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Division of Water Rights
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DRAFT

Study Plan for the Development of an Integrated Groundwater-Surface Water Model of the Ventura River Watershed

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ABBREVIATIONS

AAEE	absolute average estimation error
ASTM	American Society for Testing and Materials
CEDEN	California Environmental Data Exchange Network
CDFW	California Department of Fish and Wildlife
CIMIS	California Irrigation Management Information System
CMWD	Casitas Municipal Water District
DBS&A	Daniel B. Stephens & Associates
DEM	digital elevation model
DPWM	distributed parameter watershed model
DWR	Department of Water Resources
EVT	evapotranspiration
GAMA	Groundwater Ambient Monitoring and Assessment Program

GHB	general-head boundary
GSFLOW	Groundwater and Surface-water Flow
GSP	Groundwater Sustainability Plans
HRU	Hydrologic Response Unit
HSPF	Hydrological Simulation Program in Fortran
HFB	horizontal flow barrier
IDE	inverse distance elevation
IHM	Integrated Hydrologic Model
MAE	mean absolute error
ME	mean error
MODFLOW	Modular Ground-Water Flow Model
MODFLOW-NWT	Modular Ground-Water Flow Model – Newton Formulation
MT3D-USGS	Groundwater Solute Transport Simulator
NCDC	National Climatic Data Center
NLCD	National Land Cover Dataset
NRCS	National Resources Conservation Service
NSME	Nash-Sutcliffe model efficiency
OBGM	Ojai Basin Groundwater Model
OBGMA	Ojai Basin Groundwater Management Agency
OVSD	Ojai Valley Sanitation District
OWHM	One World Hydrologic Model
OWTS	onsite wastewater treatment systems
PAEE	percent average estimation error
PPCP	pharmaceuticals and personal care products
PEST	Model-Independent Parameter Estimation and Uncertainty Analysis
POI	points of interest
PRMS	Precipitation-Runoff Modeling System
R	correlation coefficient
RCH	recharge
RMSE	root-mean square error
SBCK	Santa Barbara Channel Keeper
SFR	streamflow routing
SGMA	Sustainable Groundwater Management Act
TMDL	total maximum daily load
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
UVRGSA	Upper Ventura River Groundwater Sustainability Agency
UZF	unsaturated-zone flow
VCAC	Ventura County Agricultural Commissioner
VCAILG	Ventura County Agricultural Irrigated Lands Group

VCWPD	Ventura County Watershed Protection District
VSWHM	Ventura Surface Water Hydrology Model
WAP	Water Action Plan
WEL	specified flux
WY	water year

1. INTRODUCTION

This Study Plan was developed by Geosyntec Consultants (Geosyntec) and Daniel B. Stephens & Associates, Inc. (DBS&A) and describes the overall approach that will be taken to develop an integrated groundwater – surface water model for the Ventura River Watershed for the State Water Resources Control Board (State Water Board).

1.1 Background

The Ventura River in Santa Barbara and Ventura Counties was identified as one of five priority stream systems in the California Water Action Plan (WAP) enacted in January 2014 by Governor Edmund G. Brown Jr. Action four (4) of the WAP, to "Protect and Restore Important Ecosystems", contains a sub-action that states the following:

> *The State Water Resources Control Board and the Department of Fish and Wildlife will implement a suite of individual and coordinated administrative efforts to enhance flows statewide in at least five stream systems that support critical habitat for anadromous fish. These actions include developing defensible, cost-effective, and time-sensitive approaches to establish instream flows using sound science and a transparent public process. When developing and implementing this action, the State Water Resources Control Board and the Department of Fish and Wildlife will consider their public trust responsibility and existing statutory authorities such as maintaining fish in good condition.*

The State Water Board and California Department of Fish and Wildlife (CDFW) are currently working to identify potential actions that may be taken to enhance and establish instream flow for anadromous fish in the Ventura River watershed (and the other four priority watersheds). The integrated groundwater – surface water model developed in this project will provide a better understanding of water supply, water demand, and instream flow needs in the Ventura River watershed.

Furthermore, in 2012, the Los Angeles Regional Water Quality Control Board (Los Angeles Regional Water Board) adopted a total maximum daily load (TMDL) for algae, eutrophic conditions, and nutrients in the Ventura River Watershed (Los Angeles Regional Water Board, 2012a, 2012b). At the time of Algae TMDL development, a source assessment for agricultural discharges of nutrients to surface water via groundwater flow was not possible. The nitrogen transport model developed in this project will aid in the Algae TMDL implementation by providing a tool for nitrogen source assessment.

1.2 Goals and Objectives of the Model

The overall goal of the integrated groundwater – surface water model and nutrient transport model for the Ventura River Watershed is to provide a defensible, scientifically sound, and publicly transparent[1] tool that can be used for the following objectives;

- Estimation of existing instream flows[2] at multiple points of interest (POI) throughout the mainstem Ventura River Watershed and its tributaries where no flow measurement data are available.
- Estimation of unimpaired flows[3] at each POI that would occur with no water diversions, pumping, or storage.
- Model water use and other human activities that impact instream flows and how these activities affect the water balance.
- Model wide range of water year types, from drought to flood years (achieved through a sufficiently long simulation period).
- Create a tool to assist the State Water Board in establishing instream flows that support critical habitat for anadromous fish in the watershed.
- Create a tool to assist the Los Angeles Regional Water Board in refining information related to the nitrogen source assessment and load allocations in support of the Los Angeles Regional Water Board's Algae TMDL.

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[1] Public transparency will be achieved through conducting multiple public outreach meetings with stakeholders, meetings with and reviews by a technical advisory committee (comprised of experts from academia, public agencies, water districts, and local consultants), development of comprehensive modeling documentation, and using an open-source, freely available modeling platform.

[2] The instream flows consistent with the most recent and complete land use data set, at the time of the model development, will be considered as "existing instream flows" or "Existing Conditions."

[3] Unimpaired flow is the flow that would have occurred had the natural flow regime remained unaltered in rivers instead of being stored in reservoirs, imported, exported, or diverted. Unimpaired flow is a modeled flow generally based on historical gage data with factors applied to primarily remove the effects of dams and diversion within the watersheds. Unimpaired flow differs from full natural flow in that the modeled unimpaired flow does not remove changes that have occurred such as channelization and levees, loss of floodplain and wetlands, deforestation, and urbanization. Where no diversion, storage, or consumptive use exists in the watershed, the historical gage data is often assumed to represent unimpaired flow.

When evaluating modeling platforms for the current study, the State Water Board and Los Angeles Regional Water Board (Water Boards) considered other model capabilities that may support future studies and planning efforts. Although these capabilities may require future model refinements or linkages to other models, the base hydrologic modeling system will be developed in a manner that supports these potential future upgrades or linkages. Additional capabilities of interest include:

- Support assessments of habitat for important species.
- Model water rights priority system to evaluate water management scenarios.
- Model climate change and future water demands scenarios.
- Model different nutrient source management scenarios, other water quality characteristics, and water temperature or ability to link the integrated groundwater – surface water model to separate water quality or water temperature models.

1.3 Overview of Report

Section 2 describes the different modeling platforms that Geosyntec and DBS&A considered, including the basis for the final decision, made in consultation with the Water Boards, to use the Groundwater and Surface-water FLOW (GSFLOW) model.

Section 3 provides an overview of GSFLOW and the proposed approach. Section 4 and Section 5 describe the development approach of the surface water model and groundwater model, including the data sources to be used, respectively. Next, Section 6 describes the GSFLOW model calibration process, including discussion of modeling period and model calibration goals.

Finally, Section 7 describes the proposed approach, including data sources, to develop a groundwater nitrogen transport model using the Groundwater Solute Transport Simulator for Modular Ground-Water Flow Model (MODFLOW/MT3D-USGS) platform.

2. MODEL METHODOLOGY SELECTION

Several integrated platforms models have been developed for groundwater/surface-water modeling, including commercial and fully publicly-available codes. This section describes the process of selecting the platform that will be used to conduct the Ventura River watershed study and briefly describes previous modeling efforts.

2.1 Overview of Existing Models

Two significant numerical modeling efforts have previously been completed in the watershed that can be used as the starting point for new model development: (1) the Ojai Basin Groundwater Model (OBGM), and (2) Ventura Surface Water Hydrology Model (VSWHM). Each of these models are described below.

2.1.1 Ojai Basin Groundwater Model

The OBGM was developed by DBS&A for the Ojai Basin Groundwater Management Agency (OBGMA), and was funded primarily through a California Department of Water Resources (DWR) Local Groundwater Assistance grant. The original model was finalized in 2011 (DBS&A, 2011), and was subsequently updated in 2014 (DBS&A, 2014).

The model was developed using the MODFLOW-SURFACT computer code, which is an upgraded and proprietary version of the widely used U.S. Geological Survey (USGS) MODFLOW code. Because recharge from precipitation was observed to have a significant impact on groundwater elevations in the Ojai Basin, an analytical watershed model developed by DBS&A, the distributed parameter watershed model (DPWM), was used to estimate the transient distribution and magnitude of recharge for input to the groundwater model.

Laterally, the groundwater model covers the geographic and vertical extent of alluvial deposits in the Ojai Basin (Figure 2.1). Vertically, the model extends to the estimated depth of the alluvial deposits, and vertical model discretization is based on analysis of geophysical logs from 24 wells located within the basin. The model is discretized into time periods that apply average values of recharge, extraction, and other inflows and outflows, termed “stress periods,” that correspond to three-month water-year quarters. A model time step, the time period over which the model computes the groundwater elevation and flux solution, is different than the model stress period. A model time step is typically on the order of several days. The model was calibrated from 1970 to 2013.

The model mass balance indicated that the vast majority of water inflow into the Ojai Basin is from recharge from precipitation, and the primary outflows are groundwater extraction in wells and groundwater discharge to surface streams. The model was used for several predictive simulations, including evaluation of the basin response to extended droughts and wet periods, model investigation of the basin safe yield, and assessment of the basin response to the San Antonio Creek Spreading Grounds Rehabilitation Project.

2.1.2 Ventura Surface Water Hydrology Model

The VSWHM is a Hydrologic Simulation Program in Fortran (HSPF) model of the entire Ventura River Watershed. The model was originally created in 2007 by Tetra Tech (2009) and calibrated to water years 1996 – 2007 and validated to water years 1986 – 1996. In 2012 the model was updated and simplified by Ventura County Watershed Protection District (VCWPD, 2012) and calibrated for 1996 through 2005. The model uses sub-daily timesteps and is geared towards predicting peak flows from large storm events for hydraulic design of flood control infrastructure. It is a lumped parameter model with sub-basin sizes ranging from approximately 100 acres to more than 6,000 acres, compared to the OBGM which has a grid area of 40,000 square feet, or 0.9 acres.

Groundwater inflows and outflows from the VSWHM were estimated, and no dynamic modeling or coupling of surface water flows with groundwater was included, which limited the accuracy of the models at low flows. Improvement of the ability to accurately model low flows is one of the primary goals in the current development of a new integrated groundwater-surface water model.

2.2 Model Selection Criteria

Available integrated groundwater – surface water modeling methods were researched and evaluated for their ability to meet project needs. It was important that the modeling approach meet DWR Sustainable Groundwater Management Act (SGMA) public domain requirements, so many models not meeting this requirement were not considered. Additional model selection criteria included:

- Capability to accurately model essential groundwater – surface water functions, including rainfall-runoff relationships, streamflow accumulation, surface-water hydrology, variable groundwater elevations, perennial groundwater discharge to surface-water, and precipitation and irrigation-related recharge to groundwater
- Perceived credibility, for instance as demonstrated by citation in the peer-reviewed literature
- Ability to model nitrogen fate and transport and track sources through groundwater to surface water
- Meets DWR SGMA public domain requirements

- Ability to model recharge from irrigation and septic systems
- Ability to meet project requirements within the defined scope and budget
- Longevity of model, availability of support/updates
- Transparency
- Degree of leveraging previous models OBGM and VSWHM
- Proven use for similar applications

2.3 Available Integrated Groundwater - Surface Water Models

Based on a review of available models that appear to potentially meet the requirements listed above, the following modeling options were evaluated:

1. Custom dynamic two-way local coupling of HSPF & MODFLOW/MT3D-USGS
2. Custom dynamic two-way coupling of HSPF & MODFLOW/M3TD-USGS & DPWM
3. GSFLOW with custom coding to link to MT3D-USGS for nitrogen transport
4. MODFLOW-One World Hydrologic Model (OWHM)/MT3D-USGS
5. Integrated Hydrologic Model (IHM)/MT3D-USGS

2.3.1 MODFLOW/MT3D-USGS + HSPF

Dynamic two-way coupling of HSPF and MODFLOW would require that HSPF pass recharge from the active groundwater component of each hydrologic response unit (HRU) to the appropriate MODFLOW cells; MODFLOW would be required to pass hydraulic head information to HSPF for simulation of lower-zone storage processes and discharge of groundwater to stream reaches (e.g., Bent et al., 2011). The dynamic linking would also need to overcome differences in spatial and temporal discretization between the two models. A custom code to dynamically couple the models would need to be developed. The MODFLOW version used would be MODFLOW-NWT (Niswonger et al., 2011). The custom code would need to also handle nitrogen transport in groundwater and discharge to surface water by linking to MT3D-USGS (Bedekar et al., 2016).

This approach would bring flexibility to the project, as the team would be able to customize the dynamic linkage, provides sufficiently accurate physical representation of hydrologic processes, leverages the existing models, and would be fully public-domain/open source. However, developing a new custom code would require significant project resources (e.g., time and budget). The existing HSPF model may need to be revised to allow for finer discretization of HRUs in order to account for spatially variable processes (e.g., recharge) that impact the groundwater model.

Based on an initial review this model option was retained for further consideration.

2.3.2 MODFLOW/MT3D-USGS + DPWM + HSPF

This approach is similar to Option #1, above, but would also make use of the DPWM, which was used in development of the OBGM to represent the temporally and spatially variable precipitation-related groundwater recharge in the Ojai Basin. HSPF model results for groundwater recharge would be matched to DPWM on a HRU-scale, and then DPWM would be used to determine spatially-variable recharge for input into MODFLOW.

This approach would leverage the existing OBGM DPWM and provide spatially-variable groundwater recharge on a finer scale than HSPF; in addition, DPWM provides a more rigorous approach for estimation of groundwater recharge (percolation past the root zone). The DPWM executable and documentation is publicly available, has been used to provide spatially-variable recharge input to numerical models developed in other California groundwater basins, and DPWM is currently being used by DBS&A in support of development of Groundwater Sustainability Plans (GSPs) under SGMA in the Fox Canyon Groundwater Management Area of Ventura County.

However, application of DPWM in addition to HSPF and MODFLOW will complicate dynamic coupling, and will introduce potential issues with differences in methodology and assumptions between HSPF and DPWM. The work required to achieve coupling will require significant project resources and time

Given the impact that this approach would have on project schedule and resources, and considering that HSPF (and other methods described below) can provide sufficiently accurate representation of hydrologic processes including groundwater recharge, this method was not considered further. Existing DPWM results for the OBGM can be used as a check on the new model-applied groundwater recharge values in the Ojai Basin.

2.3.3 GSFLOW + MT3D-USGS

GSFLOW is a coupled groundwater and watershed flow model based on integration of the USGS Precipitation-Runoff Modeling System (PRMS) and MODFLOW. Recent updates to GSFLOW bring compatibility with the latest version of MODFLOW (MODFLOW-NWT), which is necessary for representation of variable groundwater levels in the Ojai Basin. GSFLOW was developed to simulate coupled groundwater –

surface water flow in one or more watersheds by simultaneously simulating flow across the land surface, within subsurface saturated and unsaturated materials, and within streams and lakes (Markstrom et al., 2008; Regan et al., 2016). PRMS simulates similar hydrologic processes as compared to HSPF.

GSFLOW is a pre-existing integrated hydrologic model that is actively supported and updated by USGS, and is fully publicly available. No coding by the project team would be required for integrated groundwater – surface water modeling.

Based on personal communication with USGS staff (Morway, 2017), GSFLOW does not currently support transport simulations. Custom coding would be required to link GSFLOW to MT3D-USGS for nitrogen transport simulations. For example, custom coding could be used to develop a separate MODFLOW model with boundary conditions assigned from GSFLOW. This MODFLOW model could then be used to develop the necessary 'linker' file required to run transport simulations with MT3D-USGS. Based on personal communication with USGS staff (Morway, 2017), this approach should be possible.

This approach will bring the advantages of GSFLOW, adding in the capability for nitrogen transport simulations. However, custom coding to link GSFLOW and MT3D-USGS will require significant project resources and time. Based on personal communication with USGS staff, there may be unforeseen problems in developing the linker file and implementing transport (Morway, 2017). Use of GSFLOW would leverage the existing VSWHM to a lesser extent as compared to other options that use HSPF.

This option meets all project needs and was retained for further consideration.

2.3.4 MODFLOW-OWHM/MT3D-USGS

MODFLOW-OWHM (Hanson et al., 2014) has been developed by USGS to evaluate water management in a physically-based supply-and-demand framework. The primary difference between MODFLOW-OWHM and GSFLOW is that GSFLOW is intended to link MODFLOW with the watershed model PRMS, whereas MODFLOW-OWHM links MODFLOW to models of human water-resource infrastructure needed for conjunctive-use analysis. MODFLOW-OWHM does not solve the rainfall-runoff equation and does not solve the surface water problem on the scale of a watershed. Rather, time series rainfall, evaporation, and lateral flows are assigned to every surface water reach.

MODFLOW-OWHM offers linkages to MODFLOW packages, such as the Farm Package, that could be used to estimate agricultural pumping in areas or time periods without sufficient pumping data. MODFLOW-OWHM is primarily intended for evaluating conjunctive use scenarios, and would be useful for those analyses.

MODFLOW-OWHM does not solve the rainfall-runoff equation, and therefore does not provide sufficient physical representation of surface water hydrology necessary to build a fully-integrated groundwater – surface water model. Therefore, MODFLOW-OWHM was not considered further.

2.3.5 Integrated Hydrologic Model (IHM)/MT3D-USGS

The Integrated Hydrologic Model (IHM) was previously developed to dynamically link HSPF and MODFLOW, and is referenced in the scientific literature (e.g., Hosseinipour, 2006). IHM was developed as a collaborative effort including South Florida Water Management District (Tampa Bay Water, 2017). IHM has been used in Florida to evaluate effects of the proposed increase in pumping on nearby spring flow, streamflow, and aquifer levels (Intera, 2017). As a pre-existing linkage between MODFLOW and HSPF, IHM may offer advantages as starting point for Ventura River Watershed model development. However, IHM does not appear to be in the public domain. Capabilities of IHM are also unclear and user guidance and detailed model description and assumptions may be limited. It is also unclear if IHM is compatible with MODFLOW-NWT or MT3D-USGS. For these reasons, IHM was not retained for further evaluation.

2.4 Model Selection

The two options retained for further consideration were Option #1 - MODFLOW/MT3D-USGS + HSPF and Option #3 - GSFLOW + MT3D-USGS. A selection matrix was developed as a basis for selecting the model platform (Table 2.1). For the purpose of the selection matrix a Score of 1 (worst) to 3 (best) was applied to each of the selection criteria for each model platform. In addition, weighting factors were applied to the selection criteria based on input from the Water Boards. Overall Option #3 (GSFLOW + MT3D-USGS) received a greater score as compared to Option #1.

Table 2.1 Modeling Platform Selection Matrix

Importance	Weight (0 to 5)	Factor / Criteria	Score (1 = worst, 3 = best)	
			Custom 2-way Coupling of HSPF-MODFLOW, with Separate MT3D	GSFLOW with MT3D
more	5	Capability to accurately model essential gw-sw/watershed functions	3	3
↕	5	Perceived credibility	2	3
	5	Ability to track nitrogen sources through groundwater to surface water	3	3
	5	Ability to model irrigation and septics	3	2
	3	Model in public domain / meet DWR SGMA requirements	3	3
	3	Project resources required (schedule/budget)	1	2
	3	Ability to model sub-daily temperature	3	2
	2	Longevity of model	1	2
less	2	Support/updates	1	2
		FINAL SCORE	**80**	**84**

GSFLOW was seen as offering the key advantages of high level of credibility and transparency, the need for less custom coding, online training availability, widespread use, and thorough public documentation. Based on these considerations GSFLOW + MT3D-USGS was selected as the modeling platform for the project.

3. OVERVIEW OF GSFLOW AND APPROACH

This section provides an overview of GSFLOW, the modeling platform chosen to develop the integrated groundwater – surface water model (Section 2), and the overall approach that will be used to develop the integrated GSFLOW model and nitrogen groundwater model.

3.1 Overview of GSFLOW

GSFLOW is an integrated hydrologic model developed by the USGS to simulate coupled ground-water and surface-water resources (Markstrom et al., 2008). The model is based on the integration of the PRMS (Markstrom et al., 2015) and MODFLOW. As detailed in the GSFLOW documentation (Markstrom et al., 2008), additional model components were developed, and existing components were modified, to facilitate integration of the models. GSFLOW runs on a daily timestep. Methods were developed to route flow among the PRMS HRUs and between the HRUs and the MODFLOW finite-difference cells. An important aspect of the integrated model design is its ability to conserve water mass and to provide comprehensive water budgets for a location of interest. In addition to running integrated simulations, GSFLOW can also be run in PRMS-only or MODFLOW-only modes.

GSFLOW is conceptualized as three regions with exchanges of flow between them, as illustrated in Figure 3.1. The first region includes the plant canopy, snowpack, impervious storage, and soil zone, and is simulated with the PRMS modules. The second region consists of streams and lakes, and is simulated using the MODFLOW-NWT packages (after a recent update from MODFLOW-2005). Thus, the stream-routing modules of PRMS are not used when GSFLOW is run in coupled mode. However, the PRMS stream-routing modules are used when GSFLOW is run in PRMS-only mode (e.g., during an initial surface water calibration). The third region, or subsurface, is beneath regions 1 and 2 and consists of the unsaturated and saturated zones. Region 3 also uses MODFLOW-NWT packages.

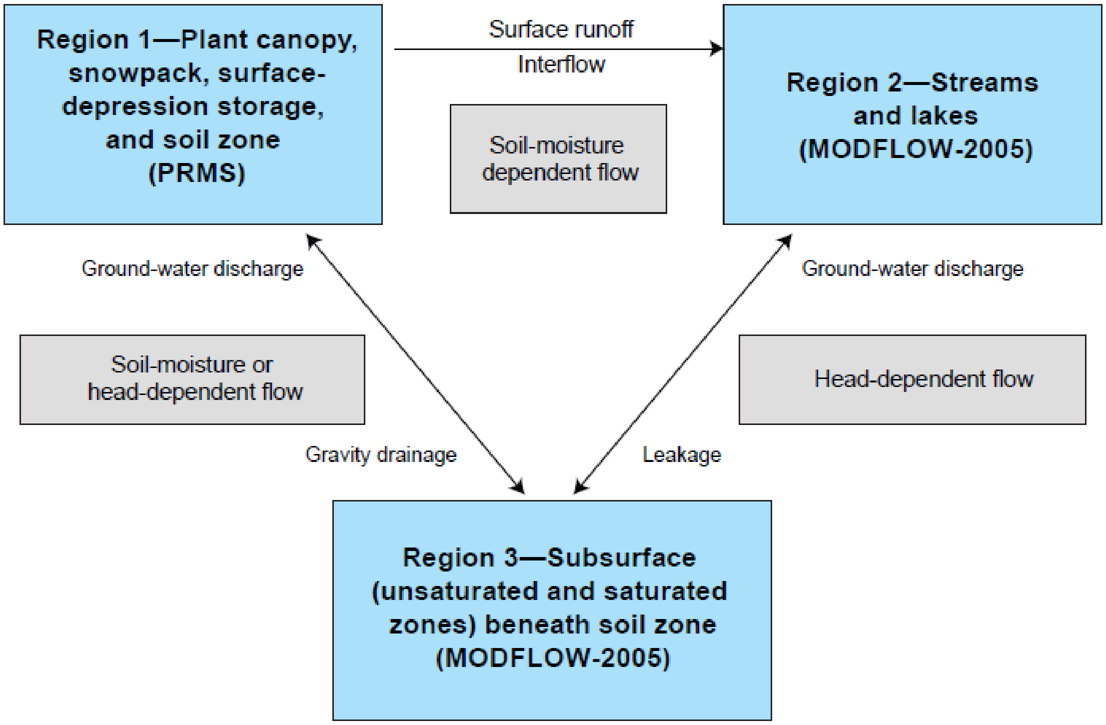

Figure 3.1 Schematic diagram of the exchange of flow among the three regions in GSFLOW (Markstrom et al., 2008). The MODFLOW-2005 packages were recently updated to MODFLOW-NWT.

The functionality and flows between the three regions depicted in Figure 3.1 are well described in the USGS GSFLOW report (Markstrom et al., 2008), viz:

> *Specified inputs of precipitation and temperature and specified inputs or model-estimated potential solar radiation are distributed to each HRU to compute energy budgets, flow, and storage within region 1. A portion of the water entering region 1 infiltrates into the soil zone, where it is evaporated and transpired back to the atmosphere, flows to streams and lakes (region 2), and (or) drains to the deeper unsaturated and saturated zones (region 3).*
>
> *The rate at which water flows from the soil zone to streams and lakes is dependent on: (1) the rate at which water is added to the land surface by snowmelt and rain, (2) the rate of infiltration into the soil zone, and (3) the antecedent soil-zone storage. Water that flows from the soil zone to the unsaturated and saturated zones (region 3) is called gravity drainage. Gravity drainage is dependent on the vertical hydraulic conductivity of the unsaturated zone and the volume of water stored in the soil zone. Additionally, gravity drainage ceases as the water table rises into the soil zone. Water also can flow from the saturated zone into the soil zone as ground-water*

> *discharge; the rate of discharge is dependent on the hydraulic conductivity and ground-water head relative to the altitude of the soil-zone base. Flow between the unsaturated and saturated zones to streams and lakes is dependent on the ground-water head in relation to the stream- or lake-surface altitude, the hydraulic properties of the streambed and lakebed sediments, and the hydraulic properties of the unsaturated and saturated zones.*

Additional descriptions of the GSFLOW model, including detailed descriptions of PRMS and MODFLOW and how they were integrated, the equations and order of calculations used, modeling assumptions and limitations, and data-input requirements are provided in the GSFLOW report (Markstrom et al., 2008).

3.2 Development Approach

The general approach for model development will consist of the following steps:

1. Develop PRMS model and calibrate primarily to wet-weather flow (PRMS-only)
2. Develop MODFLOW files and perform initial simulations (MODFLOW-only)
3. Integrate PRMS and MODFLOW in GSFLOW and perform comprehensive calibration to groundwater and surface-water targets
4. Based on GSFLOW flow output, develop a standalone MODFLOW model for nitrogen transport modeling with MT3D-USGS

Step 1 involves the development of the PRMS-only surface water model, as detailed in Section 4. The PRMS-only model will be calibrated to wet-weather flow, leveraging the wet-weather calibration parameters from the VSWHM (see Section 4.1). Calibration of dry-weather flows will be delayed until integration with the groundwater model in GSFLOW (Section 6), since the low flows inherently depend upon interaction with groundwater.

Step 2 will be carried out in parallel with Step 1 and involves the development of the MODFLOW-only groundwater model (see Section 5). The purpose of this step is to develop the groundwater model files and ensure the model runs without errors and flow patterns are in general agreement with conceptual understanding of the basins. Full calibration of the groundwater model will be made when the model is integrated in GSFLOW.

The PRMS and MODFLOW models will be integrated in GSFLOW in Step 3 (see Section 6), at which point the model will be calibrated for dry-weather surface flows and groundwater elevations as described in Section 6.2.

Finally, the standalone groundwater model for nitrogen transport simulations will be developed with MT3D-USGS in Step 4, as discussed in Section 7.

4. SURFACE WATER MODEL DEVELOPMENT

This section describes how the PRMS-only surface water model will be developed, including leveraging the existing VSWHM, datasets and sources to be used to provide model inputs (including discussions of data quality checks and gap filling) and for calibration. The PRMS-only model will be calibrated to wet-weather flows, while the full model calibration will be conducted for the integrated GSFLOW model, as described in Section 6.

4.1 Leveraging the Existing VSWHM

The existing VSWHM, HSPF based, was developed and calibrated focusing primarily on high-flow events, in contrast to the current project which focuses on low flows (see Section 2.1.2). However, the VSWHM still represents a substantial effort that should be leveraged as much as possible in the current modeling effort. A summary of the similarities and differences between HSPF and PRMS, along with discussion of how VSWHM's calibrated input parameter values may be used to inform the initial set-up of the PRMS model, are provided below.

PRMS and HSPF are both lumped parameter models that rely on attributes of different HRUs to assign parameters to control the water balance on the land surface and direct surface runoff, interflow, and active groundwater flow to downstream stream segments. The VSWHM will be a useful resource in development of the PRMS model due to the relative similarity of their inputs. For example, VHSWM will be used to inform irrigation rates applied to urban landscaped areas; geometry, attributes, and connectivity of the stream network; diversion operations; point source discharges; HRU's to be used; stage-storage curves and operation rules of the dams, reservoirs, debris basins, and other infrastructure; as well as a useful starting point for assigning key model parameter values prior to calibration.

While similar, PRMS differs from HSPF in several respects. For example, PRMS implements soil layers and irrigation differently than HSPF. PRMS is also able to route flows from one HRU to another (instead of only to the stream). In addition, to aid in the dynamic coupling between PRMS and MODFLOW, a grid-based land representation (i.e., using the same horizontal grid as the groundwater model) will be used in PRMS drather than a polygon-based representation. The PRMS model will also contain updated meteorological input and other data not available or not used in the VSWHM model. So, while the VSWHM will certainly inform the development of the PRMS model, the PRMS model will need to be developed independently.

4.2 Datasets and Sources

The data that will be used to develop and calibrate the PRMS model are shown in Table 4.1 and are described briefly in the following sections.

4.2.1 Precipitation Data

Precipitation data sources are similar to those used in the VSWHM model, but periods of record will be extended through 2016 (and ultimately through 2018, see Section 6.1), and precipitation will be input on a daily-average basis for consistency with GSFLOW daily time-step. Figure 4.1 provides a map indicating the gages that were used in the VSWHM and additional rain gages that were not used previously. In general, it is anticipated that the same gages used in the VSWHM will be used in the current modeling. However, it is noted that several gages were discontinued in recent years, as indicated in Figure 4.2. For example, gages 300, 301, 302, 303, and 46910 were discontinued from between 2010 and 2013. These gages are located near the perimeter of the watershed, and do not have nearby gages that can readily be used to replace them. Instead, and in order to include important orographic effects that may be captured by these gages, correlations to other gages based on the period of over lapping records will be developed as necessary to fill these gaps.

Precipitation data are critical in that they drive the flows and water balance in the entire model. Inverse distance and elevation (IDE) weighting (Markstrom et al., 2015) will be used within PRMS to interpolate data between different rain gages. Rain gage data used as input into the PRMS model will be checked for quality, consistency, and completeness. Precipitation data from VCWPD have already had all gaps filled and accumulations removed as part of the VCWPD quality assurance process. Gages used from other sources will be examined for gaps and accumulations in the precipitation record. Gaps will be filled by scaling data from nearby gages based on a comparison of their annual precipitation depths. If precipitation data from a gage need to be disaggregated to a finer time step, this will similarly be done using a gage at the finer time step based on their annual precipitation depths.

4.2.2 Potential Evapotranspiration Data

Potential evapotranspiration data for reference crops are available from California Irrigation Management Information System (CIMIS), and specific evapotranspiration data for different crop types within Ventura County are available from DWR. Crop coefficients for estimating potential evapotranspiration for different vegetation from reference crops are available from the VSWHM. Where gaps exist in these data, potential evapotranspiration can be estimated from air temperature data using the Hamon method

(Hamon, 1961). This is commonly done to fill gaps in and/or supplement potential evapotranspiration data.

Table 4.1 Data Anticipated to be Used to Develop PRMS Model

Need for PRMS Model	Anticipated Data to be Used
(a) Data for Creating PRMS Land Grid and Attributes	
Precipitation	VCWPD data, National Climatic Data Center (NCDC) data, and Casitas Municipal Water District (CMWD) data
Potential Evapotranspiration	CIMIS ETo data for reference crop, Crop coefficients from LA County and DWR, Air temperatures from VCWPD
Land surface elevations	USGS digital elevation model (DEM)
Soil attributes	Natural Resources Conservation Service (NRCS)
Land use	National Land Cover Dataset (NLCD) 2011, DWR Crop Survey, Ventura County Agricultural Commissioner (VCAC) Crops Now, United States Forest Service (USFS) Landfire, Ventura County Environmental Health Department [VCEHD] parcels with onsite wastewater treatment systems (OWTS) (2016), Parcels from Los Angeles Regional Water Board
Imperviousness	NLCD 2011
Irrigation rates and attributes for urban landscaping	Previous HSPF Model, DWR annual irrigation rates
Irrigation application rates by crop type	DWR county-level application rates by crop
(b) Data for Creating Stream Routing in PRMS in PRMS-only Model (will be removed once coupled)	
Stream network	Previous HSPF Model
Stream geometry and other attributes	Previous HSPF Model F-tables, USGS transects
Reservoir volumes, control curves, evaporation volumes, etc.	CMWD Hydrology Reports
Diversions and withdrawals	CMWD Hydrology Reports, Casitas UWMP-AWMP, Ventura Comprehensive Water Resources Reports, USGS 11118400 Gage
Debris Basins geometry and curves	Previous HSPF Model
Ojai Valley WWTP discharges	Daily records from Ojai Valley Sanitary District (OVSD)
(c) Data useful to calibrate/validate PRMS Pre- and Post- Coupling	

Streamflow gage data	VCWPD, USGS, Casitas MWD Hydrology Reports
Wet-dry data	CDFW, municipal water supplier, and OBGMA maps

4.2.3 Topography

The data used to determine slopes, connectivity, and elevations will come from a USGS digital elevation model (DEM), as was done for the VSWHM, and supplemented with LiDAR data where/if available. A grid-based land representation (rather than the more traditional polygon-based representation) will be used to aid in the dynamic coupling between PRMS and MODFLOW (see, e.g., Woolfenden et al., 2014). Specifically, the same horizontal grid used in the groundwater model (Section 5.3) will be used to develop the PRMS model.

The DEM will be processed using the USGS Cascade Routing Tool (Henson et al., 2013), or similar software, to define the cascading surfaces and subsurface flow paths for the grid-based domain. If necessary, the grid-scale DEM will be conditioned to fill unintended swales and provide continuous down-sloping HRUs.

4.2.4 Land-use

Soil attributes will be assigned to HRUs based on the NRCS soil survey data, which was also done for the VSWHM. Land uses will be fixed (i.e., temporally static) in the PRMS baseline model to simplify comparisons with other scenarios. The NLCD 2011 dataset (Figure 4.3) is a good, grid-based representation of land uses in the watershed and will be used as a base land use layer. Visual comparisons between NLCD 2001 and NLCD 2011 data indicate minimal changes in the watershed, at least at the scale of the watershed, and as such the use of the 2011 data should be reasonably representative of much of the modeling period.

The NLCD 2011 land use data will be combined with spatial crop data from DWR (years 2000 and 2014, Figures 4.4a and 4.4b, respectively) and VCAC (year 2016, Figure 4.5) to provide a more detailed characterization of different crop types than what is provided in the NLCD agricultural areas. The land use dataset will also be combined with the USFS Landfire dataset (Figure 4.6) in natural areas to provide more detail on natural vegetation types.

Data reflecting the assumed locations of parcels with OWTS (2016 data from VCEHD) (Figure 4.7), agricultural parcels (from Los Angeles Regional Water Board), and parcels with horses present (from Los Angeles Regional Water Board) will be used to further refine the land use dataset to the necessary HRU categories for modeling. These data will also be critical in determining loadings for the nitrogen model (Section 7). Each grid will be assigned to the dominant HRU category.

Finally, imperviousness of each grid will be determined from the NLCD 2011 dataset (Figure 4.8). Visual comparisons between NLCD 2001 and NLCD 2011 data indicate minimal changes in the watershed, at least at the scale of the watershed, and as such the use of the 2011 data should be reasonably representative of much of the modeling period.

4.2.5 Irrigation Data

Irrigation application rates in urban areas are less important in this watershed due to limited urban development, but irrigation in urban landscaped areas still plays a minor role in the water balance. Urban irrigation rates and attributes will be determined based on the VSWHM model and evaluation of pumping data for municipal wells and surface water diversion data (as available, see Section 5.2).

Irrigation on agricultural areas (defined by the agricultural parcel data from Los Angeles Regional Water Board) is important to the water balance as well as the nitrogen model (see Section 7). Annual irrigation rates by crop type in Ventura County are available from DWR between 1998 and 2010. These will be evaluated to provide irrigation estimates for model input. If feasible, these data will be used, together with meteorological data and/or seasonal variation, soil-type, and geology, to develop irrigation "rules" and rates for each crop type. A rules-based approach is preferable to using data directly, as this allows for the extension of the modeling period as well as comparison to other modeling scenarios from the baseline. Pumping data for agricultural wells and surface water diversion data (as available) will also be assessed for consistency with the irrigation rates, and the assumed irrigation rates will be consistent with those used to estimate well extraction for the purposes of the groundwater model (see Section 5.2).

Additionally, the Upper Ventura River Groundwater Sustainability Agency (UVRGSA) has commissioned an infrared aerial imagery survey in the Upper Ventura Basin to evaluate irrigation practices. Results of this study are unlikely to be available during the data collection period, but they may be used later as a check on assigned irrigation rates.

4.2.6 Stream Connectivities

Streamflow and routing will be handled by MODFLOW once PRMS is coupled to MODFLOW. However, to get an initial calibration of PRMS, some stream routing is necessary. Most of the stream connectivities and attributes can be taken directly from the HSPF model files for the purposes of the PRMS-only model. These will be checked for consistency with the gridded topography and may be supplemented with transects available from USGS and topographic information from CDFW (used to develop one- and two-dimensional river models) which will likely be used as part of development of the MODFLOW model. Additional information that may be used include dams, diversions, debris basins, withdrawals, and other anthropogenic changes in flow routing will be implemented into the model using estimates derived from information and data available in the reports in Table 4.1.

4.2.7 Streamflow Gages

Calibration will be achieved by comparing model-predicted flows to the streamflow gages available primarily from VCWPD as well as potentially to the Casitas MWD and USGS gages (Table 4.1). Figure 4.9 indicates 18 streamflow gages that are available to be used. The temporal coverage of these gages is illustrated in Figure 4.10, and indicates that four new gages were installed in late 2013. Specifically, gage 605A was added to replace gage 605 that was removed. Gages 648, 649, and 650 were added in the upper reach of San Antonio Creek (Figure 4.9), with gages 648 and 650 subsequently being removed. These new gages, and in particular gage 649, will be useful for calibration of the model in the upper San Antonio Creek sub-watershed.

In addition to data from the existing streamflow gages, the State Water Board is working with the DWR, USGS, and VCWPD to collect additional data as follows:

- Working with VCWPD on installation of a new permanent, year-round, telemetered streamflow gage on San Antonio Creek at Camp Comfort. The State Water Board is including budget for two years of operations and maintenance, including biweekly manual streamflow measurements. Data will be viewable, in real time, on the VCWPD hydrology website. The State Water Board is looking for local organizations to take over funding the VCWPD to continue operations and maintenance of the new gage in perpetuity.
- Working with DWR and USGS on weekly manual streamflow measurements of Ventura River near Ventura (USGS 11118500) streamflow gage from Fall 2017 to October 31, 2018

Collection of these data is expected to begin in late 2017 or 2018. It is anticipated that these data will not be available in time for direct use in the development of the PRMS-only model, but they will be used for validation of the GSFLOW model (see Section 6.1).

4.2.8 Wet-dry Maps

CDFW and various local water agency staff (e.g., Meiners Oaks Water District, Casitas Municipal Water District, and Ojai Basin Groundwater Management Agency) conduct observations and surveys of the river and stream channels in the Ventura River Watershed to generate wet-dry maps such as those presented in Figure 4.11. These maps can be used to verify model predicted reaches as being wet, dry, or intermittent at periods in the simulation like those observed. This will be done once the PRMS model and groundwater model are integrated in GSFLOW (see Section 6).

5. GROUNDWATER MODEL DEVELOPMENT

This section describes how the MODFLOW-only groundwater model will be developed, including the model input data, data gaps, model domain and discretization, and boundary conditions. The goal of the MODFLOW-only model development will be to ensure that the groundwater model runs without errors, and that the groundwater flow system is generally consistent with understanding of the groundwater basins. The full model calibration will be conducted for the integrated GSFLOW model, as described in Section 6.

5.1 Model Input Data

The following input data will be used to develop the groundwater model, and are broken-out by (1) input parameters that are anticipated to remain the same before and after MODFLOW-PRMS model integration; (2) input parameters that are anticipated to come primarily from PRMS, and therefore initial placeholder values are used in the MODFLOW-only model, and (3) input parameters that are anticipated to be adjusted during calibration of the integrated model.

Parameters that will remain the same in integrated model:

- Extent and thickness of model layers representative of alluvial aquifers based on review of geologic maps, boring logs, existing geologic studies and cross-sections (see Section 5.3).
- Groundwater extraction from municipal wells will be based on agency pumping records, including Casitas Municipal Water District, Meiners Oaks Water District, the City of Ventura, and Ventura River Water District, and small water suppliers (i.e., those listed for the Upper and Ventura River Basins in Walter, 2015). State Water Board has taken the lead on requesting data from these agencies.
- Agricultural and domestic well extraction will be based on pumping reported to OBGMA for the Ojai Basin. Pumping for agricultural and domestic wells in the Upper Ventura, Lower Ventura, and Upper Ojai Basins is identified as a data gap (see Section 5.2).
- Recharge from OWTS systems and water and sewer-line leakage.

Parameters that will come from PRMS:

The following parameters are estimated by PRMS, and average estimates will be applied for the purpose of the preliminary initial MODFLOW-only simulations.

- Recharge from deep percolation of precipitation (including within stream bottoms) and irrigation.
- Recharge from spreading grounds.
- Riparian evapotranspiration of shallow groundwater.

Parameters that will be adjusted during calibration:

- Hydraulic conductivity and storage coefficient are the primary model calibration parameters and will initially be based on calibrated values for the OBGM in the Ojai Basin and based on available aquifer-test and/or specific-capacity tests for remaining Basins. These values will be adjusted during model calibration (see Section 6).

5.2 Data Gaps

Primary data gaps for the groundwater model include (1) annual extraction rates for agricultural and domestic wells in the Upper Ventura, Lower Ventura and Upper Ojai Basins; and (2) monthly extraction rates for all wells in all Basins.

Agricultural and domestic well extraction rates have not historically been systematically collected and reported in the Upper Ventura, Lower Ventura and Upper Ojai Basins. In the Ojai Basin, extraction rates have been reported to OBGMA since 1996. Extraction rates will be estimated for wells without records. Irrigation water supply within the Basins is supplied from both groundwater and surface-water sources (e.g., from Lake Casitas). Agricultural groundwater extraction rates will be estimated for each well based on:

- Area irrigated by the well and crop coverage, determined from surrounding land-use for each well (land-use coverage consistent with those used for the PRMS-model, see Section 4.2.3), and well records available from VCWPD.
- Irrigation rates, determined by crop-type and available irrigation estimates consistent with those used in the PRMS-only model (see Section 4.2.4).
- The fraction of irrigation supply sources from groundwater versus surface-water (including how this varies in dry versus wet precipitation years), determined based on review of Casitas surface-water delivery records and consultation with local growers.

There are approximately 53 active agricultural wells in the Upper and Lower Ventura River Basins, and 34 active agricultural wells in the Upper Ojai Basin (Figure 5.1). To the extent possible, the Project Team will coordinate with the UVRGSA to identify growers to interview regarding the area supplied by each well, crop coverage, and to what extent surface-water supplies are used for irrigation. In addition, the Project Team will coordinate with Casitas Municipal Water District (CMWD) staff to obtain data on surface-water deliveries used for irrigation in order to inform how surface-water supplies are used for irrigation. The Project Team will also evaluate how well extraction rates change for wells in the Ojai Basin that report to OBGMA, as another line of evidence for how the proportion of surface-water versus groundwater has varied over time. Lastly, the UVRGSA has commissioned an aerial crop survey and inventory of wells in the Upper Ventura Basin with meters in order to evaluate irrigation and groundwater extraction practices. If results of this study are available during the data collection period they will also be used as a basis for assigning extraction rates.

Domestic groundwater extraction rates will be estimated based on assumed domestic water consumption, including domestic irrigation. Domestic irrigation rates will be based on analysis of available local water use data for domestic well users that are reported to OBGMA and analysis of County-level water usage data (e.g., USGS, 2000), and will be consistent with those used in the PRMS-only model (Section 4.2.4).

Groundwater was historically extracted from the alluvium in the Lower Ventura River Basin during oil extraction by Aera Energy LLC and its predecessors; however extraction rates are not currently available (DBS&A, 2010). The Project Team will seek out records of historical Aera extraction and include pumping from these wells if possible.

The final integrated model will include monthly MODFLOW stress periods; therefore extraction rates will need to be assigned on a monthly basis for all wells. Even for those wells with reported extraction rates in the Ojai Basin, extraction has historically been reported on a semi-annual basis, with recent implementation of quarterly reporting. It is assumed that monthly extraction data will be available for municipal wells from water agencies and mutual water companies.

For agricultural and domestic wells, monthly extraction rates will be estimated from extraction statements for the Ojai Basin, and annual estimates for remaining areas, based on the growing season for agricultural crops and the fraction of reference evapotranspiration that occurs each month, using methods consistent with those used for the OBGM (DBS&A, 2011). This approach assumes that extraction rates are related directly to reference evapotranspiration rates and is based on the relationship among reference evapotranspiration, irrigation requirements, and groundwater extraction rates. This assumption is reasonable for agricultural wells, mixed use domestic/agricultural wells, and domestic wells that are used primarily for landscape irrigation. However, this assumption would not be appropriate for wells used strictly for nonirrigation supply. It will be assumed that even domestic wells in the Ojai Basin are used partially for landscape irrigation. For example, for those wells in the OBGMA with a use description, 90 percent of them are either agricultural or domestic/landscape. Initial monthly reference evapotranspiration rates will be taken from CIMIS (1999); and eventually will be replaced with monthly reference evapotranspiration rates from the PRMS model.

5.2.1 New Groundwater Monitoring

The State Water Board is working with the VCWPD on new quarterly monitoring of groundwater levels at an existing well upstream of Camino Cielo bridge, at the beginning of the Upper Ventura basin. Measurements will begin in fall 2017. The State Water Board will fund VCWPD to conduct this monitoring for two years. The State Water Board is working with the Upper Ventura Groundwater Management Agency on this effort.

Collection of these data is expected to begin in late 2017 or 2018. It is anticipated that these data will not be available in time for direct use in the development of the PRMS-only model, but they will be used for validation of the GSFLOW model (see Section 6.1).

5.3 Model domain and spatial discretization

The active groundwater model domain will include the full extent and depth of alluvial aquifers. Horizontally, the model domain will be uniformly divided into grid cells 200 feet on a side, consistent with the OBGM. If, during model development, it is determined that the 200-ft grid results in a model that is overly computationally intensive, requiring very long model run times, a coarser grid cell size will be used in consultation with the Water Boards.

Geologic maps, boring logs, existing geologic studies and cross-sections, and the current Bulletin-118 (DWR, 2016a) basin boundaries will be reviewed in order assess the extent of alluvial aquifers. Geologic maps are available in GIS format from the California Geologic Survey (Gutierrez et al., 2008). Previous studies of the extent and thickness of alluvium in the Basins include DBS&A (2011), Turner (1971), Kear (2016a, 2016b), Fugro (2002) and Hopkins (2007). Boring logs are available from VCWPD, Hopkins (2007), municipal water providers and from Cleanup and Waste Discharge Sites on the State Water Board Geotracker[4] website (State Water Board, 2017b). The State Water

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[4] GeoTracker is the State Water Boards' data management system for sites that impact, or have the potential to impact, water quality in California, with emphasis on groundwater. GeoTracker contains records for sites that require cleanup, such as Leaking Underground Storage Tank (LUST) Sites, Department of Defense Sites, and Cleanup Program Sites. GeoTracker also contains records for various unregulated projects as well as permitted facilities including: Irrigated Lands, Oil and Gas production, operating Permitted USTs, and Land Disposal Sites.

Board is currently obtaining available boring logs from VCWPD and municipal water providers.

Figures 5.2a through 5.2e display the current Bulletin 118 basin boundaries (or alternatively the extent of the OBGM for the Ojai Basin) overlaid on geologic maps, and also display the location of existing geologic cross-sections from previous studies. For the Lower Ventura and Upper Ojai Basins, the Bulletin 118 boundaries largely correspond to the extent of surficial alluvium, and for these two basins, it is anticipated that the active groundwater model domain will be similar to the Bulletin 118 boundaries. For the Upper Ventura Basin, alluvium to the east of the river in the vicinity of Kear section C-C' and Turner section D-D' and alluvium west of the river, in the vicinity of the western part of Kear section B-B' (Figure 5.2c) formally was included in the Bulletin 118 boundary prior to Basin boundary modification. These areas were removed as it was determined that alluvium in these areas is thin and non-water bearing (Kear, 2016a; DWR, 2016b). Available boring logs and previous studies will be reviewed to determine if this area will be included in the active model domain. Otherwise, the Bulletin-118 boundary for the Upper Ventura River Basin is largely consistent with the extent of alluvium, and is anticipated to be used as the active model domain boundary. For the Ojai Basin, the extent of the OBGM, which was based on the extent of alluvium in the Basin, will be retained.

For all basins, thin alluvial channels that bound creeks in the surrounding bedrock-areas may be included in the active domain; or alternatively, underflow from these areas may be included as model boundary conditions as was done for the OBGM (Section 5.3). In addition to the Bulletin-118 basins, alluvium in the vicinity of San Antonio Creek between the Ojai and Ventura River Basins will be included in the active model domain, and the active wash deposits associated with Lion Creek between the Upper Ojai and alluvium associated with San Antonio Creek will be included in the domain. The currently anticipated active model domain is shown on Figure 2.1, but is subject to change based on further analysis.

The thickness of the active model layers will be based on the thickness of alluvial sediments, determined from review of boring logs, geophysical logs, and previous geologic studies. The State Water Board performed the first round of review of boring logs available from VCWPD in the Upper Ventura, Lower Ventura and Upper Ojai Basins to determine the depth of alluvium for each well. The State Water Board analysis will be reviewed against available boring logs and previous geologic studies; boring log locations are shown on Figures 5.2a through 5.2d and Figure 5.3. Based on this review, maps of the thickness of alluvium within the active model domain will be generated.

In addition, new geologic cross-sections will be developed displaying alluvial thickness, major surface-water features, major geologic features, faults, bedrock geologic units in contact with alluvium, and Basin/model boundaries. We anticipate generation of six geologic cross-sections, with general locations displayed on Figure 5.3. Preliminary cross-section locations on Figure 5.3 were selected based on the following:

- Section A-A’ was selected to follow the main stem of the Ventura River; within the Upper Ventura Basin this location is coincident with section A-A’ from Kear (2016b).
- Section B-B’ was selected to pass through the Upper Ventura Basin and into the Ojai Basin; this section is coincident with section B-B’ from Kear (2016b) within the Upper Ventura Basin and section A-A’ from DBS&A (2011) within the Ojai Basin
- Section C-C’ was selected to follow San Antonio Creek, and is coincident with section C-C’ from DBS&A (2011) within the Ojai Basin
- Section D-D’ is located within the Ojai Basin, and is coincident with section B-B’ from DBS&A (2011)
- Section E-E’ was selected to pass through the widest area of alluvium in the Lower Ventura Basin, and is also located based on availability of boring-log data
- Section F-F’ was selected to pass through the Upper Ventura Basin, the area of alluvium associated with San Antonio Creek, Lion Creek, and the Upper Ojai Basin; this section is coincident with Section C-C’ from Kear (2016a) within the Upper Ventura Basin and the area around San Antonio Creek

For the OBGM, 10 model layers were included to represent alternative aquifer and aquiclude units within alluvial sediments, based on analysis and correlation of geophysical well logs (DBS&A, 2011). Representation of these units is important for the OBGM to simulate confining conditions that result in artesian conditions that exist for certain wells in the basin following heavy precipitation. It is anticipated that model layering and total model thickness will be adopted for the Ojai Basin directly from the OBGM. Boring logs, and geophysical well logs if available, will be reviewed to determine appropriate model layering for remaining basins.

GSFLOW requires that the groundwater and surface water model domains be the same; therefore, areas outside of the active alluvium will be assigned as low-permeability and thin for the groundwater model, similar to previous GSFLOW studies (e.g., Huntington and Niswonger, 2012).

5.4 Model boundary conditions

Groundwater model boundary conditions govern interaction of the modeled groundwater system with surrounding features that may provide inflow or outflow of water from the groundwater model domain. Model boundary conditions and how they will be implemented are listed below:

- Recharge from precipitation and irrigation will come from the PRMS model in the final integrated GSFLOW model. For the purpose of initial MODFLOW-only simulations placeholder values will be used based on DPWM output for the Ojai Basin, and based on simple fractions of total precipitation and irrigation for the remaining basins using the MODFLOW recharge (RCH) package or unsaturated-zone flow (UZF) package.
- Recharge from spreading grounds, including the San Antonio Creek Spreading Grounds will be based on recorded diversions to the spreading grounds and will be implemented as infiltration and recharge specified flux using the MODFLOW recharge (RCH) package or unsaturated-zone flow (UZF) package in the preliminary model. It is expected that recharge from spreading grounds will be implemented in PRMS in the final integrated model.
- Recharge from OWTS systems will be implemented as specified flux (WEL) boundaries in the preliminary MODFLOW-only simulations and GSFLOW model.
- Riparian evapotranspiration will come from the PRMS model in the final integrated GSFLOW model. For the purpose of initial MODFLOW-only simulations, evapotranspiration will be represented with the MODFLOW evapotranspiration (EVT) package, based on mapped areas of riparian coverage.
- Flow between groundwater and stream channels will be represented by the MODFLOW streamflow routing (SFR) package in both GSFLOW and the preliminary MODFLOW runs. Placeholder values that govern flow in the streams at domain boundaries will be used for the MODFLOW-only simulations.
- Groundwater exchange between bedrock units and alluvial aquifers along the bottom model boundary will be represented with the MODFLOW general-head boundary (GHB), consistent with the approach in the OBGM. The GHB package is used to calculate variable exchange at model boundaries using Darcy’s law and based on a specified transmissivity of the boundary cell, a specified constant hydraulic head for the boundary, and the hydraulic head of the active model cell in contact with the boundary. Transmissivity and hydraulic head of the bedrock units will be based on available well logs and previous studies.
- Geologic fault-zones present in the watershed may in some cases act as a partial barrier to groundwater flow. The potential for fault zones to act as a barrier to groundwater flow will be evaluated based on available geologic-cross sections,

geophysical studies and groundwater elevation data. For wider fault zones that approximate the model grid cell width (200 feet), faults will be represented by assigning low hydraulic conductivity to the grid cells in the area; for thinner zones faults will be represented with the horizontal flow barrier (HFB) MODFLOW package.

- Groundwater extraction will be implemented using the MODFLOW multi-node well (MNW) package.
- If small alluvial wash deposits upgradient of the basins are not directly implemented as active groundwater model cells, inflow from upgradient alluvial channels will be assigned as specified flux boundaries (WEL) based on the amount of recharge in the channels as estimated by PRMS for the final GSFLOW model. Placeholder values will be assigned for the purpose of initial MODFLOW simulations.
- Groundwater outflow and/or inflow from the Lower Ventura Basin to the Pacific Ocean will be represented with the MODFLOW GHB package, assigning a groundwater elevation of mean-sea level to the boundary.
- Groundwater flow at the location of the groundwater divide in the Upper Ojai Basin (between the Ventura River and Santa Clara River watersheds) will be represented with the MODFLOW GHB package, assigning groundwater elevations based on observed groundwater levels at that location (e.g., using data from wells 04N22W12F01S/F04S, see Figure 5.5).

5.5 Preliminary Groundwater Model Simulations

The purpose of preliminary MODFLOW-only simulations is to ensure that the groundwater model runs without errors (e.g., due to clerical mistakes in the input files), and to ensure that the groundwater flow system is generally consistent with understanding of the Basins. For example, groundwater flow directions should proceed generally to the south for the Upper and Lower Ventura River Basins, towards the southwest for the Ojai Basin, and towards the west for the Upper Ojai Basin. Groundwater levels should be roughly consistent with the range of water level observations in the wells in the Basins, and should respond to dry and wet-weather cycles. The initial MODFLOW-only simulations will be run for a representative period of three years.

To the extent any parameters are adjusted for the MODFLOW-only model it will be to ensure the model operates without errors and groundwater flow is consistent with conceptual understanding of the Basins. Because key model inputs and boundary conditions will be provided by PRMS, full model calibration will proceed only after coupling with the PRMS model in GSFLOW (see Section 6).

6. GSFLOW MODEL CALIBRATION

Model calibration will in general consist of history-matching of simulated groundwater levels to water level measurements from wells in the Basins and simulated surface-water flow to available streamflow gage data. Additional spatial comparisons will also be made to dry weather wet-dry observation data. This section describes the calibration process, including the modeling period, calibration approach and parameters, and specific calibration goals.

6.1 Modeling Period

The GSFLOW modeling period will be from WY1995[5] through WY2018. This period enables leveraging of the existing VSWHM (1987 – 2006), the existing OBGM (1970 – 2013), the groundwater budget study by DBS&A (2010) for the upper basins (1997 – 2007), and use of new streamflow data that will be collected (Section 4.2.6).

The modeling period will be divided into a 21-year calibration period (WY1995 through WY2015) and a three-year validation period (WY2016 through WY2018). This approach enables a sufficiently long period to calibrate the groundwater portion of the model, while also enabling recent and to-be-collected streamflow data (Section 4.2.6) to be used within the project lifetime. The model calibration period is also hydrologically representative of the longer period of record, and includes multiple wet years (e.g., WY1998 and WY2005) and a prolonged dry period (WY2012 – WY2015). Specifically, rain gage data at Ojai County Fire Station indicate that the 25th percentile, median, average, and 75th percentile are 11.9, 19.5, 20.6, and 24.1 inches, respectively, for WY1995 – WY2015, compared with 13.3, 18.9, 20.9, and 26.1 inches, respectively, for WY1906 – WY2016.

6.2 Calibration Approach and Parameters

The model calibration approach and parameters that will be adjusted for the surface water and groundwater portions of the model are summarized in the following sections. While the surface water and groundwater calibration calibrations are discussed in separate sections, the final calibrations will be performed together in the coupled GSFLOW model.

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[5] WY = water year, defined as October 1 through September 30. For example, WY1995 is from October 1, 1994 through September 30, 1995.

6.2.1 Surface Water

The surface water portion of the GSFLOW model will *initially* be run in PRMS-only mode based on the existing VSWHM model parameterization and then calibrated by comparing model-predicted flows to wet season flow data from streamflow gages (Section 4.2.6). Calibrating the model for wet-weather flows in advance of integrating the models will aid the calibration of the groundwater portion of the model in GSFLOW by providing a well-defined spatial representation of groundwater recharge from rain events (see, e.g., Allander et al., 2014). The dry-weather surface water flows will be calibrated within the integrated GSFLOW model (i.e., in conjunction with the groundwater calibration described in Section 6.2.2), due to the inherent dependence of the low flows on the groundwater model. The calibration of dry-weather flows will be based upon comparison to streamflow gages, manual streamflow measurements, and wet-dry maps across different seasons and years (Section 4.2.7).

In PRMS, like other lumped-parameter watershed models, a suite of parameters control the distribution of incoming precipitation and irrigation between runoff, percolation, interflow, active groundwater flow, evapotranspiration, and losses to deep groundwater.

Imperviousness, infiltration parameters, irrigation parameters, and interception parameters, along with slope, length of flow, and roughness, dictate runoff volume and flowrates from modeled watersheds. These parameters typically have the strongest effect on the peak of the hydrograph for a storm event. Parameters governing soil infiltration rates and storage and release to interflow typically have the greatest effect on the “tails” of the hydrographs of a storm event. Parameters affecting groundwater storage and release/split to the stream typically affect the periods in between peaks (baseflow). Adjustment of the parameters that control runoff rates, in addition to vertical and horizontal hydraulic conductivities and soil storage, will be used to predict the total volume of flow to the stream (runoff, interflow, and active groundwater flow) versus other endpoints. Model parameters will be adjusted to reduce the error between predicted and measured flowrates as discussed in Section 6.3 below.

In addition to adjusting model parameters for calibration, there may be a need to adjust other model inputs that were estimated due to a lack of specific data. For example, the estimated irrigation rates may be adjusted to improve dry-weather flow calibration.

6.2.2 Groundwater

GSFLOW calibration will include matching of simulated groundwater levels to available groundwater-level data. Observed groundwater levels are available from the VCWPD, which conducts a quarterly groundwater monitoring program throughout the watershed, and from selected Geotracker cleanup sites. Available VCWPD and Geotracker records have been preliminarily evaluated to identify wells with data for calibration. For the Ojai Basin, the same calibration wells will be used as for OBGM development. Well locations are shown on Figure 5.5. Each well on Figure 5.5 will be evaluated to ensure that the well is screened exclusively within the alluvium; if wells are fully or partially screened within bedrock units they will not be used for calibration. In addition, calibration will include matching simulated groundwater elevations to stream elevations in reaches identified as perennially wetted.

Groundwater-level calibration will be conducted consistent with standard protocols and best practices as defined by DWR (2016c) and ASTM (2008). Calibration consists of adjusting model parameters to minimize the difference (‘residual’) between the simulated groundwater level at a specific location and observed groundwater level data from a well at that location. Calibration will also include consideration of dry-weather flows and wetted portions of the stream channels, as discussed above.

Parameters adjusted during the calibration process (i.e., calibration parameters) will include hydraulic conductivity and storage coefficient of each model layer. Values of hydraulic conductivity and storage coefficient from available aquifer tests and specific capacity measurements will be used to constrain calibration goals. For example, for the OBGM the calibrated hydraulic conductivity and storage coefficient values were within the range of available aquifer test results (DBS&A, 2011). In general, values of these parameters in the model should be similar, but do not have to be identical to field observations; the field observations have errors themselves (often an order of magnitude). There are also differences in the associated scale of aquifer-test results (i.e., the volume of aquifer stressed) versus what is implemented in a regional groundwater model (ASTM, 2008).

6.3 Calibration Goals

The model calibration goals for the surface water and groundwater portions of the model are presented in the following sections. While the surface water and groundwater calibration goals are discussed in separate sections, the final calibrations will be performed together in the coupled GSFLOW model.

6.3.1 Surface Water

It is generally accepted that a ‘weight of evidence’ approach be adopted when calibrating continuous output hydrological simulations (Donigian, 2002), whereby both qualitative graphical comparisons and quantitative statistical comparisons are made. Graphical comparisons will generally include visual evaluation of timeseries plots comparing the measured and modeled flow rates at key locations, while quantitative comparisons may include calculating a range of standard statistical measures.

In general, model accuracy cannot exceed the accuracy or uncertainty associated with the data used to develop and calibrate the model. This is particularly relevant when considering low flows since the accuracy of automated streamflow gage measurements at low flows tends to be of low accuracy, in general. Streamflow is typically measured by measuring the flow depth and computing a stage-discharge relationship that is periodically calibrated through manual measurement. When channels are even slightly irregular (e.g., due to cobbles and rocks), or subject to modification through sediment erosion and deposition, in the cross-section of the stream, the streamflow measurement may be significantly inaccurate at low flows.

Donigian (2002) states "Given the uncertain state-of-the-art in model performance criteria, the inherent errors in input and observed data, and the approximate nature of model formulations, *absolute* criteria for watershed model acceptance or rejection are not generally considered appropriate by most modeling professionals." Thus, it is recognized that it is often difficult to pre-define specific calibration goals. With this in mind, relative calibration goals are proposed based on guidance from USGS (Woolfenden et al., 2014) specific to GSFLOW application. These goals are discussed in more detail below.

During the calibration, measured and modeled daily mean, moving three-day daily mean streamflow, monthly mean streamflow, and annual mean streamflow will be compared visually with hydrographs and flow-duration curves and also through goodness-of-fit statistics. These goodness-of-fit statistics include the percent average estimation error (PAEE), the absolute average estimation error (AAEE), and the Nash-Sutcliffe model efficiency (NSME). The PAEE and AAEE measure the model bias or systematic error, but cannot provide a definitive measure of goodness of fit alone. The NSME provides a measure of the mean square error, similar to the normalized root mean square error, and can be a good indicator of the goodness of fit, but can still have substantial estimation bias. Therefore, the combination of the aforementioned statistics are used to represent goodness of fit. A model that exactly matches observed results would have PAEE and AAEE values of 0 and a NSME value of 1.0 (e.g., Woolfenden et al., 2014).

Table 6.1 shows the ranges of the goodness of fit statistics that are associated with overall classifications ranging from fair to excellent. Comparisons will be made between measured and simulated daily mean[6] and monthly mean streamflow, and the weighted average statistics for these comparisons will be considered. The goal of the calibration will be to achieve "very good" classifications for the PAEE and AAEE and a NSME value

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[6] The moving three-day average may be used, instead of the daily mean, if there are potential backwater conditions caused by high flows.

of 0.7 or greater[7] per guidance from the USGS (Woolfenden et al., 2014). Although the goals will be considered for both comparison of daily means and monthly mean streamflow, statistics for the monthly averages are expected to be superior to the daily averages (Caldwell et al., 2015).

Table 6.1 Summary of Goodness of Fit Statistics for Daily or Monthly Mean Streamflow

Goodness of fit Category	PAEE (%)	AAEE (%)	NSME
Excellent	-5 to 5	≤ 0.5	≥ 0.95
Very good	-10 to -5 or 5 to 10	0.5 - 10	0.85 - 0.94
Good	-15 to -10 or 10 to 15	10 - 15	0.75 - 0.84
Fair	-25 to -15 or 15 to 25	15 - 25	0.6 - 0.74

Although the model calibration goal will be to achieve "very good" classifications, it is noted that in practice this is often not achieved at every gage location. Specifically, in the USGS study by Woolfenden et al. (2014), the "very good" classification was only met or exceeded at six of the twelve gage locations for calibration of daily flow, and in nine of the twelve gage locations for calibration of monthly flow. For validation, the "very good" classification was only met at one of six locations for daily flow, and three of six locations for monthly flow. Other studies using GSFLOW have similar results. For example, the USGS study by Hunt et al. (2013) only achieved "very good" calibration of monthly flows at one of five gage locations (NSME = 0.86) with the NSME ranging from 0.045 to 0.57 at the other four locations. The ability to achieve desired calibration goals is dependent upon the nature of the specific watershed including the accuracy of input data and flow gages.

In considering the Ventura River Watershed it is useful assess the previous surface water modeling efforts. The VSWHM calibration established target criteria of ±30% for volume of flow over different seasons (Tetra Tech, 2009, Table 5-3), but these targets were not always achieved. For example, the seasonal goals relevant to wet-weather (i.e., winter and spring volume error criterion) were achieved at seven of the eight gages used

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[7] Per Table 6.1, a NSME value of 0.7 is classified as a "fair" model performance. However, it is noted that other authors use different classifications. For example, Caldwell et al. (2015) considers NSME values (for comparison of monthly average streamflow) greater than 0.50, 0.65, and 0.75 to be considered satisfactory, good, and very good performance, respectively. Therefore, under these classifications, a NSME value of 0.7 is considered "good" model performance.

for calibration[8], while the seasonal goals relevant to dry-weather (i.e., summer and fall volume error criterion) were achieved at five of the eight gages.

The addition of the groundwater component in GSFLOW is expected to result in substantially improved ability to model dry-weather flows, compared to the VSWHM which had noted difficulty modeling low flows. These large discrepancies may in part reflect the difficulties in calibrating to low flow rates, including the uncertainties in the accuracies of various streamflow gages. For example, more than one-third of the automated measurements at streamflow VCWPD Gage 608 (operated by USGS as gage 11118500, Ventura River near Ventura) (see Figure 4.9 for location) have poor data quality with errors in excess of 15 % (Tetra Tech, 2012). Measurement errors would not be accounted for in model prediction error estimates, so these errors would be compounded to reflect true model accuracy. The likely accuracy of flow gages, including owner/operator quality control practices, morphological stability at gaging location, and how frequently or recently the rating curve was updated, will be taken into account in the assessment of the model calibration.

An important part of the calibration for dry-weather flows will be qualitative and semi-quantitative comparisons to the wet-dry maps described in Section 4.2.7. These represent key data that will demonstrate the ability of the model to predict gaining and losing reaches during different seasons and different water year types. Output from the model will be extracted to re-create the spatial and temporal information in the maps to enable a qualitative visual (i.e., side-by-side) comparison. The percent of river channel correctly predicted as wet, dry, or intermittent, will also be calculated.

It is noted that the groundwater-portion of the model domain will play a key role in the determination of wet-dry regions. In particular, the locations of the wet and gaining reaches during dry-weather will primarily depend upon the calculated groundwater head elevation. As such, the groundwater calibration (discussed next) will be conducted in conjunction with the surface water model dry-weather flow calibration. It is noted that it will be challenging to perfectly match these wet-dry maps since locations of surface water upwellings will be highly sensitive to the modeled groundwater elevations.

6.3.2 Groundwater

Groundwater model calibration results are typically presented in terms of several statistical measures, including mean error (ME), mean-absolute error (MAE), root-mean

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[8] It is noted that wet-weather calibration in GSFLOW may be more challenging due to the use of a daily time-step that may not fully take into account differences in storm intensities.

square error (RMSE) and the correlation coefficient (R) between simulated and observed values:

- The ME is a simple average of the residual error between observed and simulated water levels, and therefore, positive values will offset negative values. A positive value of ME indicates that, on average, simulated hydraulic heads are lower than observed hydraulic heads, while a negative value indicates the opposite.
- MAE is similar to the ME, with the important distinction that the sum of the absolute values of the residuals is calculated, thereby eliminating the offset that occurs by adding positive and negative values. The MAE, therefore, is always positive and represents the average difference between observed and simulated hydraulic head values.
- The RMSE is similar to the MAE, although negative values of the residual between observed and simulated hydraulic heads are eliminated by squaring the difference, and then the square root of the sum is determined prior to computing the average. This approach is analogous to the computation of the variance that would be conducted for a linear regression.
- The correlation coefficient (R) is a measure of the linear correlation between the simulated and observed groundwater levels (DWR, 2016c). R may range from negative 1.0 (-1.0) to 1.0. A correlation of -1.0 indicates a perfect negative correlation, while a correlation of 1.0 indicates a perfect positive correlation.

The primary goals of model calibration are to reduce the value of the MAE and RMSE, bring the ME as close as possible to a value of zero, and bring the value of R as close as possible to 1.0, using model input values consistent with observed data or realistic estimates.

Measures of model calibration such as the MAE and the RMSE are often evaluated relative to the total head loss across the hydrogeologic system (e.g., Anderson and Woessner, 2002; ASTM, 2008). For example, the scaled RMSE is equal to the RMSE divided by the observed hydraulic head drop that occurs across the model domain.

Calibration goals for groundwater levels will include:

- Scaled RMSE will be less than 10 percent for each basin (for example, if the total observed head-change in a basin is 400 feet, the RMSE will be less than 40 feet).
- R will be greater than 0.90 for each basin (DWR, 2016c; Hill and Tiedman, 2007).

Initial model calibration will be conducted by the traditional manual (or ‘trial-and-error’) approach, which consists of changing model inputs, running the program with the new input, and then comparing results to calibration targets (ASTM, 2008). Automated calibration, using software such as Model-Independent Parameter Estimation and Uncertainty Analysis (PEST; Doherty, 2015), relies on a computer code to adjust model inputs to iteratively improve model simulations and reduce residuals and will be tested and utilized if found to efficiently reduce residual values compared to the manual approach.

7. NITROGEN TRANSPORT MODEL DEVELOPMENT

This section describes how the groundwater nitrogen transport model will be developed in MT3D-USGS using MODFLOW and using calibrated flows from the integrated GSFLOW model, and a nitrogen mass balance approach to account for nitrogen sources from the soil zone that is not modeled in MT3D-USGS. Datasets and sources to be used to provide model inputs and for calibration are described, as well as the calibration process and goals.

7.1 Mass Balance Approach

The emphasis of the nitrogen modeling will be characterizing nitrogen loading from OWTS effluent, ranching activities, and agricultural fertilizer and irrigation to groundwater, and then transport to surface water. A mass balance approach (e.g., Viers et al., 2012) considering the sources of nitrogen listed above, together with estimates for atmospheric deposition of nitrogen, nitrogen fixation by plants, uptake of nitrogen by plants, and loss of nitrogen to the atmosphere, will be used to estimate the loading and transformation of nitrogen from the soil zone[9] to the groundwater in the subsurface[10]. This relatively simple mass balance approach has been shown to be comparable to more complex two- and three-dimensional modeling approaches in terms of yielding estimates for nitrogen loading to groundwater (Botros et al., 2012).

The mass balance will consider nitrate, nitrite, ammonia, and organic nitrogen, but will assume that the species are converted to nitrate form by the time it is transported to the groundwater (e.g., Harter, 2017, and Viers et al., 2012). Therefore, the MT3D-USGS groundwater model will only model nitrate. This approach is generally supported by the limited available ammonia data (three data points from three different wells) that indicate non-detects in the groundwater (State Water Board Groundwater Ambient Monitoring and Assessment Program [GAMA]), and will be further confirmed as sampling results for nitrate, nitrite, ammonia, and total nitrogen at approximately 20 groundwater locations become available from the ongoing VCEHD OWTS Study. If necessary, the model will also consider nitrogen lost from the system due to denitrification.

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[9] The soil zone is defined with respect to the GSFLOW terminology in Figure 3.1. The soil zone is not modeled explicitly with MODFLOW + MT3D-USGS, but will rather be accounted for using a mass balance approach.

[10] The subsurface comprises the unsaturated and saturated zones, as defined with respect to the GSFLOW terminology in Figure 3.1. The subsurface is modeled by MODFLOW + MT3D-USGS.

7.2 Implementing Flows from GSFLOW into MT3D-USGS

MT3D-USGS will be the modeling platform for groundwater nitrate transport simulations (Bedekar et al., 2016). MT3D-USGS is a solute transport model designed to be run in conjunction with MODFLOW, and represents saturated and unsaturated-zone transport, advection, dispersion, solute exchange between groundwater and surface-water, transport within streams and lakes, chemical reactions and degradation, and sorption of solutes to aquifer media. MT3D-USGS will be used to simulate nitrate loading from land sources and transport through the unsaturated zone and groundwater. In cases where groundwater flow discharges to surface-water, MT3D-USGS will represent loading of nitrate from groundwater to surface-water.

MT3D-USGS is not directly compatible with GSFLOW (Morway, 2017), but rather is designed to run with output from MODFLOW-only, including a designated output ‘linker’ file that provides flow information to MT3D-USGS from MODFLOW. Therefore, a separate MODFLOW model will be developed for the purpose of linking to MT3D-USGS and running transport simulations. The MODFLOW model will be developed from the calibrated GSFLOW flow model (i.e., the flow rates for exchange between the surface water and groundwater will be determined from the calibration of the integrated GSFLOW model described in Section 6). Custom coding will be used to assign MODFLOW boundary conditions from the calibrated GSFLOW model. For example, PRMS-assigned recharge from precipitation and irrigation will be converted to the format of the MODFLOW recharge package (RCH). In this way, the MODFLOW model will be fully consistent with the flow terms in the calibrated GSFLOW model, but will allow for application of MT3D-USGS.

In addition to the flow boundary conditions that will be extracted from the calibrated GSFLOW model, the MT3D-USGS model will require nitrate concentrations to be specified at the top of the subsurface (for fluxes from the soil zone) and for surface water percolation. These concentrations will be estimated from mass balance calculations as described above, and surface water concentrations, using data described below.

7.3 Datasets and Sources

A range of datasets (see Table 7.1) will be used to determine inflow nitrate concentrations from the soil zone (not modeled in MT3D-USGS) to groundwater, and from surface water in losing stream reaches. Additional datasets, such as measured dry weather surface water nitrate loads, will be used for model calibration to verify that the model is able to represent the watershed nitrate mass balance and predict transport of nitrate from groundwater to surface water in gaining reaches.

7.3.1 Nitrate Concentrations from the Soil Zone to Groundwater

Because direct measurements of nitrogen concentrations in the soil zone pore-water are not available, mass balance calculations (described above) will be made based on available nitrogen data from within the watershed and published data on nitrogen loading to the subsurface from contributing sources. The goal of these calculations will be to estimate the nitrate concentrations that reach groundwater in MT3D-USGS for different land-use types, such as urban, open land, and agriculture (likely for one representative crop), while also including specific information and data, such as those related to nitrogen loadings from OWTS (see Section 4.2.3 and Figure 4.7).

Multiple sources of nitrogen to the soil zone must be accounted for to estimate nitrogen concentrations from the soil zone to the subsurface. These sources and data used to characterize them are summarized in Table 7.1(a) and include fertilizers from residential and commercial landscaping, fertilizers from agricultural crops, animal manure from agricultural crops and horse facilities, OWTS effluent, sanitary sewer leaks, and background loading from natural soils and atmospheric deposition. In addition, the mass balance calculations will require estimates of the uptake of nitrogen by crops and plants in the soil zone (Table 7.1(a)).

The outcome of the mass balance calculations will be an estimate of the nitrate load from the soil zone to groundwater as a function of land-use. Land-use in the MT3D-USGS model will be the same as used for the GSFLOW model (see Section 4.2.3). The nitrate loads will be converted to concentrations and applied with the flow rates determined from the integrated GSFLOW model (Table 7.1(b)), as described in Section 7.2.

It is recognized that the mass balance calculations may include a certain degree of uncertainty (e.g., due to ranges in literature values for nitrogen applications, farming practices, sewer and OWTS exfiltration, plant uptake rates, timing of fertilizer application, and antecedent soil moisture), and as such bracketed ranges of nitrogen loads and concentrations to the subsurface groundwater may be developed. Mid-range values will be chosen for initial model development, and if necessary these will be adjusted and refined during the calibration process (see Section 7.4).

Table 7.1 Data Anticipated to be Used to Develop, Calibrate, and Validate the Nitrogen Transport Model

Need for Nitrogen Transport Model	Anticipated Data to be Used
(a) Data for mass balance calculations to estimate nitrogen concentrations from the soil layer to the subsurface layer	
Nitrogen loading from urban areas	Literature values for residential and commercial fertilizer application
Nitrogen loading from agriculture fertilization	Literature values for nitrogen application rates by crop type in California and nitrogen fixation from leguminous crops if applicable
Nitrogen loading from animal manure	Published manure application by crop type and loading from horse facilities
OWTS loading	OVSD nitrogen data, published nitrogen removal for OWTS
Nitrogen loading from sanitary sewer leaks	Published sewer exfiltration rates
Nitrogen loading from background sources (natural soils and atmospheric deposition)	Published nitrate concentrations for groundwater in natural areas not impacted by upgradient/upstream development
Nitrogen uptake rates by plants and crops	Published literature values
(b) Data for modeling nitrate transport through the subsurface in MT3D-USGS	
Flow rates to the land surface and groundwater	Output from integrated GSFLOW model
Nitrate concentrations from the soil zone to subsurface groundwater	Published literature and mass balance calculations from above
Surface water nitrogen concentration data (ammonia, nitrate, nitrite, and total nitrogen) in losing reaches	OVSD, VCWPD, CEDEN, CMWD, VCAILG, SBCK
(c) Data useful to calibrate/validate nitrate transport in MT3D-USGS	
Surface water nitrogen concentration data in gaining reaches	OVSD, VCWPD, CEDEN, CMWD, VCAILG, SBCK
Groundwater nitrate concentration data	VCWPD, State Water Board GAMA
Surface water and groundwater nitrogen concentration data (ammonia, nitrate, nitrite, and total nitrogen), nitrate isotope ratios, and chemical sewage markers (Pharmaceuticals and Personal Care Products [PPCPs])	VCEHD (Study of Water Quality Impairments attributable to OWTS in the Ventura River Watershed)

7.3.2 Nitrate Concentrations from Surface Water to Groundwater

Nitrogen inputs to the groundwater from surface waters in losing reaches (i.e., where there is a net loss of surface water to groundwater) will be incorporated as boundary conditions to the MT3D-USGS model using measured surface water nitrogen concentrations, coupled with flow rates from the integrated GSFLOW model (see Section 7.2). Surface water concentration data are available from more than 50 locations in the watershed as indicated in Figure 7.1, and include data from Ojai Valley Sanitary District (OVSD), VCWPD, California Environmental Data Exchange Network (CEDEN), CMWD, Ventura County Agricultural Irrigated Lands Group (VCAILG), and Santa Barbara Channel Keeper (SBCK) (see Table 7.1(b)).

7.3.3 Data to be Used for Calibration

Surface water nitrate concentration data (Figure 7.1) in gaining reaches (i.e., where there is a net gain of surface water from groundwater) and the groundwater nitrate concentration data (Figure 7.2) will be used to compare to the MT3D-USGS model output for calibration purposes as described in Section 7.4. The groundwater nitrate data are from the VCWPD and Water Boards GAMA, as summarized in Table 7.1(c).

Other key information that will be used to inform the calibration, and specifically the nitrate in the surface waters and groundwater attributable to OWTS, are the results of the ongoing VCEHD Study of Water Quality Impairments attributable to OWTS in the Ventura River watershed, using isotope ratios and chemical sewage markers. Geosyntec is managing this State grant funded study in coordination with VCEHD. Results of this study are anticipated to be available in January 2018.

7.4 Calibration Approach and Parameters

Nitrate-transport simulations will be calibrated by comparison of simulated values in the groundwater model to available data from groundwater monitoring wells and comparison of simulated and measured values in the surface water in gaining reaches

Initial nitrate-transport calibration will consist of adjusting the following transport parameters:

- Dispersivity
- Effective porosity
- Decay rates (e.g., denitrification rate)
- Nitrate concentrations from the soil layer (see Section 7.3.1)

If necessary to obtain an adequate calibration, additional parameters may be considered for adjustment in consultation with the Water Boards, including the hydraulic conductivity and storage coefficient values assigned in the original GSFLOW flow model. If hydraulic conductivity and storage coefficient values are adjusted, this will necessitate revisiting the original flow model calibration to ensure that adjusted values are within acceptable limits and adjustment does not result in the flow-model calibration falling outside of designated calibration goals (Section 6.3.2).

7.5 Calibration Goals

The objective of model calibration will be to minimize the difference between simulated nitrate concentrations in groundwater and observed results. Nutrient calibration results will be presented in terms of the statistical measures ME, MAE, RMSE and R, as described in Section 6.3.2. The calibration goal for nutrients will be a scaled RMSE (RMSE divided by the observed range in nutrient concentrations in the watershed) (Zheng et al., 2012; Hill and Tiedeman, 2007) of less than 20 percent. For example, if the total range in nitrate concentrations in the watershed is 5 mg N/L, the calibration goal will be a RMSE of less than 1 mg N/L.

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