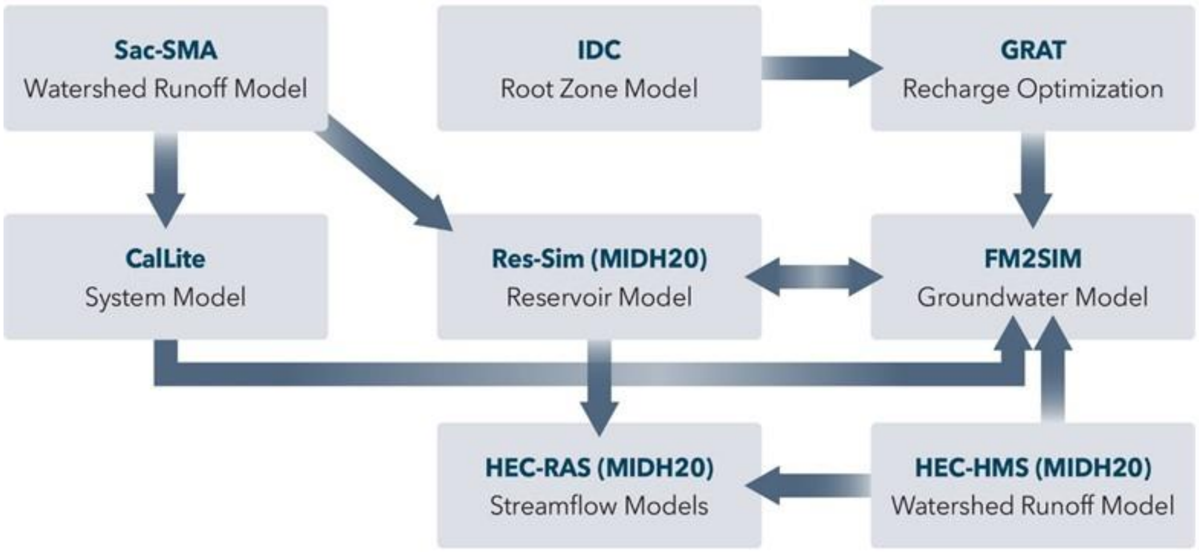
State of California
California Natural Resources Agency
Department of Water Resources

Merced River Watershed Flood-MAR Reconnaissance Study

Analytical Tools Integration



Technical Information Record

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Acronyms and Abbreviations

AF/A	acre-feet per acre
Cal-SIMETAW	California Simulation of Evapotranspiration of Applied Water
CalLite	Central Valley Water Management Screening Model
CCC	crop compatibility calendar
CDEC	*California Data Exchange Center*
cfs	cubic feet per second
CIMIS	California Irrigation Management Information System
CMIP5	Fifth Coupled Model Intercomparison Project
CVP	Central Valley Project
CVS	Central Valley Water System
C2VSimFG	Central Valley Simulation Fine Grid
DAC	disadvantaged communities
CVPDelta	Sacramento-San Joaquin Delta
DWR	California Department of Water Resources
ETc	crop evapotranspiration
FERC	Federal Energy Regulatory Commission
Flood-MAR	floodwater used for managed aquifer recharge
FM2SIM	Flood-MAR Merced Groundwater-Surface Water Simulation Model
GIS	geographic information system
GRAT	Groundwater Recharge Assessment Tool
HEC_DSS	Hydrologic Engineering Center Data Storage System
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center River Analysis System
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation
HMS	hydrologic modeling system
IDC	IWFM Demand Calculator

IPCC	Intergovernmental Panel on Climate Change
ITRC	Irrigation Training & Research Center
IWFM	integrated water flow model
MID	Merced Irrigation District
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe efficiency
NWS	National Weather Service
pdf	probability distribution function
QA/QC	quality assurance/quality control
RMA	recharge management area
SAC-SMA	Sacramento Soil Moisture Accounting
SAC-SMA-DS	Sacramento Soil Moisture Accounting Hydrologic Model
SAGBI	Soil Agricultural Groundwater Banking Index
SGMA	Sustainable Groundwater Management Act
State	State of California
Study	Merced River Watershed Flood-MAR Reconnaissance Study
SWP	State Water Project
USACE	U.S. Army Corps of Engineers
WAFR	water available for rechange
°C	degrees Celsius

Chapter 1. Introduction

1.1 Background

California is known for its variable climate, particularly its perennial oscillation between drought and flood events. This past decade, California has seen two significant multi-year droughts (2012–2016 and 2020–2022) and two significant flood years (2017 and 2023). Climate change is anticipated to exacerbate California's climate variability and consequent vulnerability to extreme climate events. These projected changes will affect, directly and indirectly, different components of the hydrologic cycle, including precipitation, snowmelt, and evapotranspiration processes, which all are linked to water demand and supply (Garrote et al. 2015).

The California Department of Water Resources (DWR) anticipates that the projected changes in California weather patterns could exacerbate both droughts and flood risks and increase challenges for water supply management (California Department of Water Resources 2019). Projections of temperatures suggest greater increases in summer temperatures than in winter temperatures and the intensification of hot extreme temperatures. Also, most climate model precipitation projections anticipate drier conditions in Southern California, heavier and warmer winter precipitation in Northern California, and greater amounts of winter precipitation falling as rain instead of snow (Yoon et al. 2015). In addition, hydrologists associate atmospheric rivers as the main source of 30 to 50 percent of total precipitation occurring in the west coast; these atmospheric rivers also serve as the principal cause of winter floods in California (Dettinger et al. 2014). It is expected that climate change will also affect atmospheric rivers' duration, frequency, and intensity.

This likely condition, which poses a serious threat to California water resources, can also provide an opportunity to use winter floods for groundwater recharge, simultaneously supporting groundwater sustainability, reducing California's vulnerability to flooding risk, and enhancing water for ecosystems. Using floodwaters for managed aquifer recharge (Flood-MAR) is part of the State of California's (State's) strategy to modernize its green-grey infrastructure and comanage the State's entire water portfolio for multiple public and private benefits and water resiliency.

Flood-MAR is an integrated and voluntary resource management strategy that uses floodwater resulting from, or in anticipation of, excess rainfall or snowmelt for managed aquifer recharge on agricultural lands, working landscapes, and managed natural landscapes, including refuges, floodplains, and flood bypasses. The water available for recharge (WAFR) is water that is in excess of all existing uses associated with a stream, within the operational constraints at a diversion location. The WAFR is the key input for Flood-MAR's implementation. Flood-MAR can implement at multiple scales, from individual landowners diverting flood water with existing infrastructure, to using extensive detention and recharge areas and modernizing flood management infrastructure and operations.

Flood-MAR provides the unique opportunity for an integrated partnership of landowners, flood management agencies, water management agencies (surface and groundwater), and reservoir operators that can coordinate operations to achieve flood-risk reduction and increase groundwater recharge benefits through the early evacuation of surface storage to large areas of land for infiltration into groundwater basins.

Many water managers in California see a need to move to integrated watershed management. Working at the watershed scale with multiple water management sectors can improve the ability to advance sustainability. The analytical approach described in this technical information record (TIR) seeks to provide a foundation for integrated watershed planning and management. More specifically, the integrated toolset provides a shared set of analytics across multiple water management sectors, including flood risk, water supply (surface and groundwater) and ecosystems. To mitigate the effect of water management sectors working in siloes, the integrated toolset has been designed to provide analytics with a shared hydrology. Consequently, the analytics collected from each tool in this and following TIRs are based on the same shared hydrology. The analytics for flood, surface and groundwater supply, and ecosystems are intended to be sufficient to meaningfully engage water managers from each of the sectors, as well as landowners.

As noted in *Technical Information Record, Plan of Study*, the Merced River Watershed Flood-MAR Reconnaissance Study (study) is being completed in two phases: (1) a climate vulnerability assessment, and (2) an adaptation assessment that evaluates the performance of Flood-MAR adaptation scenarios. Improved understanding of watershed vulnerability to climate change provides an essential foundation in planning and managing for resilience. An integrated and shared understanding of vulnerabilities across several sectors can effectively motivate collective action and multi-sector solutions. The integrated toolset is designed to provide meaningful assessments of climate vulnerability and adaptation performance for the water management sectors described above.

1.2 Overview of the Climate Change Hydrology and Paleo Streamflow

Several studies have forewarned that climate change will exacerbate California’s climate variability and consequent vulnerability to extreme climate events. These exacerbations are predicted to affect the different components of the hydrologic cycle including precipitation, snowmelt, evapotranspiration, and surface runoff generation, and, consequently, stream flows.

In an integrated approach such as Flood-MAR, it is essential to have the same foundation. Accordingly, all analytical models use, or are based on, the same hydrology to improve understanding of climate change and potential measures affecting water resources. The study uses a paleo reconstruction of daily hydroclimate information that feeds different models (Sacramento Soil Moisture Accounting Hydrologic Model [SAC-SMA-DS], Hydrologic Engineering Center Reservoir System Simulation [HEC-ResSim], and Central Valley Water Management Screening Model [CalLite] as described in following chapters). Specific to this TIR is a chapter (Chapter 2) that provides extensive information on how the hydroclimate reconstruction hydrology is generated based on the University of Arizona’s methodology.

1.3 Overview of the Flood-MAR Modeling Integration Approach

Flood-MAR requires the implementation of an integrated surface-ground water resources approach that can address watershed hydrologic processes from the headwaters to the valley floor and the groundwater systems. To properly address and to integrate these hydrologic processes, there is a need to deploy different modeling tools. These models simulate current and past conditions and would predict future hydro-climatological conditions. For that reason, model development and model integration are fundamental parts of the simulation workflow needed to represent Flood-MAR at the watershed scale.

1.4 Purpose of the Study

DWR, in partnership with the Merced Irrigation District (MID), is conducting a study to explore the potential of implementing Flood-MAR in the Merced River watershed within the San Joaquin Valley. The study is a proof of concept, evaluating the feasibility and effectiveness of Flood-MAR and testing theories in overcoming barriers and challenges to project planning and implementation.

The purpose of this TIR is to describe the innovative modeling integration, use of the modeling tools, and data set needed for this reconnaissance study of climate vulnerability and Flood-MAR adaptation. The modeling tools integrate hydrological processes and watershed management to quantitatively evaluate water flows from headwaters of the Merced River watershed to the valley floor and groundwater, including irrigation and potential recharge using agricultural fields, conveyance facilities, recharge basins and other locations within the MID area.

1.5 Objectives of the Study

Because the modeling tools effectively integrate flood, ecosystem, surface and groundwater analyses, assessing multi-benefits, and supporting sustainable and integrated resources management, they can serve as a template for future studies by documenting the process of planning, modeling, and analyzing a Flood-MAR project at the watershed scale.

The objective of this TIR is to describe the modeling integration process and the utilization of the different models developed for the study. The description focuses on inputs and outputs of the eight different models and how they communicate with each other. The eight models used for the study are:

1. Sacramento Soil Moisture Accounting Hydrologic Model (SAC-SMA-DS)
2. Central Valley Water Management Screening Model (CalLite)
3. Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)
4. Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim)
5. Integrated Water Flow Model Demand Calculator (IDC)
6. Groundwater Recharge Assessment Tool (GRAT)
7. Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)
8. Hydrologic Engineering Center River Analysis System (HEC-RAS)

Chapter 2. Climate Change Hydrology and Paleo Streamflow

2.1 Climate Change Analysis

Improved understanding of climate change and potential measured effects on water resources hydrology is an essential anticipated outcome of this study. The climate change analysis adopted enables planning for future changes that is informed by the best available science but is not dependent on precise prediction of future values. Instead, the process focuses on incorporating credible information on future changes within traditional risk-based planning approaches and combining historical trends with future expectations. These effects are delineated through a climate stress test, also known as "decision scaling" that is independent of projections of future climate. A more detailed description of climate vulnerability and presentation of climate change vulnerability assessments for flood risk, water supply, and ecosystem is included in *Technical Information Record, Baseline Performance and Climate Change Vulnerability.*

2.2 Climate Change Scenarios

The explored range of exposure to changes in average annual temperature and precipitation was informed by Intergovernmental Panel on Climate Change's (IPCC's) Fifth Coupled Model Intercomparison Project (CMIP5) climate change projections spatially averaged over watershed areas contributing flow to the Central Valley Water System (CVS) (Taylor et al. 2012).

In this study, a total of 30 100-year daily weather traces were generated to cover temperature change (+0 degree Celsius [°C] to +4 °C, by 1-°C increments) and precipitation change (-20 percent to +30 percent, by 10-percent increments) shifted from historical averages. These climate traces, constructed using the simple delta method (which applies additive change to daily temperature and ratio [change factor] to daily precipitation), are identical to the historical in internal variability (the historical observed sequence of wet and dry years) but unique in average temperature and precipitation.

The climate traces of daily precipitation and temperature are input to the hydrologic model SAC-SMA-DS to generate streamflow for subsequent input to the reservoir simulation models HEC-ResSim and CalLite 3.0, outputs of which are integrated into the remaining models in the study. The outcome of this integrated climate stress test process allows the systematic exploration of climate change vulnerability of the water system in response to a wide range of meteorological input.

2.3 Risk

To develop a single “most likely” future system performance condition, the system response under each of the 30 alternative climate states is combined with a probabilistic estimate of the future climate state at a selected time horizon. This is accomplished through defining a probability distribution function (pdf) for the average precipitation and temperature change domain projected by the general circulation models at any user-selected 30-year period. This approach allows developing a probabilistic description of the impact of future climate changes on system performance, which enables and supports risk-based decision analysis.

2.4 Use of Paleo Reconstructions in the Development of Daily Hydroclimate

Hydroclimate reconstructions were released in 2014 using updated tree-ring chronologies for the Klamath, San Joaquin, and Sacramento River basins (Meko 2014). The paleo reconstructions, prepared by the University of Arizona, allow assessment of hydrologic variability over the course of centuries and millennia and provide a historical context for assessing recent droughts. In the study, the most recent century of the paleo reconstructed record of San Joaquin four-river annual streamflow was coupled with historical daily temperature and precipitation from 1950 through 2013 (Livneh et al. 2013) to generate a 100-year daily climate trace (Water Years 1900 through 1999). (The San Joaquin four-river annual streamflow is the sum of water year [October 1 through September 30] Stanislaus River inflow to New Melones Lake, Tuolumne River inflow to New Don Pedro Reservoir, Merced River inflow to Lake McClure, and San Joaquin River inflow to Millerton Lake.) The paleo reconstructed San Joaquin four-river streamflow provides additional natural climatic variability to the study by enabling inclusion of wet and dry cycles occurring in the first half of the 20th century. Details of the steps to construct the paleo informed sequence are available in Appendix A, “Climate Change Hydrology and Paleo Streamflow.”

Chapter 3. Flood-MAR Modeling Integration Approach

3.1 Investigation of Flood-MAR Concepts

To fully investigate the Flood-MAR concepts in the Merced River watershed as described in the Flood-MAR white paper (California Department of Water Resources 2018), there is an imperative need to properly understand the watershed physical processes and management practices. These watershed processes and practices are studied for historical and potential future conditions to promote a coordinated development and management of water, land, and related resources to maximize the resultant economic and social welfare in an equitable manner, including ecosystem improvements. Flood-MAR has been conceptualized to be a multi-benefit approach providing flood risk reduction, drought preparedness, aquifer replenishment, ecosystem enhancement, and other potential benefits, including meeting the water supply needs and existing commitments and demands of participating water agencies and reservoir operators. Flood-MAR is also a promising climate change adaptation strategy that takes an integrated approach to help address two of the most challenging elements of future climate changes: more intense and flash flood flows and longer, deeper droughts. In addition, agricultural lands and working landscapes are assets as they become effective and essential pathways to storage. These different Flood-MAR elements are investigated in the study through the development and application of an analytical set of modeling tools as described below.

3.2 Integration of Surface and Groundwater Analyses and Models

Simulation of watershed hydrological processes involves the integration of atmosphere, surface water, unsaturated/soil zone, and groundwater subsystems processes of the hydrologic cycle and their dynamic interactions. Hydrologic subsystems can have different spatial and temporal scales. Similarly, there are different levels of integration of hydrologic subsystems: stream system and groundwater; land surface processes, agriculture, and groundwater;and climate, soil and root zones, surface water, and groundwater. The integration of these hydrologic subsystems can be implemented through different approaches. A relatively basic approach for model integration involves models that can be coupled in one direction to pass water information from one subsystem to another. This approach is relatively simple, inexpensive, and easy to implement but it can potentially bypass important feedback effects because of the one-way information flow. An intermedium approach is when coupled models interactively solve other subsystems independently and system information is passed back and forth at every timestep between models. This approach increases complexity, computational cost, and response to a nonlinear set of responses, but produces more precise results when compared with the results from a one-way direction modeling approach. The most complex approach is when models are fully coupled solving all subsystems simultaneously using a series of equations governing the conditions of each system and their interaction. This approach offers a detailed representation of physical processes, but it is computationally more expensive and has a high degree of parameterization. In the study, as it is described below, a hybrid approach was selected. This approach has some models with least need for iteration, coupled in one direction, and other models that require more iteration to achieve the accuracy of the outcome linked iteratively to pass system information back and forth, and a model that simulates dynamic, integrated systems.

3.3 Model Integration: How It Is All Brought Together

Models used in the study focused on existing and publicly available models. The source of models used here falls under three main categories: models modified for Flood-MAR purposes, models created exclusively for study purposes, and models used for Flood-MAR purposes as they were conceptualized and originally built. The models modified for Flood-MAR purposes were collected from other agencies or institutions that developed the models for purposes other than the Merced Flood-MAR analysis. These models were modified and adapted to respond to the needs of the project. The models under this category are: HEC-HMS, HEC-ResSim, GRAT, FM2Sim, and HEC-RAS. The second category corresponds to models developed for Flood-MAR purposes, designed to easily respond to the specific needs of the study. The model under this category is IDC. The third model category are models used to generate information as they were originally conceptualized without any modification. These models are SAC-SMA-DS and CalLite.

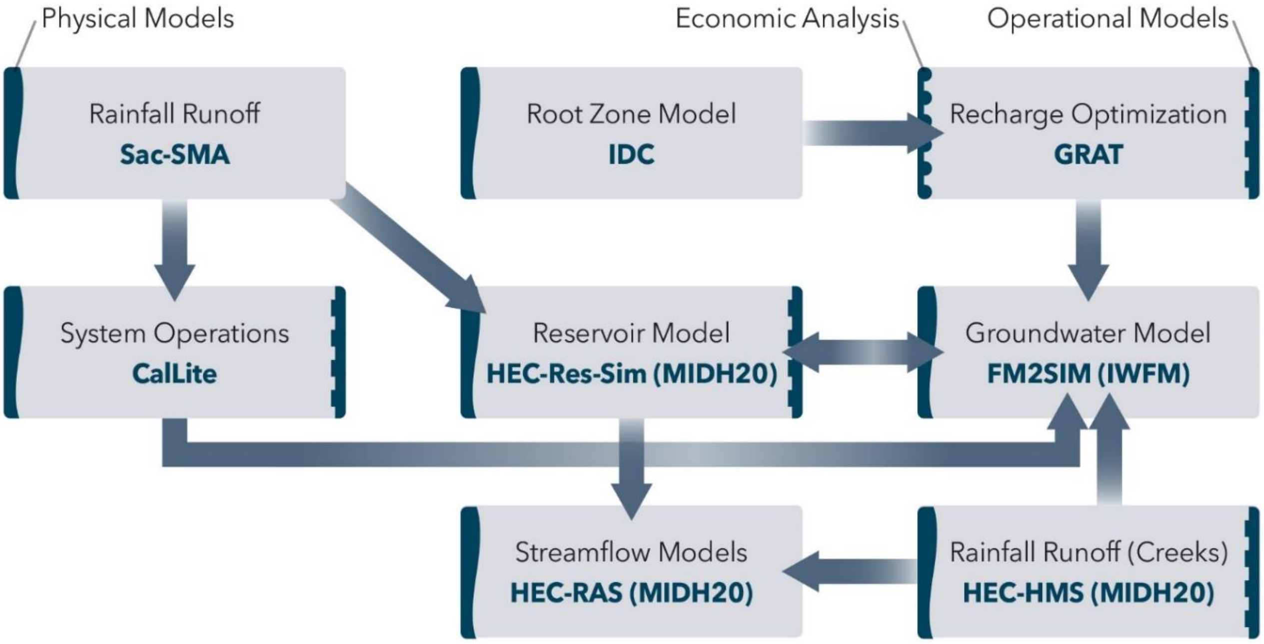
The integration approach for these models and the communication and flow of information among various models is shown in Figure 3-1. Because of the nature of information and the accuracy needed for the study results, most models were integrated in one-way direction:

- SAC-SMA-DS → CalLite → FM2Sim,
- SAC-SMA-DS → HEC-ResSim,
- IDC → GRAT → FM2Sim,
- HEC-ResSim → HEC-RAS,
- HEC-HMS → FM2Sim,
- HEC-HMS → HEC-RAS,
- HEC-HMS → GRAT, and
- GRAT → FM2Sim.

Some models, however, were iteratively coupled, passing back and forth results. These models coupled to pass information back and forth are:

- GRAT ↔ HEC-ResSim,
- FM2Sim ↔ HEC-ResSim, and
- HEC-ResSim ↔ CalLite.

Figure 3-1 Models Integration and How the Models Communicate to Each Other



Individual models simulate specific hydrologic and watershed management processes. But, when they are grouped together and allow one model to pass information to the next model, the grouped models can simulate the response for watershed-based water management solutions. All the models except for IDC and GRAT are used to define baseline scenario to determine the watershed system vulnerability. IDC and GRAT are added to the baseline models and used collectively to define the Flood-MAR scenario modeling to support the assessment of vulnerability and Flood-MAR adaptations that can support decision-making for potential project implementation. HEC-ResSim, FM2Sim, GRAT, and HEC-RAS respond to sustainable and integrated water resources management assessments supporting decision-making related to flood, surface to groundwater, water supply, and ecosystems. Because FM2Sim is the ultimate model that assess the bottom-line benefits and impacts, and the efficiency of any Flood-MAR project scenario in the groundwater system and other subsystems interacting with groundwater, the FM2Sim turns out to be hub for exchange and integration of information among other models and subsystems.

Details of models’ integration and use, spatial, and temporal steps for inputs and outputs, formats, and any other type of details are described in each model’s description chapter of this TIR.

Chapter 4. Sacramento Soil Moisture Accounting Hydrologic Model for Decision Scaling (SAC-SMA-DS)

4.1 Model Description and Purpose

As part of DWR’s bottom-up climate change vulnerability assessment for the State Water Project (SWP), DWR pursued development of a distributed, physically based hydrologic model capable of rapid rainfall and runoff simulation of upper watersheds that inflow to the CVS. The Sacramento Soil Moisture Accounting (SAC-SMA) model was chosen as the conceptual hydrological model. The model is employed by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) to produce river and flash flood forecasts for the United States (Burnash 1973; Burnash 1995; McEnery et al. 2005). The hydrologic model was coupled with a river routing model (Lohmann et al. 1998) for application to the large, distributed watershed system consisting of approximately 1,000 1/8th-degree grid cells. The coupled model is referred to as SAC-SMA-DS, distinguishing it from the distributed version of SAC-SMA previously developed by the NWS. SAC-SMA-DS is composed of hydrologic process modules that represent soil moisture accounting, potential evapotranspiration (Hamon 1961), snow processes (Anderson 1976), and flow routing, that operates in grid formulation on a daily time-step.

4.2 Model Alterations and Model Purpose for Flood-MAR

No alterations were made to the SAC-SMA-DS model for purposes of the study because calibration and parameterization of the model had been completed as part of a previous DWR study. Model input and output was sufficient for fulfilling Flood-MAR requirements.

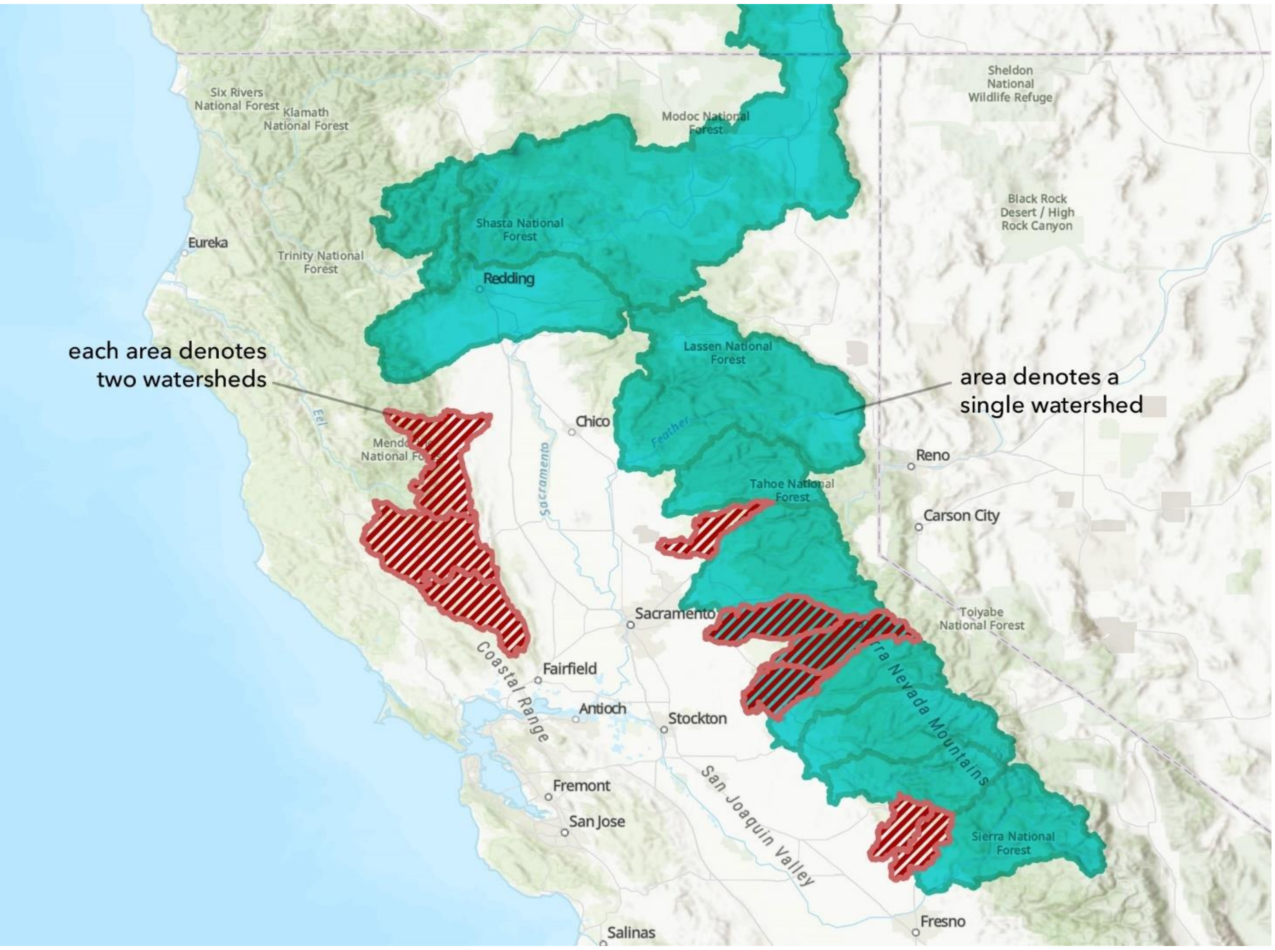
The SAC-SMA-DS model was used to generate daily unimpaired runoff from the upper Merced River watershed and routed to the downstream outlet above Lake McClure.

4.3 Model Integration and Input/Output Data

4.3.1 Input/Output

The SAC-SMA-DS hydrologic model is used to simulate streamflow at 32 upper watershed locations, shown in Figure 4-1, across the CVS. Total daily precipitation and average temperature at 1/8th-degree gridded resolution are the meteorological inputs entered into the SAC-SMA-DS model. Each watershed location includes its own set of calibrated parameters, as well as grid information for each of the overlying 1/8th-degree gridded cells.

Figure 4-1 **Map of 32 Watershed Outflow Locations Simulated with SAC-SMA-DS**



4.3.2 Integration with Other Models

The Merced Reservoir simulation model (HEC-Res-Sim) uses the daily streamflow simulated at the Merced River watershed. The input generation process for CalLite 3.0 uses monthly streamflows simulated for 12 major rim inflow locations, 11 observed gauge locations, and nine unimpaired small watershed locations. Details on the development of hydrologic inputs for decision scaling analysis with CalLite are available in Appendix B, "Sacramento Soil Moisture Accounting Hydrologic Model for Decision Scaling (SAC-SMA-DS)" and in *Decision Scaling Evaluation of Climate Change Driven Hydrologic Risk to the State Water Project Final Report* (California Department of Water Resources 2019).

4.4 Model Calibration and Results

The SAC-SMA-DS was calibrated at a monthly timestep with a generic optimization algorithm to maximize the Nash-Sutcliffe efficiency (NSE). NSEs evaluated on the monthly simulated streamflow show values of above 0.9 for all the watersheds except for the Mokelumne subbasin (Table 4-1). Specifically, the validation period NSE for the Merced Subbasin is 0.93. According to Moriasi et al. (2007), model simulations can be assumed as satisfactory when NSE is greater than 0.5. Calibration results together with a description of the average annual precipitation-streamflow response exhibited by SAC-SMA-DS are further explored in Appendix B, "Sacramento Soil Moisture Accounting Hydrologic Model for Decision Scaling (SAC-SMA-DS)."

Table 4-1 Hydrologic Model Performance by Subbasin

Subbasin	**Nash Sutcliffe Efficiency**	
	Calibration (1951–1980)	**Validation** (1981–2002)
American	0.96	0.94
Merced	0.95	0.93
Stanislaus	0.91	0.90
San Joaquin	0.92	0.90
Mokelumne	0.77	0.85
Calaveras	0.96	0.93
Feather	0.95	0.94
Tuolumne	0.94	0.93
Sacramento	0.97	0.97
Trinity	0.94	0.89

Subbasin	**Nash Sutcliffe Efficiency**	
	Calibration (1951–1980)	**Validation** (1981–2002)
Yuba	0.91	0.95
Clear Creek	0.95	0.93

Chapter 5. Central Valley Water Management Screening Model (CalLite)

5.1 Model Description and Purpose

CalLite 3.0 is a screening level planning tool developed by DWR and the United States Bureau of Reclamation to simulate the coordinated operations of the intertied CVS. CalLite 3.0 (Islam et al. 2011) is the faster, streamlined version of CalSim-II (Draper et al. 2004), designed to be accessible to policy and stakeholder demands for rapid and interactive policy evaluations.

5.2 Model Alterations and Model Purpose for Flood-MAR

CalLite 3.0 is the water resources system model used in the study to provide boundary conditions for the FM2Sim model and constraints for Flood-MAR operations based on excess or balance conditions in the Sacramento-San Joaquin Delta (Delta). Because the study uses the HEC-ResSim model to simulate Lake McClure reservoir operations and water allocations for the Merced watershed, a decision was made to use the HEC-ResSim Merced River outflows as a direct input fixed time series to CalLite 3.0 and completely remove all dynamically simulated system components (i.e., Lake McClure operations, streamflow diversions, groundwater pumping, return flows) from the CalLite 3.0 model.

5.3 Model Integration and Input/Output Data

5.3.1 Input

Details on the development of inputs for decision scaling climate change vulnerability analysis are available in the *Decision Scaling Evaluation of Climate Change Driven Hydrologic Risk to the State Water Project Final Report* (California Department of Water Resources 2019).

5.3.2 Output

CalLite outputs the stream inflow for all major rivers and irrigation diversions in FM2Sim domain except Merced River. Appendix C, “Central Valley Water Management Screening Model (CalLite)” provides the details for FM2Sim stream inflows and diversions linked to CalLite 3.0. Several of the CalLite outputs were disaggregated in proportion to historical flow splits into multiple input components which have greater spatial detail in FM2Sim. Finally, CalLite outputs representing flow and water quality conditions in the Sacramento San-Joaquin Delta were post-processed to categorize "Delta Conditions" (a key constraint for WAFR) at each time step in the model simulation period.

5.3.3 Integration with Other Models

The HEC-ResSim model for Merced River outflows was originally generated based on integration with FM2Sim, which had initially used surface water rim inflows and diversions from the unmodified CalLite 3.0 model runs. So, to fully complete the integration of the three models after the Merced system modifications to CalLite 3.0, additional iterations between the three models would need to be done. The computational expense of this exercise did not justify the expected improvement in Merced River outflow representation and so was not completed.

5.4 Model Setup, Calibration, and Results

CalLite 3.0 represents reservoir operations, SWP and Central Valley Project (CVP) operations and delivery allocation decisions, existing water sharing agreements, effect of sea level rise on the water system, and Delta salinity responses to river flow and export changes on a monthly time-step. CalLite 3.0, released in 2014, has 796 input parameters and approximately 240 additional data tables that store all relational data, such as reservoir area-elevation-capacity data, wetness-index dependent flow standards, and monthly flood control requirements. Output includes water supply indicators, environmental indicators, and water-use metrics (Islam et al. 2011; California Department of Water Resources and United States Bureau of Reclamation 2011).

CalLite's design and substantial intricacy enable better fidelity to the mechanics of CVS water allocation rules and water sharing agreements. That said, the model contains many approximations of site-specific values for which historical observations are scarce and includes poorly understood empirically based relationships that pose challenges related to water system simulation under wide-ranging conditions of climate uncertainty.

CalLite 3.0 Validation

Details on the validation of CalLite simulations using the modified input development procedure for decision scaling climate change vulnerability are available in *Decision Scaling Evaluation of Climate Change Driven Hydrologic Risk to the State Water Project Final Report* (California Department of Water Resources 2019).

Validation of “Merced-Fixed” Alteration

To validate the modification of the Merced system representation in CalLite 3.0, model results were compared before and after fixing the Merced River operations. The Merced River system modifications to CalLite 3.0 did not significantly corrupt or alter CalLite’s representation of the integrated CVP/SWP system (see Appendix C, “Central Valley Water Management Screening Model (CalLite)” for more information).

Chapter 6. Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)

6.1 Model Description and Purpose

The Merced Streams Group HMS model simulates streamflow, rainfall-runoff response, and associated hydrologic processes in the Merced Streams Group watershed. The Merced Streams Group watershed encompasses the geographic region generally bounded by the Merced River to the north and east, the Chowchilla River to the south and east, and the San Joaquin River to the west (see Figure D-1 in Appendix D, "Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)" for more information). Because this area encompasses lands within the MID boundaries, as well as most of the Merced Groundwater Subbasin, an accurate representation of the available surface water, including the necessary surface water to meet MID's water supply needs and existing commitments and obligations in this region was necessary to include in the study as part of the overall basin water balance. Given the limited availability of surface water data, it was necessary to develop a model to simulate the available surface water produced by the streams in this region. Surface water output from the Merced Streams Group HMS model ultimately was used as input for the study's groundwater (FM2Sim), reservoir operations (HEC-ResSim), and flood control (HEC-RAS) modeling.

6.1.1 Model Source

The original Merced Streams Group HMS model was developed as part of the MID-H2O modeling suite. MID-H2O is a suite of models (hydrologic, reservoir operations, and hydraulic routing) used by MID to forecast flood control and water supply operations on the Merced River and the Merced Streams Group (Merced Irrigation District 2020). The Merced Streams Group HMS model has been used primarily to help inform the district the potential flows from various USACE flood control reservoirs during storm events at various points of interests, such as, Bear Creek at Mckee Road as it flows through the City of Merced. As such, the original model was developed with a high-level of detail for streamflow and runoff routing and used a timestep of one hour. Some of this detail was ultimately unnecessary for the simulations and model output needed for this study.

6.2 Model Alterations and Justifications

After review of the original model, it was determined that a number of simplifications could be made to reduce the model run time and data output/file size and still meet all of the data and input requirements for the other Merced Flood-MAR study models. The alterations made to the original model and the associated assumptions and justification are described in Table 6-1.

Table 6-1 HMS Model Alterations

Model Alteration	Assumptions and Justification
Model Timestep	The model timestep was revised from an hourly to a daily timestep because: • Input precipitation data was available at a daily timestep. As such, a shorter timestep would have not resulted in a more accurate simulation output for use in the Bear Creek HEC-RAS model. • The change to the daily timestep reduced the model runtime and model output file size. • Model output used by the FM2Sim model is only needed at a monthly timestep.
Model Extent	The model extent was trimmed to include only streams and drainage subbasins that were subsequently used in the FM2Sim, Bear Creek HEC-RAS, and Merced River HEC-ResSim models. This resulted in two significant changes to the original model: • Removal of creeks/drainages west of Canal Creek. • Removal of stream sections and subbasins downstream of the locations used for input to subsequent models (FM2Sim, HEC-RAS, and HEC-ResSim).
Model Detail	To further reduce the model run time and output file size, several elements of the original model were reduced or eliminated. These changes were largely justifiable given the change to the model’s timestep.

Model Alteration	Assumptions and Justification
	The additional precision provided by the detailed stream routing and subbasin delineation in the original model no longer provided additional accuracy when the model timestep was changed to a daily timestep. In summary, the following changes were made to the model detail: • Removal of all detailed representations of stream routing. • Subbasin aggregation throughout most of the model extent, but particularly of the subbasins in the upper reaches of the larger creeks (Burns, Bear, Owens, Mariposa, Deadman, and Dutchman). Subbasin aggregation and trimming of the model extents resulted in a reduction of the total number of subbasins in the model from 43 to 14.
Hydrologic Simulation Methods	To improve model performance, some of the hydrologic methods were changed from the original model. These changes include: • The original loss method, Deficit and Constant (Hydrologic Engineering Center Hydrologic Modeling System 2018), for the upper drainage areas of the major creeks (Black Rascal, Burns, Bear, Miles, Owens, Mariposa, Deadman, and Dutchman) was changed to the SMAM (Hydrologic Engineering Center Hydrologic Modeling System 2018). The SMAM allows for better representation of soil moisture lost to deep percolation and groundwater storage and any subsequent return of that water to baseflow. This provided improved modeling of rainfall runoff and creek baseflow. The loss method was changed only for the subbasins noted above because these subbasins drain into the creeks used by the FM2Sim model. As such, it was most important to accurately model surface runoff response for these subbasins. • The baseflow method for all of the subbasins was changed from the recession to the linear reservoir method (Hydrologic Engineering Center Hydrologic Modeling System 2018). This method

Model Alteration	Assumptions and Justification
	allows for improved refinements to baseflow modeling and is recommended when using the SMAM.
Evapotranspiration	A representation of evapotranspiration was added to the meteorological model in the HMS model. Given the lack of available long-term shortwave radiation, windspeed, and other meteorological data, historical average monthly evapotranspiration data was used as the model's representation for evapotranspiration.

Notes:

HEC-RAS = Hydrologic Engineering Center River Analysis System

HEC-ResSim = Hydrologic Engineering Center Reservoir System Simulation

HMS = hydrologic modeling system

FM2Sim = Flood-MAR Merced Groundwater-Surface Water Simulation Model

SMAM = Soil Moisture Accounting Method

6.2.1 Flood-MAR Purpose

The primary purpose of the Merced Streams Group HMS model is to simulate surface water conditions in the Merced Streams Group creeks for subsequent input to the FM2Sim, Bear Creek HEC-RAS, and Merced River HEC-ResSim models. The streamflow data and locations output from the Merced Streams Group HMS model, and subsequently used by each model, are summarized and presented in Appendix D, "Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)."

6.3 Model Integration and Input/Output Data

The model sources a variety of data for input and simulation purposes and serves to inform the calibration process. A full description of each dataset, including the source and use in the model, is presented in Appendix D, "Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)."

6.3.1 Model Input Data

The meteorological model (within HEC-HMS) uses input average monthly evapotranspiration data to simulate evapotranspiration in each subbasin included in the Merced Streams Group HMS model. Average monthly evapotranspiration data from California Irrigation Management Information

System (CIMIS) station #148 (Merced) was used as the monthly evapotranspiration data input to the model (California Irrigation Management Information System 2019). CIMIS station #148 is located within the Merced Streams Group watershed and has a continuous monthly dataset from January 1999 through the present. As the data provided is reference evapotranspiration, the correction coefficient in the HMS meteorological model was kept at 1.0. The average monthly reference evapotranspiration from CIMIS station #148 is summarized below in Table 6-2.

Table 6-2 Average Monthly Reference Evapotranspiration Data for CIMIS Station #148 (Merced)

Month	Reference Evapotranspiration (inches)
January	1.26
February	1.98
March	3.66
April	4.97
May	6.99
June	7.99
July	8.48
August	7.63
September	5.61
October	3.59
November	1.78
December	1.11

The meteorological model (within HEC-HMS) was also revised to accept gridded precipitation for the Merced Streams Group area. Gridded precipitation data that had been developed for use in the SAC-SMA-DS model was formatted for use in the Merced Streams group HMS model. The additional formatting required converting the precipitation data from a 1/8th-degree grid cell size to 1000-meter grid cell size. For purposes of the model's calibration and verification process, historical daily gridded precipitation data was available for the period of January 1, 1950, through December 31, 2013.

6.3.2 Calibration Data

As the primary purpose of the Merced Streams Group HMS model is to simulate streamflow conditions in the Merced Streams Group, the only way to verify performance of the model's accuracy was through calibration to observed data. For the Merced Streams Group, the only creeks with reliable, continuous, and extended streamflow datasets were the four creeks with flood control dams: Burns, Bear, Owens, and Mariposa. Mostly continuous, daily inflow and full-natural flow data is available for each of these creeks from January 1, 1932, through the present (U.S. Army Corps of Engineers 2019). The observed streamflow data was used to compare daily and monthly flow volumes and patterns using a variety of statistical performance metrics that are detailed in Section 6.4. The Merced Streams Group HMS model was able to simulate streamflows well, as discussed in Appendix D, "Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)."

6.4 Model Setup and Calibration

The goal of the model calibration was to develop the model's hydrologic input parameters to produce an accurate and robust representation of the historical streamflow. Calibration simulations for individual water years (1983, 1998, and 2011) were performed using a comparison of average monthly and average annual streamflow volumes and calculated statistical calibration performance metrics for the daily data (Moriasi 2007). Calibration metrics were calculated for simulative streamflow compared to observed streamflow at each of the four available U.S. Army Corps of Engineers (USACE) Flood Control Dams (Bear, Burns, Mariposa, Owens). Results and individual model performance in each calibration are described and summarized in Appendix D, "Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)." For each calibration simulation, the model's base parameters were adjusted to improve the model's simulation of the historical streamflow in each calibration period.

Additionally, the model was run over the full overlapping period of available data between historical precipitation and streamflow data. The final model parameters used in the full-period verification simulation and all subsequent study model runs were based largely on an average of the model parameters developed among the three calibration simulations.

The final model developed for the full-period verification simulation was also used to simulate the baseline and climate change conditions used for the subsequent Flood-MAR baseline and climate vulnerability studies. Table 6-3 summarizes the average monthly and water year flow volumes for Bear, Burns, Owens, and Mariposa creeks under the Baseline model run. The monthly and water year volumes under the Baseline conditions are consistent with those seen under the historical hydrology of the full-period verification simulation. This was largely expected, and further demonstrates the acceptable performance of the Merced Streams Group HMS model.

Table 6-3 Simulated Streamflow for the Baseline Simulation (volumes in acre-feet)

Month	Burns Creek	Bear Creek	Owens Creek	Mariposa Creek
October	58	50	13	69
November	1,126	1,107	323	1,364
December	2,963	2,886	1,042	4,175
January	4,403	4,478	1,726	6,869
February	4,339	4,898	1,680	7,626
March	3,309	3,989	1,353	6,382
April	1,669	2,057	704	3,073
May	647	836	274	1,175
June	192	282	79	366
July	63	101	24	122
August	21	36	7	40
September	44	44	9	47
Total	**18,834**	**20,763**	**7,234**	**31,307**

Merced Streams Group HMS model runs with the baseline and climate change conditions were completed, with the 100-year daily streamflow outputs subsequently used by FM2Sim to inform surface water availability in the Merced Streams Group region and by GRAT to inform WAFR from Bear Creek and Mariposa Creek.

Chapter 7. Merced River Hydrologic Engineering Center Reservoir System Simulation (Merced River HEC-ResSim)

7.1 Model Description and Purpose

The HEC-ResSim or USACE reservoir operations model simulates flood control, water supply, ecosystem, and Flood-MAR operations for the study (U.S. Army Corps of Engineers 2022). The model includes Lake McClure, the largest reservoir in the Merced River system, and three small regulating reservoirs: Lake McSwain, Merced Falls, and Crocker-Huffman Dam. The model used in the study is originally from the MIDH2O set of models owned by MID. MID has been using the MIDH2O HEC-ResSim model as one of the short-term forecasting tools to help inform their daily operations. For the study, the MIDH2O HEC-ResSim model was modified from a short-term forecasting model (Merced River HEC-ResSim model) focusing on flood-control operations to a long-term planning level model.

The Merced River HEC-ResSim model is used in the study in two ways: (1) to assess the vulnerability of reservoir operations that are affected by changing hydrology, by evaluating the effects of climate change on flood management, water supply reliability, and drought resiliency, and (2) to estimate the amount of water available that can be diverted from the Merced River for Flood-MAR, after meetings MID’s water supply needs and existing commitments and obligations. The model is used to explore multiple Flood-MAR operation scenarios, including modified reservoir operations.

Model results include changes in Lake McClure storage, Merced River flow, irrigation diversions, and water available for Flood-MAR diversion based on Flood-MAR operations.

7.2 Model Modifications and Calibration

The Merced River HEC-ResSim model preserves the layout of network elements and physical parameters of infrastructure as they exist in the MIDH2O HEC-ResSim model and adds new operational rules and scripting to convert it to a long-term planning level model. Operational rules were updated using information from the Merced River Hydroelectricity Project (Federal Energy Regulatory Commission [FERC] Project No. 2179 2010).

1. Time step and modeling timeframe. The model runs on a three-hour time step, and the simulation timeframe is 100 years, from October 1, 1899, through September 30, 1999. The scripted rules accommodate the three-hour time step using a conversion factor. Time for pool decrease for the Induced Surcharge function was set to six hours to be a multiple of three-hour time step. Simulation times, including start date, lookback date, and end date, are a multiple of the three-hour time step.
2. Flood control operations. Flood control operations in the model have been simplified compared to the actual operations at the reservoir. Flood control releases are made to maintain required flood space defined by the flood control diagram to not exceed maximum channel capacity at critical downstream location along Merced River.
    a. Maximum channel capacity. The maximum channel capacity is 6,000 cubic feet per second (cfs) at DWR’s Cressy gage. When the Lake McClure storage is above the flood control diagram, the maximum flood control release of the main outlet is set to 6,000 cfs at the dam. Since the Dry Creek flow contributions to the Merced River could not be modeled in this study, when the storage is below the flood control diagram, the maximum release of the main outlet is 4,500 cfs. The 4,500 cfs flow triggers flood monitoring on Merced River and attempts to account for Dry Creek inflow that could not be modeled.
    b. Snowmelt release. While actual snowmelt operations at the reservoir can extend to September in wetter years, in the model, snowmelt releases are made from March 1 to June 30 to create conditional space in Lake McClure. Snowmelt release is calculated on March 1, April 1, May 1, and June 1 and adjusted by monthly scaling factors with the goal to keep the reservoir full at the end of June. The snowmelt release is calculated using available space in the reservoir and perfect forecast of the inflow and releases for irrigation demands, minimum flow requirements, and stream loss in Merced River.

3. Minimum downstream flow requirements by year type. Minimum flow release is modeled by year type according to flow requirements set by the current FERC license. These flow requirements are defined by the year type according to inflows to Lake McClure. If the forecasted inflow volume from April 1 to July 31 exceeds or is equal to 450,000 acre-feet, then the year type is considered normal; otherwise, the year type is considered dry. The year type is set in the ResSim model on May 1. Table 7-1 shows minimum downstream flow requirements at Shaffer Bridge.

Table 7-1 Minimum Downstream Flow Requirements

Minimum Downstream Flow Requirements (cfs)		
Period	**Normal Year**	**Dry Year**
January 1 – May 31	75	60
June 1 – October 14	25	15
October 15 – October 31	75	60
November 1 – December 31	100	75

Notes: cfs = cubic feet per second.

4. Fall fishery release. Lake McClure makes a fall fishery release of 12,500 acre-feet in October. Water is released to meet the fall fisheries requirements.
5. Irrigation deliveries. All irrigation demands were split between six service areas: the MID, Stevinson Water District, former El Nido Irrigation District, Merced National Wildlife Refugees, Northside Canal, and Cowell Agreement Diverters service areas. The irrigation deliveries are being distributed through Main Canal, Northside Canal, and Cowell Ditch diversions. The irrigation demands for all service areas are estimated by the groundwater model (FM2Sim) and provided on a monthly timestep.
6. All remaining diversions and local inflows were considered negligible and set to zero. Because the model was originally developed for the short-term forecasting type reservoir operations, the model had other diversions and local inflows along the Merced riverbed. These diversions correspond to small pumping stations and canals diverting small amount of water directly from Merced River. All of these diversions and local inflows were considered negligible and set to zero for the long-term planning purposes.

7. Merced River stream loss. The stream loss is estimated by the groundwater model (FM2Sim) and provided on a monthly timestep. The stream loss in the Merced River is considered from Merced Falls Forebay to Shaffer Bridge only and modeled as a diversion in the Merced River HEC-ResSim model. All the stream gain is incidental and is considered negligible. Lake McClure operations account for the stream loss and make releases to meet the minimum downstream flow requirements at Shaffer Bridge.
8. Flood-MAR diversion and operations. The Flood-MAR diversion was added to the model network at the location of the Main Canal diversion to estimate water available for Flood-MAR operations. The WAFR is intended to be diverted through the Main Canal conveyance system and is an addition to any irrigation water already conveyed through the head of Main Canal. The Flood-MAR diversion accounts for the Flood-MAR operations time window, flow downstream of Crocker Huffman Dam, maximum capacity of Main Canal, a check whether the Delta is in an excess condition, and groundwater recharge capacity of the region. The CalLite model provides a Delta Conditions check time series. GRAT provides feedback on the groundwater recharge capacity.
9. Hydropower generation. Hydropower generation was not simulated in the Merced River HEC-ResSim model. MID generates power through New Exchequer and McSwain in all year types. The reservoir is operated for water supply purposes and generation is maximized based on water releases. In the model, the flood control diagram was modified to simulate hydropower releases affecting carryover storage in Lake McClure. The flood control diagram defined in the Conservation Storage Zone was modified from June 30 to October 31 to accommodate for the power draw down storage.
10. Lake McSwain. All the operational rules were transferred from Lake McSwain to Lake McClure. Lake McSwain operation was set to inflow equals outflow. Lake McSwain was modified to operate as a bypass reservoir because, compared to the storage capacity in Lake McClure, its storage capacity is small (approximately 1 percent of Lake McClure).
11. Merced Falls Forebay. Merced Falls Forebay operation was set to inflow equals outflow to operate it as a bypass reservoir.
12. Crocker Huffman Dam. Crocker Huffman reservoir was deleted from the Merced ResSim model Reservoir Network and Crocker Huffman river

reach was added to operate it as inflow equals outflow. The modification was needed to improve the model stability because the storage capacity in Crocker Huffman was very small.

7.2.1 Model Testing, Calibration, and Validation

Historical hydrology data from October 1, 1969, through September 30, 2017, was used to test and calibrate the Merced River HEC-ResSim model. Observed Lake McClure storage capacity and outflow was used to validate model performance. More information on the testing, calibration, and validation of the Merced River HEC-ResSim model is available in the Appendix E, "Merced River Hydrologic Engineering Center's Reservoir System Simulation (Merced River HEC-ResSim)."

7.3 Model Integration and Input/Output Data

The Merced River HEC-ResSim model iterates with the groundwater model (FM2Sim), the recharge allocation model (GRAT), SAC-SMA-DS, and the System-Wide Operations model (CalLite). The Merced River HEC-ResSim model receives input data from SAC-SMA-DS, FM2Sim model and transfer output data to GRAT, CalLite, and back to FM2Sim models. The datasets that are transferred between models have a format of a timeseries with different timesteps and measure units as described below.

1. SAC-SMA-DS iteration. Paleohydrology (synthetic hydrology) from October 1, 1899, through September 30, 1999, generated by the SAC-SMA-DS hydrologic model was used as an input to simulate inflow into Lake McClure. The inflow time-series was generated on the daily time step and was converted to a three-hour time step to be used in model. (Paleohydrology was prepared by DWR's Climate Change Program, based on the methodology described in Chapter 2 of this report.)
2. FM2Sim iteration. In transferring of data between models, the Merced River HEC-ResSim model takes monthly irrigation demands and stream loss from the FM2Sim model output and calculates irrigation deliveries at the diversion locations and outflow at Merced Falls Forebay. The FM2Sim model takes the irrigation demands and outflow times-series on the three-hour time step and calculates monthly irrigation demands and stream loss. The monthly irrigation demands and stream loss results are compared to the results from previous iteration to evaluate the

difference. The iterations are repeated until the results converge and the difference is negligible. The last iteration contains final results to be evaluated by metric results analysis.

3. GRAT iteration. The Merced River HEC-ResSim model estimates water available for Flood-MAR at the head of Main Canal and transfers the Flood-MAR diversion time-series to GRAT model. The output data is converted from a time-series in cfs in a three-hour time step into a table organized by water year and Flood-MAR volume in acre-feet in a daily time step. The GRAT model allocates water available to the available agricultural fields and basins to maximize recharge. The GRAT model accounts for the simultaneous recharge through the Main Canal conveyance system. The remaining unused WAFR is returned to Merced River HEC-ResSim model as a time-series to be added back to the Merced River flow.
4. CalLite iteration. The CalLite model receives Merced River flow time-series from the Merced River HEC-ResSim model and uses it as an input at the confluence with San Joaquin River. Using the same Merced River flow aligns Lake McClure operations and provides consistency for the irrigation diversions, minimum flow requirements, and groundwater-surface water interaction between the two models. The time-series is converted from the three-hour time step into a monthly time step and is split into multiple periods acceptable to run CalLite model.

   The CalLite model results are post-processed to evaluate the Sacramento-San Joaquin Delta conditions for each of the 30 climate scenarios. The Delta conditions check is used in Merced River HEC-ResSim model to limit Flood-MAR diversion during balanced and excess with restriction months.

Chapter 8. Integrated Water Flow Model Demand Calculator (IDC)

8.1 Model Purpose and Description

A conceptual IDC model was developed for this study with the purpose to calculate the amount and frequency of flood water that can be applied based on soil water content thresholds, crop type, physical soil parameters, and other parameters.

The Integrated Water Flow Model Demand Calculator (IDC) (IDC v4.0.) is a stand-alone root zone component of the integrated water flow model (IWFM) that calculates agricultural and urban water demands. Agricultural water demand is calculated based on climate data, crop types, crop acreages, soil properties, and irrigation methods. IDC computes applied water demands for ponded and non-ponded crops at each grid cell under user-specified climatic and irrigation management settings. For all land-use types, precipitation, as well as applied water, if any, is routed through the root zone.

The conceptual IDC model is a grid-cell array with six columns by four rows, and each grid cell has a total area of 1 acre. The conceptual IDC model was set up so that each grid cell has a specific combination of a crop type (columns) and soil type (rows). Figure F-1 in Appendix F, “Integrated Water Flow Model Demand Calculator (IDC)” shows the model’s setup, crop type, and physical soil properties. The land-use and crop type was defined by identifying the top crops from the 2014 Land IQ database within the MID boundaries. The top six land-use and crop types are alfalfa/pasture, almonds, pistachios, vineyards, walnuts, and idle (or winter fallow land). Idle includes the idle land (referred to as fallow land hereafter) and the compatible crop land that is fallow during the winter period. These crops are potatoes and sweet potatoes, cotton, and tomatoes. In this fallow land, flood water can be applied during the winter season because the land is not used for agriculture. Soil type corresponds to the top four Soil Agricultural Groundwater Banking Index (SAGBI) suitability indexes (Excellent, Good, Moderately Good, and Moderately Poor) with corresponding physical soil properties taken from Rawls et al. 1982.

8.2 Model Alterations, Quality Control, and Underlying Assumptions

8.2.1 Model Alterations

The conceptual IDC model was built from scratch specifically for this study to calculate the available WAFR and frequency to apply based on crop types, physical soil properties, and a suitability index soil type.

8.2.2 Quality Assurance and Quality Control

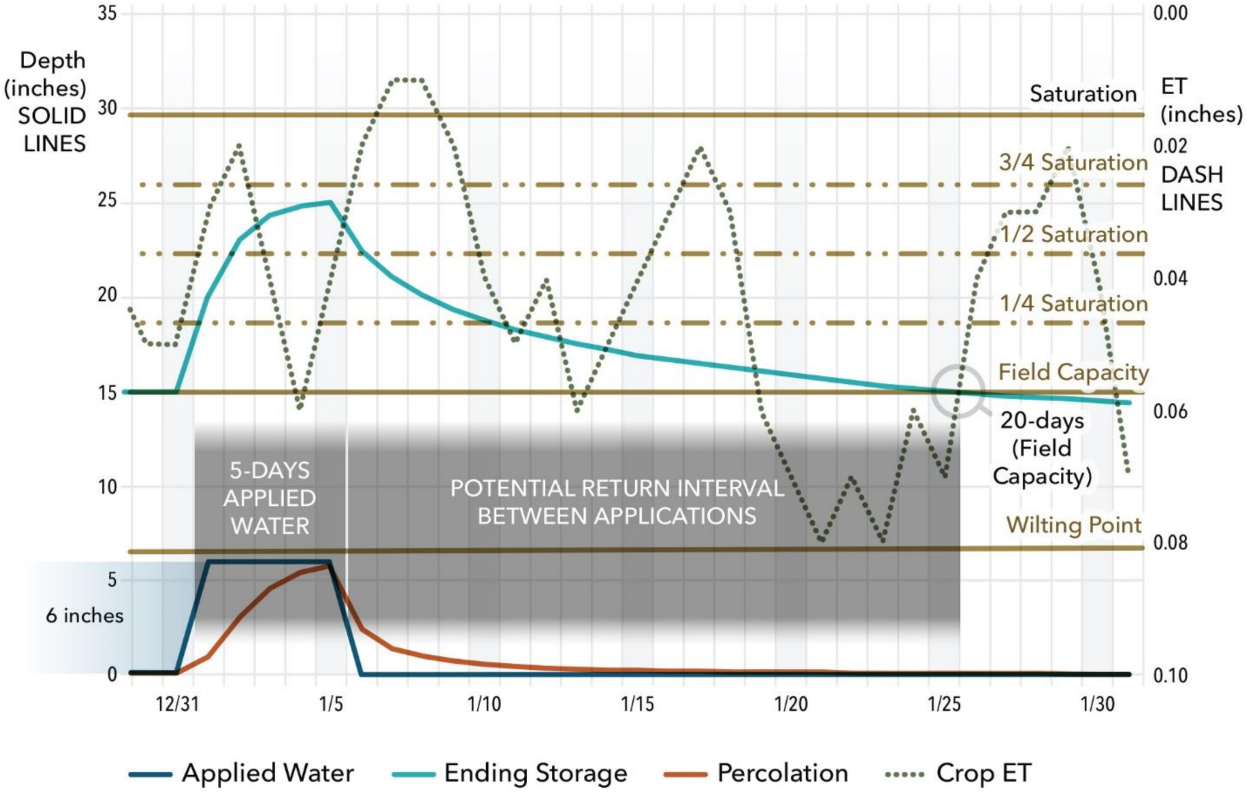
The conceptual model and model's results were reviewed and validated by Woodard & Curran, experts on IWFM (Woodard & Curran 2023). An exhaustive revision of the model's setup, inputs, and outputs was performed. As part of the quality assurance and quality control exercise, Woodard & Curran experts ensured that the datasets for the inputs (e.g., physical soil parameters, crop evapotranspiration, soil depth, and rooting depth) were reasonable and aligned with the FM2Sim Groundwater model inputs, where appropriate. Technical feedback was provided and implemented in the final IDC conceptual model.

8.2.3 Underlaying Assumptions

The conceptual IDC model was built to determine, based on amount of applied WAFR, crop type, physical soil properties, and initial soil moisture content, the time it would take for the water to percolate and the root zone water content to return to an acceptable level to allow the next application of flood water. IDC estimates the timing of water to infiltrate and to reach a specific soil moisture content threshold (i.e., field capacity) that determines when flood water can be re-applied. This information is transferred to GRAT's crop compatibility calendar (CCC), which adjusts the timing for application based on constraints of the crop life cycle (e.g., bloom, dormancy, etc.), field operation (e.g., pruning, timing of fertilizer application), and other practices that protect crop health and crop management. The CCC informs GRAT about how much water can be applied throughout a crop cycle on a daily time-step, and GRAT takes precipitation into account to determine the total potential applied surface water for recharge.

Figure 8-1 shows results for an almonds conceptual model with a moderately good SAGBI suitability index soil type. In this example, 6 inches of water are applied over five consecutive days and the potential return interval between applications is 20 days when the field capacity moisture content threshold is reached. For this example, the soil water content reaches almost 3/4 saturation by day five and the percolation rate is almost 6 inches per day.

Figure 8-1 Results for an Almonds Conceptual Model with a moderately good SAGBI Suitability Index Soil Type



8.3 Spatial and Temporal Configuration

8.3.1 Spatial Configuration

For the conceptual IDC model, each element in the grid was defined by a single grid of 1-acre area. Each element represents a specific combination of crop type and soil type as described in Figure F-1 in Appendix F, "Integrated Water Flow Model Demand Calculator (IDC)."

8.3.2 Temporal Configuration

For the conceptual IDC model, a one-day time step length was used. Further detail information about file formats for inputs and outputs is available in the IWFM Demand Calculator Theoretical Documentation and User Manual (IDC v4.0.) (California Department of Water Resources 2012).

8.4 Model Setup and Results

8.4.1 Model Setup

Model setup includes the following:

1. Initial soil moisture content: An initial soil water content of field capacity was assumed for winter and spring seasons because these seasons overlapped with the rainy season. For the summer and fall seasons when precipitation is mainly absent, the initial soil water content assumed was halfway between wilting point and field capacity (see Conceptual IDC Model Assumptions in Appendix F, "Integrated Water Flow Model Demand Calculator (IDC)" for more information).
2. Applied WAFR: The applied water available for replenishment can be defined as the total volume of WAFR applied to agricultural fields per day independently of site suitability, crop suitability, conveyance or agricultural management practices associated with agricultural crops. The depth of flood water per unit area and per day was defined as 6 inches over five, six, and seven consecutive days (Figure 8-1 shows five consecutive days application of flood water).
3. Soil oxygen content: Soil oxygen content in the root zone is important to consider because low oxygen levels in soils can inhibit plant respiration and growth. To ensure that the conceptual IDC model takes this important factor into consideration, it was necessary to define the level of saturation in the root zone that would not affect plant bioprocesses. To this end, the soil oxygen content threshold was based on Bachand et al. (2017) whose findings were that oxygen levels below 10 kilopascals are generally associated with percent saturation of 74 percent or greater. Although a significant variance was associated with that threshold, it suggests that other factors affect the decline in oxygen content. So, in the conceptual IDC model, the applied WAFR was limited by the potential oxygen decline and set at a threshold of 75 percent saturation.
4. Crop evapotranspiration (ETc): ETc values for the five active crops (alfalfa, almonds, pistachios, vineyards, and walnuts) and the evaporation from fallow land simulated in the conceptual IDC model were determined by the California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW) model on a daily time step. These Cal-SIMETAW ETc values were validated using the Irrigation Training &

Research Center at California Polytechnic State University (ITRC) evapotranspiration data for the CIMIS ETo map zone 15 Merced. The 1998 wet year was used for Cal-SIMETAW and ITRC to compare both datasets (see Figure F-2 in Appendix F, "Integrated Water Flow Model Demand Calculator (IDC)" for more information).

8.4.2 Model Results

By running the conceptual IDC model and by applying WAFR until the peak soil moisture threshold is reached, average seasonal evapotranspiration is used to determine how long it would take to reach field capacity moisture content threshold, so water can be re-applied. The reapplying interval is defined by the physical soil type properties and the specific climate-driven crop evapotranspiration rate. Figure 8-2 shows an example for Almonds where 6 inches of water are applied over five consecutive days during the four seasons: fall (October 1–5), winter (January 1–5), spring (April 1–5), and summer (July 1–5).

Figure 8-2 Ending Soil Water Content in inches for Almonds with a Sandy Loam Soil Type

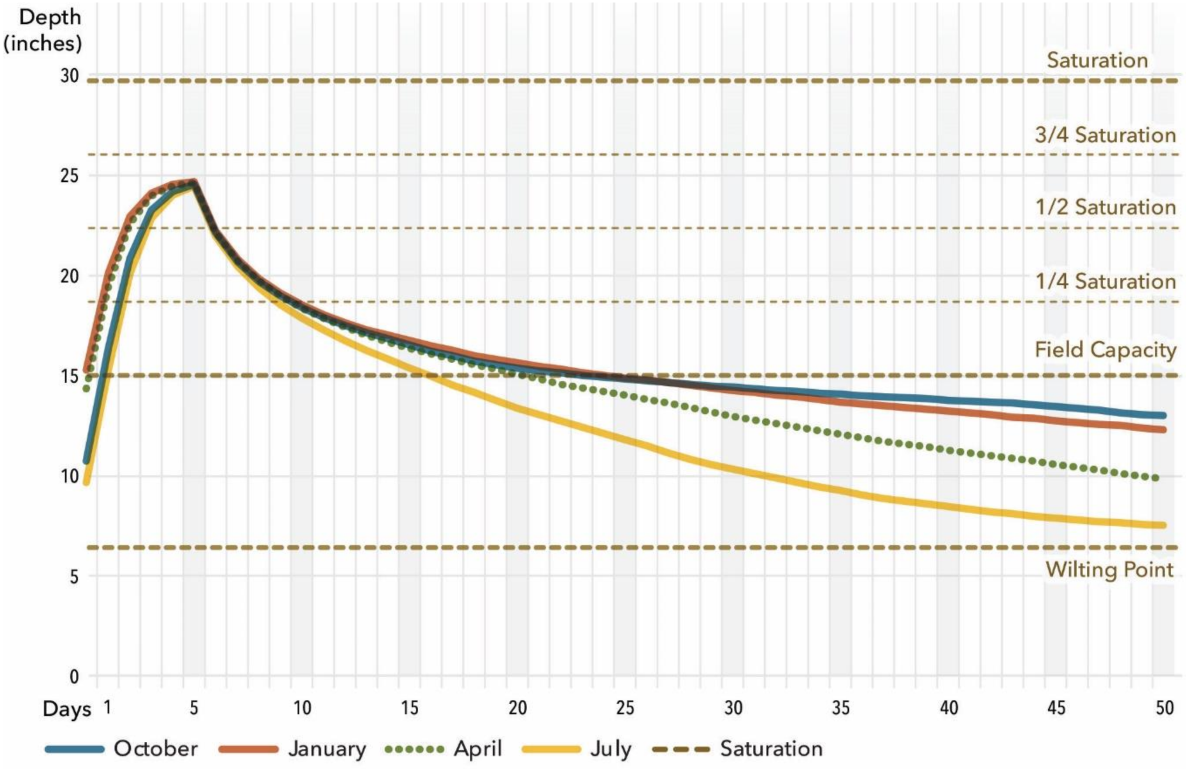


Figure 8-2 shows that if 6 inches of WAFR are applied over five consecutive days, the soil water content by day 5 is almost 3/4 saturation (24.7 inches) on average over the 6 feet depth soil profile. During winter, the soil profile should take approximately 17 days (orange bar) to drain down to reach the field capacity threshold, and during summer, the soil profile takes only 10 days (yellow bar).

The drain-down interval between day 6, when adding water stops and when field capacity is reached, is used to define the “black-out period” in the CCC when no additional WAFR will be applied to the field based on crop and soil type. This black-out period used in the model may be longer than actual practice by farmers who may desire to reapply water or take some risk applying water if WAFR is available. The more conservative black-out period is used in the GRAT model to avoid over estimating potential recharge, although it may result in missing the opportunity to capture available WAFR.

Chapter 9. Groundwater Recharge Assessment Tool (GRAT)

9.1 Model Purpose and Description

The GRAT application was built for the purpose of identifying a diverse recharge portfolio, across multiple promising recharge methods. This includes estimating the cumulative recharge capacity across many different methods, such as canal seepage, in-lieu recharge, dedicated recharge basins, fallow recharge, and recharging agricultural lands. GRAT was designed to provide irrigation districts with a geographic information system (GIS) decision support tool that enables them to easily create, visualize, and assess recharge scenarios. The tool enables water managers to evaluate where (active cropland, fallow land, and dedicated recharge basins), when (which weeks across multiple water year types, across a 20-year Sustainable Groundwater Management Act [SGMA] planning horizon) and how much water will be recharged based on best available data and hydrologic, agronomic, and geologic science.

Recharge capacity for each recharge method is based on a combination of localized hydraulic conductivity, water manager’s observed data, and average crop tolerance (see Figure G-1 in Appendix G, “Groundwater Recharge Assessment Tool (GRAT)” for more information).

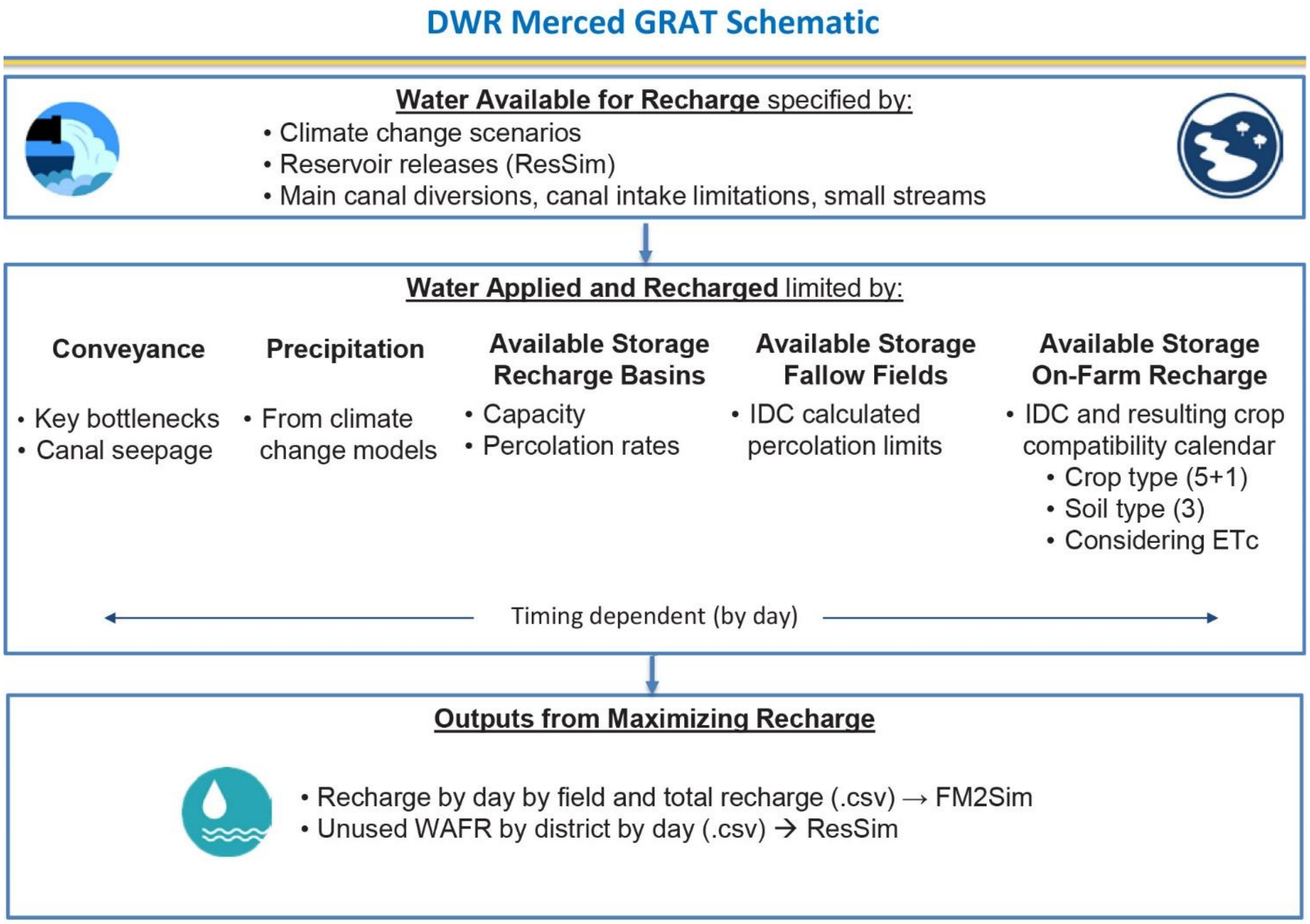
The tool relies heavily on local datasets provided by the water district, including conveyance and delivery capacity and canal and basin infiltration rates, as model inputs required to ensure the tool can best approximate water operations.

9.2. Model Alteration and Purpose for Flood-MAR

The purpose of integrating GRAT into the Flood-MAR study is to spatially and temporally allocate available water from ResSim scenarios to identify limiting components (available water, recharge capacity, or conveyance capacity) for maximizing WAFR capture and recharge. GRAT also identifies the quantity and timing of water that can enter the groundwater system (FM2Sim) and can be used to prioritize spatial allocation to achieve alternative groundwater management objectives (retention, disadvantaged communities [DAC] water supply, groundwater-dependent ecosystem protection, subsidence avoidance). When combined in successive scenario runs, the interaction between water availability and management objectives can be compared to understand where future management choices and investments could be made to maximize benefits.

Specific to the GRAT model used for the study, a high-level schematic that has been implemented is presented in Figure 9-1.

Figure 9-1 GRAT High-Level Schematic used in the Merced River Watershed Flood-MAR Reconnaissance Study



DWR Merced GRAT Schematic

Water Available for Recharge specified by:
- Climate change scenarios
- Reservoir releases (ResSim)
- Main canal diversions, canal intake limitations, small streams

Water Applied and Recharged limited by:

Conveyance
- Key bottlenecks
- Canal seepage

Precipitation
- From climate change models

Available Storage Recharge Basins
- Capacity
- Percolation rates

Available Storage Fallow Fields
- IDC calculated percolation limits

Available Storage On-Farm Recharge
- IDC and resulting crop compatibility calendar
  - Crop type (5+1)
  - Soil type (3)
  - Considering ETc

Timing dependent (by day)

Outputs from Maximizing Recharge
- Recharge by day by field and total recharge (.csv) → FM2Sim
- Unused WAFR by district by day (.csv) → ResSim

The next several subsections describe how the data and GRAT model were constructed uniquely for the study and the underlying assumptions that were used. Appendix G, "Groundwater Recharge Assessment Tool (GRAT)" includes a detailed section about recharge calculations.

9.2.1 Water Sources and Conveyance

Water Available for Recharge (WAFR)

There are several sources of WAFR in the study, including the Merced River and several smaller creeks that enter the MID conveyance facilties from the eastern foothills. These sources are identified using the HMS stream group regions. Each of the water sources has an associated set of fields where MID can deliver the water. GRAT currently prioritizes the diversion and recharge of available creek water before allocating Main Canal water from the Merced River.

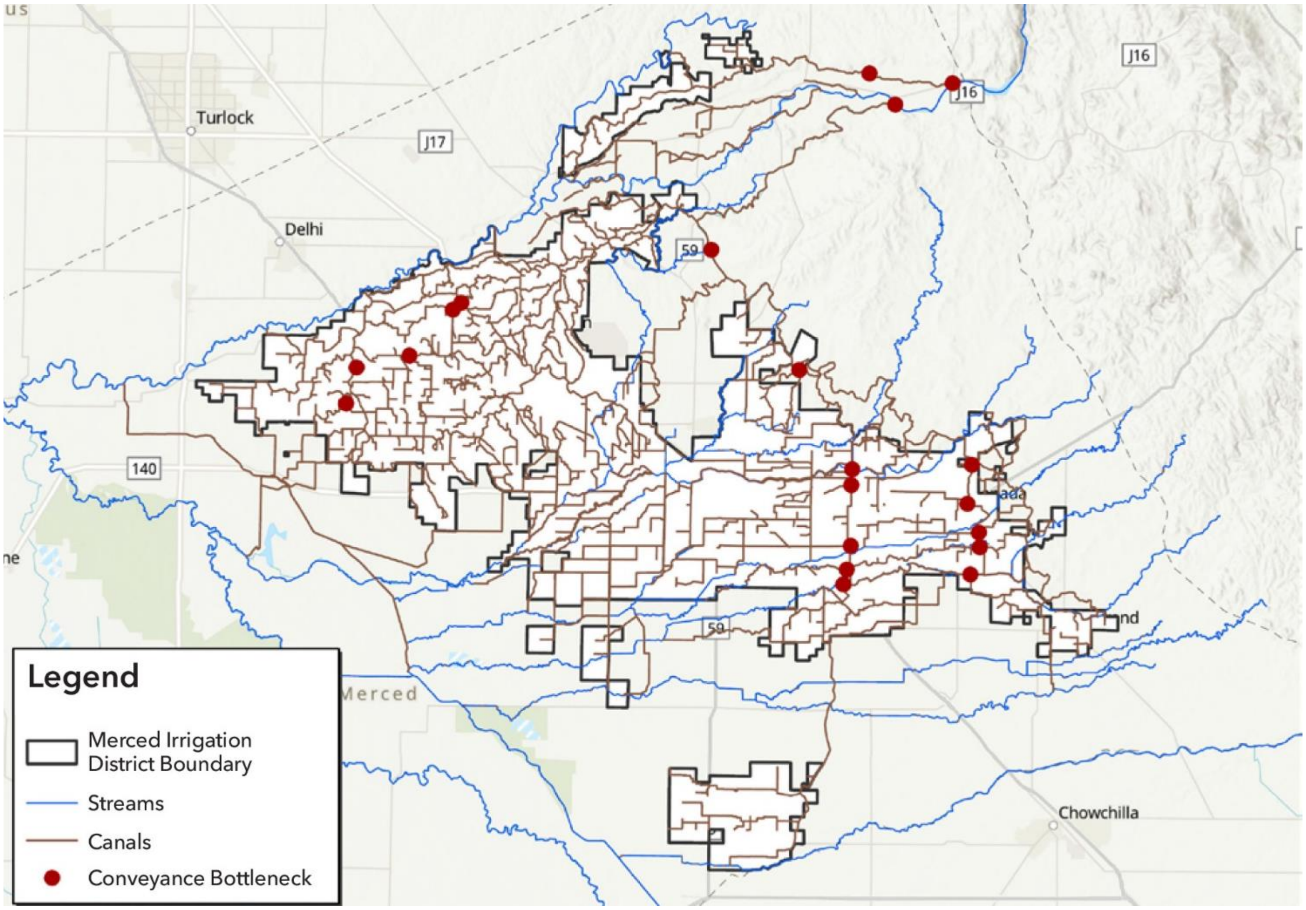
Precipitation

When calculating the potential water that can be applied by field by day, the precipitation is counted first as “water applied” and then, any additional “water applied” will be sourced from the available WAFR up to each recharge field’s maximum limit as provided by the CCC.

Capacity Constraints

Conveyance capacity constraints are set at key bottlenecks in the system. MID identified 20 conveyance capacity constraints to include in the model, as shown in Figure 9-2. With the proliferation of pressurized irrigation systems, there are also capacity constraints with delivering water from district canals onto agricultural parcels as the flow rate for a pressurized system is often less that the actual capacity of the turnout. Therefore, an average flow of 5 cfs was assumed for baseline calculations.

Figure 9-2 Key Bottlenecks Identified in MID System



9.2.2 Recharge Types

Recharge Type 1. Canal Recharge (seepage)

Canal seepage is the estimated recharge from the conveyance system. This is the first-priority recharge type. GRAT is configured to use available WAFR to completely fill the canals before filling any recharge sites. It will then calculate the canal seepage by day using the canal seepage percolation rate (acre-feet per day), reducing available WAFR by that quantity before applying any water to sites. Every day it will use any available WAFR to first fill the canals to capacity, backfilling water that has seeped the previous day.

Recharge Type 2. Dedicated Basins

Dedicated basin recharge calculates the estimated water recharged per basin and is the second-priority recharge type. The water applied to a basin for a single day is calculated by comparing the basin capacity to the amount of water currently in the basin (considering how filled it is after the previous day and any precipitation falling on that basin on that day). The basins are filled in the sequence provided by MID and using the WAFR source rules until all the daily WAFR is used up or the basins are filled. The tool then uses the percolation rate for each basin to determine how much water is recharged for that day. A basin percolates every day there is water in it.

Recharge Type 3. On-farm and Idle Field Recharge

On-farm recharge calculates the estimated water recharged per acre of existing fields under production for crops included in the CCC including idle lands. The maximum volume of water that can be applied by day per field is specified by the CCC as a function of the crop and soil type for all six SAGBI soil types. Only fields with crops currently in the CCC are included in on-farm calculations. Water is allocated to each potential field based on an indexing method that prioritizes fields according to the most suitable crops, soils, geology and groundwater storage capacity. The amount of water that can be applied per field is also constrained by canal turnout size. An average 5 cfs rate was initially assumed in Level 1 but expanded to 10 or 15 cfs in later runs as long as application rates did not cause soil saturation in excess of 75 percent on cropped fields or ponding in excess of 6 inches on idle fields according to the CCC. The water applied comes from two sources: the amount of rainfall falling on that field unit for that day of the year, and the amount of water applied from the MID canal system (using the WAFR), up to the maximum specified by the CCC.

GRAT assigns WAFR application according to the recharge types and methods described above and in Recharge Calculations, Section G-2 of Appendix G, “Groundwater Recharge Assessment Tool (GRAT),” and GRAT then reports recharge by all respective recharge types. Those WAFR and recharge totals are then reported by GRAT for use in other models.

9.3 Model Integration and Input/Output Data

The GRAT analysis described above was created by working directly with the MID to gather specific operational data most relevant to the local area.

9.3.1 Integration with Other Models

How GRAT interacts with other models is summarized in the previous sections on ResSim (Chapter 7) and IDC (Chapter 8), and in the next section on FM2Sim (Chapter 10). The descriptions below explain in more detail how

GRAT integrates with these three models.

GRAT Iteration with IDC

Based on amount of applied flood water, crop type, physical soil properties, and initial soil moisture content, the conceptual IDC model was configured to determine the time it would take for the water to percolate and the root zone water content to return to an acceptable level (field capacity) to allow the next application of flood water. This temporal information was manually interpreted and incorporated into the GRAT's CCC, which adjusts the timing for application based on constraints of the crop life cycle (e.g. bloom and dormancy), field operation (e.g. pruning and timing of fertilizer application), and other practices that protect crop health and crop management. The CCC spreadsheet provides the daily maximum inches of water that can be applied by crop and soil type and is used by GRAT to allocate WAFR throughout the annual crop cycle on a daily time-step. GRAT first takes precipitation into account before using the CCC to determine the total additional surface water that can be applied for recharge.

GRAT Iteration with ResSim

The Merced River HEC-ResSim model estimates water available for Flood-MAR at the head of Main Canal and transfers the Flood-MAR diversion time-series to the GRAT model. The output data is converted from a time-series in cfs in a three-hour time step into a table organized by water year and Flood-MAR volume in acre-feet in a daily time step. The WAFR data for the Main Canal is compiled alongside daily water available for Flood-MAR from five additional small stream diversions (Upper Canal, Upper Canal-Livingston, Fahrens, Mariposa, and Bear creeks) and provided to GRAT as an input table by WAFR source for each climate scenario.

The GRAT model allocates each WAFR source to the available agricultural fields and basins served by each diversion to maximize recharge up to the limits allowed by the CCC. The GRAT model accounts for the daily canal recharge occurring through the MID conveyance system. The remaining unused WAFR is returned to Merced River HEC-ResSim model as a time-series table to be added back to the Merced River flow.

GRAT Iteration with FM2Sim

The GRAT model outputs a spatially explicit tabular summary of acre-feet of recharge by day by field across the 100-year time horizon. This is converted to a monthly timestep and then summed up by each FM2Sim finite element, which is stored in a spreadsheet output file that can then be read by FM2Sim.

The GRAT model outputs were evaluated through the FM2Sim model to determine if the applied recharge volume leads to localized water logging as a result of groundwater mounding over the 100-year simulation period. The groundwater levels simulated by FM2Sim were analyzed and there was no indication of prolonged water logging, so the decision was made to not iterate between GRAT and FM2Sim. There is the potential to use the short-term mounding results to further refine the GRAT site suitability and applied recharge by location.

9.4 Model Setup, Calibration, and Results

Recharge Management Areas (RMAs)

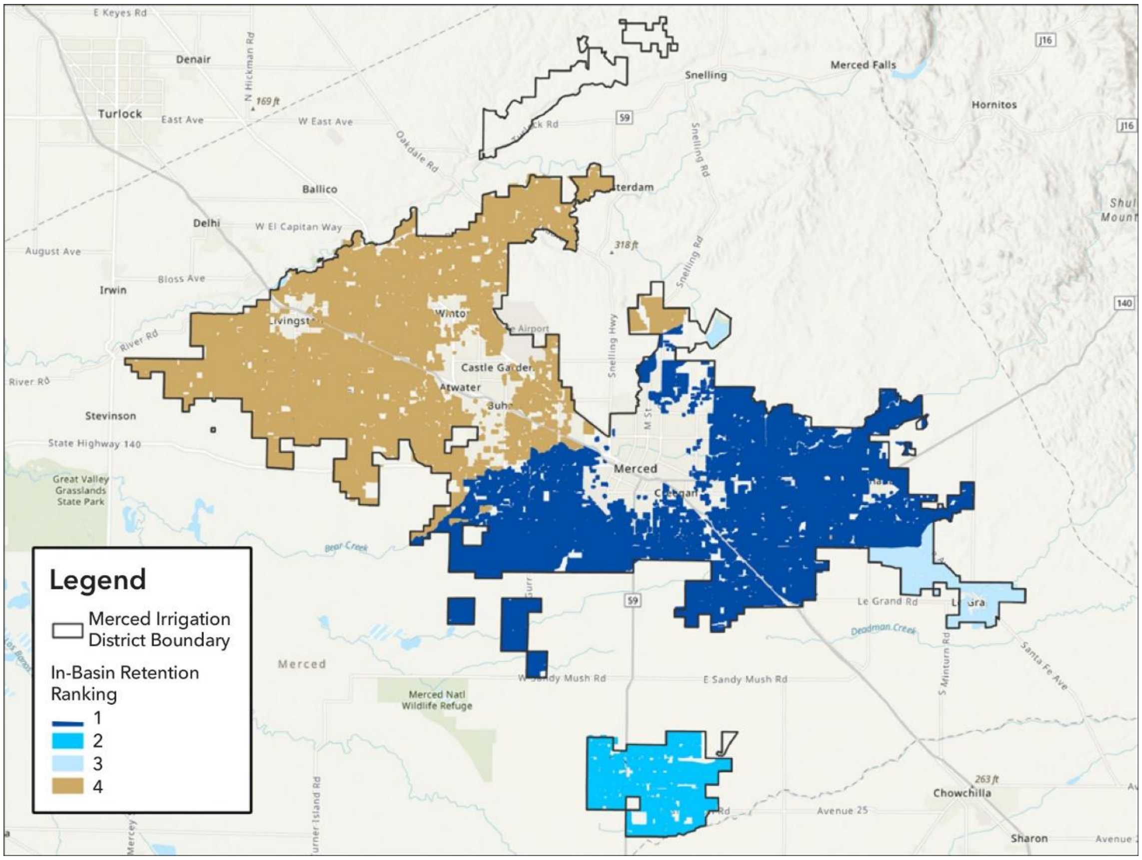
Level 1 GRAT setup was designed to allocate WAFR to the sites with the greatest capacity to capture and infiltrate water to replenish the aquifer. This approach maximized the ability to capture daily WAFR but did not necessarily achieve some of the other Flood-MAR social and environmental objectives. In Levels 2 and 3, additional GRAT functions were added to identify regions (RMAs) of the district where recharge was expected to result in targeted groundwater benefits:

1. Groundwater Retention: Outputs of the subsurface flows from the baseline groundwater model run using the 100 years of hydrology were used to determine the fields to target for in-basin retention. Current groundwater conditions and subsurface flows in the Merced subbasin may differ from these modeled conditions.

   This recharge management area prioritized placing available water on fields where recharge was most likely to remain within the Merced groundwater basin. Optimal field delineations were developed to avoid regions with the greatest risk of lateral movement to adjacent basins based on Level 1 groundwater modelling of intra-basin gradients.

   Figure 9-3 shows priority fields for recharge (highest priority in dark blue) in the management area targeted for greatest in-basin retention.

Figure 9-3 Priority Recharge Fields Targeted for Basin Retention



2. DAC Drinking Water Well Protection: This RMA targeted recharge to field locations that would replenish groundwater for public and private wells identified as most at risk of going dry. Changes in groundwater levels predicted over 100-year baseline model runs were compared with well completion records to identify at-risk well depths. Because the study area includes many DAC communities, they were prioritized into three categories based on the number of potentially impacted residents (see Figure G-3 in Appendix G, “Groundwater Recharge Assessment Tool (GRAT)” for more information).

3. Subsidence: This RMA targeted recharge in the southern portion of the district in the El Nido area because of the expanding subsidence issue from the Chowchilla groundwater basin.

4. Groundwater Dependent Ecosystems: This RMA targeted recharge to fields where recharge would provide the greatest benefit to riparian vegetation that was at risk of groundwater levels dropping below the maximum root depth of 30 feet. The primary area of concern for this

issue is in the northwest portion of the groundwater basin at the confluence of the Merced and San Joaquin rivers (see Figure G-4 in Appendix G, "Groundwater Recharge Assessment Tool (GRAT)" for more information).

5. Migratory Bird Habitat: This RMA was added to ensure that some of the available water was applied on lands with slow drainage during critical time periods to provide suitable wetted conditions for migrating wading birds. These sites were located out of the flight path of airports and on annual cropped lands with water conveyance infrastructure (see Figure G-4 in Appendix G, "Groundwater Recharge Assessment Tool (GRAT)" for more information).

6. Each of these RMAs delineated in GIS were included in GRAT and the WAFR allocation process was programmed to prioritize water to these areas first before seeking other suitable locations for the remaining WAFR. Within each RMA, fields were ranked and allocated water based on standard GRAT indexing described previously. Use of the RMAs did shift more of the WAFR to the targeted areas (see Figure G-5 in Appendix G, "Groundwater Recharge Assessment Tool (GRAT)" for more information) but did not significantly alter the total amount of water recharged within the MID. Long-term groundwater effects were detectable in the FM2Sim results for most of the RMAs.

Validation

GRAT model results produce tables showing recharge potential by field per year or average over the 100 years of the model runs. These projected quantities were compared with recharge demonstration and monitoring sites to confirm that GRAT was estimating realistic magnitude of recharge volume. Average annual recharge amounts generated by GRAT ranged from 0 to 4 acre-feet per acre (AF/A). This range is entirely consistent with field data that range from a few inches to 16 AF/A in wet years. Assuming water availability for recharge every four years, an average annual maximum of four AF/A aligns with actual recharge results.

Chapter 10. Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)

10.1 Model Description and Purpose

The FM2Sim model is an IWFM application used specifically for evaluating the benefits and impacts of Flood-MAR on the groundwater system in the Merced Subbasin. FM2Sim is a clipped version of Central Valley Simulation Fine Grid model (C2VSimFG), an IWFM model that spans the entire Central Valley (California Department of Water Resources 2020). The FM2Sim model extent includes Subregion 10 through Subregion 13 in the C2VSimFG model, which encompasses the Merced Subbasin (see Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for more information).

10.2 Model Alterations and Model Purpose for Flood-MAR

Specifically, the purpose of FM2Sim is to examine the impacts of Flood-MAR on the groundwater system and other subsystems interacting with the groundwater system. These impacts include change in groundwater storage, subsurface flows across subbasin boundaries, stream-aquifer interactions, and groundwater levels. The HEC-ResSim model (Chapter 7) determines the WAFR and the GRAT model (Chapter 9) optimizes location and amount of applied WAFR water, whereas the FM2Sim model tracks the fate of the recharged water through the groundwater system and other inter-related subsystems.

The use of FM2Sim exemplifies how C2VSimFG can be adapted for innovative local studies. The version of C2VSimFG used for this study was the BETA2 version, as the final calibration process and activities were in progress during the development of FM2Sim. Several modifications were made to the C2VSimFG input data sets to better represent local operations and features. These modifications are listed below, and further details are available in the Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)."

- Expanded the representation of local creeks in the Merced Subbasin to include the following creeks: Bear, Dutchman, Black Rascal, Miles, Owens (Lower and Upper), Mariposa, and Deadman.
- Modified diversions and delivery areas. FM2Sim updated the diversions and deliveries areas (see Figures H-1 and H-2 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for more information) to better align with local operations represented in HEC-ResSim.
- Refined stream parameters. FM2Sim includes refined stream depth-flow rating tables, wetted perimeters, and streambed conductance (see Figure H-3 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for more information).
- Added boundary conditions. The north and south boundary conditions are defined as timeseries of monthly specified groundwater heads from C2VSimFG, repeating Water Year 2015, the latest year in the period of record for C2VSimFG simulation.
- Updated initial conditions. The initial conditions from C2VSimFG were replaced with the initial conditions from fall 2018 (see Figure H-4 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for more information).
- Established baseline land use. The historical annual land use timeseries from C2VSimFG was replaced with a constant, existing conditions land use for the baseline model. The land use data was sourced from DWR's Land IQ 2014 dataset, the most recent, comprehensive source of land use data at the time of processing (see Figure H-5 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for more information).

Through the modifications mentioned above, FM2Sim was transformed into a baseline model that could be used to evaluate Flood-MAR in the Merced Subbasin. See Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for more information.

10.3 Model Setup and Integration

10.3.1 Setup

FM2Sim requires the standard IWFM preprocessor and simulation input files. The preprocessor files are used to establish the fundamentals of the model and include information about FM2Sim elements, nodes, aquifer layers, and stream configuration (Dogrul and Kadir 2020). Figure H-6 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" summarizes the FM2Sim preprocessor input files and names.

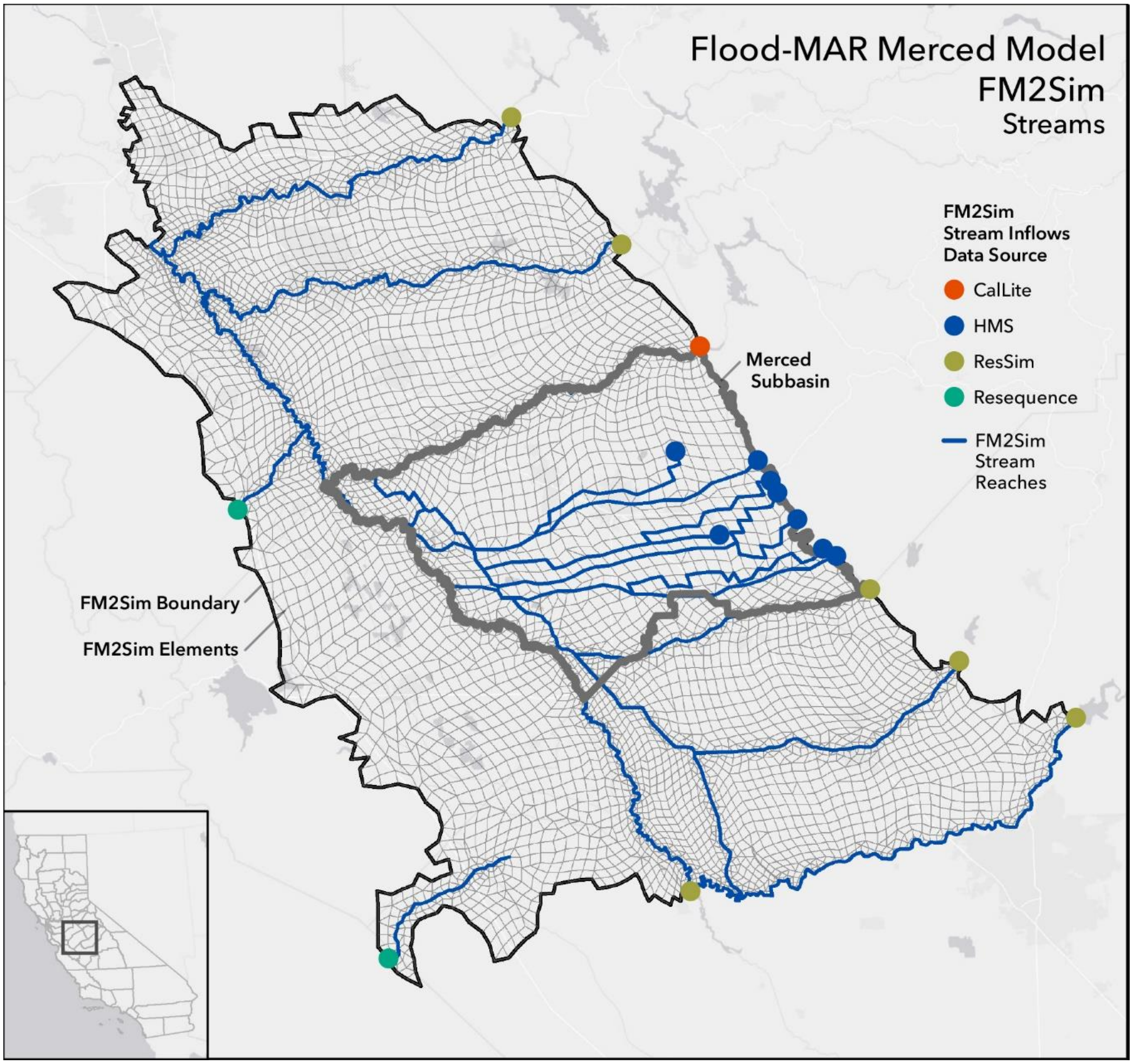
After the preprocessor files are initiated, FM2Sim then simulates water flow and mass balance processes including groundwater, land surface, root zone, stream, and unsaturated zones. In addition to the IWFM input files included in C2VSimFG, FM2Sim also includes specified head boundary conditions input file for the northern and southern boundary of FM2Sim, where it was clipped from C2VSimFG. Figure H-7 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" summarizes the model input files required to perform FM2Sim. More information about IWFM and C2VSimFG are documented on the DWR website (California Department of Water Resources 2021).

10.3.2 Integration with Other Models

Integration of FM2Sim with other models was performed through automated scripts to modify relevant input data during an iterative process.

CalLite streamflow and surface water diversion output data are processed and used as inputs for the stream inflow for all major rivers and irrigation diversions in FM2Sim domain except Merced River. HEC-HMS output data are processed and used as input data to estimate the stream inflows to the smaller streams in the domain area. Merced River inflow at the model boundary and irrigation diversions are provided by the Merced River HEC-ResSim model. Figure 10-1 illustrates the stream inflow locations from CaLite, HMS, and HEC-ResSim models. For the Flood-MAR scenarios, the spatial and temporal distribution of the recharge water is provided by GRAT.

Figure 10-1 Stream Inflow Timeseries Sources from CalLite, HMS, and HEC-ResSim Models



Appendices C, D, E, and G provide the details for FM2Sim stream inflows and diversions linked to CalLite, HEC-HMS, HEC-ResSim, and GRAT models, respectively. Because of the differences in simulation and output time steps of the models, the data was converted to monthly time steps before being incorporated into FM2Sim. The data from GRAT, after aggregating to the monthly timestep, is then distributed to FM2Sim model elements. See Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" for further details.

To establish consistent mass balance calculations in the Merced River, FM2Sim is iteratively run with the Merced River HEC-ResSim model and feedback is provided in terms of irrigation demands and stream accretions and depletions from Merced River upstream of Shaffer Bridge (Reach 5) as estimated by FM2Sim.

FM2Sim can also be iteratively run with GRAT to provide feedback regarding the distribution of recharge. A manual feedback loop is initiated if the recharge results in water logging.

10.4 Model Calibration and Results

10.4.1 Model Calibration

Considering that land use and other demands were held constant because of the current conditions baseline assumptions, the model was verified by comparing the land and water use budget and groundwater budget under similar hydrologic conditions to the baseline conditions from the local Merced Integrated Water Resources Model (Woodard & Curran 2019). Root zone, aquifer, and small watershed parameters were not changed from C2VSimFG BETA2, which were previously calibrated for the C2VSimFG historical model for Water Years 1973 through 2015.

Additionally, trends in observed groundwater levels were used to verify model results relative to historical groundwater levels for similar hydrologic conditions. The selection of calibration wells and their corresponding layer were used from C2VSimFG (see Figure H-13 in Appendix H, “Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)” for more information) and further information about model calibration are available in Appendix H, “Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim).”

10.4.2 Model Results

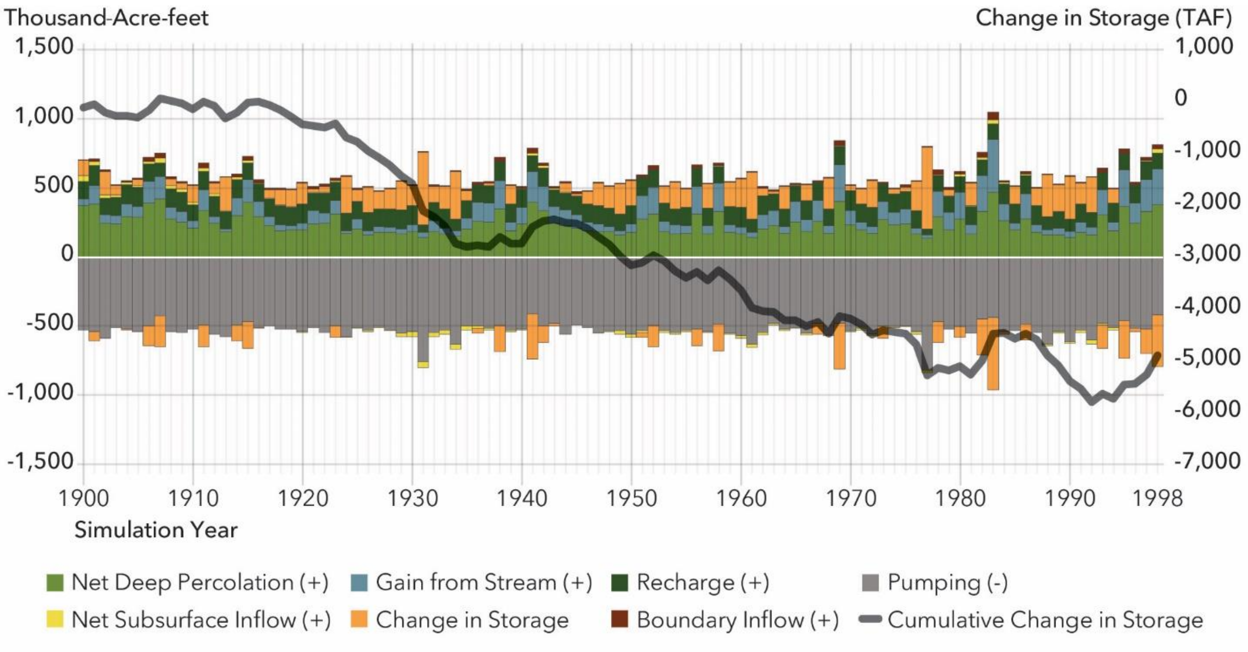
Once integrated with other models and input data is verified, FM2Sim provides water budget information about the groundwater, land surface, stream systems, and other integrated hydrologic systems. The groundwater budget illustrates all of the inflows to and outflows from the aquifer system. Inflows include deep percolation from the root zone, recharge from canal seepage and applied water recharge, and boundary inflows from the Sierra Nevada foothills. Outflows are primarily groundwater extraction. Stream-aquifer nteractions and subsurface flows between neighboring subbasins can be both inflows and outflows, depending on the location, timing, and direction of flow. The difference between the inflows and outflows is the change in groundwater storage. On average, under current conditions without the impact of climate change or Flood-MAR, the Merced Subbasin groundwater storage has a deficit of approximately 49,000 acre-feet per year from 1900-1999. This result is reasonable compared to the estimated deficit of 52,000 acre-feet per year in the 50-year simulation period 1969-2018 made by the Merced Water Resources Model in the Merced Groundwater Subbasin Groundwater Sustainability Plan. Figure 10-2 illustrations the annual inflows and outflows and the cumulative change in storage over the 100-year simulation period.

The land and water use budget provides monthly time series demands and supplies on an elemental basis. The stream budget indicates all of the inflows to and outflows from the stream system by stream reach, which are specified in the model generally by river or segments with stream gages. The groundwater budget, land and water use budget, and stream budget are the most frequently used outputs in the study. Figure H-8 in Appendix H, "Flood-MAR Merced Groundwater-Surface Water Simulation Model (FM2Sim)" summarizes all of the outputs produced by FM2Sim.

FM2Sim is developed to assess the feasibility of Flood-MAR project in the Merced Subbasin as a reconnaissance study. The FM2Sim model is currently based on the C2VSimFG model, and, as such, includes the fundamental features of the C2VSimFG model, including the spatial and temporal resolution. The hydrologic period of record is based on paleohydrology of a 500-year sequence. For production purposes, the model sequence of hydrology was reduced to a 100-year representative period, which reduces the run time, and provides for a more efficient integration and iteration process with other models, including the reservoir operations model.

The model limitations include uncertainties on land and water data, synthetic hydrologic conditions, spatial resolution, and limitations on representation of the physical features, such as irrigation canals and distribution systems. However, given that FM2Sim and all associated models it integrates with are designed and developed for assessing long-term planning and high-level feasibility of Flood-MAR projects, the model features with the spatial and temporal resolution are the most appropriate numerical tool available.

Figure 10-2 **Average Annual Baseline Groundwater Budget of the Merced Subbasin (1900-1999) under Current Conditions**



Because of the type of information, processes simulated, and information generated by FM2Sim, this model is the ultimate model that assess the bottom-line benefits and impacts, and the efficiency of any FloodMAR project scenarios in the groundwater system and other subsystems interacting with groundwater, including the benefits to the ecosystem and groundwater-dependent ecosystem, as well as interactions with the neighboring subbasins.

Chapter 11. Merced River Hydrologic Engineering Center River Analysis System (HEC-RAS)

11.1 Model Description and Purpose

HEC-RAS is designed to perform one and two-dimensional hydraulic calculations for a full network of natural and constructed channels. The study utilizes HEC-RAS 5.0.4 to determine the extent of flooding occurring along the Merced River. The extent of the model is from Crocker Huffman Dam to the confluence of the Merced River with the San Joaquin River.

The model was originally developed by Dewberry for MID as part of the MID-H2O modeling suite and consisted of only the river stream reach and cross-sections along the reach, as shown in Figure 11-1. For the study, the RAS model was modified to include the overbank and floodplain areas along the Merced River to model channel overtopping and the extent and depth of flooding outside the main channel, as shown in Figure 11-2.

The Merced River HEC-RAS model was used in the study to assess the flow and inundation area habitat potential of the main channel and off-channel areas of the Merced River; this is done by modeling the flow/stage relationship of the Merced River from very low flows to the channel capacity flow.

Figure 11-1 **Original MIDH20 HEC-RAS Model Geometry**

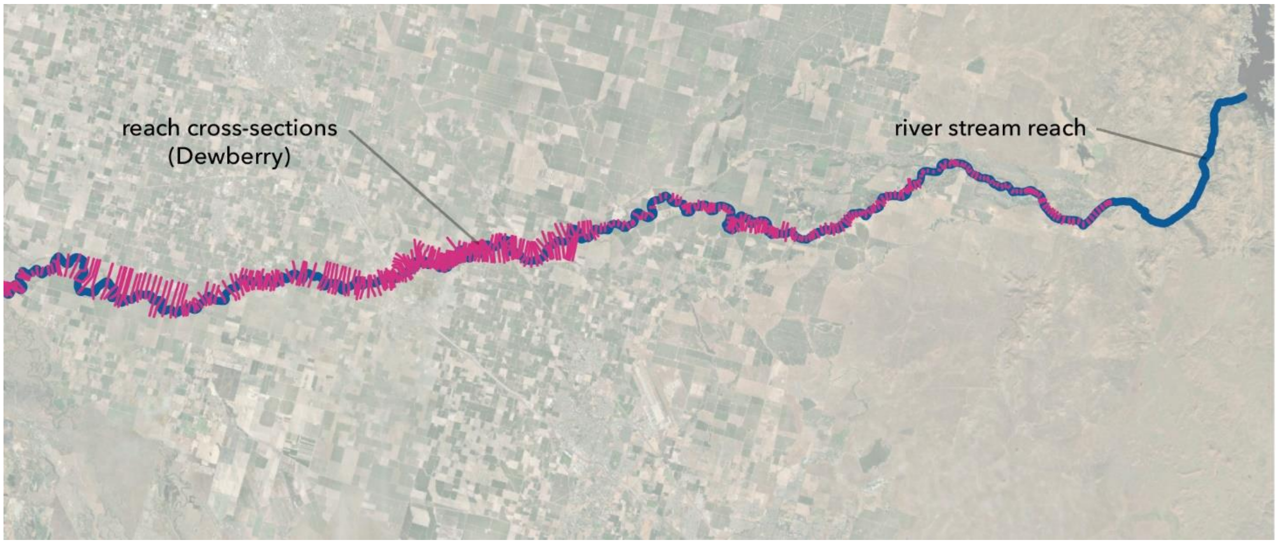
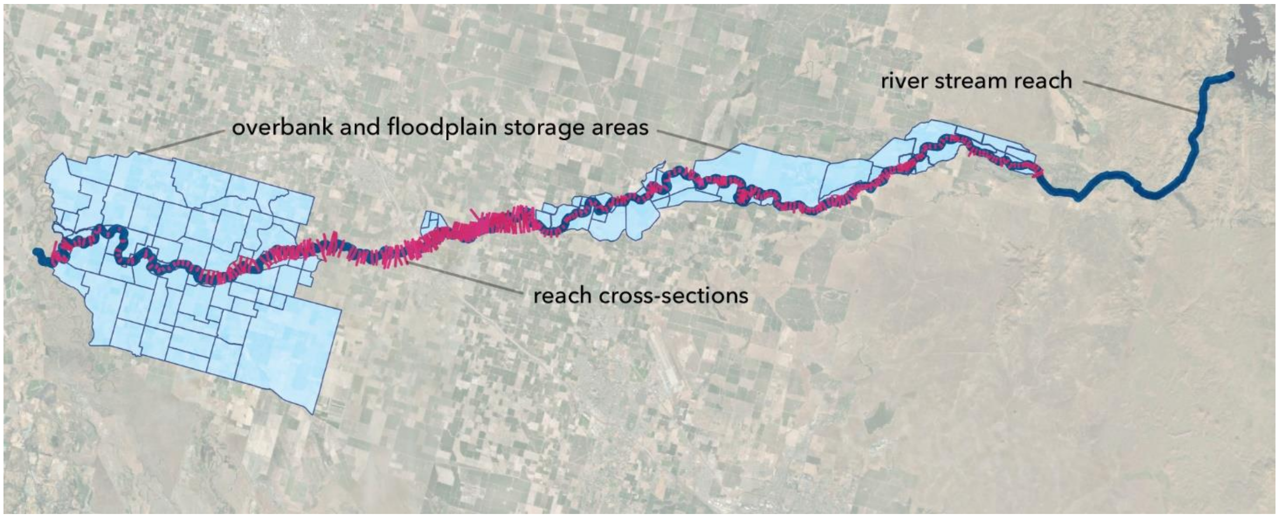


Figure 11-2 **Final Merced HEC-RAS Model Geometry**



11.2 Model Alterations and Purpose for Flood-MAR

The Merced River HEC-RAS model preserved most of the existing geometry of the MID-H2O model. Alterations were then made to better represent the overbank and floodplain areas while trying to minimize model run times. The purpose of these modifications was to better capture the results of potentially high flow events resulting from climate change that would be beyond any flows historically observed and to depict channel inundation more accurately at both low and high flows. The following model alterations were made to the model.

- One-dimensional storage areas were added to represent the floodplain areas. Storage areas from the 2017 Central Valley Flood Protection Plan Update HEC-RAS model were used for the lower portion of the Merced River. For storage areas in the upper and mid Merced River, a combination of 1-meter and 30-meter terrain data was used to create these storage areas. The 1-meter terrain data was obtained from the Central Valley Floodplain and Delineation Program and the 30-meter terrain data was obtained from United States Geological Survey.
- Cross-sections were expanded on one or both banks in regions where the terrain was relatively flat. In regions where the terrain becomes highly complex or variable, the cross-sections were trimmed at their peak left-bank and right-bank channel elevations (as determined by terrain data) to accommodate storage areas.
- Cross-sections upstream of Crocker-Huffman Dam were removed.
- Detailed modifications are available in Appendix I, "Merced River Hydrologic Engineering Center's River Analysis System (HEC-RAS)."

11.3 Model Integration and Input/Output Data

The Merced River HEC-RAS model receives input data from the Merced River HEC-ResSim model. This data is the Crocker-Huffman dam outflow time-series at a three-hour timestep. The RAS model produces stage and flow timeseries results at each cross-section and each storage area of the model at a one-hour timestep. The RAS model also produces in-channel and off-channel inundation maps for numerous stream flow thresholds for the entire reach of the Merced River.

The output timeseries are used for the ecosystem analysis for potential fish habitat. The inundation maps were used to help calculate the flow-habitat relationship of the Merced River.

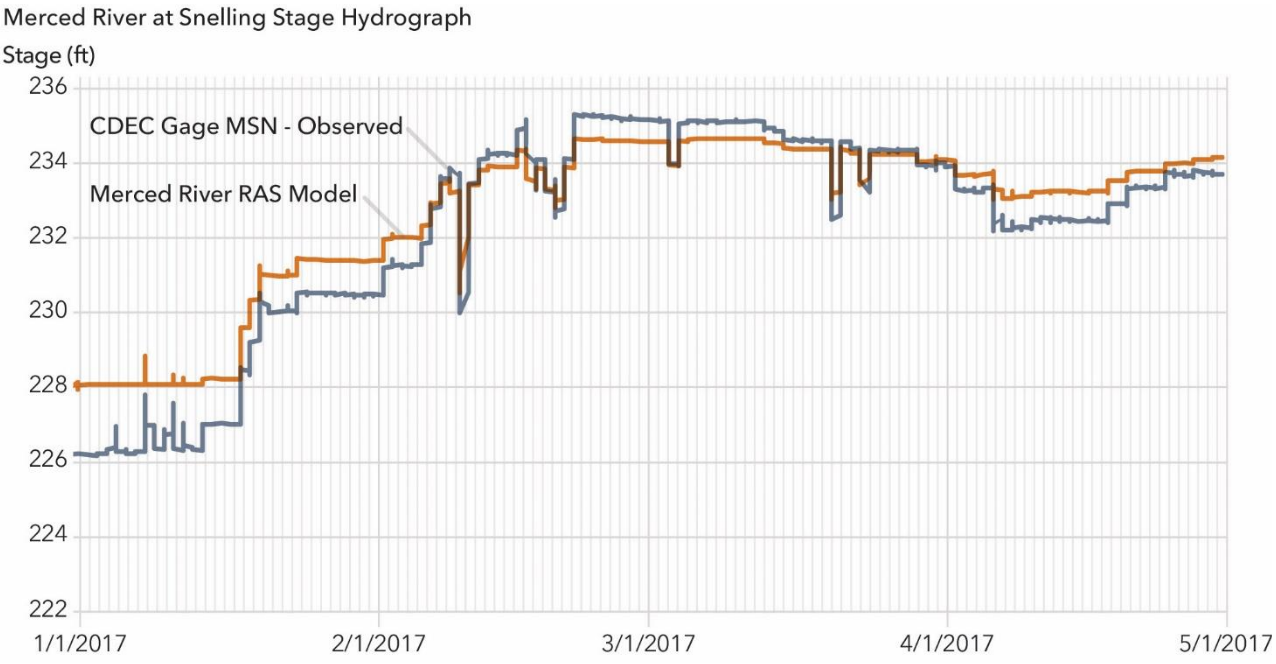
11.4 Model Testing, Calibration, and Results

11.4.1 Model Calibration

Four California Data Exchange Center (CDEC) gages were identified and used for model calibration: (1) Merced River below Merced Falls (MMF), (2) Merced River Near Snelling (MSN), (3) Merced River at Shaffer Bridge (MBN), and (4) Merced River at Cressey (CRS). The MMF gage was used for the input flow hydrograph in the model; the other three gages were used to compare the observed and modeled stage hydrographs. Hydrology from the 2017 flood event was used to calibrate and validate the model. A time period from January 1, 2017, to April 30, 2017, with flow for the event ranging from 500 to 7,700cfs.

Figure 11-3 shows the comparison of the observed and modeled stage hydrograph for this calibration event. Stage hydrograph comparison for the other two CDEC gages can be found in the Appendix I, “Merced River Hydrologic Engineering Center's River Analysis System (HEC-RAS).”

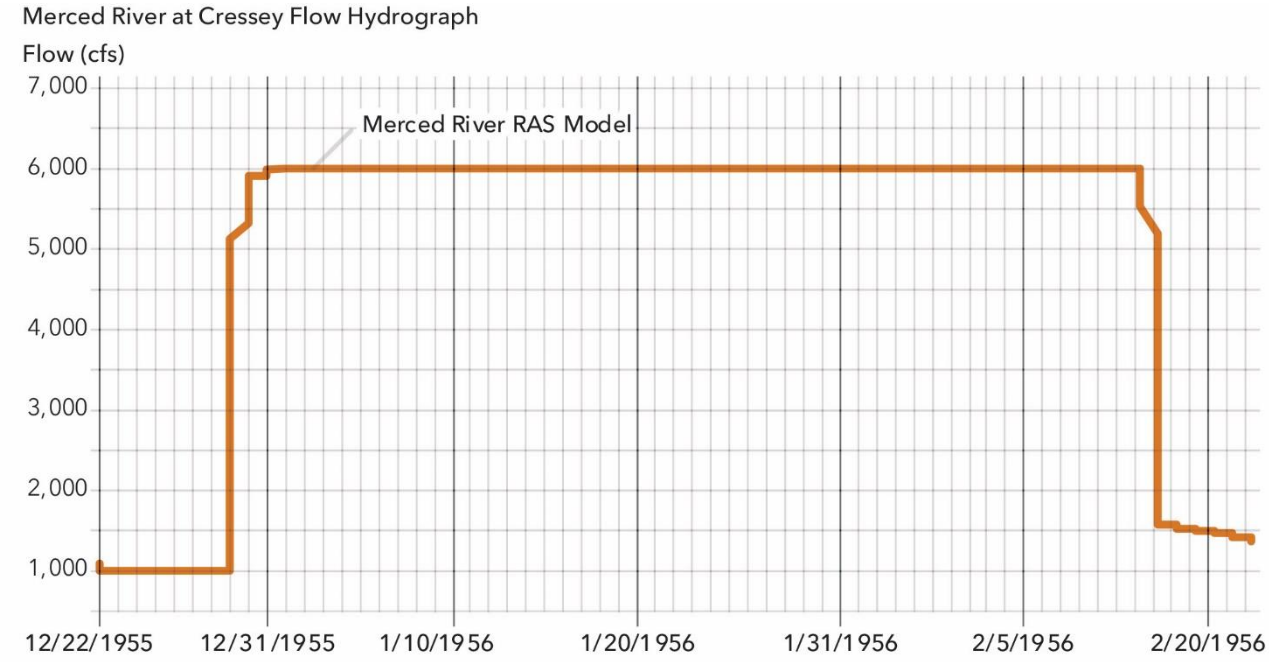
Figure 11-3 **Stage Hydrograph Calibration Comparison**



11.4.2 Model Results

Figure 11-4 shows an example model result flow hydrograph output at the MSN gage location. These results are of the simulated 1956 event for the current conditions hydrology. Outflow from the HEC-ResSim model for this event was used as the input flow. This flood event peaked at approximately 6,000cfs on January 1, 1956, and held at that flow rate up to February 16, 1956.

Figure 11-4 **Stage Hydrograph Calibration Comparison**



Chapter 12. Summary, Lessons Learned, and Identified Issues

12.1 The Flood-MAR Modeling Watershed Study Integration Approach

DWR encourages the implementation of Flood-MAR to reduce multiple threats that California's water resources sectors now face. By identifying and addressing these threats, in this case, through implementation of Flood-MAR concepts, California's water managers have opportunity to explore and understand how to use winter's high flows for groundwater recharge, simultaneously supporting groundwater sustainability, reducing vulnerability to flood risk, and enhancing ecosystems. Using high flows for managed aquifer recharge is part of California's strategy to modernize its green and grey infrastructure and comanage the water portfolio for multiple public and private benefits and resiliency. This TIR provides information of how to implement the Flood-MAR modeling watershed study integration approach with the details needed in inputs, assumptions, and processing of outputs of the eight different deployed models and how they communicate with each other to successfully implement this novel approach.

The analytical approach described in this TIR provides a foundation for integrated watershed planning and management. More specifically, the integrated toolset provides shared hydrology and analytics across multiple water management sectors, including flood risk, surface and groundwater water supply and ecosystems. Results for flood, surface and groundwater supply, and ecosystems are sufficient to meaningfully engage water managers from each of the sectors at the watershed scale.

12.2 Lessons Learned of the Climate Change Analysis

The essential outcomes of the Flood-MAR modeling approach were to improve the understanding of climate change and the potential measured effects upon water resources hydrology. The study focused on incorporating credible information on future changes within traditional risk-based planning approaches and combining historical trends with future expectations. These effects were delineated through a climate stress test known as "decision scaling" that was independent of projections of future climate. A total of 30

100-year daily weather traces were generated to cover temperature (from 0 °C to +4 °C, by 1 °C increments) and precipitation (-20 percent to +30 percent, by 10 percent increments) changes from historical averages. These climate traces were identical to the historical in internal variability (the historical observed sequence of wet and dry years) but unique in average temperature and precipitation.

12.3 The Use of Paleo Reconstructions in the Development of Daily Hydroclimate

The paleo reconstructed San Joaquin four-river streamflow provided additional natural climatic variability to the study by enabling inclusion of wet and dry cycles occurring in the first half of the 20th century.

The Flood-MAR analytical models were based on the same hydrology to improve understanding of climate change and potential measures effecting water resources. During the implementation some caveats were identified for the use of Paleo reconstruction hydrology. The original dataset of the hydrology spanned 1,100 years. Because of the number of models and climate scenarios that would be run, it would have been far too time consuming to run the full 1,100 years of the data. A simplification was made to run the last 100 years (Water Years 1900 through 1999).

12.4 Issues identified of the Flood-MAR Modeling Integration Approach

Throughout implementation of the Flood-MAR modeling integration approach some issues were identified. These issues challenged the implementation of the modeling integration as most of the eight deployed models had to communicate with each other and transfer information. These issues which are different in nature are described here and how they were resolved.

12.4.1 File Formats: Text, Spreadsheet, HEC-DSS

Eight different models were deployed with different file formats for input timeseries data. The file formats of the input timeseries data ranged from text (TXT) to spreadsheet (Microsoft Excel) to the USACE’s Hydrologic Engineering Center Data Storage System (HEC-DSS) format.

The TXT format is considered the original text file format and the equivalent of the binary file. Because a TXT file doesn't contain any formatting, no separate software is needed to open or edit it thus is used by different models. The spreadsheet format (e.g., XLS or XLSX) is the format cells used to modify the formatting of cell numbers without modifying the actual number. It is widely used to process datasets and produce input-output timeseries in all models. Microsoft Excel was the default used software. The HEC-DSS is a database system designed to efficiently store and retrieve scientific data that is typically sequential. Such data types include, but are not limited to, time series data, curve data, spatial-oriented gridded data, and others. This HEC-DSS format is used by all HEC family models (e.g., HEC-ResSim and HEC-RAS). Data in HEC-DSS database files can be graphed, tabulated, edited and manipulated with HEC-DSSVue.

All input and output datasets had to be extracted and processed before being used either by another model or presented as a result; depending on the model’s particularity, the modeler had to use one, two, or three of the file formats listed here. A significant amount of work had to be dedicated to this data processing to ensure quality assurance/quality control (QA/QC) of datasets and results.

12.4.2 Timestep: Hourly, Daily, Monthly

The deployed models run at different timesteps that ranged from hourly to daily to monthly timesteps. HEC-ResSim is the model with the finest timestep which is a three-hour timestep (e.g., 0300, 0600, 0900, and so on). HEC-ResSim requires that all input timeseries data have the HEC-DSS format with a three-hour timestep. Calculations are done on the same timestep, and outputs and results are generated in the same timestep. This information had to be converted to daily timestep to be used by other models such as GRAT or CalLite, or even monthly time step for FM2Sim. The opposite timestep conversion (from monthly to daily and hourly time step) was performed when for example FM2Sim model provided information to HEC-ResSim model. Similarly, a significant dedication in time and efforts was demanded by these processes on transferring information between models that had to be dedicated to ensuring QA/QC of datasets. Table 12-1 lists the eight deployed models and corresponding timesteps.

Table 12-1 **Deployed Models and Timesteps**

Model	Model Acronym	Timestep
Rainfall Runoff	Sac-SMA	Daily
System Operations	CalLite	Monthly
Root Zone Model	IDC	Daily
Recharge Optimization	GRAT	Daily
Groundwater Operations	FM2Sim	Monthly
Rainfall Runoff (Creeks)	HEC-HMS	Daily
Reservoir Operations	HEC-ResSim	Hourly (3 hours)
Streamflow	HEC-RAS	Hourly (3 hours)

Notes:

SAC-SMA = Sacramento Soil Moisture Accounting

CalLite = Central Valley Water Management Screening Model

IDC = IWFM Demand Calculator

GRAT = Groundwater Recharge Assessment Tool

FM2Sim = Flood-MAR Merced Groundwater-Surface Water Simulation Model

HEC-HMS = Hydrologic Engineering Center Hydrologic Modeling System

HEC-ResSim = Hydrologic Engineering Center Reservoir System Simulation

HEC-RAS = Hydrologic Engineering Center River Analysis System

12.4.3 Models' Runtimes – Minutes to Days

Model run time varies widely among all models. Some models, such as the root zone model (IDC), have a very short run time of two to three minutes per run of a single year for all agricultural landscapes. Additionally, the IDC modeling run was perfromed only once during the whole modeling implementation. Conversely, other models, such as FM2Sim, have a run time of two to five hours for a 100-year simulation on a monthly timestep, depending on the computer and how many scenarios are run at once.

Additional to the run time, the extraction and data processing time should be added. These facts made the model integration approach highly time and resource intensive.

12.4.4 Modeling Sequencing and Iterations

Deployed models simulated physical and operational processes at the watershed scale, and the sequencing of the models replicated those processes in the order that physical processes occur in nature. After models ran and produced outputs, some of those outputs were used as inputs for other models and some models provide information to each other. This process of passing back and forward information between models is called model linking. In the case that the linked models provide information to each other, their convergence was ensured by iterations. To be computationally efficient while producing reliable estimates, the number of iterations was kept at a level that numerical redundancy was acceptable.

This type of iteration happened mainly between the groundwater operation model (FM2Sim) and the reservoir operations model (HEC-ResSim) to ensure the convergence of stream-aquifer interaction estimates.

12.4.5 Quality Control

Models' quality control was a big challenge faced by the modeling team. The way that quality control was achieved for each model was different. Each model was verified and validated by consultation of model results with expert modelers who have worked extensively with these models in the private sector as well with the local water agency (MID) and State and federal agencies. These expert modelers validated model performance and model results for historical conditions and for modeled future scenarios. Expert modelers reviewed and validated model input datasets and model assumptions to make sure that models were completely reliable.

It is acknowledged that models did not have a strict peer-review process and most models did not have statistical calibration parameters to describe performance. However, all models went through a process of model results approval by MID and State and federal agency experts.

12.5 Data Generation and Analysis of Results and Metrics

Another significant challenge identified in the Flood-MAR modeling approach was the extensive output datasets that were generated in many of the model runs. Data generation was in the range of 100 megabytes up to 10 gigabytes by single climate change condition. These huge output datasets were manipulated and processed to produce results that represented headwaters to groundwater processes in the watershed. Although each model provides insightful results, together they provided decision-makers with the larger picture of the entire watershed. Extensive output dataset processing was needed to provide a comprehensive assessment of the Flood-MAR approach by combining results from various analytical models and tracking the system-wide performance metrics in four categories: flood risk, surface water supply, groundwater supply (and sustainability), and ecosystems. The objective was to evaluate the vulnerability of baseline conditions under a range of potential climate change futures and demonstrate added resilience from implementing Flood-MAR operations. Thus, results were pulled from models to tell a fuller story about the effect of Flood-MAR on watershed management. Scripting was the main tool used to extract, process results, and produce metrics to evaluate watershed performance.

12.6 Needs and Simplifications, Tradeoffs

The study illustrates that an integrated headwater-to-groundwater modeling toolset capable of modeling physical and operational processes representing the movement of water from the upper watershed through the reservoir, downstream river channel, rechargeable landscapes, and the underlying groundwater aquifer, is foundational to understanding watershed-scale challenges and Flood-MAR adaptation performance. A watershed-scale toolset with physical and operational processes properly represented by integrated modeling tools will inform water managers, decisionmakers, and the public.

The aim of this TIR is to describe the use of the modeling tools, modeling integration, and data set needed for a reconnaissance study of climate vulnerability and Flood-MAR adaptations. The modeling tools of this study integrate hydrological processes and watershed management to quantitatively evaluate water flows from headwaters to the valley floor and groundwater. These physical and operational processes were simulated by models, but their deployment and implementation are resource intensive, including time, human and monetary resources. A primary objective of the study was to provide a shared analysis of flood, ecosystem, and surface and groundwater assessments of climate vulnerability and Flood-MAR project performance at the watershed scale.

The development and implementation of the integrated toolset highlighted a tradeoff between the level of effort needed for deploying modeling tools and the level of precision and reliability of results for the simulated processes in the watershed. More time and resources invested in the deployment of models resulted in improved simulation of watershed processes.

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