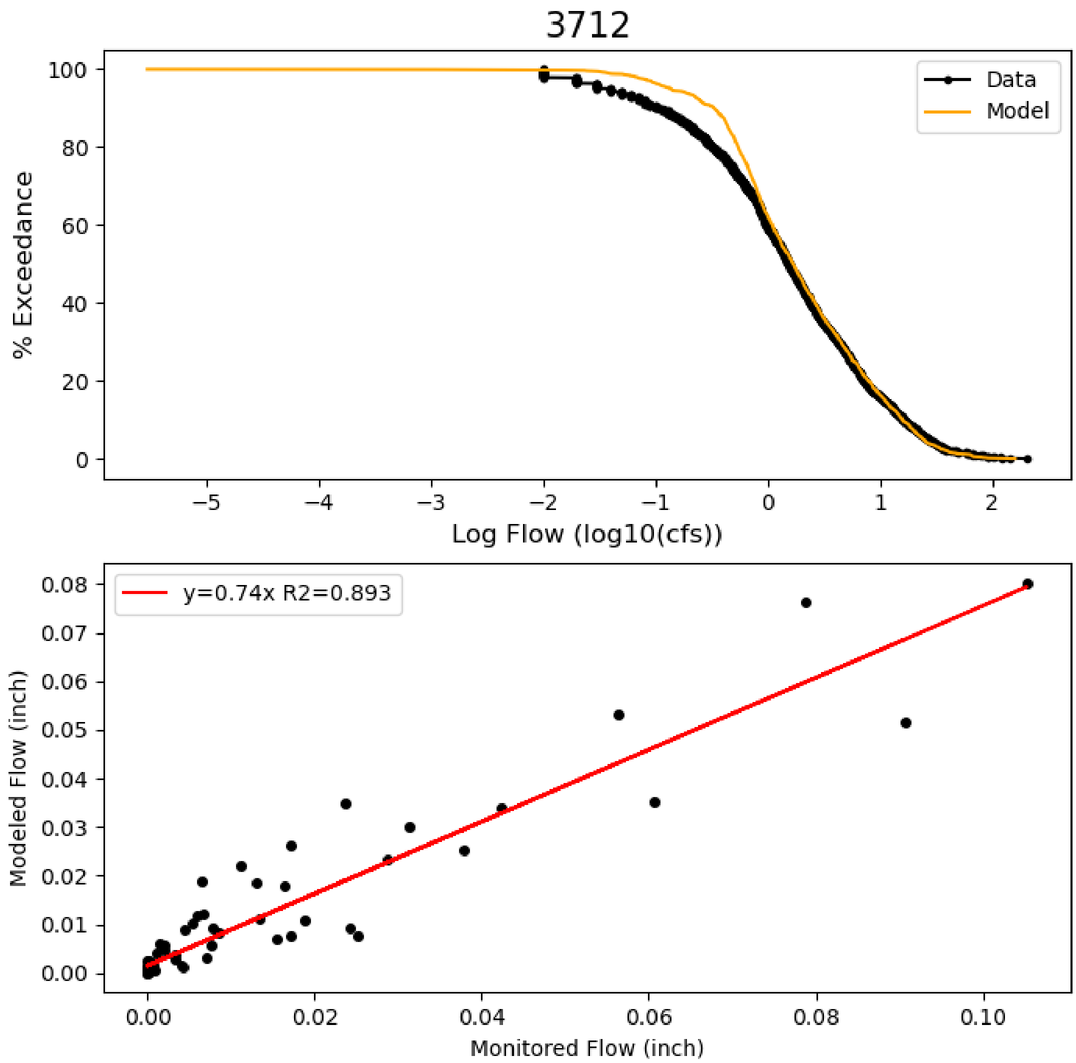

Fig 9b. Top: Stream flow exceedance curve for subwatershed 3712 (USGS gauge name: DRY C A UNION CITY CA, USGS gauge ID: 11180500). Bottom: Monthly modeled versus monitored flow scatter plot

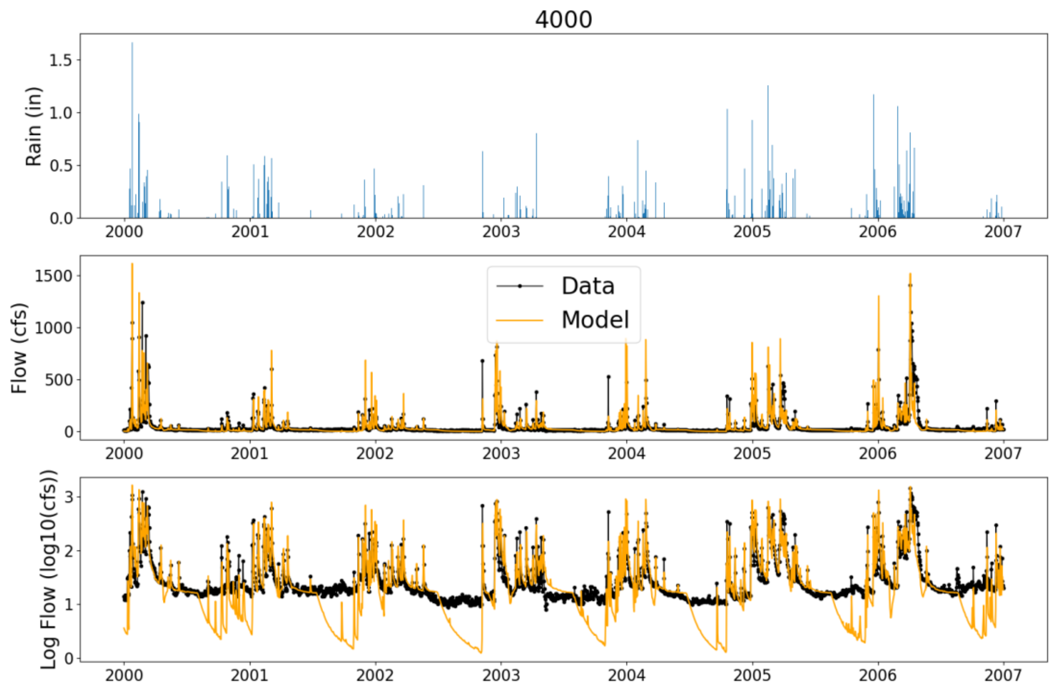

Fig 10a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4000 (USGS gauge name: COYOTE C AB HWY 237 A MILPITAS CA, USGS gauge ID: 11172175)

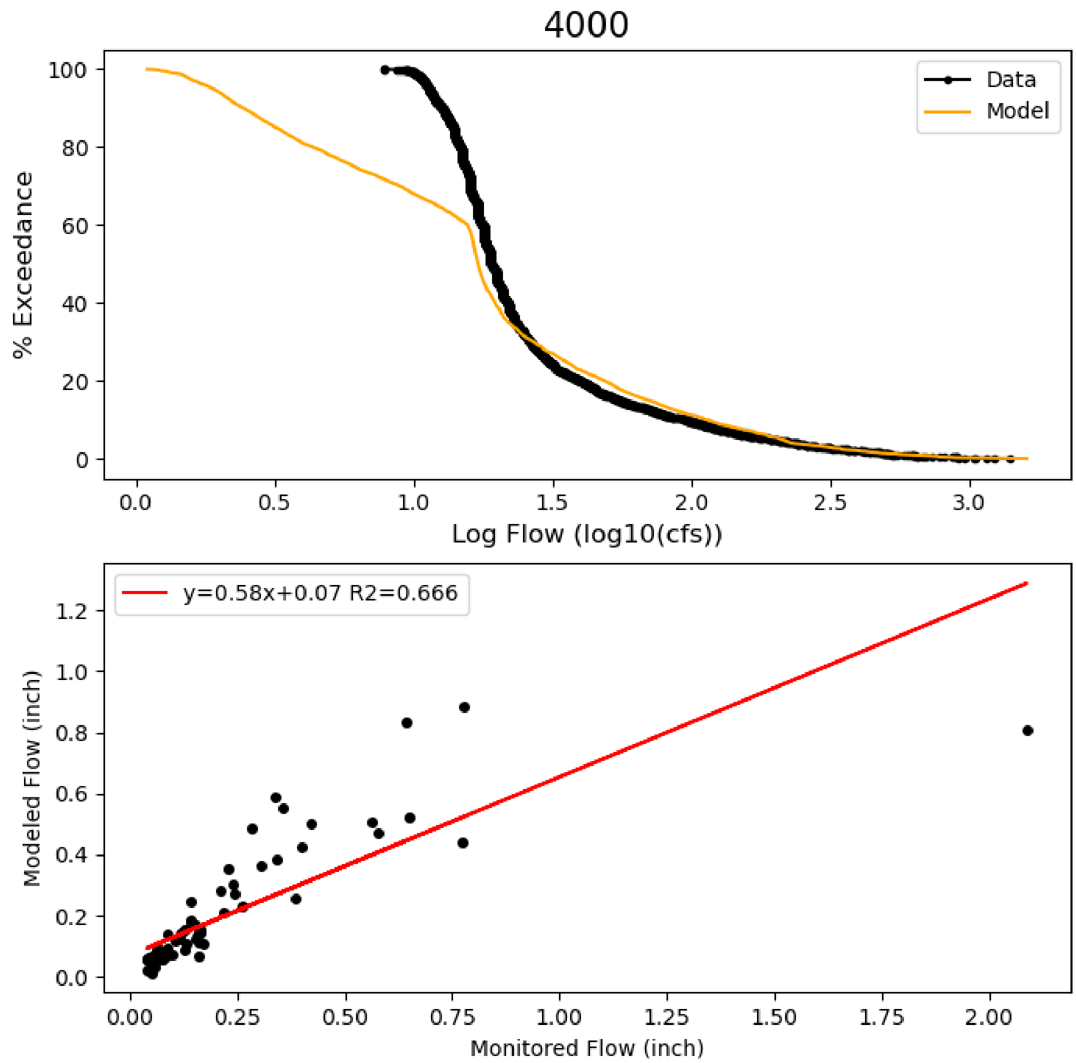

Fig 10b. Top: Stream flow exceedance curve for subwatershed 4000 (USGS gauge name: COYOTE C AB HWY 237 A MILPITAS CA, USGS gauge ID: 11172175). Bottom: Monthly modeled versus monitored flow scatter plot

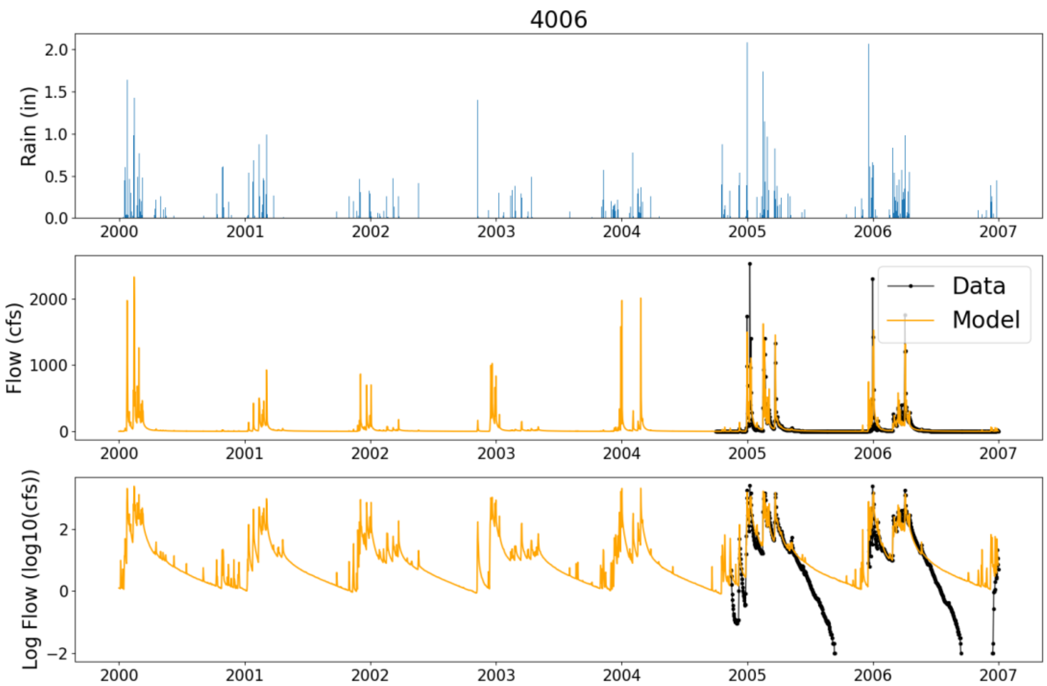

Fig 11a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4006 (USGS gauge name: COYOTE C NR GILROY CA, USGS gauge ID: 11169800)

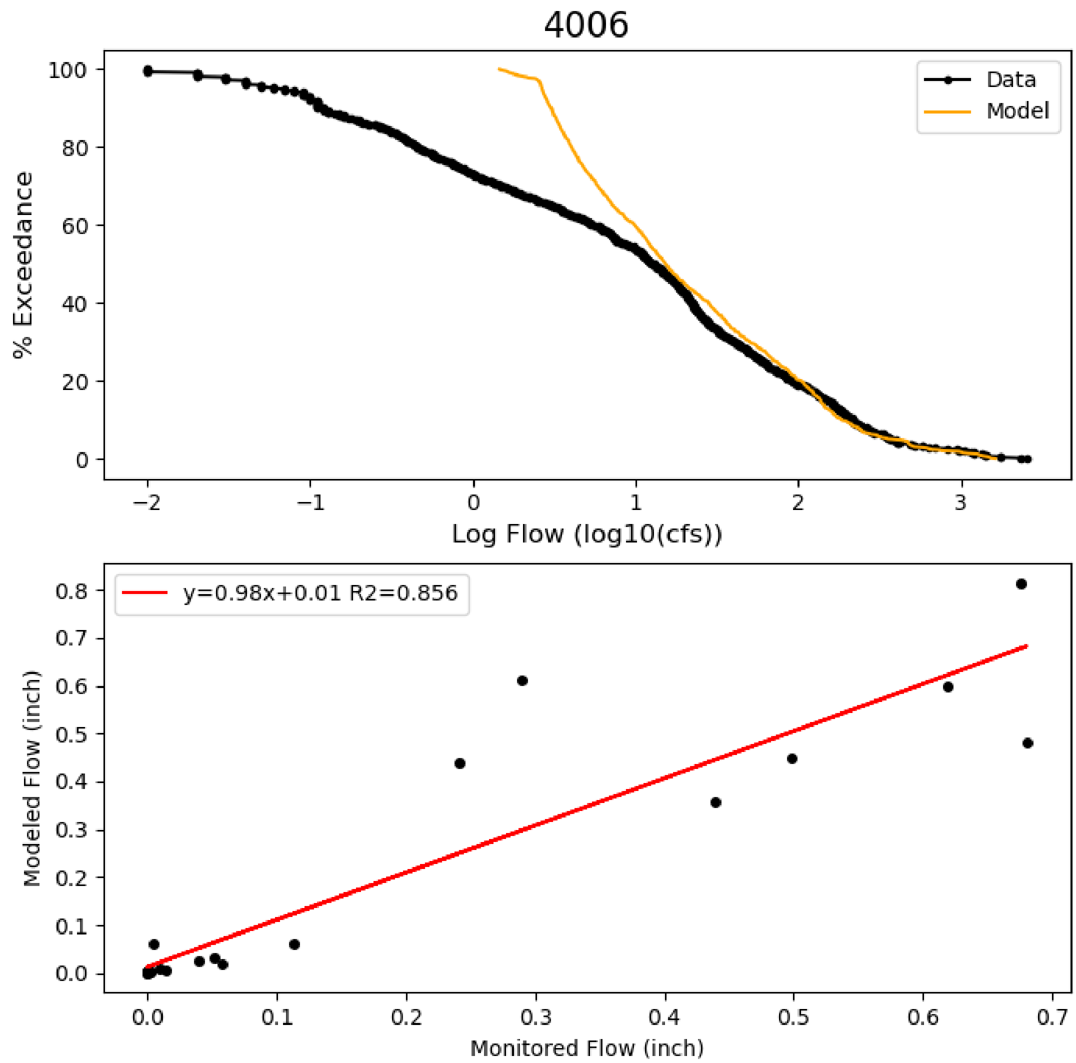

Fig 11b. Top: Stream flow exceedance curve for subwatershed 4006 (USGS gauge name: COYOTE C NR GILROY CA, USGS gauge ID: 11169800). Bottom: Monthly modeled versus monitored flow scatter plot

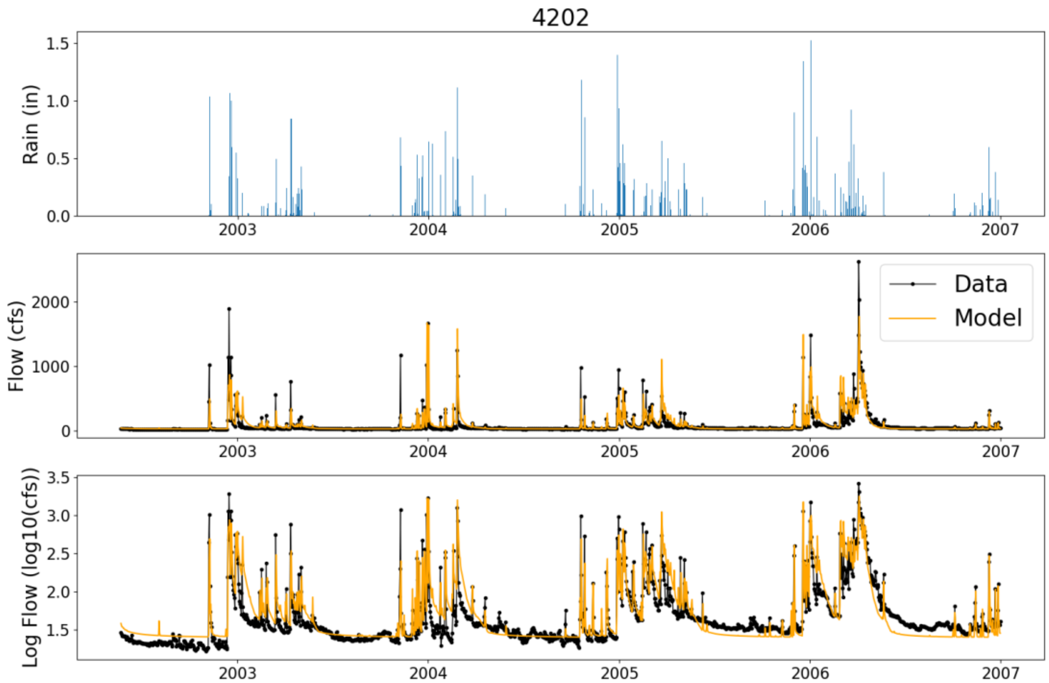

Fig 12a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4202 (USGS gauge name: GUADALUPE R ABV HWY 101 A SAN JOSE CA, USGS gauge ID: 11169025)

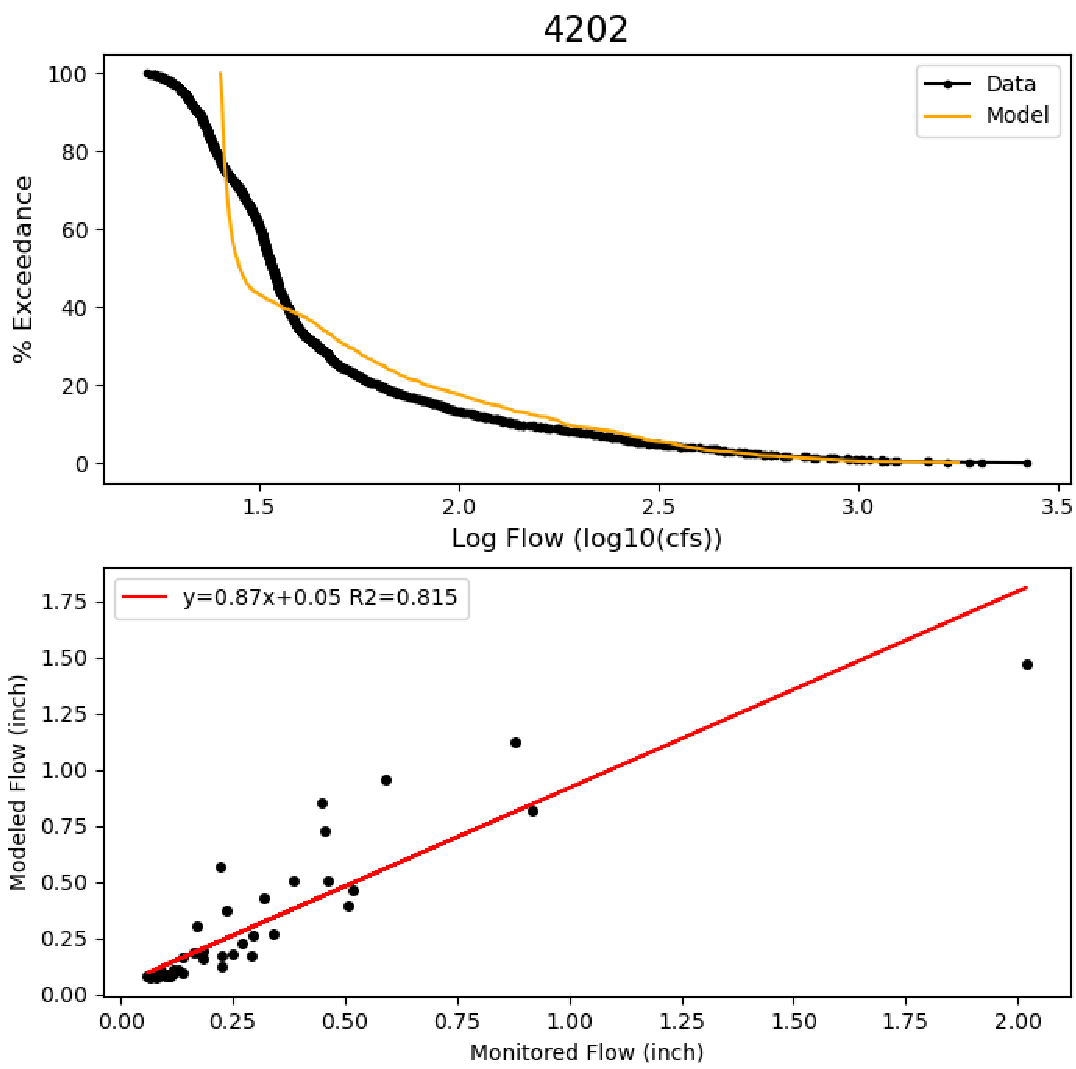

Fig 12b. Top: Stream flow exceedance curve for subwatershed 4202 (USGS gauge name: GUADALUPE R ABV HWY 101 A SAN JOSE CA, USGS gauge ID: 11169025). Bottom: Monthly modeled versus monitored flow scatter plot

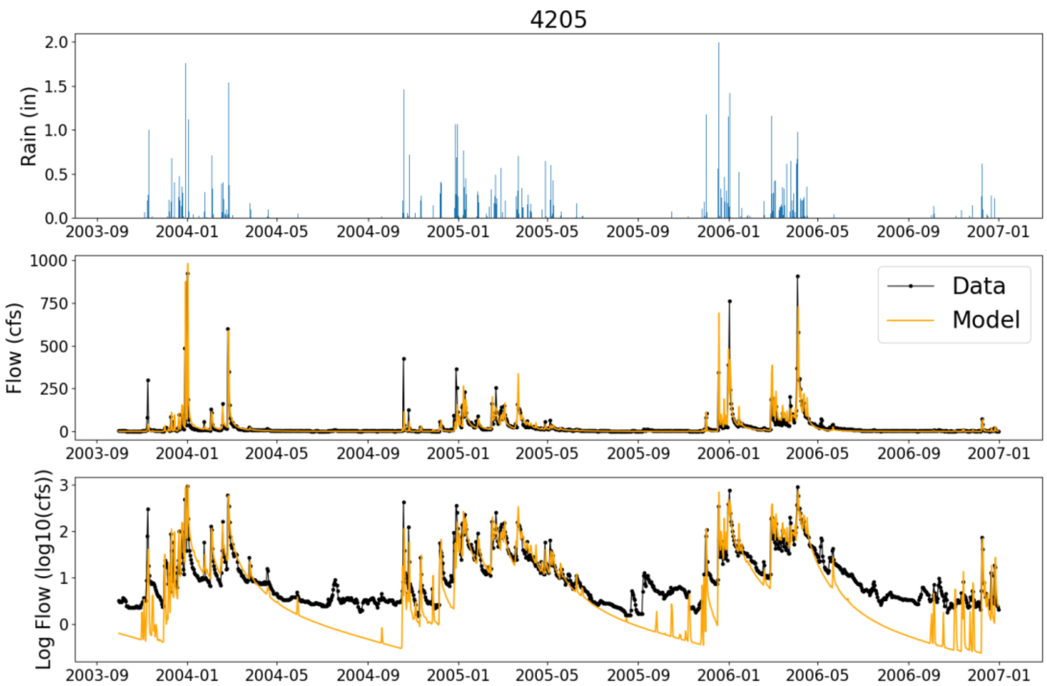

Fig 13a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4205 (USGS gauge name: GUADALUPE R AB ALMADEN EXPRESSWAY A SAN JOSE CA, USGS gauge ID: 11167800)

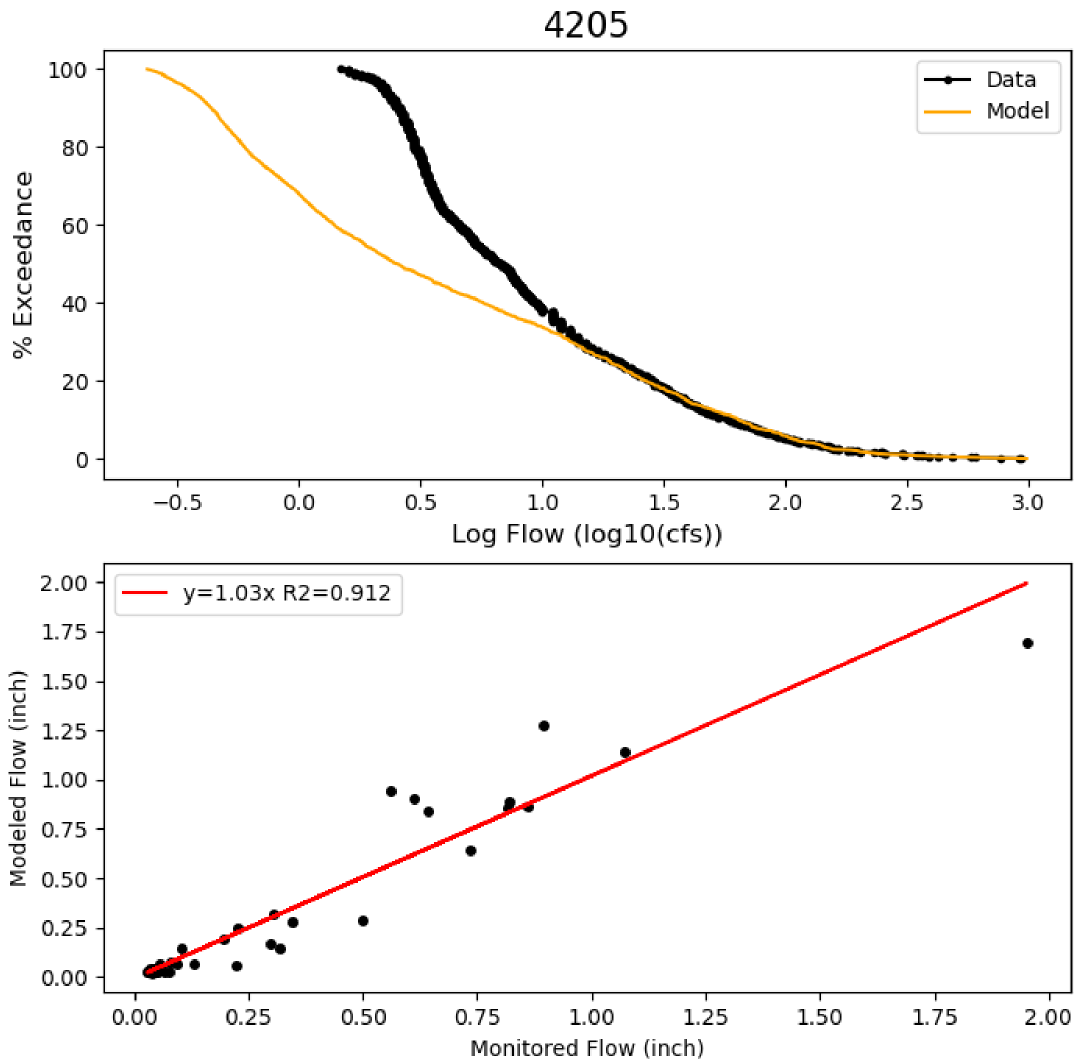

Fig 13b. Top: Stream flow exceedance curve for subwatershed 4205 (USGS gauge name: GUADALUPE R AB ALMADEN EXPRESSWAY A SAN JOSE CA, USGS gauge ID: 11167800). Bottom: Monthly modeled versus monitored flow scatter plot

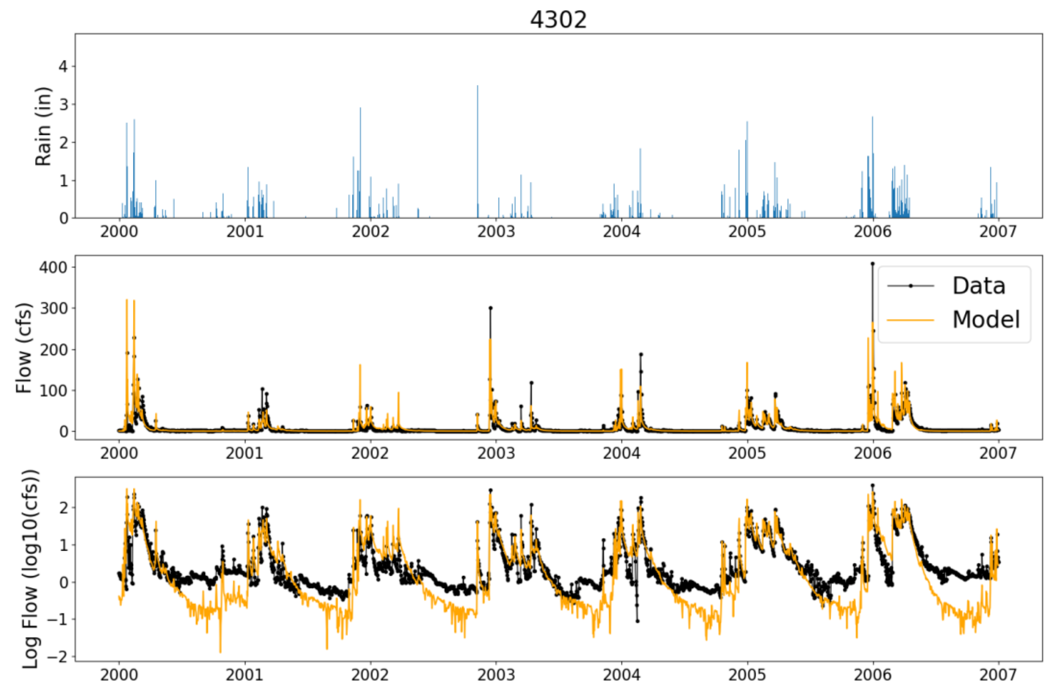

Fig 14a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4302 (USGS gauge name: SARATOGA C A SARATOGA CA, USGS gauge ID: 11169500)

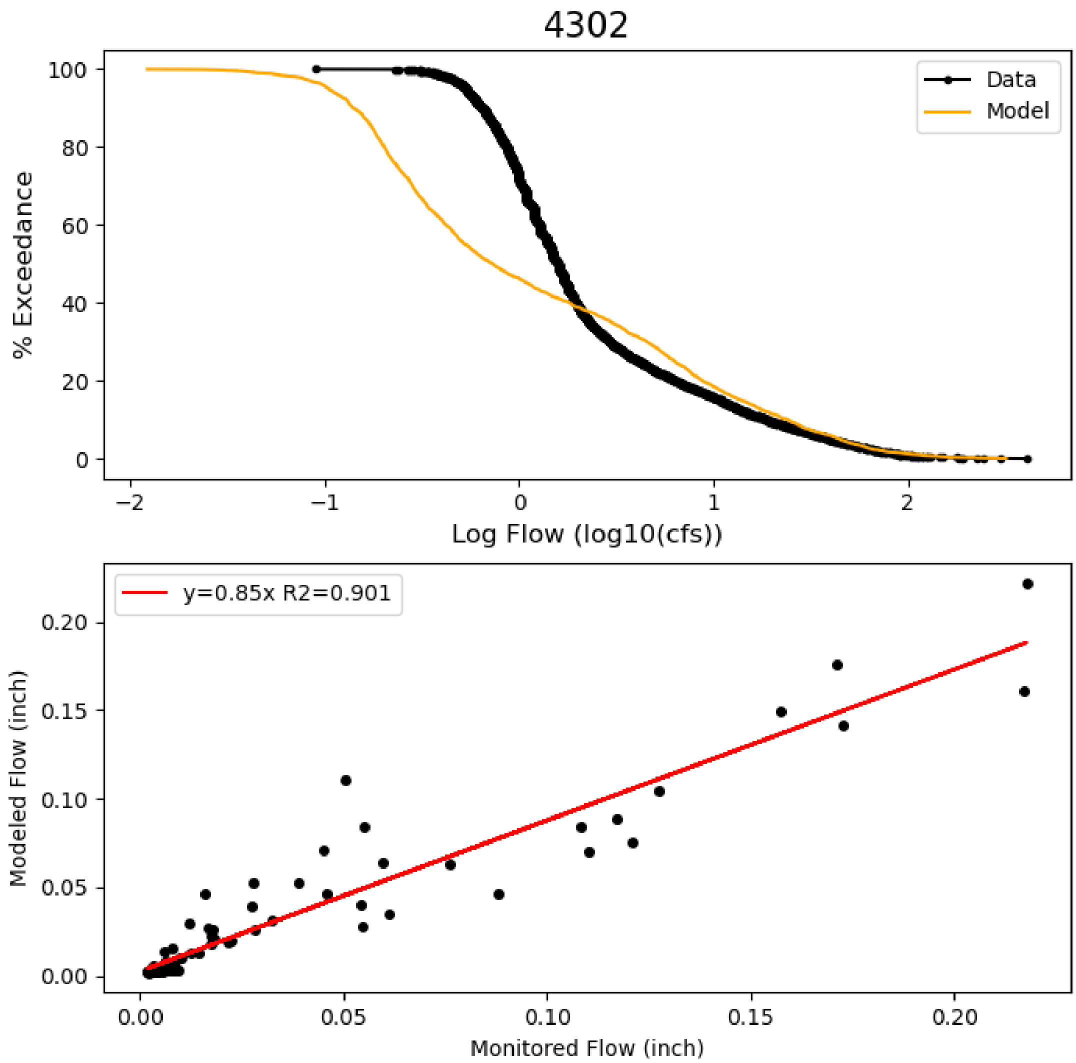

Fig 14b. Top: Stream flow exceedance curve for subwatershed 4302 (USGS gauge name: SARATOGA C A SARATOGA CA, USGS gauge ID: 11169500). Bottom: Monthly modeled versus monitored flow scatter plot

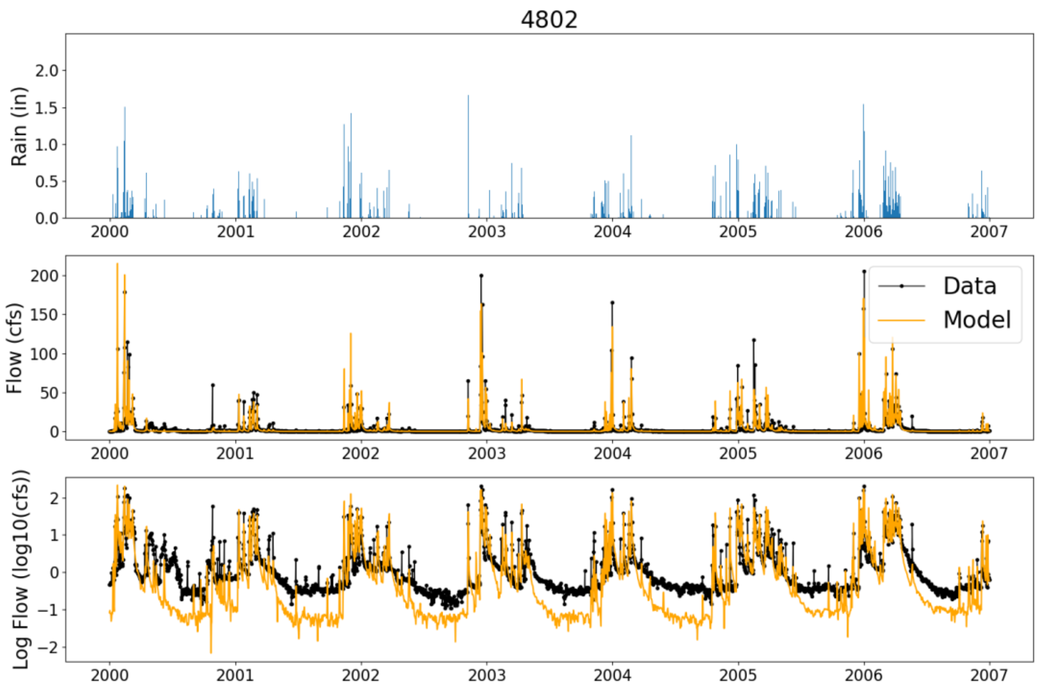

Fig 15a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4802 (USGS gauge name: MATADERO C A PALO ALTO CA, USGS gauge ID: 11166000)

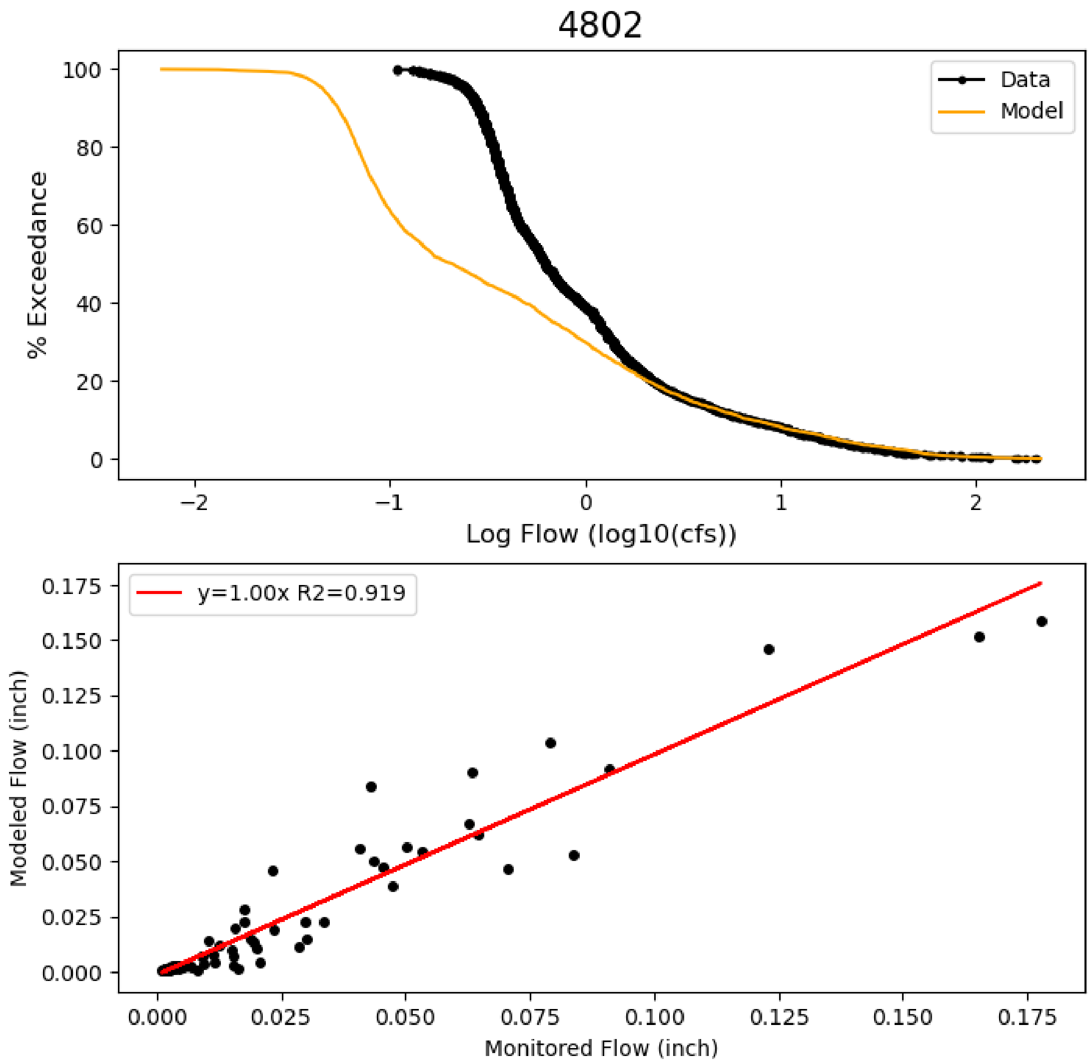

Fig 15b. Top: Stream flow exceedance curve for subwatershed 4802 (USGS gauge name: MATADERO C A PALO ALTO CA, USGS gauge ID: 11166000). Bottom: Monthly modeled versus monitored flow scatter plot

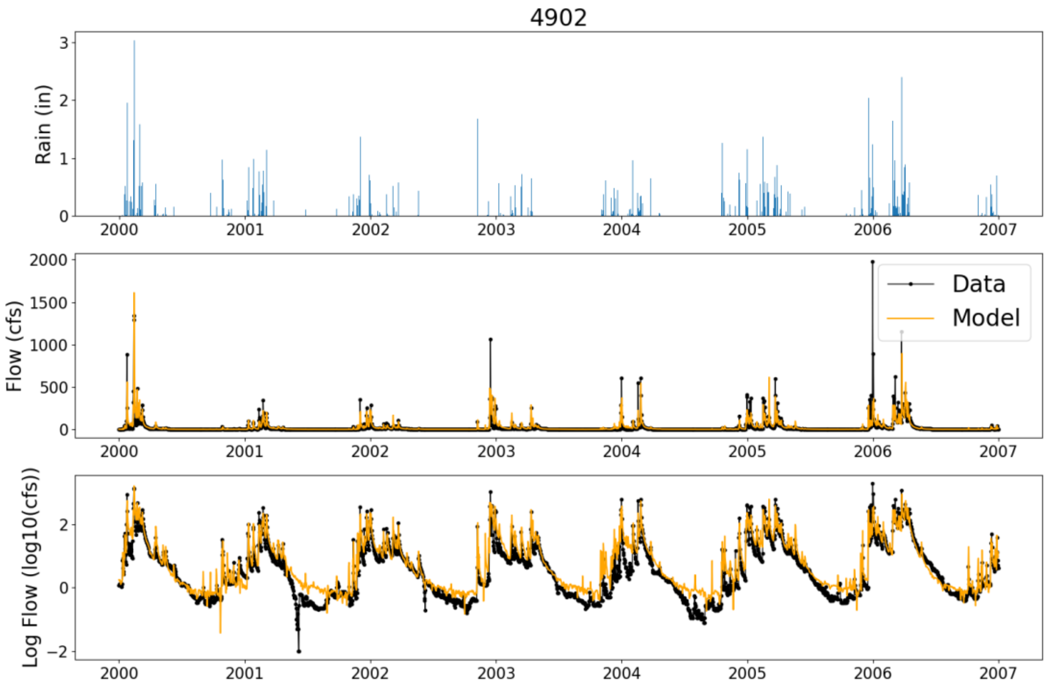

Fig 16a. Rainfall, daily hydrograph, and log-hydrograph for subwatershed 4902 (USGS gauge name: SAN FRANCISQUITO C A STANFORD UNIVERSITY CA, USGS gauge ID: 11164500)

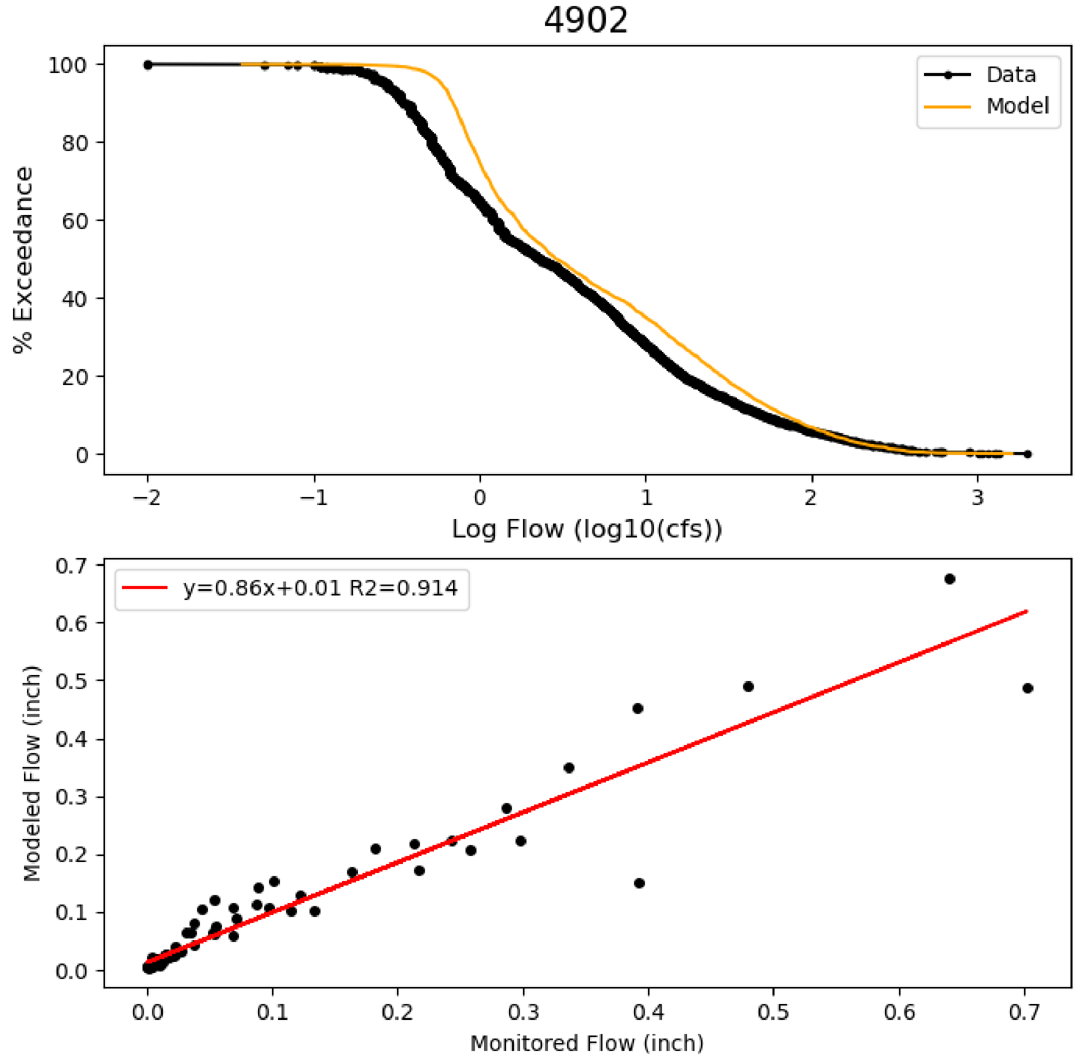

Fig 16b. Top: Stream flow exceedance curve for subwatershed 4902 (USGS gauge name: SAN FRANCISQUITO C A STANFORD UNIVERSITY CA, USGS gauge ID: 11164500). Bottom: Monthly modeled versus monitored flow scatter plot

Appendix B. Range of Major Model Parameters and Reference Summary Table

Name	Definition	Units	Range of values	Reference Range*
LZSN	Lower zone nominal soil moisture storage	inches	3-15	2-15
INFILT	Index to infiltration capacity	in/hr	0.001-1	0.001-1
LSUR	Length of overland flow	feet	100-500	100-700
SLSUR	Slope of overland flow plane	ft/ft	0.015-0.3	0.001-0.3
KVARY	Variable groundwater recession	1/in	0-5	0-5
AGWRC	Base groundwater recession	none	0.85-0.999	0.85-0.999
DEEPFR	Fraction groundwater inflow to deep recharge	none	0-0.3	0-0.5
BASETP	Fraction of remaining ET from baseflow	none	0-0.1	0-0.2
AGWETP	Fraction of remaining ET from active groundwater	none	0-0.05	0-0.2
CEPSC	Interception storage capacity	inches	0.02-0.19	0.01-0.4
UZSN	Upper zone nominal soil moisture storage	inches	0.05-1.5	0.05-2
NSUR	Manning's n for overland flow	none	0.05-0.35	0.05-0.5
INTFW	Interflow inflow parameter	none	1-5	1-10
IRC	interflow recession parameter	none	0.3-0.85	0.3-0.85
LZETP	Lower zone ET parameter	none	0.1-0.6	0.1-0.9

*Reference range values are from:

United States. Environmental Protection Agency. Office of Water, 2000. BASINS technical note 6 estimating hydrology and hydraulic parameters for HSPF. Washington, D.C., United States. Environmental Protection Agency, Office of Water. https://www.epa.gov/sites/production/files/2019-03/documents/basins4.5coremanual.2019.03.pdf