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Technical Memorandum

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Limitations:

This document was prepared solely for the Monterey County Water Resources Agency (MCWRA) in accordance with professional standards at the time the services were performed and in accordance with the contract between MCWRA and Brown and Caldwell dated July 3, 2014. This document is governed by the specific scope of work authorized by MCWRA; it is not intended to be relied upon by any other party except for regulatory authorities contemplated by the scope of work. We have relied on information or instructions provided by MCWRA and other parties and, unless otherwise expressly indicated, have made no independent investigation as to the validity, completeness, or accuracy of such information.

Table of Contents

List of Figures

List of Tables

Section 1: Introduction

This Technical Memorandum (TM) is a brief assessment of the available modeling tools (i.e., model codes or software packages) in terms of their ability to satisfy the goals of the Salinas River Groundwater Basin Investigation (Investigation). Relying largely on existing comparative analyses, this TM discusses the strengths and weaknesses of several existing modeling codes and then examines the differences between a selected subset. In large part, the discussion of this TM focuses on the MODFLOW and IGSM-IWFM families of codes.

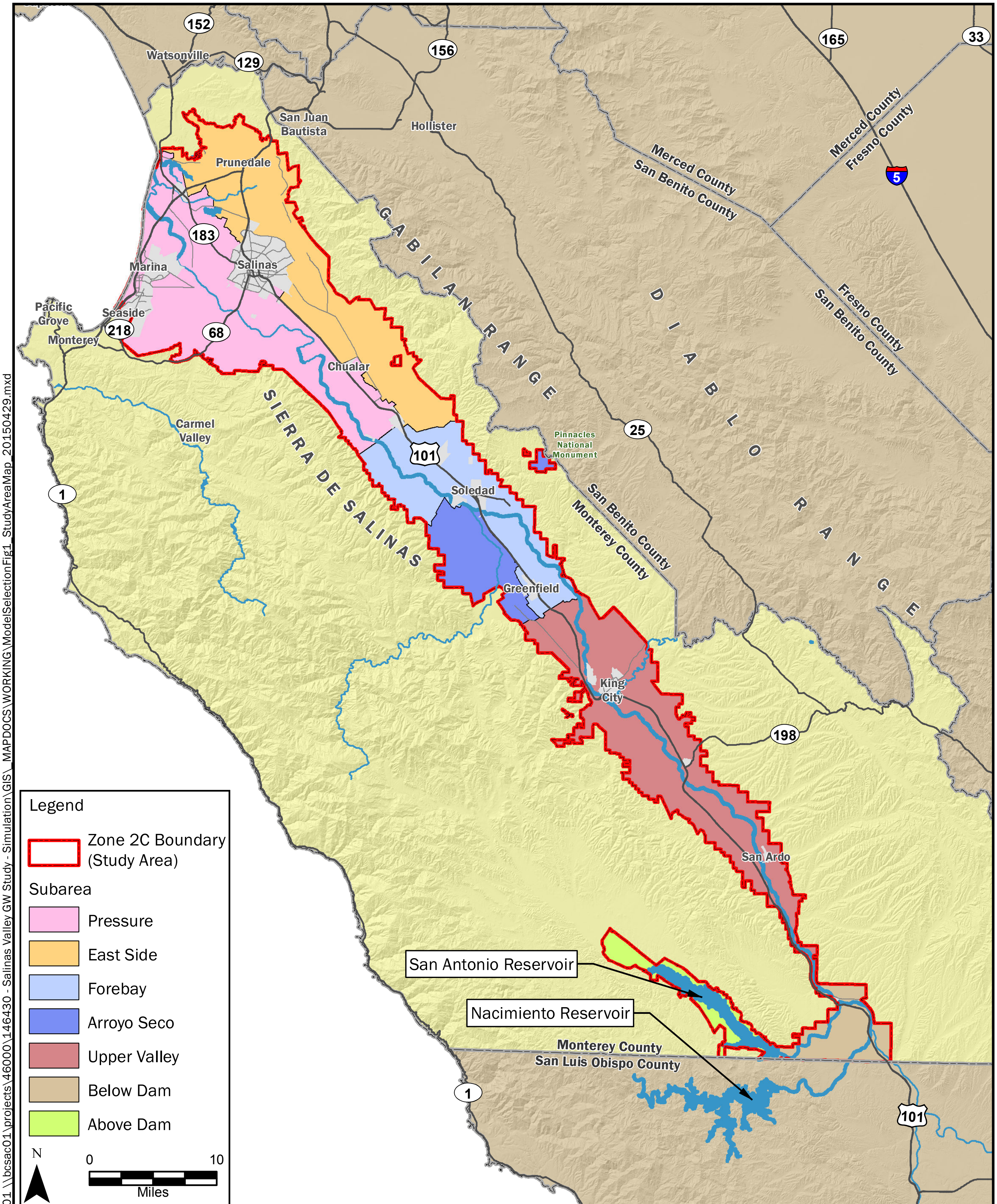
The Investigation is being performed to fulfill the Scope of Work prepared by Brown and Caldwell (BC) for the Monterey County Resource Management Agency (RMA), dated 22 May 2014, as well as the proposed amended Scope of Work dated 9 February 2015.

The study area for this project is within the Salinas River Groundwater Basin (Basin), which is located in the Coast Ranges in Central California (Figure 1). The hydrology and hydrogeology of the study area have been described in detail in other reports (e.g. Brown and Caldwell, 2015), and will be only briefly summarized here. The study area stretches approximately 100 miles from the confluence of the Nacimiento and Salinas Rivers to Monterey Bay. The climate of the Basin is Mediterranean, with mild, wet winters and warm, dry summers. The major surface water feature is the Salinas River and its tributaries, which drain a watershed that includes parts of Monterey, San Luis Obispo, and San Benito Counties. Additionally, there are two reservoirs present southwest of the southern tip of the Basin, the Nacimiento and San Antonio Reservoirs. South of about Chualar, groundwater flows approximately northwest, parallel to the axis of the valley; north of Chualar, groundwater flow bifurcates, with one flow path toward Monterey Bay and the other toward a deep trough in groundwater head in the area northeast of Salinas. Decades of groundwater extraction has resulted in the occurrence of extensive and persistent sub-sea level groundwater heads in the northern part of the Basin. This has resulted in seawater intrusion which now extends several miles inland in the major groundwater-producing aquifers.

1.1 Scope and Purpose

BC is working with RMA and the Monterey County Water Resources Agency (MCWRA) to provide technical assistance to the County of Monterey (County) in response to Settlement Agreement (M109451) related to the County's 2010 General Plan between several stakeholder groups and the County. BC's scope of work (dated 22 May 2014) calls for the completion of two projects:

- **Project 1.** Conduct a near-term assessment of the health and status of the Basin. The primary objective of this project is to evaluate if immediate steps are required to address current water supply conditions due to the continuing drought conditions in the Central Coast.
- **Project 2.** Conduct a detailed study of the Basin, focusing on the part of the Basin designated as Zone 2C (Figure 1). The primary objective of Project 2 is to assess the general ability of the Basin to meet demand within Zone 2C under land use as projected to the year 2030.



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DATE	PROJECT	SITE
05/05/15	146430	**Salinas River Groundwater Basin Investigation**

Brown AND Caldwell

TITLE

Study Area Map

Figure 1

BC completed Project 1 and submitted the *State of the Salinas River Groundwater Basin* report (Brown and Caldwell, 2015) to the County in January 2015. BC is currently performing work activities for Project 2, and the assessment presented herein addresses Task 4 of the Project 2 scope of work. Specifically, this TM provides an assessment of model codes currently available for developing a numerical model that simulates groundwater-surface water interactions at a basin scale. The following objectives have been achieved:

- Prepare a list of modeling tools that includes model codes that are widely used to numerically simulate groundwater and surface water flow at the basin scale.
- Present the capabilities of each of the modeling tools for addressing the goals of the project as described in Section 1.2 below.
- Discuss the strengths and weaknesses of the model codes and highlight the differences between them.

1.2 Project 2 Goals Related to Numerical Modeling

The 22 May 2014 Scope of Work called for the construction of a numerical groundwater-surface water interaction model (Project 2, Task 5) as a tool for simulating the effects of projected conditions of land use under climatic conditions similar to the past 40 years. In addition, the numerical model is to be used to simulate the effects of climate change and sea level rise (Task 1 of the 9 February 2015 proposed amended Scope of Work). The goals of Project 2 (as described in the 22 May 2014 Scope of Work and updated in the 9 February 2015 proposed amended Scope of Work) are as follows:

1. Evaluate existing data for seawater intrusion and groundwater levels collected by Monterey County Water Resources Agency (MCWRA) as of the date the study is commenced;
2. Evaluate the total water demand for existing uses and future uses designated in the General Plan EIR for the year 2030, reassessed and updated as described in the 9 February 2015 proposed amended Scope of Work;
3. Assess and provide conclusions regarding the degree to which the 2030 total water demand is likely to be reached or exceeded;
4. Evaluate on an annual basis during the study period groundwater elevations and the seawater intrusion boundary;
5. Evaluate and provide conclusions regarding future trends and expected changes of groundwater elevations and the seawater intrusion boundary based on historical data and the data produced by the study; and
6. Make recommendations on measures the County could take to address these conditions, should the study conclude that:
   a. 2030 total water demand is likely to be exceeded,
   b. groundwater elevations are likely to decline by the year 2030, or
   c. the seawater intrusion boundary is likely to advance inland by the year 2030.

Goals 3, 4, 5, and 6 will be addressed using the numerical groundwater-surface water model.

1.3 Model Code Evaluation Criteria

In order to identify the model code that is most appropriate for the Basin numerical model, a list of required and desired capabilities is introduced here. It is understood that no model code can be expected to perfectly fulfill all of the capabilities listed. Model codes are evaluated on their ability to meet as many of the important criteria as possible. This list is divided into two sections, primary (largely technical in nature) and secondary (largely related to ease of use) evaluation criteria.

This list of evaluation criteria was prepared in the context of the Project 2 goals listed in Sections 1.1 and 1.2. As stated above, the overall goal of the numerical model is to simulate the dynamic and integrated movement of water through the groundwater and surface water systems. The simulations will be performed in the context of historical and projected hydrology and land use conditions, with irrigation demand determined by land use and availability of groundwater and surface water sources (including releases from the Nacimiento and San Antonio Reservoirs). In addition, the occurrence of seawater intrusion in the northern part of the Basin must be simulated.

Primary Evaluation Criteria:

- Three-dimensional multi-layer groundwater flow – the model must be capable of simulating groundwater flow in three dimensions in multiple model layers (representing multiple aquifers).
- Two-dimensional surface water flow – the model must be capable of simulating surface water flow (rivers and streams) within the watershed of the Salinas River; in particular, the model must be able to simulate routing within the Salinas River and its tributaries, predict inundation of the floodplain, and incorporate reservoir operations and future engineering projects.
- Dynamic groundwater-surface water interaction – the model should be able to simulate the movement and routing of both groundwater and surface water through the model domain, and the interaction between the two, based on river bed hydraulic parameters and simulated wetted perimeter and stream stage.
- Seawater intrusion – the model should be capable of simulating the intrusion of seawater into the freshwater system based on the simulated groundwater conditions, using either a density-dependent flow model or an analytical approximation; the model should be capable of simulating the effect of sea level rise under climate change projections.
- Dynamic demand estimation – the model should be able to calculate groundwater and surface water demand based on land use, climatic conditions, and availability of supply.
- Dynamic integration of reservoir operations – the model should be capable of simulating the operation of the Nacimiento and San Antonio reservoirs, including storage volume and release rate based on groundwater and surface water conditions within the model, calculated demand, and a set of reservoir operation rules.
- Surface water rights priorities – the model should be able to prioritize surface water deliveries based on a set of rules dictated by surface water rights and operational constraints.
- Multi-aquifer wells – the model should be capable of dynamically apportioning pumping to multiple model layers in wells that are screened across multiple aquifers; in addition, the model should be able to simulate inter-aquifer flow through the bores of active and inactive (but not destroyed) wells.
- Soil moisture budget – the model should be able to track the storage of moisture in the soil over time, so that the effect of particularly wet or dry periods on subsequent periods can be simulated.
- Limited number of operational steps – the model will be designed so that it can be turned over to a user so that various management alternatives can be simulated; therefore, the steps required to execute the model should be limited, and model codes that can simulate the entire hydrologic system (i.e., can satisfy as many of the criteria above as possible) are preferred.

Secondary Evaluation Criteria:

- Model execution time – the time required to execute the model (including pre- and post-processing) should be minimized to the extent possible, as long as model code capabilities are not sacrificed.
- GUI availability – the availability of a robust graphical user interface (GUI) eases the preparation and interpretation of model input and output files.
- Model acceptance – the model should be widely used and accepted and rigorously tested and reviewed.

- Pre- and post-processing – the model input files should be straightforward and easy to prepare, and output files should be simple to interpret; alternatively, sophisticated tools should be available that assist pre- and post-processing.
- Model grid flexibility – the size and shape of model grid cells should be spatially flexible so that grid resolution can be increased in areas of importance (such as near pumping wells and surface water bodies) and decreased in areas where the increased resolution is not needed.
- Capital cost – the cost of acquiring the model code and associated programs (such as a GUI), software upgrades, and long-term maintenance should be minimized, where possible.

1.4 List of Selected Available Model Codes

A selected list of model codes that are, at a minimum, capable of simulating three-dimensional groundwater flow, is presented here. This list is not intended to be exhaustive. Not all of these model codes are capable of fulfilling the Investigation goals presented above, as will be discussed in Section 2.

- The MODFLOW family of codes, including MODFLOW-2005 (Harbaugh, 2005), MODFLOW-OWHM (Hanson et al., 2014), GSFLOW (Markstrom et al., 2008), and MT3DMS (Zheng, 2010);
- The California Department of Water Resources (DWR) integrated water resource (IWR) models, Integrated Groundwater and Surface Water Model (IGSM) and Integrated Water Flow Model (IWFM; DWR, 2014a and 2014b);
- HydroGeoSphere (HGS; Brunner and Simmons, 2012);
- SWATMOD/SWAT-MODFLOW (Kim et al., 2008);
- MIKE SHE (DHI, 1998);
- ParFlow-CLM (Maxwell et al., 2014); and
- WEAP (SEI, 2011).

1.5 Salinas Valley Integrated Groundwater-Surface Water Model

As the most widely-used tool for simulating the movement of integrated groundwater and surface water in the Basin, the Salinas Valley Integrated Groundwater-Surface Water Model (SVIGSM) merits some discussion here. This model was developed by Montgomery Watson to support the analysis of alternatives under the Salinas River Basin Management Plan (MW, 1997). It was used to support the Historical Benefits Analysis that evaluated the effects of the Nacimiento and San Antonio Reservoirs on conditions within the Salinas Valley (MW, 1998). The model has recently been updated to evaluate the effect of the Monterey Peninsula Water Supply Project (LSCE, 2014).

The SVIGSM domain covers the Salinas Valley from the San Luis Obispo County Line to the coast of Monterey Bay. It simulates the generation and movement of surface water, flow of groundwater, and the interaction of groundwater and surface water. The model uses land use data to estimate agricultural demands in the Basin, and uses available precipitation and surface water to satisfy that demand, with groundwater supplies making up any shortfall. MW (1997) provides a list of uses for the model:

- “Provide a better understanding of the nature of the physical and hydrological processes that govern the ground water flow system in the Salinas River Basin. This includes natural and operational factors that influence the rate and areal extent of intrusion of seawater at the Monterey Bay.
- “Analyze the hydrologic impacts of the Salinas River Basin Management Plan (BMP), and provide sufficient information to the decision makers and stakeholders for screening of alternatives, and selection of the preferred alternative.
- “Assist in the allocation of the amount and area of BMP water delivery, in order to meet the goals of the BMP.”

Additionally, MW (1997) lists various model features:

- “Simulation of the ground water flow in the Salinas Valley through the various water bearing material underlying the valley and their vertical interactions, including:
  - “the 180 foot, 400 foot, and the Deep Aquifer in the Pressure subarea;
  - “the East Side Shallow, East Side Deep, and the Deep Aquifer in the East Side subarea;
  - “the Shallow and Deep Aquifers in the Forebay subarea; and
  - “the unconfined aquifer in the Upper Valley subarea.
- “Simulation of the [*sic*] in the Salinas River and its major tributaries from Nacimiento and San Antonio Reservoirs to the Monterey Bay. The interaction between the Salinas River and its tributaries with the ground water system is an integral part of the model.
- “The model does not simulate surface and/or ground water rights in the legal sense. However, in terms of any surface water diversions, it can honor priorities for operation of the upstream reservoirs, such as, releasing water for maintaining certain flow in the river channel.
- “Simulation of the rate and extent of seawater intrusion.
- “Simulation of the agricultural water use requirements based on crop irrigated acreage, crop potential evapotranspiration, minimum soil moisture requirements, and crop irrigation efficiency.
- “Simulation of direct runoff and deep percolation from rainfall and irrigation applied water.”

The update by LSCE (2014) did not make major modifications to the structure of the model; the update was performed primarily to extend the simulation up to 2011 as it originally ended in 1994.

Section 2: Model Code Strengths and Weaknesses

This section presents the abilities of each of the above model codes to address the goals of the numerical modeling study presented in Section 1.2. Much of the information in this section comes from reports comparing multiple model codes (Dogrul et al., 2011; Harter and Morel-Seytoux, 2013; Taghavi et al., 2013). Table 1 is a matrix showing the capabilities of these model codes to meet the evaluation criteria presented in Section 1.3.

2.1 The MODFLOW Family of Codes

The USGS groundwater modeling code MODFLOW is the industry standard numerical groundwater modeling code in the U.S. This code is public domain and open-source, though some of the refinements designed by those outside the USGS are proprietary. It has a modular design, meaning that selected processes can be added to and removed from the model code depending on the needs of the modeler. MODFLOW has gone through several major revisions over its more-than-30-year history, with the capabilities of the model code increasing over time. MODFLOW is a finite-difference code, and is restricted to a rectangular grid with grid resolution stretching to the model edges. The latest revision, MODFLOW-USG, transformed MODFLOW into a control volume finite-difference code, which allows much more flexibility in grid construction (Panday et al., 2013).

Several features of MODFLOW and its related codes relate directly to the goals of this study, and bear mentioning here, though not all of these features are compatible with each other. Under the name GSFLOW (Markstrom et al., 2008), MODFLOW has been coupled to a rainfall-runoff model (the Precipitation Runoff Modeling System, PRMS; Leavesley et al., 1983). This code simulates the generation of runoff in the whole watershed of the groundwater basin, routes surface water flow through the surface water system, and simulates interaction between the surface water and groundwater systems.

Table 1. Matrix of Capabilities of Model Codes to Fulfill Evaluation Criteria

Primary Criteria	MODFLOW-OWHM with PRMS	IWFM	HydroGeoSphere	SWAT-MODFLOW	MIKE SHE	ParFlow-CLM	WEAP
Three-dimensional multi-layer groundwater flow	y	y	y	y	y	y	y
Two-dimensional surface water flow	y	y	y	n	n[1]	y	n
Dynamic groundwater-surface water interaction	y	y	y	Simplified (RIV-like)[2]	Simplified (RIV-like)	y	Simplified or with MODFLOW
Seawater intrusion	y	n	y	n	y	y	n
Dynamic demand estimation	y	y	n	y[3]	y	n	y
Dynamic integration of reservoir operations	n	n	n	n	n	n	y
Surface water rights priorities	y	n	n	n	n	n	y
Multi-aquifer wells	y	Simplified[4]	y	n	y	y	n
Soil moisture budget	n	y	y	y	y	y	y
Limited number of operational steps	n[5]	n[6]	n[7]	n[8]	n[9]	n[10]	n[6]
Secondary Criteria	**MODFLOW-OWHM with PRMS**	**IWFM**	**HydroGeoSphere**	**SWAT-MODFLOW**	**MIKE SHE**	**ParFlow-CLM**	**WEAP**
Model execution time	Low	High	High	Medium	High	High	Medium
GUI availability	y	y	y	y	y	n	y
Model acceptance	High	CA-centric	Medium	Medium	High	Low	Medium
Pre- and post-processing	y	y	y	n	No water balance	n	Limited
Model grid flexibility[11]	FD	FE	CVFE	FD	FD	FCV (Surface)/ FD (Subsurface)	AE
Capital cost[12]	OS	OS	Prop.	OS	Prop.	OS	Prop.

Notes:

[1] Overland flow is two-dimensional, while channel flow is one-dimensional. Overbank flooding can be simulated.

[2] RIV is the MODFLOW River package.

[3] Demand for a hydrologic response unit (HRU) can only be met by a single source, not multiple sources.

[4] Not capable of dynamically calculating transmissivity, or of simulating groundwater flow between aquifers through the well bore.

[5] PRMS (or another rainfall-runoff model) would have to be run separately to create input streamflow.

[6] Seawater intrusion would have to be run outside the model.

[7] Demand and reservoir operations would need to be calculated outside the model.

[8] Surface water flow and seawater intrusion would have to be simulated outside the model.

[9] Surface water flow would have to be simulated outside the model.

[10] The supply and demand system would have to be simulated outside the model.

[11] FD = finite difference; FE = finite element; CVFE = control volume finite element; FCV = finite control volume; AE = analytical element.

[12] OS = open source; Prop. = proprietary.

An additional set of codes has been created to simulate conjunctive use of surface water and groundwater within a supply and demand framework, starting with the MODFLOW Farm Process (Schmid et al., 2006; Schmid and Hanson, 2009) and leading most recently to the One-Water Hydrologic Flow Model (MODFLOW-OWHM; Hanson et al., 2014). This set of codes calculates the crop irrigation demand based on evapotranspiration, irrigation efficiency, and precipitation, uses available surface water sources to satisfy the irrigation demand, and simulates any groundwater pumping necessary to meet unmet demand. These codes can consider water rights priorities and prioritization rules in the event that demand cannot be met.

MODFLOW has also been extended in different ways to simulate seawater intrusion into freshwater aquifers. SEAWAT (Langevin et al., 2007) is a version of MODFLOW based on MODFLOW-2000 and MT3DMS that is capable of simulating solute transport in settings where solute concentrations (or heat) affect the properties of the fluid (including density and viscosity). For seawater intrusion, this approach requires relatively fine vertical discretization in order to produce a reasonably fine resolution for the seawater-freshwater interface. More recently, the USGS introduced the Seawater Intrusion (SWI2) package (Bakker et al., 2013), which uses an approach that does not require fine vertical discretization to approximate the shape and location of the interface.

MODFLOW also has flexibility in its approach to simulating wells that are screened across multiple aquifers using the Multi-Node Well (MNW2) package (Konikow et al., 2009). This package adds multiple capabilities regarding this type of well. The pumping rate applied to each layer in which the well is screened is dynamically determined by the model code using the transmissivity of each layer. Also, the model code does not require that a well be screened throughout the entire thickness of each aquifer. Finally, the model code simulates well-bore flow between aquifers, which can be a very important transfer route for water and contamination.

Groundwater flow through the unsaturated zone can be simulated in MODFLOW using the Unsaturated-Zone Flow (UZF1) package. This approach uses a one-dimensional (vertical) kinematic wave approximation to the Richards' equation to simulate the downward flux of groundwater through the vadose zone.

The strengths of MODFLOW include the following:

- it has a wide variety of capabilities that are continually being maintained and expanded;
- it is open-source and freely available, and authors of the many modules are frequently available to answer questions and provide clarification;
- it has the ability to dynamically simulate demand and apportion it to various supply pools (including groundwater and surface water);
- several different graphical user interfaces (GUIs) have been developed, including one that the USGS makes freely available; and
- all of the MODFLOW versions and modules published by the USGS have been thoroughly documented, and it is widely accepted as a modeling tool and widely used.

Weaknesses of the MODFLOW family of codes include the following (Dogrul et al., 2011):

- the finite difference formulation of the code precludes the ability to increase model grid resolution in important areas without carrying that increased resolution to the edges of the model grid, leading to fine resolution in distal parts of the model that may not be important and may unnecessarily increase CPU time and resources. While this weakness has been resolved by the introduction of MODFLOW-USG, few of the packages are currently compatible with MODFLOW-USG;
- there is no simulation of soil water storage, meaning that water cannot be stored in the soil zone and made available for evapotranspiration in subsequent stress periods, nor can the effect of a dry period on soil water storage, which can require additional irrigation to make up for storage deficits; and

- it currently does not have the capability to interface with any solute transport code (e.g. MT3DMS), although it can be used with particle tracking programs (Harter and Morel-Seytoux, 2013).

The weaknesses listed above do not preclude MODFLOW from use in this Investigation; MODFLOW-OWHM, being the version of MODFLOW most fitting to the study goals, is one of the model codes to be considered further in the next section. MODFLOW-OWHM includes the Farm Process and is compatible with the SWI2, MNW2, and UZF1 packages, as well as multiple surface water packages.

2.2 IGSM/IWFM

The integrated water resource (IWR) model codes created by DWR, IGSM and IWFM, simulate the full water cycle, including estimation of demand in a way similar to MODFLOW-OWHM. It uses land use (i.e., crop type) information, precipitation, and stored soil moisture to determine the crop irrigation demand, then calculates the amount of groundwater needed to make up unmet demand after surface water sources have been exhausted. IGSM represents the early version of this model code, which has been revised over time and has been given the name IWFM to indicate that it simulates the whole terrestrial water cycle. Like MODFLOW, this model is open-source and freely available.

Many of the strengths of IWFM are similar to those of MODFLOW-OWHM:

- it simulates surface water generation (using a different approach from MODFLOW-OWHM), dynamically determines agricultural demand and apportions it to various supply pools, and simulates groundwater-surface water interaction;
- it is open-source and freely available, and DWR staff are available to assist with its implementation;
- a GUI was recently introduced for IWFM that is based in ArcGIS;
- unlike MODFLOW, IWFM is a finite element model, meaning that the grid construction is very flexible, giving the ability to increase resolution in critical areas without affecting the grid resolution in outlying areas; and
- it has been tested in various California settings, and an IGSM model already exists for the study area, SVIGSM (MW, 1997).

Weaknesses of IWFM include the following (Dogrul et al., 2011):

- it is not capable of simulating evapotranspiration directly from groundwater uptake (i.e., phreatophytic ET);
- its handling of wells screened across multiple aquifers is fairly basic, using an equation that accounts for partial penetration to partition pumping between layers, and also not allowing for well-bore flow between aquifers;
- its approach to simulating stream leakage in cases where streams are disconnected from the saturated zone is simplistic;
- there is no mechanism for considering the priority of surface water rights when allocating surface water deliveries;
- evapotranspiration is simulated as a single component, which does not allow for the investigation of the efficiency of different irrigation approaches; and
- there is no transport component in IWFM, and no handling of the effect of density on groundwater flow, so that the code cannot rigorously simulate seawater intrusion.

IGSM has additional weaknesses that have been addressed by IWFM (these issues are noted here because of the fact that the existing Salinas Basin model is in the IGSM model code (a.k.a. SVIGSM), and has not been upgraded to IWFM), including the fact that the boundary condition at the Monterey Bay uses constant head cells, which do not allow for changing sea level over time (LSCE, 2014).

The weaknesses listed above do not preclude IWFM from use in the Investigation; IWFM is one of the model codes to be considered further in the next section.

2.3 HydroGeoSphere

HydroGeoSphere (HGS) is an integrated surface water-groundwater model that simulates two-dimensional surface water flow and three-dimensional subsurface water flow. HGS is more integrated than MODFLOW and IWFM, simulating surface and subsurface processes together; unlike MODFLOW and IWFM, HGS simulates the subsurface unsaturated and saturated zones as a single continuous system using the Richards' equation (Harter and Morel-Seytoux, 2013). HGS is a control-volume finite element code, providing a great deal of flexibility in the construction of the model grid, with freedom to increase the grid resolution in important areas such as the near-stream environment and around pumping wells. HGS is also able to simulate the effects of density variations (due to both heat and solute concentration variations) on groundwater flow, an important factor for simulating seawater intrusion.

Reviews indicate that HGS can provide, all else being equal, the most realistic simulation of an integrated groundwater-surface water system. However, the cost in terms of computational load is very high. Dogrul et al. (2011) noted that simulating conditions in a large basin over long simulation times results in very long computational time; the size of the Basin and the 40-year simulation period described in the Scope of Work would point to such a situation in this study.

In addition, Harter and Morel-Seytoux (2013) note that HGS does not have any capacity to perform either economic or water management modeling; because of this, it is not capable of calculating irrigation demand based on crop irrigation requirements and climatic conditions, meaning that it cannot dynamically determine the amount of agricultural pumping required to fulfill crop demand. Harter and Morel-Seytoux (2013) note that this determination can be made outside of the model by considering the crop evapotranspiration requirement and the availability of precipitation and surface water, but this does not consider the effect of groundwater-surface water exchange on the availability of surface water. HGS is proprietary software, and is not open-source. Because of the high computational demand and the lack of a management capability, HGS is not considered an appropriate model code for the Investigation.

2.4 SWATMOD/SWAT-MODFLOW

SWAT-MODFLOW (previously SWATMOD) couples the Soil and Water Assessment Tool (SWAT) to MODFLOW. The purpose of SWAT is to simulate the effects of water management decisions on the movement of water, sediments, and nutrients in ungauged agricultural watersheds, thus predicting the effects on agricultural yield (Gassman et al., 2007). This model, unlike MODFLOW-OWHM, simulates the soil moisture budget, and, unlike IWFM, simulates evapotranspiration from groundwater (Dogrul et al., 2011). SWAT has been designed to utilize ArcGIS as an interface for building, executing, and post-processing models, meaning that the GUI is straightforward for those already familiar with ArcGIS. SWAT is freely available.

Dogrul et al. (2011) list several limitations that indicate that SWAT-MODFLOW would not be appropriate for the Investigation:

- it uses the basic evapotranspiration package in MODFLOW, which can greatly overestimate evapotranspiration from groundwater;
- it does not include the capability to simulate unsaturated zone flow;
- the outer boundaries of models are constrained by watershed boundaries;
- it does not include any consideration of surface water rights;
- it does not have the capability to include head or flow rate constraints for wells screened across multiple aquifers;

- surface water-groundwater exchange is simulated based on the basic MODFLOW river package, which only uses stream stage to calculate exchange, as opposed to more complex packages that route surface water flow and dynamically calculate stream stage.

Because of the weaknesses listed above, SWAT-MODFLOW is not considered an appropriate tool for the Investigation.

2.5 MIKE SHE

MIKE SHE, developed by the Danish Hydrologic Institute (DHI), is an integrated finite difference groundwater-surface water modeling system. Dogrul et al. (2011) describe MIKE SHE as the "most fully coupled hydrologic model" of those they considered. It simulates the full water cycle, starting with rainfall and extending to both surface water and groundwater flow. It uses a one-dimensional Richards' equation approach to simulating unsaturated zone flow, which is a more rigorous approach than the simplified processes included in MODFLOW and IWFM. MIKE SHE also includes both solute transport and particle tracking.

As noted in Dogrul et al. (2011), weaknesses of MIKE SHE include the following:

- the grid spacing is not variable;
- the groundwater-surface water interaction is performed using an approach similar to that of the basic MODFLOW river package, which uses a prescribed head rather than a dynamically calculated stage based on streamflow;
- because it uses the full Richards' equation to simulate unsaturated zone flow, numerous soil parameters are required that may be unavailable and difficult to estimate;
- it does not have a capability to export water balances for units used to estimate demand (e.g. farms in MODFLOW-OWHM);
- MIKE SHE is a proprietary software, meaning that it is not free or open-source.

Because of the above weaknesses, MIKE SHE is not considered an appropriate tool for this study.

2.6 ParFlow-CLM

Similar to HGS, ParFlow is a three-dimensional, variably-saturated groundwater flow model code that has been coupled to the land surface model CLM. It solves the three-dimensional Richards' equation for subsurface flow while simultaneously simulating surface flow. The model code is freely available and open-source. ParFlow includes the capability for utilizing parallel processing, helping reduce computational time. Weaknesses for this model code are similar to those for HGS:

- the computational load is very high for the large spatial and temporal extents required for the Investigation;
- there is no capability for performing the demand estimation included in MODFLOW and IWFM within ParFlow;
- there is no GUI available for ParFlow, which can make rapid familiarity with the model code difficult for the beginning user.

For these reasons, ParFlow-CLM is not considered an appropriate model code for the Investigation.

2.7 WEAP

The Water Evaluation and Planning (WEAP) system was developed by the Stockholm Environmental Institute (SEI) to simulate integrated groundwater-surface water systems, with a focus on water use planning. The purpose of this model code is to simulate the sustainability of existing supply-demand patterns and the sustainability of alternative future scenarios (Taghavi et al., 2013). The model code has been linked to other model codes, including MODFLOW and MODPATH.

Weaknesses of the WEAP model code include:

- it can only be linked to MODFLOW-2000 and hence lacks many of the features that have been added to MODFLOW-2005 and MODFLOW-OWHM;
- it does not allow for prioritization of different crops, meaning that a supply shortage is shared equally between all crops;
- it is proprietary, and not open-source.

These issues preclude this model code from being appropriate to the Investigation.

2.8 Summary

This Section provided brief synopses of seven different model codes (the MODFLOW family of codes, IGSM/IWFM, HydroGeoSphere, SWATMOD/SWAT-MODFLOW, MIKE SHE, ParFlow-CLM, and WEAP) and a selection of important strengths and weaknesses of each code that impact its ability to fulfill the requirements of this study. Based on these strengths and weaknesses and the model goals and evaluation criteria presented in Sections 1.2 and 1.3, MODFLOW-OWHM and IWFM were judged to be the most appropriate codes for the numerical model. The differences between these two model codes are discussed in some detail in the next section.

Section 3: Differences between IWFM and MODFLOW-OWHM

As noted in the previous section, IWFM and MODFLOW-OWHM seem to be the model codes most appropriate for satisfying the goals of the Investigation because of their ability to meet the evaluation criteria presented in Section 1.3. This section describes some of the technical differences between the IWFM and MODFLOW with the Farm Process (MF-FMP), upon which MODFLOW-OWHM is based, and the impact that these differences have. This information comes from the comparative studies referenced above (Dogrul et al., 2011; Harter and Morel-Seytoux, 2013) as well as another study that simulated the same hypothetical physical setting in both IWFM and MF-FMP and discussed the differences in the results between the two model codes (Schmid et al., 2011). The reader is referred to these references and to the model code documentation for more technical details. Attachment A is Table 2 from Dogrul et al. (2011), which provides a detailed summary of how IWFM and MF-FMP handle various processes and situations. Some of the important differences are discussed below.

3.1 Spatial Discretization

As noted above, IWFM is a finite element model code, while MF-FMP is a finite difference model code. Although these two approaches are both widely used and produce acceptable results, there is a practical effect introduced by this difference. A finite element code does not have a rigid structure imposed, meaning that the elements can be any size, shape, and orientation (note that IWFM requires that all cells be either triangular in shape or quadrilaterals). This allows the model builder to increase grid resolution (i.e. decrease element size) in selected areas where this resolution is helpful, such as in the area of surface water features to improve the simulation of groundwater-surface water interaction, or near pumping wells to better simulate the shape of the drawdown cone. For IWFM in particular, the finite element approach could theoretically allow for the assignment of elements to match the boundaries of individual farms or groups of farms that are growing the same crop with the same irrigation practices; this approach was not taken with the existing SVIGSM.

The finite difference approach used by MF-FMP requires that the grid be made up of rectangular cells. Row and column widths must be carried to the edge of the model. The modeler can increase grid resolution in important areas, such as near surface water features and pumping wells, but this increased grid resolution must be carried through to distant parts of the model where increased resolution is not helpful. This increases the time required to run the model. As noted above, the newest version of MODFLOW, MODFLOW-USG, eliminates this issue by changing the model code to a control-volume finite-difference approach, which allows for an unstructured horizontal grid, but MODFLOW-USG is not currently compatible with MF-FMP.

3.2 Evapotranspiration

IWFM computes evapotranspiration (ET) as a single term for each model element. The user specifies a time series of potential ET for each crop (ET_{c0})[1]. ET_{c0} is then turned into actual crop ET (ET_c) using a calculation that depends on the soil moisture in the root zone. If the soil moisture (θ) is more than half the field capacity (θ_f, defined as the soil moisture that would be left in a soil after allowing drainage under gravity for some amount of time), ET_c is equal to ET_{c0}. If θ is half or less of θ_f, ET_c is reduced linearly in proportion to the ratio of θ to θ_f. IWFM thus accounts for the effect of low soil moisture (wilting) on ET, but it does not explicitly handle other factors that may reduce ET, such as high soil moisture (leading to anoxia), non-uniform irrigation, low soil fertility, high salt concentrations, pests, and diseases. These other factors can be simulated by including them in the estimation of ET_{c0}; this must be done by the user.

ET_{c0} in IWFM is assigned by the user for each subregion (a grouping of elements) of the model. Further, ET is calculated for a representative crop for each subregion, computed by area-weighted averaging of ET for the individual crops present within the subregion. If a subregion covers a large spatial area of the model, the assigned values of ET_{c0} and calculated values of ET may not be representative of the variable conditions in certain parts of the subregion. This problem can be avoided for ET_{c0} by making the subregions equivalent to the individual elements. ET for a single-element subregion is still calculated based on the representative crop.

MF-FMP computes ET as six different terms by separating evaporation (E) and transpiration (T) and calculating these two terms separately for E and T from precipitation, irrigation, and groundwater. This allows for investigations into the efficacy of different irrigation methods. Unlike IWFM, MF-FMP allows for ET directly from groundwater, which can be very important when the water table is close to the land surface. However, unlike IWFM, MF-FMP does not simulate soil moisture storage, meaning that ET is only derived from the inputs available during the stress period for which ET is being calculated.

Like IWFM, MF-FMP uses a time series of either ET_0 plus crop coefficients or ET_{c0}, specified on a cell-by-cell basis. ET_c is calculated using ET_{c0} and the groundwater head elevation, and can be optionally reduced under conditions of wilting or anoxia.

The differences between IWFM and MF-FMP can have a large impact on the calculation of ET. Schmid et al. (2011) found for their hypothetical test case that MF-FMP calculated ET at about 72% of the level simulated by IWFM. This has wide-ranging effects on the other components of the numerical models. The higher ET in IWFM led to higher crop demand, greater usage of surface water supplies, and increased groundwater pumping to satisfy unmet demand.

[1] Reference ET (ET_0) is the rate of ET for an idealized crop, usually grass, under well-watered conditions – it is generally transformed into ET_{c0} using crop-specific coefficients

3.3 Soil Moisture Storage

As noted in Sections 2.1 and 2.2, IWFM includes a soil moisture storage component, while MF-FMP does not. IWFM uses the stored soil moisture as a source for ET, and calculates deep percolation based on the soil moisture. MF-FMP, on the other hand, derives ET from precipitation, irrigation, and groundwater uptake that occur during a stress period. The practical effect of this is that IWFM may simulate less irrigation demand during stress periods that are preceded by particularly wet conditions (because soil moisture storage may be high), and more irrigation demand during stress periods that are preceded by particularly dry conditions (because soil moisture must be brought up to field capacity in addition to the crop irrigation requirements). Dogrul et al. (2011) note that the effect of soil moisture storage is lessened if longer stress periods (i.e. months rather than days or weeks) are used.

3.4 Multiple-Aquifer Wells

As noted in Section 2.1 and 2.2, the approach differs between IWFM and MF-FMP for allocating pumping to individual layers for wells that are screened across multiple model layers. IWFM uses the Kozeny equation to partition flow between layers, which is an empirical equation that calculates a vertical distribution factor for each model layer (DWR, 2014a):

$$Q_{P_m} = Q_{P_T} \frac{f_m T_m}{\sum_{i=1}^{N_L} f_i T_i}$$

where Q_{P_m} is the pumping from aquifer layer m, Q_{P_T} is the total pumping from the well, f_m is the vertical distribution fraction for layer *m*, T_m is the transmissivity of layer *m*, and N_L is the number of layers in which the well is screened. The vertical distribution fraction is calculated by the empirical Kozeny equation:

$$f_m = l_{sm}\left[1 + 7\sqrt{\frac{r}{2b_m l_{sm}}}\cos\left(\frac{\pi l_{sm}}{2}\right)\right]$$

where l_s is the well screen length as a fraction of the aquifer thickness in layer *m*, *r* is the well radius, and b_m is the aquifer thickness of layer *m*. It is unclear from the documentation of IWFM whether or not the value of f_m is static throughout the simulation, or whether it can vary with changes in T_m (due, for example, to changes in the position of the water table in an unconfined aquifer).

MF-FMP is compatible with the MNW2 package, which provides a more dynamic approach to allocating pumping to layers. It also apportions pumping by aquifer layer according to the conductance between the well and the aquifer, which includes the effects of head losses due to the discrepancy between the well radius and cell size, the skin effect, and turbulent flow near the well. The pumping is apportioned by layer dynamically, meaning that the head during a given stress period is used to determine the transmissivity in the aquifer.

MF-FMP, using MNW2, also has the ability to simulate inter-wellbore flow, a feature not present in IWFM. This means that the wellbore can be a route for groundwater exchange between aquifers in which the well is mutually screened, if a head difference exists between the aquifers. This can be a very important process in areas with many wells with long screens, typical of agricultural areas. MNW2 also can include head and flow constraints to limit pumping in wells.

3.5 Surface Water Deliveries and Priorities

Surface water deliveries are handled differently in IWFM and MF-FMP. In IWFM, deliveries can either be imported from outside the model domain, or they can originate from streamflow within the model. MF-FMP subdivides surface water deliveries into non-routed deliveries (those from outside the model), semi-routed deliveries (streamflow diversions without simulation of routed conveyance to the farm), and fully-routed deliveries (streamflow diversions with simulation of routed conveyance), providing more options for deliveries than IWFM. For both codes, the surface water deliveries can be driven by the irrigation demand but constrained by available streamflow, although deliveries in MF-FMP can also be constrained by a user-defined maximum, which can represent either a legal or structural maximum (e.g., surface water rights priorities).

The two model codes also handle surface water deliveries differently in the case where the supply is insufficient to meet demand. In IWFM, all surface water deliveries are assigned equal priority, and are therefore adjusted equally. In MF-FMP, the user can choose to use equal appropriation (similar to the IWFM approach) or prior appropriation, with priority ranking assigned by farm. This means that MF-FMP is able to simulate more accurately situations where the crop irrigation demand in excess of precipitation is greater than the surface water right, and can prioritize based on actual water rights priorities when demand exceeds supply.

3.6 Surface Runoff from Irrigation

The amount of irrigation water that becomes surface runoff (i.e., return flow), and is therefore not used as a source for ET, is calculated differently in the two model codes. In IWFM, surface runoff from irrigation is computed as a user-defined fraction of the total irrigation. In MF-FMP, this component is calculated after ET is removed from the total irrigation; the remainder, representing the crop-inefficient losses, is divided between surface runoff and deep percolation according to a user-defined fraction.

3.7 Deep Percolation

The calculation of deep percolation in MF-FMP, as noted above, is calculated as a user-defined fraction of the crop-inefficient losses, the difference between the total irrigation and ET. In IWFM, deep percolation is calculated as a function of soil moisture, with the rate of deep percolation set equal to the unsaturated vertical hydraulic conductivity (which is a function of the saturated hydraulic conductivity and θ). The amount of deep percolation occurring during a stress period affects the amount of soil moisture in storage, which in turn affects the irrigation demand for the next stress period, as the soil moisture storage may need to be brought up to field capacity.

3.8 Stream-Aquifer Interaction

In losing reaches of streams, the infiltration of streamflow into an aquifer is calculated by both model codes using a similar approach based on Darcy's law. However, the head difference between the stream and the aquifer used in this calculation is different between the two codes when the stream is hydraulically disconnected from the aquifer (i.e. there is an unsaturated zone beneath the stream). In MF-FMP, the head difference is equal to the thickness of the stream bed plus the stream stage; in IWFM, the head difference is equal to the thickness of the stream bed.

3.9 Time Scale Difference between Groundwater and Surface Water Simulations

Because of the very different time scales of groundwater and surface water flow, the movement of water in these two systems is best simulated using two different time scales (weeks, months, or more for groundwater flow and hours, days, or weeks for surface water flow). If groundwater and surface water flow are simulated on the same time scale, the time steps have to be either so short (e.g. days) that simulation of groundwater flow throughout the basin is unmanageable, or so long (e.g. months) that the model cannot properly simulate the temporal variability of streamflow. Some integrated groundwater-surface water modeling tools, such as MODFLOW-OWHM with the Surface Water Routing (SWR1) package, provide the ability to simulate multiple surface water flow time steps during each groundwater flow time step, assuming that the groundwater flow system remains at steady state during any given groundwater flow time step. IWFM does not have this capability, and surface water and groundwater flow are both modeled using the same time step length.

3.10 Model Execution Time

The computational time needed to run a model can have an effect on the extent of calibration that can be performed. Because of the many differences between IWFM and MF-FMP, it is difficult to compare model execution times conclusively. Schmid et al. (2011) created a hypothetical example problem designed to illustrate the effect of the differences between the two model codes, selecting options to attempt to make the approaches of the two codes as similar as possible. This hypothetical model was completed in 4 minutes using MF-FMP and 58 minutes in IWFM, including automated post-processing to export water budgets. This rather large difference cannot be assumed to apply to a model that would be created as part of this study, but may be indicative of greater numerical efficiency in MF-FMP.

Section 4: Summary and Conclusions

This TM addresses the available model codes that may be applicable to the numerical groundwater-surface water interaction modeling as part of the Salinas River Groundwater Basin Investigation. Several model codes were reviewed, and the DWR code IWFM and USGS code MODFLOW-OWHM are considered the most appropriate for the Investigation.

IWFM and MF-FMP (MODFLOW-OWHM was based on MF-FMP, and has mostly identical features) were compared to each other in order to assess which code should be used when constructing the numerical model. Although there are many differences between the codes (see Section 3 and Attachment A), those with the greatest bearing on this study include the following:

- IWFM is a finite element code, while MF-FMP is a finite difference code. This gives IWFM great flexibility in terms of the shape and size of its elements, allowing for greater resolution in areas where it is helpful, such as around surface water bodies and pumping wells. Grid refinement in MF-FMP must be carried to the edges of the model.
- Unlike IWFM, MF-FMP does not simulate soil water storage, meaning that there is no carryover from stress period to stress period of either soil water surplus or deficit. This can lead to over-estimation of irrigation demand following particularly wet months and under-estimation following particularly dry months.
- IWFM does not simulate ET uptake from groundwater, while MF-FMP does. MF-FMP also provides more detail on the sources of E and T, which are not differentiated in IWFM.

- The approach to apportioning pumping between model layers in wells that are screened across multiple layers is less complex in IWFM than in MF-FMP, and does not allow for a dynamic apportioning. In addition, MF-FMP includes the capacity to simulate inter-wellbore flow, which can be important in areas with many wells that have very long screened intervals straddling multiple aquifers (typical of agricultural areas). MF-FMP also can incorporate head and flow limits to more realistically simulate pumping-related constraints in wells.
- In cases where the crop irrigation demand is greater than available supplies, MF-FMP has the capacity to apportion surface water deliveries based on the water rights prioirites. In addition, delivery maxima can be set that represent either legal (water rights) or structural (delivery system capacity) limits.
- MF-FMP interfaces with other modules in the MODFLOW family of codes. While Harter and Morel-Seytoux (2013) note that MF-FMP is not capable of linking to the sophisticated transport code MT3DMS (note that the online guide to MODFLOW-OWHM, http://water.usgs.gov/ogw/modflow-owhm/Guide/index.html, indicates that it does create the linking file to MT3DMS), MODFLOW-OWHM does interface with the seawater intrusion package SWI2 (Hanson et al., 2014).

These differences do not necessarily preclude one or the other of these model codes from being used to construct the numerical model for the Investigation. However, the differences between the codes point toward MODFLOW-OWHM being the more appropriate code because of its ability to integrate seawater intrusion into the model, to represent the pumping and inter-aquifer exchange in multi-aquifer wells, and to consider the amount and priority of surface water rights when determining surface water deliveries.

The existing numerical model for the study area, SVIGSM, was constructed in IGSM, the precursor to IWFM. SVIGSM has additional limitations, including its inability to have a variable head assigned to the head boundary at the coast of the Monterey Bay. This precludes the ability to simulate the effects of climate change on sea level. Neither SVIGSM nor IWFM can simulate the shape of the seawater-freshwater interface because they do not have the capacity to simulate density-dependent flow. The results of the latest update to SVIGSM (LSCE, 2014) were used as a boundary condition for a coastal SEAWAT model that was used to simulate the position of the seawater-freshwater interface, an implicit acknowledgment of the limitations of SVIGSM in this regard.

References

Bakker, M., F. Schaars, J.D. Hughes, C.D. Langevin, and A.M. Dausman, *Documentation of the Seawater Intrusion (SWI2) Package for MODFLOW*, U.S. Geological Survey Techniques and Methods 6-A46, 2013, 47p.

Brunner, P. and C.T. Simmons, "HydroGeoSphere: a Fully Integrated, Physically Based Hydrological Model," *Groundwater*, 50(2), 2012, p.170-176.

DHI, *MIKE SHE Water Movement – User Guide and Technical Reference Manual, Edition 1.1*, Danish Hydraulic Institute, 1998.

Dogrul, E.C., W. Schmid, R.T. Hanson, T. Kadir, and F. Chung, *Integrated Water Flow Model and Modflow-Farm Process: A Comparison of Theory, Approaches, and Features of Two Integrated Hydrologic Models*, prepared by the California Department of Water Resources, Integrated Hydrological Models Development Unit, Modeling Support Branch, November 2011, 80p.

DWR, Integrated Water Flow Model IWFM-2015 Theoretical Documentation, prepared by the California Department of Water Resources, Central Valley Modeling Unit, Model Support Branch, 2014a, 186p.

DWR, *Integrated Water Flow Model IWFM-2015 User's Manual*, prepared by the California Department of Water Resources, Central Valley Modeling Unit, Model Support Branch, 2014b, 270p.

Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold, "The Soil and Water Asessment Tool: Historical Development, Applications, and Future Research Directions," Transactions of the American Society of Agricultural and Biological Engineers, 50(4), 2007, p.1,211-1,250.

Hanson, R.T., S.E. Boyce, W. Schmid, J.D. Hughes, S.M. Mehl, S.A. Leake, T. Maddock III, and R.G. Niswonger, *One-Water Hydrologic Flow Model (MODFLOW-OWHM)*, U.S. Geological Survey Techniques and Methods 6-A51, 2014, 134p.

Harbaugh, A.W., *MODFLOW-2005, the U.S. Geological Survey Modular Ground-Water Model – the Ground-Water Flow Process*, U.S. Geological Survey Techniques and Methods 6-A16, 2005, 253p.

Harter, T. and H. Morel-Seytoux, *Peer Review of the IWFM, MODFLOW and HGS Model Codes: Potential for Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins*, California Water and Environmental Modeling Forum, 31 July 2013, 121p.

Kim, N.W., I.M. Chung, Y.S. Won, and J.G. Arnold, "Development and Application of the Integrated SWAT-MODFLOW Model," *Journal of Hydrology*, 356(1-2), 2008, p.1-16.

Konikow, L.F., G.Z. Hornberger, K.J. Halford, and R.T. Hanson, *Revised Multi-Node Well (MNW2) Package for MODFLOW Ground-Water Flow Model*, U.S. Geological Survey Techniques and Methods 6-A30, 2009, 67p.

Langevin, C.D., D.T. Thorne Jr., A.M. Dausman, M.C. Sukop, and W. Guo, *SEAWAT Version 4: a Computer Program for Simulation of Multi-Species Solute and Heat Transport*, U.S. Geological Survey Techniques and Methods 6-A22, 2007, 39p.

Leavesley, G.H., R.W. Lichty, B.M. Troutman, and L.G. Saindon, *Precipitation-Runoff Modeling System – User's Manual*, U.S. Geological Survey Water-Resources Investigations Report 83-4238, 1983, 207p.

LSCE, *Hydrologic Modeling of the Monterey Peninsula Water Supply Project Using the Salinas Valley Integrated Ground and Surface Water Model*, prepared for Geoscience by Luhdorff and Scalmanini, Consulting Engineers, December 2014, 193p.

Markstrom, S.L., R.G. Niswonger, R.S. Regan, D.E. Prudic, and P.M. Barlow, *GSFLOW – Coupled Ground-Water and Surface-Water Flow Model Based on the Integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005)*, U.S. Geological Survey Techniques and Methods 6-D1, 2008, 254p.

Maxwell, R.M., S.J. Kollet, S.G. Smith, C.S. Woodward, R.D. Falgout, I.M. Ferguson, N. Engdahl, L.E. Condon, S. Lopez, J. Gilbert, L. Bearup, J. Jefferson, C. Prilbulick, C. Baldwin, W.J. Bosl, R. Hornung, and S. Ashby, *ParFlow User's Manual*, International Ground Water Modeling Center, July 2014, 165p.

MW, *Salinas Valley Integrated Ground Water and Surface Model Update*, prepared for the Monterey County Water Resources Agency by Montgomery Watson, May 1997, 188p.

MW, *Salinas Valley Historical Benefits Analysis (HBA), Final Report*, prepared for the Monterey County Water Resources Agency by Montgomery Watson, in association with CH2MHILL and Shaaf and Wheeler Associates, April 1998, 294p.

Niswonger, R.G., D.E. Prudic, and R.S. Regan, *Documentation of the Unsaturated-Zone Flow (UZF1) Package for Modeling Unsaturated Flow Between the Land Surface and the Water Table with MODFLOW-2005*, U.S. Geological Survey Techniques and Methods 6-A19, 2006, 71p.

Panday, S., C.D. Langevin, R.G. Niswonger, M. Ibaraki, and J.D. Hughes, *MODFLOW-USG Version 1: an Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation*, U.S. Geological Survey Techniques and Methods 6-A45, 2013, 66p.

Schmid, W. and R.T. Hanson, *The Farm Process Version 2 (FMP2) for MODFLOW-2005 – Modifications and Upgrades to FMP1*, U.S. Geological Survey Techniques and Methods 6-A32, 2009, 102p.

Schmid, W., R.T. Hanson, T.M. Maddock III, and S.A. Leake, *User's Guide for the Farm Process (FMP) for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, MODFLOW-2000*, U.S. Geological Survey Techniques and Methods 6-A17, 2006, 127p.

Schmid, W., E.C. Dogrul, R.T. Hanson, T. Kadir, and F. Chung, *Comparison of Simulations of Land-use Specific Water Demand and Irrigation Water Supply by MF-FMP and IWFM*, prepared by the U.S. Geological Survey, California Water Science Center, November 2011, 80p.

SEI, *Water Evaluation and Planning System (WEAP) User Guide*, Stockholm Environment Institute, May 2011, 343p.

Taghavi, A., R. Namvar, S. Najmus, and M. Cayer, "Integrated Water Resources Models to Support Analysis of Integrated Regional Water Management Programs in California," *British Journal of Environment and Climate Change*, 3(3), 2013, p.333-377.

Zheng, C., *MT3DMS v5.3 Supplemental User's Guide*, Technical Report prepared for U.S. Army Corps of Engineers, February 2010, 56p.

Attachment A: Comparison of Features, Conceptualization, and Simulation Methods Pertaining to IWFM and MF-FMP

Table 2 from Dogrul et al. (2011).

Component	IWFM	MF-FMP
Physical water budgeting unit	Individual land use areas (agricultural, urban, native vegetation, riparian vegetation) in each subregion (defined by one or more cells)	Individual cell and cells aggregated over a farm or virtual farm (water-accounting units) for supply and demand components and for all inflow and outflow components (rates and cumulative volumes)
Economic water budgeting unit	Individual land use areas in each subregion	Same as above
Land use types	• Four pre-specified land use types (agricultural, urban, native vegetation, riparian vegetation) • Agricultural type is further divided into user-specified crops • User-specified time series data for areas of four land use types for each cell • User-specified land use and crop properties • Land use properties are weighted-averaged by land use area for each subregion	• User-specified crop types (irrigated agriculture, irrigated urban landscape, non-irrigated dry-land farming, native and riparian vegetation) • User-specified time series data for crop type for each cell • User-specified crop properties • Urban demand (specified as negative supply) • Aquifer-Storage-and-Recovery Units
Soil types	• Each cell is assigned a soil type • User-specified soil properties • Soil properties are weighted-averages by land use area for each subregion	• Each cell is assigned a soil type • Pre-specified or user-specified soil properties including capillary fringes to account for evaporation extinction.
Soil moisture	• Simulated soil moisture storage computed by solving conservation equation in the root zone implicitly every time step • User-defined depletion limit to trigger irrigation for agricultural lands • Unsaturated zone module to simulate flow between root zone and groundwater table	• Changes in soil moisture not computed for root zone (sources for and sinks of consumptive use are assumed to be at steady state with no net change in soil moisture over simulated time steps) • Storage changes are computed for deeper vadose zone between root zone and water table by link to UZF package, which simulates delayed recharge between root zone and groundwater table.
Precipitation, P	Time series input for each cell	Time series input for each cell
Direct runoff from precipitation, R_p	Modified SCS curve number method (Schroeder et al., 1994)	User-specified fraction of total losses from precipitation or based on local slope of each cell

Table 2 Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Component	IWFM	MF-FMP
Irrigation water, *I*	• Used only for urban and agricultural areas • User-specified or calculated for a subregion based on input data for precipitation, $ET_{c\text{-}pot}$, return flow and re-use fractions, and dynamically updated soil moisture in the root zone.	• Used only for urban and agricultural areas • Calculated for each cell, on an iterative level, and based on a dynamically updated groundwater head-dependent evapotranspirative crop irrigation requirement
Irrigation efficiency, *e*	• Not specified explicitly; instead specified in terms of return flow and re-use factors as a fraction of total irrigation water	• User-defined for each farm and crop • Dynamic efficiency based on conservation water use
Irrigation return flow, R_i	• Initial return flow is computed as a fraction of irrigation water • Net return flow is computed as initial return flow less re-use of irrigation water	• User-specified fraction of total losses from irrigation • User-specified fate of return flow of excess imported water to stream network or injection into farm wells • Semi-routed return flows to stream network facilitate the simulation of extensive drain networks and lined canals
Surface water deliveries	• Deliveries can be imported from outside the model area • Specified or computed deliveries originating from user-specified stream segments • Some or all deliveries can be dynamically adjusted to meet the water demand; however, deliveries originating from modeled stream nodes are limited by available in-stream flows	• Non-routed Deliveries (unlimited number of ranked water market components) • Semi-routed Deliveries (linkage to SFR package stream network and simulated diversion points) with no simulation of routed conveyance between diversion points and farm. • Fully-Routed Deliveries (linkage to SFR package) with simulation of routed conveyance to the farm. • All deliveries are demand-driven but supply constrained
Surface water appropriations	• All deliveries have equal priority	• User-defined equal appropriation or prior appropriation • Prior appropriation ranked by farm number for priority of surface water right deliveries
Groundwater pumpage	• Well pumping (individual wells are simulated) or element pumping (cluster of wells are simulated) • Lumped pumping can be distributed to individual wells/elements based on user-specified fractions • Pumping at a well and element is distributed to aquifer layers using Kozeny equation and user-specified fractions, respectively • Pumping can be exported outside a subregion • Pumping is limited by the amount of groundwater storage at the well location	• Single-aquifer farm wells pumpage based on fraction of total pumping capacity of all wells associated with a farm • Multi-aquifer farm wells linked to MNW package • Wells associated with Farm but not limited to Farm domain • Series of ranked well fields can export water to individual farms, which import this water as simulated non-routed deliveries (WELLFIELD option)

Table 2 *(continued)* Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Component	IWFM	MF-FMP
Re-use of irrigation water, *U*	• Computed as a fraction of the total irrigation water • Irrigation return flow can be directed to user-specified stream segments which can be re-used by downstream diversions	• Redirected inefficient losses as runoff from both precipitation and irrigation losses can be returned to point of diversion to augment stream flow available for diversion. • Re-use of artificially recharged water (ASR operation) through recovery wells (WELLFIELD option)
Deep percolation, *DP*	• Computed using physically-based approach assuming unit vertical hydraulic gradient and negligible residual water content • Unsaturated zone module to simulate flow between root zone and groundwater table • Contributes to water demand	• Computed as the sum of user-specified fractions of total losses from precipitation and irrigation for individual crop types • Simulated unsaturated infiltration between root zone and water table through linkage with UZF package • Simulated unsaturated infiltration below rivers and lakes with SFR and LAK package
Evapotranspiration, *ET*	• Computed as a single term on an element or subregional basis • Time series of $ET_{c\text{-}pot}$ for each crop is user-specified • Contributions from P and I are not tracked • ET from groundwater uptake is not simulated • Input $ET_{c\text{-}pot}$ is crop-area-weighted averaged for an $ET_{c\text{-}pot}$ of a representative crop in each subregion • Actual ET, $ET_{c\text{-}act}$, is computed as a function of soil moisture and field capacity • Anoxic conditions are not simulated • Wilting conditions are simulated: computed $ET_{c\text{-}act}$ is less than $ET_{c\text{-}pot}$ if soil moisture falls below half of field capacity	• Computed as a summation of evaporation, E, and transpiration, T, on a cell-by-cell basis • ET reduction from land use fractions, crop-stress coefficients, and anoxia and/or wilting • Time series of $ET_{c\text{-}pot}$ or reference ET_r and crop coefficients K_c for each crop are user-specified; time variable fractions are used to separate $ET_{c\text{-}pot}$ into $E_{c\text{-}pot}$ and $T_{c\text{-}pot}$ • Contributions from P and I to E and T are tracked separately as E_p, E_i, T_p, and T_i, • E and T from groundwater uptake are simulated • “Concept 1:” $ET_{c\text{-}act}$ is always less than $ET_{c\text{-}pot}$ for variably saturated conditions. Vertical steady-state pressure-head distributions are matched with defined ranges of negative or positive pressure heads at which stresses of anoxia or wilting eliminate uptake. Positive pressure heads can be set to allow or eliminate transpiration under fully saturated conditions, e.g., for rice or riparian vegetation. • “Concept 2:”, $ET_{c\text{-}act}$ is only less than $ET_{c\text{-}pot}$ for water levels rising above the bottom of the root zone. Anoxia is assumed only to occur for fully saturated conditions: $ET_{c\text{-}act}$ is linearly reduced proportional to reduction of active unsaturated root zone due to anoxia by rising water level.

Table 2 *(continued)* Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP

Component	IWFM	MODFLOW
Water demand	• Uses input $ET_{c\text{-}pot}$ as the target crop consumptive use to meet • Defined as the amount of water to bring the soil moisture from a threshold level (equivalent to maximum allowable depletion) to field capacity, increased by net irrigation return flow and deep percolation • Agricultural water demand can be either computed or specified as time series data by the user • Urban water demand is user-specified time series data • Agricultural and urban water demands are tracked separately in each subregion	• Uses iteratively updated $ET_{c\text{-}act}$ as the target crop consumptive use to meet • Defined as the portion of $ET_{c\text{-}act}$ that is not met by precipitation and uptake from groundwater, increased by the inefficiency losses from irrigation • Irrigation water demand of irrigated agriculture or irrigated urban landscapes is always computed • Municipal and industrial urban water demand is user-specified as negative supplies • Agricultural and urban water demands are tracked separately in separate "virtual farms"
Water supply	• Precipitation, stream diversions, pumping, soil moisture in storage and imported water from outside the model area are the water supply to meet demand • Supply for agricultural and urban water demand is simulated separately in a subregion • Stream diversions and/or pumping can be adjusted or kept at user-specified values through time series "supply adjustment flags" to meet the demand; if both diversions and pumping are to be adjusted, diversions are adjusted first • Diversions and pumping are limited only by the available storage in the stream or aquifer	• Precipitation, stream diversions, pumping, root uptake from groundwater and imported water from outside the model area are the water supply to meet demand • A single supply amount is simulated to meet the lumped agricultural and urban water demand in a farm • Non-routed deliveries are the first source of supply, then semi-routed deliveries and finally pumping is used as source of water • Diversions and pumping are limited to user-specified maximums or available storage in the stream/aquifer, whichever is smaller
Balance between water supply and demand	• Unmet demand or moisture in excess of meeting the demand in a time step can be carried forward to effect the demand in the next time step(s); maximum demand is field capacity increased by net irrigation return flow and deep percolation • Choice to enforce a balance between supply and demand or not • When supply-demand balance is enforced, user-specified sources of supply are adjusted to meet the agricultural demand, urban demand or both (all adjusted sources of supply are assumed to have equal priority) • When supply-demand balance is not enforced, change in soil moisture due to supply in excess or deficit of demand affects demand in following time step(s)	• Unmet demand is simulated by drought response scenarios that optimize deficit irrigation within the same time step in which deficiency occurs • Drought scenario option with acreage optimization based on cost and maximum profit • Drought scenario option with deficit irrigation • Drought scenario option with water stacking onto priority crops • Supply in excess of crop water demand in a time step is discarded as either deep percolation or return flow in the same time step • Supply of imported water in excess of total demand (delivery requirement) is discharged either back into the conveyance network or into injection wells

Table 2 *(continued)* Comparison of features, conceptualization and simulation methods pertaining to IWFM and MF-FMP