Projecting Forward
A Framework for Groundwater Model Development under SGMA

Tara Moran



Stanford | Water in the West

Stanford Law School
Martin Daniel Gould
Center for Conflict
Resolution Programs

About the Report and Groundwater Data Workshop Series

This report builds on a discussion paper entitled, "Groundwater Models in the SGMA Context: Tools to Support Sustainable Groundwater Management," which was developed for a groundwater model workshop held at Stanford University in November, 2015. The groundwater model workshop was the first in a four-part groundwater data workshop series hosted by Stanford University's Water in the West Program, The Gould Center for Conflict Resolution and Sacramento State University's Center for Collaborative Policy. The workshop series brought together a select group of groundwater managers, county and state representatives, and technical and water policy experts to identify data-related challenges of implementing SGMA and to identify regulatory and policy solutions. Workshop topics included: (1) groundwater models; (2) groundwater data; (3) tools to support decision-making; and (4) geophysical methods for sustainable groundwater management. Additional information on the workshop series, including workshop agendas, participant lists, speaker presentations and summary notes, can be found at: http://stanford.io/2em2aaD

Water in the West wishes to express its sincere gratitude to Dr. Janet Martinez, Director of Stanford Law School's Gould Center for Conflict Resolution and to David Ceppos and Marci DuPraw, Associate Director and Director of Practice Development, respectively at CSUS Center for Collaborative Policy for their wisdom, guidance and partnership throughout the series.

Acknowledgements

There are many individuals who have helped in writing this report. I would like to thank Annika Deurlington for her help in drafting the MODFLOW and IWFM overviews provided in appendices A and B of this report, respectively, as well as with the report glossary. I would also like to thank Steve Phillips of the United States Geologic Survey for comments and feedback on the MODFLOW overview and Tariq Kadir and Charlie Brush from the California Department of Water Resources, Integrated Hydrological Model Development Unit, Bay-Delta Office for review of the Integrated Flow Model (IWFM) overview. Thank you to Esther Conrad and Janny Choy for their diligent notetaking during the groundwater model workshop and to the many individuals listed below for their thoughtful review of this report. Finally, thank you to the S.D. Bechtel, Jr. Foundation for your ongoing financial support for this work.

Report Reviewers (in alphabetical order):
William Blomquist, Indiana University Purdue University of Indianapolis
Charlie Brush, California Department of Water Resources
Juliet Christian-Smith, Union of Concerned Scientists
Esther Conrad, Stanford University
Marci DuPraw, California State University Sacramento Center for Collaborative Policy
Graham Fogg, University of California Davis
Paul Gosselin, Butte County Department of Water and Resource Conservation
Thomas Harter, University of California Davis
Mark Larsen, Kaweah Delta Water Conservation District
Brian Lockwood, Pajaro Valley Water Management Agency
Rosemary Knight, Stanford University
Janet Martinez, Stanford University

Dan McManus, California Department of Water Resources
Steven Phillips, U.S. Geological Survey
Max Stevenson, Yolo County Flood Control & Water Conservation District
Leon Szeptycki. Stanford University

Thank you to all of our reviewers list above. Your comments and suggestions helped to significantly improve the report. The author would like to note that reviewers were not asked to endorse the report's conclusions or recommendations, nor did they see the final version of the report. As a result, responsibility for the final content of this report rests entirely with the report's author.

Table of Contents

1.0 Executive Summary 6
2.0 List of Acronyms 7
3.0 Introduction 8
4.0 The Role of Groundwater Models in SGMA 9
4.1. Develop and Meet a Basin Sustainability Goal 11
4.2. Forecast Groundwater Management Actions 13
4.3. Data Collection, Synthesis and Coordination 13
4.4. Engage Stakeholders 14
4.5. Evaluate GSPs 15
5.0 What is a Groundwater Model? 16
5.1. Types of Groundwater Model Codes 17
5.1.1. Public domain, Proprietary, Open Source and Closed Source Model Codes 17
5.1.2. Analytical Model Codes 17
5.1.1. Numerical Model Codes 18
5.2. Types of Groundwater Models 18
5.2.1. Groundwater Flow Models 18
5.2.2. Integrated Hydrological Models 18
5.2.3. Contaminant Transport Models 19
5.2.4. Density-Dependent Flow Models 19
5.3. Groundwater Model Components 20
6.0 Key Concepts in Groundwater Model Development and Use 20
6.1. Phase 1: Model Planning, Conceptualization and Design 25
6.2. Phase 2: Construct, Calibrate and Report 27
6.3. Phase 3: Predict and Assess Uncertainty 27
6.4. Phase 4: Model Documentation and Archiving 29
6.5. Additional Considerations 29
6.5.1. Adaptive Management 29
6.5.2. Coupling with Other Models and Model Comparison 30
7.0 Guiding Principles for Groundwater Model Development 30
8.0 Glossary 32
9.0 References 34
10.0 Appendix A: Integrated Water Flow Model Overview 37
11.0 Appendix B: MODFLOW Overview 43
12.0 Appendix C. Groundwater Model Review Checklist 50

List of Tables

Table 1. SGMA requirements for groundwater model development

Table 2. Groundwater model codes commonly used in California

Table 3. A framework for groundwater model development under SGMA

Table 4. Model confidence level classification

1.0 Executive Summary

Groundwater accounts for approximately 40 percent of California's water supply during average climatic conditions. This percentage increases to nearly 60 percent during dry years or periods of drought (DWR 2013). Despite its importance, California lacked a statewide framework for regulating the resource until passage of the Sustainable Groundwater Management Act (SGMA) in 2014.

Implementation of the SGMA will require agencies throughout the state to undertake management actions that have been necessary for many years, or in some cases, decades, but have not been politically feasible without a state mandate. Specifically, agencies will need to work collaboratively with one another, land use planning agencies and interested parties within the basin to develop groundwater sustainability plans to manage groundwater sustainably in the face of uncertainties associated with changing land use practices, water supply, population growth, climate change and other factors over the 50-year planning and implementation horizon defined in SGMA. Where there are multiple groundwater management agencies in a basin, basin management, and data and monitoring efforts must be closely coordinated. Additionally, agencies must ensure that their efforts to manage sustainably do not under adversely impact neighboring basins. Groundwater models will play a critical role in achieving these goals.

While groundwater models are a simplification of reality, they can serve as powerful tools to (1) develop a better understanding of groundwater systems, (2) develop more reliable estimates of groundwater budgets, (3) ascertain future data collection needs, (4) forecast the outcome of future management actions on a groundwater basin[1] and (5) explore alternative management strategies (Barnett et al. 2012). Relatedly, groundwater models will play a critical role in simulating environmental changes during the 50-year planning and implementation horizon required under SGMA. Groundwater models provide the link between established management criteria and the management approaches necessary to achieve them. In many cases, groundwater models will form the basis of groundwater management decisions.

This report provides a framework for groundwater model development under SGMA. It provides guidance on: how and when stakeholders should be engaged in model development; milestones for third-party model review; model documentation and archiving; and communicating model outputs to non-technical audiences. While many of these practices are already occurring, there are additional opportunities during groundwater model development to encourage the active engagement of the local entities who will be impacted by management decisions, as well as DWR - the agency that is ultimately responsible for evaluating GSPs under SGMA. Finally, coordinating model development at the basin-scale and beyond can maximize efficiency, avoid conflicts over boundary issues, provide opportunities for cost sharing, and, ultimately, result in more consistent models that can be used for local and regional management.

2.0 List of Acronyms

CVHM – Central Valley Hydrologic Model

C2VSim – California Central Valley Groundwater-Surface Water Simulation Model

DWR - Department of Water Resources

GSA – Groundwater Sustainability Agency

GSP – Groundwater Sustainability Plan

IHM – Integrated Hydrological Model

IWFM – Integrated Water Flow Model

MODFLOW – Modular programming of groundwater flow

SGMA – Sustainable Groundwater Management Act of 2014

SWRCB – State Water Resources Control Board

USGS – United States Geological Survey

3.0 Introduction

Groundwater accounts for approximately 40 percent of California's water supply during average climatic conditions. This percentage increases to nearly 60 percent during dry years or periods of drought (DWR 2013). Despite its importance, California lacked a statewide framework for regulating the resource[2] until passage of the Sustainable Groundwater Management Act (SGMA) in 2014.

SGMA provides a comprehensive regime for the monitoring and management of California's 515 alluvial groundwater aquifers. The legislation requires all high- and medium-priority groundwater basins listed in California Department of Water Resources (DWR) Bulletin 118 to be managed under a Groundwater Sustainability Plan (GSP) by January 31, 2022.[3] Of the 515 basins identified in Bulletin 118, 43 are classified as high-priority and 84 as medium-priority. Taken together, these 127 basins support approximately 96 percent of groundwater use and 88 percent of the state's population. The remaining basins are classified as low- or very low-priority and are not required to develop a GSP under SGMA.[4]

SGMA requires actions that have been necessary for many years, or in some cases, decades, but have not been politically feasible without a state mandate. The formation of Groundwater Sustainability Agencies (GSAs), which will be responsible for the development and implementation of GSPs, will require local agencies to make many difficult decisions about who will govern and enforce the GSP once implemented. These entities will also have to work collaboratively to ensure that GSPs are effective, while managing in the face of uncertainties associated with changing land use practices, water supply, population growth, climate change and other factors likely to impact water management over the 50-year planning and implementation horizon defined in SGMA. Where there are multiple GSAs in a basin, basin management, and data and monitoring efforts must be closely coordinated (Cal. Code of Regulations §357.4(a)(b)(e), §352.6, §354.32, §354.32). GSAs in adjacent basins must coordinate to ensure that their efforts don't undermine those of their neighbors. **Groundwater models** will play a critical role in achieving these goals. Terms shown in bold are defined in the report's glossary (Section 9).

While groundwater models are a simplification of reality, they can serve as powerful tools to (1) develop a better understanding of groundwater systems, (2) develop more reliable estimates of groundwater budgets, (3) ascertain future data collection needs, (4) forecast the outcome of future management actions on a groundwater basin[5] and (5) explore

Box 1. Usage of the Term "Groundwater Model"

Groundwater and surface water are integrally linked. Similarly, groundwater systems should be modeled in a consistent manner using integrated hydrologic models or well-developed groundwater models. For simplicity, this report refers to both groundwater models and integrated hydrologic models as groundwater models.

[2] With the exception of adjudicated groundwater basins and special act districts.
[3] 21 of the state's high- and medium-priority basins are subject to critical conditions of overdraft and must be managed under a GSP by January 31, 2020.
[4] Low- and very low-priority basins must develop a Groundwater Sustainability Agency (GSA) or report groundwater extractions annually, but are not required to develop and implement a Groundwater Sustainability Plan (GSP) (Cal. Water Code § 5202.2).
[5] This report uses the term "basin" to refer to a basin or subbasin, as identified in DWR's Bulletin 118 (DWR, 2003).

alternative management strategies (Barnett et al. 2012). Relatedly, groundwater models will play a critical role in simulating environmental changes during the 50-year planning and implementation horizon required under SGMA. As Christian-Smith and Alvord (2016) point out, groundwater models provide the link between established management criteria and the management approaches necessary to achieve them. In many cases, groundwater models will form the basis of groundwater management decisions.

Importantly, groundwater model development can lead to an improved understanding of the groundwater system as whole, through **conceptual model** and **water budget** development, by identifying data gaps, and informing groundwater monitoring protocols and network development. The SGMA process of goal setting, threshold development and ongoing updating provides an opportunity to not only to develop groundwater models, but to update existing groundwater models, particularly as groundwater monitoring networks developed during GSP implementation reveal any shortcoming in the estimated water budget or groundwater model. For all of these reasons, groundwater models can be expected to form the basis for many groundwater management decisions for the foreseeable future.

This report builds on a discussion paper entitled, "Groundwater Models in the SGMA Context: Tools to Support Sustainable Groundwater Management," which was developed for a groundwater model workshop held at Stanford University in November, 2015. This report begins with an overview of the potential role of groundwater models in SGMA implementation and an orientation to groundwater models. It then presents a framework and recommendations for groundwater model development and evaluation under SGMA.

4.0 The Role of Groundwater Models in SGMA

Groundwater models are likely to be used by local and state agencies to meet groundwater management requirements under SGMA in a variety of ways (Table 1). Additionally, groundwater models developed under SGMA must: include publicly available supporting documentation; be based on field or laboratory measurements and calibrated against site-specific field data; and developed using public domain, open-source software (Cal. Code of Regulations §352.4(f)(1-3)).

Table 1. SGMA requirements pertaining to groundwater model development and the corresponding California Water Code or Code of Regulations sections. The table also includes the agencies responsible for implementing each requirement. SWRCB refers to the State Water Resources Control Board. SW-GW is surface water groundwater.

Management Objective	SGMA Requirements	California Water Code Section	Implementing Agency
Develop and meet a basin sustainability goal	Meet sustainability goal	• GSP(s) must be implemented to achieve sustainability goal within 20 years of plan implementation (Cal. Water Code §10727.2(b)). (See Box 2 for more details).	GSA
	Set minimum thresholds and measurable objectives	• To achieve their sustainability goal, GSPs must develop measurable objectives and minimum thresholds for each sustainability indicator under SGMA (Cal. Code of Regulations §354.28 and §354.30). (See Box 2 for more details).	GSA

Forecast groundwater management	Forecast groundwater management	• GSAs must forecast groundwater management actions over a 50-year planning and implementation horizon (Cal. Water Code §10727.2(c))	GSA
Collect, synthesize and coordinate data	Integrate, summarize, and collect data for development of conceptual models, water budgets and short and long-term groundwater trends	• GSAs must develop hydrogeological conceptual models to characterize the physical characteristics of the basin, the primary use of each aquifer and SW-GW interactions (Cal. Code of Regulations §354.28 and §354.14). • GSPs must summarize current and historical groundwater conditions (Cal. Code of Regulations §354.16). • GSPs must use a numerical groundwater model or "equally effective method, tool, or analytical model" to quantify and evaluate projected water budget conditions (Cal. Code of Regulations §354.18). • Develop monitoring networks capable of collecting sufficient data to demonstrate short-term, seasonal, and long-term trends in groundwater and surface water conditions, and provide representative information for GSP evaluation (Cal. Code of Regulations §354.34).	GSA
	Coordinate data	• GSAs developing multiple GSPs within a basin must utilize the same data and methodologies in GSP development (Cal. Water Code §10727.6). • GSAs must develop and maintain a basin-wide "coordinated data management system" capable of storing and reporting information relevant to GSP development and implementation, and for basin monitoring (Cal. Code of Regulations §357.4).	GSA
Engage stakeholders	Engage stakeholders	1. GSA(s) shall establish and maintain a list of persons interested in receiving notice regarding plan preparation (Cal. Water Code §10723.4). 2. GSA(s) shall make available to the public and DWR a written statement describing the manner in which interested parties may participate in GSP development and implementation (Cal. Water Code §10727.8(a)). 3. GSA(s) shall consider the interests of all beneficial uses and users of groundwater (Cal. Water Code §10723.2). 4. GSA(s) shall encourage the active involvement of a diverse population with the groundwater basin (Cal. Water Code §10727.8(a)).	GSA

Evaluate GSPs	Evaluate GSPs	1. Ensure that GSP(s) will achieve the basin's sustainability goal (Cal. Water Code §10733(a-b))	DWR
		2. To ensure that the implementation of a GSP will not adversely affect the ability of an adjacent basin to successfully implement its GSP (Cal. Water Code §10733(c))	DWR
		3. Designate a basin as probationary, if: (a) In consultation with DWR, the SWRCB determines that a GSP is inadequate (Cal. Water Code §10735.2)	SWRCB/DWR
		(b) The SWRCB determines that a basin is in a condition of long-term overdraft (Cal. Water Code §10735.2(5)(A)(ii))	SWRCB/DWR
		(b) The SWRCB determines that a basin is in a condition where groundwater extractions result in significant depletions of interconnected surface waters (Cal. Water Code §10735.2(5)(B)(ii))	SWRCB/DWR

4.1. Develop and Meet a Basin Sustainability Goal

SGMA requires one or more GSAs in all high- and medium-priority basins to develop and implement a single or multiple, coordinated GSPs to achieve their sustainability goal within 20 years of GSP implementation (Cal. Water Code §10727.2(b)). Achieving sustainable groundwater management requires agencies to establish a basin-wide sustainability goal that results in the absence of undesirable results within 20 years of plan implementation. Additionally, basins must demonstrate progress toward this goal through measurable objectives and minimum thresholds (see Box 2).

Groundwater models are likely to play a critical role in translating the basin sustainability goals into measurable objectives and minimum thresholds (Christian-Smith and Alvord, 2016). Because groundwater models enable users to explore the effects of different management actions on groundwater levels in a basin, groundwater models commonly serve as the basis for groundwater management decisions. For example, if a basin establishes a minimum threshold for groundwater levels in the basin, a model can help convert that threshold into the amount of groundwater pumping that can be sustained or the amount of artificial recharge needed to ensure the basin does not drop below the established threshold.

Additionally, models can be helpful in understanding how minimum thresholds developed for different undesirable results will interact with one another. Managers may be able to use their models to develop indicators or metrics that serves as proxies for several undesirable results. In some situations, groundwater managers and model developers may need to develop multiple groundwater models in a single basin to manage for multiple objectives. In others, they may need to prioritize certain management objectives over others within a given model; where such judgment calls come into play, stakeholder engagement is important to ensure that management priorities reflect the preferences of affected parties to the extent possible while still meeting legal requirements.

Box 2. What is Sustainable Groundwater Management Under SGMA?

SGMA requires all high- and medium-priority groundwater basins in the state to develop Groundwater Sustainability Plan(s) (GSPs) to achieve their respective sustainability goals within 20 years of plan implementation (Cal. Water Code **§**10727(a)).

> **Sustainability goal** means the existence and implementation of one or more [GSPs] that achieve *sustainable groundwater management* by identifying and causing the implementation of measures targeted to ensure that the applicable basin is operated within its *sustainable yield* (Cal. Water Code **§**10721(t)).
>
> **Sustainable groundwater management** means the management and use of groundwater in a manner that can be maintained during the *planning and implementation horizon* without causing *undesirable results* (Cal. Water Code **§**10721(u)).
>
> **Sustainable yield** means the maximum quantity of water, calculated over a period representative of long-term conditions in the basin and including any temporary surplus, that can be withdrawn annually from a groundwater supply with causing *undesirable results* (Cal. Water Code **§**10721(v)).
>
> **Planning and implementation horizon** means a 50-year time period over which a groundwater sustainability agency determines that plans and measures will be implemented in a basin to ensure that the basin is operated within its sustainable yield (Cal. Water Code **§**10721(q)).
>
> **Undesirable results** mean one or more of the following effects caused by groundwater conditions occurring throughout a basin:
>
> - Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon….
> - Significant and unreasonable reduction of groundwater storage.
> - Significant and unreasonable seawater intrusion.
> - Significant and unreasonable degraded water quality…
> - Significant and unreasonable land subsidence…
> - Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water (Cal. Water Code **§**10721(w)).
>
> **Sustainability Indicator** refers to any of the effects caused by groundwater conditions occurring throughout the basin that, when significant and unreasonable, cause undesirable results (Cal. Code of Regulations §351(ah)).

4.2. Forecast Groundwater Management Actions

GSPs must consider the impact that groundwater management actions will have on a basin's sustainable yield over a 50-year "planning and implementation horizon" (Cal. Water Code §10727.2(c)). Agencies must, therefore, understand the short and long-term implications of different management actions on a groundwater system, in addition to planning for the potential effects of a variety of anticipated changes, like climate change, population growth, and land use.

Given the complex nature of groundwater and the interdependent responses of the system to change, consideration of the long-term implications of different management actions on these system is virtually impossible without the use of models (Bredehoeft, 2002; Fogg and LaBolle, 2006; Gleeson et al. 2012). In addition to providing a rigorous understanding of groundwater systems and enabling users to compare and evaluate the impacts of different management actions on a groundwater basin over time (Gleeson et al. 2012), groundwater models can project the groundwater system's response to changing physical conditions (e.g., land use planning, climate change, water use, population).

GSAs have a variety of regulatory tools that can be used in order to achieve sustainable groundwater management. These include levying fees, regulating groundwater extractions, imposing spacing requirements on new wells, reducing demand, importing water, recharging water, and others. Groundwater models allow decision-makers to explore the potential impacts of different groundwater management actions on a basin and make informed decisions. As a result, groundwater models are likely to play an important role in helping GSAs to understand and project how groundwater management actions are likely to affect a basin's long-term sustainability and develop and implement effective GSPs.

4.3. Data Collection, Synthesis and Coordination

SGMA requires GSAs to monitor, manage and report data necessary for sustainable groundwater management, or collaborate with other local agencies to obtain necessary data (Cal. Water Code **§**10727.2, 10727.4 and 10727.6). These data include (1) information necessary to develop a hydrogeologic conceptual model (Cal. Code of Regulations §354.14); (2) current and historical estimates of groundwater conditions in the basin (Cal. Code of Regulations §354.16); (3) projected water budgets that incorporate change in local land use planning, population growth and climate (Cal. Code of Regulations §354.18); and (4) groundwater monitoring networks with sufficient spatial and temporal resolution to detect short- and long-term trends in groundwater levels, water quality, land subsidence, and other undesirable results (Cal. Code of Regulations §354.34).

Basins with multiple GSPs must "utilize the same data and methodologies" for the following: groundwater levels, water budget, groundwater extraction data, sustainable yield, total water use and more (Cal. Water Code **§** 10727.6). The coordination of groundwater data for GSP development will require GSAs to make many decisions about a basin's groundwater monitoring network, conceptual model, water budget, and projected water supply and demand. In many cases, these data will form the basis for groundwater model development and model refinement over the long term. Developing consensus on consistent data and methodologies at the basin-scale will not be easy. However, beginning these conversations early in the GSP planning process will help to ensure that the data monitoring protocols

developed are capable of meeting multiple objectives and that data collected from groundwater monitoring networks are of sufficient quality to be integrated into groundwater model development.

Basins must develop and maintain a "coordinated data management system" capable of storing and reporting information necessary for GSP development and implementation, as well as for basin monitoring (Cal. Code of Regulations §352.6, §357.4(e)). Early coordination of data into such a platform may also help to streamline model development and avoid disputes over groundwater model **boundary conditions**. This may be particularly relevant where more than one model is developed within a groundwater basin or between hydraulically-connected basins.

Developing functional groundwater models for hydraulically-connected basins will require groundwater flow estimates from adjacent groundwater basins. GSAs from one basin will need to work closely with GSAs from adjacent basins to ensure common groundwater boundary conditions during model development. Additionally, to evaluate the impact of one GSP on another, some level of model coordination and agreement on assumptions will be needed between adjacent groundwater basins that share a groundwater flow divide. Eleven basins in the northern Sacramento Valley have initiated a project to evaluate local and regional groundwater models in the region and develop tools or recommendations, "to account for interbasin flows and evaluate water management effects on flows between basins" (IGFP 2016).

Other states, like Texas, have chosen to address concerns about model integration and flow across hydrologically-connected boundaries, by developing models of the hydrogeologic system as a whole, rather than developing models for only portions of the system. Whether basins take a coordinated approach to modeling or choose to develop models at the hydrogeologic scale, the project goals should seek to alleviate the manufacture boundaries where they don't exist from a hydrologic standpoint, provide cost-sharing opportunities, and, ultimately, result in more consistent models that can be used for local and regional management.

Two regional models of California's Central Valley already exist: The California Central Valley Groundwater-Surface Water Simulation (C2VSim) model, developed by DWR using their Integrated Water Flow Model code (IFWM); and the Central Valley Hydrological Model (CVHM), developed by the United States Geological Survey (USGS) using their MODFLOW-2000 model code with the Farm Process (see appendices A and B, respectively for more detail). DWR will provide C2VSim and IWFM to agencies for water budget development; however, there use is not required (Cal. Code of Regulations §354.18). These models and their accompanying data can be readily accessed online. Using these regional model or the freely available model codes on which they are built may aid agencies in model coordination.

4.4. Engage Stakeholders

Stakeholder engagement plays an important role in SGMA. The legislation requires GSAs to consider the interests of all beneficial uses and users of groundwater, including overlying groundwater users, municipal well operators, local land use planning agencies, and environmental users and others (Cal. Water Code §10723.2). We refer to these entities collectively throughout this report as stakeholders and/or interested parties. However,

SGMA does not provide details on the specific form that stakeholder engagement should take. As a result, stakeholder engagement in the model development process could range from communication and feedback on model objectives, costs, and scenarios at key points during the process to the inclusion of representative stakeholders in all phases of model planning, construction, testing and reporting. For more information on stakeholder engagement under SGMA see Dobbin et al. (2015).

The groundwater model development framework presented in Table 3 identifies several steps in the process where stakeholder engagement will be especially important. It also identifies four formal review milestones. In addition to providing an opportunity for stakeholders to provide feedback on model development, these review periods provide an opportunity for technical experts, the state, adjacent basins and others to provide feedback on model development while there is still time to address model deficiencies. It also enables agencies to modify or expand groundwater monitoring protocols and networks or invest in additional studies where existing data is found to be inadequate to meet model objectives.

There is an increasing trend in water resource management toward collaborative modeling processes (Tidwell and van den Brink 2008; Langsdale et al. 2013). During this process, model developers, decision makers, stakeholders, and others work together to develop a shared understanding of the basin's management objectives and the model's role in supporting those objectives. Often the most difficult part of consensus building is getting people to agree on their central problem and the potential consequences of their actions. A collaborative modeling process can help to demonstrate issues and the corresponding outcomes, making it more likely that people can agree. Ultimately, if stakeholders understand their groundwater system and have helped develop the model that will serve as the basis for related management decisions, it is more likely that they will accept those management decisions and cooperate in implementing them (Tidwell and van den Brink 2008; van den Brink et al. 2008; Barfield 2009). That result will be critical to achieving groundwater sustainability in California.

4.5. Evaluate GSPs

DWR and SWRCB have particular responsibilities related to evaluating GSPs under SGMA (Table 1). Cal. Water Code **§**10733 requires DWR to evaluate: (1) whether the GSP(s) in a basin are likely to achieve their sustainability goal; and (2) whether groundwater management in one basin adversely affects the ability of an adjacent basin to achieve its sustainability goal. A basin may be designated as probationary if the state determines that a GSP is inadequate or is not being implemented in a manner that is likely to achieve its sustainability goal; is in a condition of long-term overdraft; or is in a condition where groundwater extractions are resulting in significant depletions of interconnected surface waters (Cal. Water Code **§**10735.2).

Groundwater models, as well as the data and assumptions underpinning them, will play a central role in GSP development. The emergency regulations developed by DWR for GSP development and evaluation require the use of numerical models (or an equally effective method, tool, or analytical model) in determining basin water budgets. Water budgets must incorporate, among other things, historical and projected water use, climate change, population and land use (Cal. Code of Regulations, § 354.18(e)). DWR will provide projections of population, climate change and sea level rise for use in the development of projected water budgets (Cal. Code of Regulations, § 354.18(d)). It does not, however,

require agencies to use this information (Cal. Code of Regulations, § 354.18(d)). This potential lack of consistency in water budget and model development may significantly hinder DWR's ability to evaluate GSPs within basins, as well as impacts between adjacent basins.

Finally, ensuring that the management actions in one basin do not adversely impact the sustainable management of another basin will also require some degree of data coordination and groundwater management planning between hydraulically-connected basins. Recognizing the need for coordinated management between adjacent basins, GSP regulations encourage the development of interbasin agreements that "facilitate the exchange of technical information between Agencies". These information may include groundwater flow estimates across basin boundaries, a common understanding of geology and hydrology of the basins, and sustainable management criteria (Cal. Code of Regulations § 357.2(b)(1-4)).

Long-term it will be essential that agencies work collaboratively both within their basin and with adjacent basins to ensure consistency of groundwater management planning. This will be particularly important in California's Central Valley, where the majority of groundwater basins are hydraulically-connected. While some agencies will choose to do so voluntary, as evidenced by the Interbasin Flow Agreement, other basin will need legislative requirements to coordinate.

5.0 What is a Groundwater Model?

There are many good overviews of groundwater models, guidelines for their use, and descriptions of model limitations. For more details on these topics, see: Anderson et al. (2015); Harter and Morel-Seytoux (2013); Bredehoeft (2012); Hunt and Zheng (2012); Gleeson et al. (2012); Barnett et al. (2012); DEQ (2014); Bredehoeft (2002); Oreskes et al. (1994).

A groundwater model is a computational approximation of a groundwater system (Anderson et al. 2015). It is a simplification of a complex reality. While this simplification can make a model's outputs subject to uncertainty, groundwater models enable users to understand the dominant processes influencing a system and explore the outcomes of different management actions on that system. Groundwater models have successfully been used for several decades to support informed groundwater management (Barnett et al. 2012).

This report focuses on the mathematical groundwater models and **model codes** used to represent groundwater systems and the surface water hydrology to which they are connected. Connections between groundwater and surface waters may be direct (through interconnected groundwater and surface water systems) or indirect (through groundwater recharge and pumping).

Box 3. What is a Groundwater Model?

Is a site-specific mathematical model developed using a model code of choice tailored to a specific site using a particular set of governing equations, **parameters**, and boundary conditions. For example, working with the USGS, Santa Clara Valley Water District used the MODFLOW-2000 model code to develop a hydrologic model for their district. This model is referred to as the Santa Clara Valley Regional Ground-Water/Surface-Water Flow Model.

5.1. Types of Groundwater Model Codes

The mathematical codes representing hydrologic systems are commonly classified into two categories, analytical models and numerical model codes (Barnett et al., 2012). Table 2 list some groundwater model codes commonly use in California.

5.1.1. Public domain, Proprietary, Open Source and Closed Source Model Codes

Analytic and numerical model codes can be found as public domain or proprietary. Public domain codes are usually free to use, while proprietary codes are usually available only for purchase. Both public domain and proprietary codes may be further bound by licensing agreements which dictate how the codes may be used and redistributed.

Both public domain and proprietary model codes may be further defined as open source or closed source. Open source model codes can be readily accessed, reviewed and modified. By contrast, closed source model codes cannot be readily accessed, reviewed or modified, which may hinder model transparency and evaluation. Open source code may be bound by additional rules within a licensing agreement, often requiring that original author be credited or that any modifications be shared back with the community.

SGMA requires all groundwater model developed in support of GSPs after June 1, 2016 to be developed using public domain, open-source software (Cal. Code of Regulations, § 352.4(f)(3)). DWR's Integrated Water Flow Model (IWFM) and the USGS's MODFLOW are both open source model codes that have been verified by subject-matter experts. Both model codes can be downloaded for free on the agencies' websites. Learn more about these model codes in appendices A and B, respectively.

5.1.2. Analytical Model Codes

Analytical model codes describe the physical processes of groundwater flow or contaminant transport using one or more governing equations. These model codes are generally a greatly simplified version of a three-dimensional flow problem and require the system to be uniform through space with highly simplified representation of boundary conditions time. The assumptions required to model groundwater systems using analytical solutions limit their application to relatively simple systems.

While analytical model codes are not typically used to represent changing conditions in space and time (DEQ, 2014), they are much faster to build and run than their numerical counterparts. Importantly, they provide excellent insight into the fundamental behavior of an aquifer system in response to pumping, recharge, or groundwater-surface water connection and how it relates to its hydrogeologic properties. Analytical models may provide excellent "book ends" to many hydrogeologic problems, without the effort of developing a complex numerical model code.

Groundwater basins with limited resources and data, and those that are not subject to rapidly expanding groundwater development, may choose to start with an analytical groundwater model. In such cases, basins should focus on improving their understanding of their basin's hydrogeology and developing a robust groundwater monitoring network, which can serve as the basis for more complex numerical models in the future.

5.1.1. Numerical Model Codes

Numerical model codes solve the same mathematical equations as analytical models. However, to accommodate complex aquifer system and boundary condition geometries, numerical models divide the physical system being modeled into discrete cells or elements. Spatial divisions across the modeled space are called the **model grid,** which defines the model cells or elements. Divisions of time are referred to as time steps and stress periods; stress periods are blocks of time representing constant stresses (e.g., pumping, recharge, etc.), and multiple time steps may occur within a stress period. The ability to model across both space and time enables the simulated environment (e.g., hydrogeologic conditions, pumping rates, etc.) to change.

Because of the complexity of aquifer systems and the extensive input requirements for numerical models, these model codes can be labor-intensive to build and calibrate (Anderson et al., 2015). Additionally, numerical model codes require sufficient data for model input and calibration (DEQ, 2014). However, when developed and calibrated appropriately numerical models can serve a powerful tool to simulate groundwater systems and forecast long-term changes to the system.

5.2. Types of Groundwater Models

Groundwater models can be used to understand water fluxes and storage in the subsurface (flow models), to understand and predict water quality and contaminant transport (contaminant transport models), and model seawater intrusion (density-dependent flow models) in a specific location. Each of these applications can be developed using a variety of model codes.

5.2.1. Groundwater Flow Models

Groundwater flow models are used to simulate groundwater flow through aquifers and confining units in the subsurface, as well as the removal and addition of water to the system from various sources (i.e. flow from surface water bodies to aquifers, precipitation, irrigation, etc.) and sinks (i.e. flow from aquifers to surface water bodies, wells used for groundwater pumping, etc.) (DEQ 2014). Simulations or calculations made in groundwater flow models are based on various inputs defining the hydrogeologic conditions in the groundwater basin (e.g., the hydraulic conductivity, the location of confining (clay) layers, etc.), as modified during model calibration.

While the inputs and outputs to a model can vary substantially depending on the model code being used, the outputs from groundwater flow model simulations always include the hydraulic heads and groundwater flow rates as a function of location and time throughout the modeled aquifer system. Groundwater flow models can also simulate future changes to the groundwater system resulting from assumed, planned or hypothesized changes in sources or sinks. These simulations are commonly referred to as “predictive simulations” and should only be run on well-calibrated flow models.

5.2.2. Integrated Hydrological Models

Unlike groundwater models, which require estimation of fluxes into and out of the groundwater system using external models, integrated hydrological models (IHMs) use internal submodels to calculate these fluxes and link them to other internal fluxes. Using internal submodels to estimate fluxes (1) can reduce uncertainty and variability between applications by providing more consistency in models developed using a specific code, (2)

allows the submodel codes to be peer reviewed and accepted as valid methods, and (c) ties internal fluxes that are not commonly measured (such as recharge to the water table or groundwater pumping) to fluxes that are more easily estimated (such as evapotranspiration and surface water diversions).

Caution should be exercised when using IHMs in areas where data are limited. IHMs are more complex than groundwater models, and, as a result, more difficult to develop and calibrate. As with any model, it is important to choose a model code consistent with the amount and quality of data available.

5.2.3. Contaminant Transport Models

Building on (calibrated) groundwater flow models, contaminant transport models simulate the transport and chemical alteration of contaminants as they move with groundwater in the subsurface. These models can simulate the addition or removal of groundwater contaminants from sources or sinks; the movement of contaminants by advection, dispersion and diffusion: and the alteration of contaminants or water quality by chemical reaction (DEQ 2014).

Similar to groundwater flow models, inputs for contaminant transport models vary depending on the model code being used. Outputs from these models generally consist of chemical concentrations as a function of location and time throughout the modeled domain. These models can also be used to make predictions about possible future impacts resulting from changes in contaminant sources or sinks, remediation or other factors affecting chemical constituents in the system.

5.2.4. Density-Dependent Flow Models

Density-dependent flow models, which account for salt concentration and the resulting change in water density, represent a different category of contaminant transport models. Density-dependent flow models are used to simulate groundwater flow in coastal aquifers experiencing seawater intrusion.

Table 2. Groundwater model codes commonly used in California.

Model Code	Developer	Model Code Categorization
GFLOW	Haitjema Sofware	Proprietary (free educational version), analytical, closed source model code with extensive documentation of model code development.
MODFLOW	USGS	Public domain, open source numerical groundwater model.
IWFM	DWR	Public domain, open source numerical integrated hydrological model.
Mike SHE	DHI	Proprietary, closed source numerical integrated hydrological model
HydroGeoSphere	Aquanty	Proprietary, closed source numerical integrated hydrological model.
MT3D	USGS	Public domain, open source numerical software that can be coupled with MODFLOW to simulate contaminant transport.
SEAWAT	USGS	Public domain, open source numerical software that combines MODFLOW and MT3DMS for density-dependent flow modeling.

FEFLOW	DHI	Proprietary, closed source numerical contaminant transport model.

5.3. Groundwater Model Components

Groundwater models are built using three key components: data, a conceptual model, and a model code (Harter and Morel-Seytoux 2013). Each of these components is described below.

1. *Data:* The data requirements for model development, testing and calibration, and prediction can vary widely. Common model data requirements include: hydraulic head measurements; aquifer parameter data used to characterize the aquifer's ability to store and transmit groundwater (**hydraulic conductivity**, transmissivity, storativity, etc.); water budget information (pumping volume and rates, streamflow data, infiltration and recharge rates, etc.); climate data, and more (Harter and Morel-Seytoux 2013). Here in California where two of the main fluxes for model development (pumping volumes and rates, and recharge) are not commonly measured, agricultural land use is often used to estimate these inputs.
2. *Conceptual model:* A conceptual model is a narrative and visual description of the physical groundwater system (Anderson et al. 2015). Conceptual models include the regional geologic and structural setting for the basin; the lateral and vertical extent of the basin; mechanisms of groundwater recharge and discharge; information on the geometry and physical properties of the principal aquifers; and confining layers in the system. All of these variables help modelers to estimate and predict the flow of groundwater.
3. *Groundwater model code:* A groundwater model code is a computer program that executes the governing equations representing the physical groundwater system. A site-specific groundwater model is the product that results when a groundwater model code is tailored to a specific region or area using the information contained in an area's conceptual model.

Once developed, models are calibrated to demonstrate the extent to which they are representative of local conditions (Cal. Code of Regulations §352.4(f)(2)). During the calibration process, model outputs are compared to an historical record of observed data. The values of different hydrogeologic aquifer properties and boundary condition properties (often referred to as aquifer parameters) are varied (within a reasonable range) in the model code to reduce the disparity between model simulation outcomes and observed field data of water levels and flows (DEQ 2014). A sensitivity analysis should be performed to compare the range of model outputs that result using different sets of reasonable parameters, both during model calibration and prediction. As new data become available, a model can be updated from time to time, which may involve a re-examination of the conceptual model and corresponding adjustments to the model setup, or changing model parameters (aquifer parameters, boundary condition parameters).

6.0 Key Concepts in Groundwater Model Development and Use

Achieving sustainable groundwater management is difficult without proper hydrogeologic monitoring and assessment for a variety of reasons (Gleeson et al. 2012). Firstly, groundwater systems are complex systems cannot be observed directly; as a result, groundwater users and managers must rely on measurements of the system to understand

the effects of groundwater use on the basin as a whole. Secondly, a groundwater system is difficult and expensive to measure, and investing in doing so still does not result in a complete understanding of the system. Thirdly, groundwater systems can have slow response times, which can make assessing the impacts of corrective actions on a system particularly challenging (Gleeson et al. 2012). Finally, because groundwater is a common pool resource, it is often difficult or impossible to understand the collective and ever-changing impacts of all groundwater users on the system (Bredehoeft 2002).

Groundwater models can help to address the challenges outlined above in a variety of ways. Firstly, groundwater models can provide an improved conceptual understanding of the system, including the essential and relevant processes and properties influencing the system (Harter and Morel-Seytoux 2013). They support decision-making by facilitating the exploration of alternative management actions (Barnett et al. 2012) and, when calibrated appropriately, can forecast short- and long-term changes to the groundwater system resulting from management actions or changing environmental conditions.

Box 4. The Cost of Groundwater Model Development

The cost to develop a groundwater model, while highly variable depending on location, need, model type, etc., can be high (from tens of thousands of dollars to millions of dollars). Additional financial and personnel costs are required for ongoing model use and maintenance. Agencies should consider model development costs carefully when deciding on model objectives and the type of model code required to meet those objectives. For example, analytical model codes with fewer input requirements are typically faster and less expensive to develop than numerical models. They also typically require less data and area easier to use. However, these models may have higher uncertainty and may not be suitable for prediction. By contrast, more complex, numerical models with greater input requirements take longer to develop, are typically more expensive, and require a high degree of technical expertise to operate and maintain. However, when developed correctly, numerical models can be powerful predictive tools.

Choosing to coordinate model development with adjacent basins may reduce agency costs, avoid boundary conflicts and results in more consistent models that can be used for local and regional management.

Groundwater models are commonly developed by highly trained professionals using the best available science, techniques and methods. However, within the model development process there are assumptions and professional judgments to be made. These decision points afford model developers an opportunity to solicit feedback from the many individuals involved in management decisions under SGMA. The framework presented in this report provides guidance on: how and when stakeholders should be engaged in model development; milestones for third-party model review; model documentation and archiving; and communicating model outputs to non-technical audiences. While many of these practices are already occurring, there are additional opportunities during groundwater model development to encourage the active engagement of the local entities who will be impacted by management decisions, as well as DWR - the agency that is ultimately responsible for evaluating GSPs under SGMA. Finally, coordinating model development at the basin-scale and beyond can maximize efficiency, avoid conflicts over boundary issues and provide the opportunity to share the costs (financial and time) of model development.

Table 3 provides a framework for groundwater model development under SGMA. The four-phase framework presented here is based on the Australian Groundwater Modeling Guidelines. It is important to note, however, that groundwater model development frameworks are not uncommon. The Bay Delta Modeling Forum has developed protocols for water and environmental Modeling (BDMF 2000). Texas, who relies heavily on groundwater availability models for water planning (Texas Water Code §35.108(d)), has developed specific modeling criteria to guide water conservation districts in model development (TWDB 2016).

Three of the four framework phases presented here pertain to model development; each phase is punctuated by substantial model reporting and a review milestone. The final phase of model development focuses on model documentation and archiving, and final model review. A final model review checklist can be found in Appendix C. It is important to note that the model development process is likely to be iterative. While the formal review process embedded throughout the framework may require model developers to revisit previous steps in model development before advancing to the next phase of model development, model developers may also choose to iterate between steps or revisit previous phases of their own accord.

Box 5. The Importance of Transparency and Local expertise in Groundwater Model Development

In 2005, Pajaro Valley Water Management Agency (PVWMA) decided to partner with the USGS to build a new hydrologic model for the basin utilizing MODFLOW. The model was developed to support basin management and planning. As part of the new model development process PVWMA wanted to ensure community "buy-in" for the model and the management scenarios that it would ultimately support. PVWMA undertook several steps to ensure transparency and the incorporation of local expert into model development, including developing a model technical advisory committee, which included Board members, technical and modeling experts from PVMWA, neighboring agencies and a local university; using a hydrogeologist, with a long history of working in the Pajaro Valley, as the moderator for the committee; and facilitating peer-review of the model. The new basin model has been used to develop the local basin management plan, develop climate change scenarios, and assess groundwater management projects.

Throughout model development, there are numerous decisions that need to be made. Many of them require modelers to make explicit assumptions and subjective judgments. These assumptions and judgment calls should be made with feedback from stakeholders, including all impacted GSAs, county and land use planning agencies, managers, neighboring basins and interested parties. Because of the significant technical expertise required for model development, many GSAs will find it useful to work with advisory committee(s) for this purpose. We refer to the inclusion of these groups, whether through advisory committees or other mechanisms, in the modeling process as the larger model development team. Technical model development meetings with the larger model development team should be augmented with public meetings at key milestones.

Table 3. A framework for groundwater model development under SGMA.

	Model Development Framework	**Specific Tasks**
Phase 1: Plan, Conceptualize, Design and Report	**1. Pre-plan:** Initial meetings to determine basin sustainability goals and groundwater model development.	**1.1** GSA(s) should host public meetings to solicit feedback on basin sustainability goals and the role of a groundwater model to meet those goals.
		1.2 Discussions on model development options (i.e. who should develop the model, how should model development be funded, what technical and financial resources will be required to maintain the model long-term, what are the potential economic and planning advantages of coordinated model development (particularly in basins with multiple GSAs or between hydraulically-connected basins), etc.), the pros and cons of each option, as well as the potential role of advisory committees in model development. These discussions should be open to the public. Many GSAs will choose to pursue the remainder of the steps below in consultation with an advisory committee, augmented with one or more public meetings.
	2. Plan: Identify model objectives, collate and integrate data, and decide on appropriate model code.	**2.1** GSA(s) should host meetings with the model developer, county and municipal agencies, managers, advisory committees and interested parties (referred to hereafter as the larger model development team) to determine the model objectives and how they fit within the broader basin management goals.
		2.2 The model developer should collate and incorporate all quality-assured data available for model development and calibration.
		2.3 The model developer should work with the larger model development team to identify data gaps, to understand the proposed future level of urban development, and to decide whether further data and/or studies are necessary to meet model objectives.
		2.4 The model developer should work with the larger model development team to decide on the model code to be used for model development. Model code selection should be consistent with the quality and amount of data available (See confidence level classification in Table 4), and should consider the pros and cons of a proprietary model that has been peer reviewed, or one that is open source and in the public domain.
		2.5 The model developer should work with neighboring GSAs to determine how to best share data and streamline data exchange and model development processes.
	3. Conceptualize: Develop and solicit review of the conceptual model that will serve as the basis for model development	**3.1** The model developer should work with the larger model development team to determine hydrogeologic conceptual model boundaries. These boundaries should be developed at a scale large enough to include the location of present and future **stresses** on the groundwater system, as well as key metrics for system health that should be included in model development.
		3.2 Model developers should develop a conceptual model using all available quality-assured data.
		3.3 The model developer should solicit broad feedback on the conceptual model and seek to develop alternative conceptual models where warranted.
	4. Design, Reporting and Review: Develop and solicit review of the model design report.	**4.1** The model developer should provide a comprehensive model design report outlining model objectives; data sources and key areas of uncertainty; model type and code; **model domain**, grid size and model time steps (where applicable); overview of model strengths, weaknesses and constraints; timeline for model development; key model outputs; and the process for model reporting and development.
		4.2 The model design report should be presented at one or more public meetings. Model development should be reviewed by the state, other experts, neighboring basins, and interested parties.
Model report and review # 1: Is model design adequate? If yes, proceed. If no, return to earliest stage necessary to correct deficiencies.		
Phase 2: Construct, Calibrate and Report	**5. Construct**: Construct model in a manner consistent with model objectives	**5.1** The model developer should proceed with model construction in accordance with model objectives and design specifications. Model construction and assumptions should be well documented and be publicly available. Model construction should be based on data and/or physically-plausible model assumptions and parametrizations. Substantial deviations from the model design should be discussed and agreed upon by GSA(s),

	Model Development Framework	**Specific Tasks**
	and design specifications.	managers, advisory committees and interested parties.
	6. Calibrate, Report and Review: Calibrate model, assess model sensitivity to parameterization. Report and solicit review of model calibration.	**6.1** Model developers should work with the larger model development team to establish performance measures in advance of model calibration. Performance measures should consider the type, amount and quality of the data available for model development and calibration. Model performance should consider both quantitative and qualitative measures.
		6.2 The model developer should proceed with model calibration using all available quality-assured data. Model calibration should focus on the use of physically-plausible parameters and/or field or laboratory estimates of model variables.
		6.3 The model developer should develop a comprehensive model construction and calibration report documenting model construction and parametrization; sensitivity analysis; model domain, grid size and model time steps (where applicable); and performance metrics.
		6.4 The model design report should be presented at one or more public meetings. Model construction and calibration should be reviewed by the state, other experts, neighboring basins, and other interested parties.
Model reporting and review # 2: Is model construction adequate? If yes, proceed. If no, return to earliest stage necessary to correct deficiencies.		
Phase 3: Predict, Analyze Uncertainty and Report	**7. Predict**: Use the model to predict management scenarios. (See confidence level classification in Table 4).	**7.1** The model developer should work with the larger model development team to develop scenarios and the underlying assumptions for each scenario.
		7.2 Modeled scenarios be presented at one or more public meetings. Modeled scenarios should be compared to a baseline scenario to assess net impact of stresses. Uncertainty in model predictions should be acknowledged, assessed and clearly communicated to all parties (see section on uncertainty below).
	8. Assess Uncertainty: Assess and communicate model uncertainty. Solicit review on scenarios and uncertainty analysis.	**8.1** The model developer should conduct an assessment of model uncertainty. Model uncertainty results from a variety of factors including model development, source data, model domain and uncertainty in scenarios. It is important that model developers convey the sources of uncertainty. Whenever possible, predictions should be reported as the difference of two model outputs
		8.2 Model scenarios and uncertainty estimates should be presented at one or more public meetings. Model scenarios and uncertainty estimates should be reviewed by the state, other experts, neighboring basins, and other interested parties.
Model review # 3: Are model predictions and uncertainty estimates adequate? If yes, proceed. If no, return to earliest stage necessary to correct deficiencies.		
Phase 4: Document and Archive	**9. Final Report and Archive:** Develop final model report and model archive.	**9.1** The model developer should develop a final model report incorporating predictive scenarios with previous reports and feedback on model objectives, conceptualization and calibration. The final model report should include components tailored to non-technical audiences and clearly communicate model uncertainty.
		9.3 A well-organized model archive should be developed to facilitate third-party review and enable model replication. Data files should be available electronically and include all necessary metadata and be in data formats that can be easily shared amongst multiple model platforms.
Final model review: Does the model meet the criteria outlined in the final model checklist (Appendix C)? If yes, proceed. If no, return to earliest stage necessary to correct deficiencies.		

Table 4. Model confidence level classification. Data requirements, calibration and prediction characteristics, key indicators and examples for groundwater model development. Table modified from Barnett et al. (2012).
Note that this table is currently attached as a separate file, but should appear here in the final report.

6.1. Phase 1: Model Planning, Conceptualization and Design

The decision to develop a groundwater model under SGMA must be based on the need to support the basin's sustainability goal, the required water budget and planning decisions of a GSP. Groundwater models are one of a number of tools that can help these inform decisions. As a result, it is imperative that GSAs within a basin work collaboratively with the model developer and the larger model development team to identify (1) the model objectives; (2) the data and resources (both monetary and personnel) available for model development and calibration; and (3) the type of model required to meet model objectives (see Table 4, Box 4) (Barnett et al. 2012).

During the model planning phase, GSAs should host public meetings to solicit feedback on basin management objectives and the role of a groundwater model in achieving those objectives. Additional meetings with GSA(s) and adjacent basins should consider model development options, including who should develop the model and how it's development will be funded; the technical and financial resources necessary to maintain and update the model long-term; the potential economic and planning advantages of coordinated model development (particularly in basins with multiple GSAs or between hydraulically-connected basins); and the potential role of advisory committees in model development. These discussions should be open to the public.

Box 6. Ongoing Groundwater Model Use and Maintenance

It is important agencies avoid "shelving" a model after investing the time and financial resources necessary for model development. Developing a plan for ongoing model maintenance and use during the preliminary stages of model development can help agencies to build the capacity necessary over years. Agencies should consider: how to use the model for both large (GSP development) and small management decisions (e.g., well permitting applications); how frequently they will update the model and what datasets will be used; and whether to invest in developing the in-house technical expertise to run and maintain the model or to rely on consultant.

While model maintenance has associated costs, these costs are likely to pale in comparison to model development costs or the cost of model updating should the model be "shelved" for a significant period of time.

Once decisions on model development options have been made, model developers should consider the type of model code to be used. As discussed previously, there are pros and cons to different model codes. Developing clear model objectives helps model developers make decisions about which model code will best meet management objectives. For example, model codes with fewer input requirements are easier to use, but often come with greater potential error or uncertainty. By contrast, more complex models with greater input requirements take longer to develop, but, when developed correctly, may have lower model uncertainty.

Agencies should consider a host of factors when deciding on the model code for their basin, including the model objectives (informed by the basin's sustainability goals), the amount and quality of data available, and the resources (technical and financial) available for model development. Agencies should also consider the pros and cons of a proprietary model that has been peer reviewed, or one that is open source and in the public domain. As discussed above, groundwater models developed after June 1, 2016 for GSP planning under SGMA must be public domain, open-source software.

After deciding on the code to be used for model development, model developers should begin collating the data necessary for model development. These data are likely to include: climate data; historic groundwater levels; hydrogeologic information from previous studies and driller's logs, groundwater extraction estimates, estimates of natural and artificial recharge, and historic land use information. The larger model development team should work collaboratively to identify data gaps and decide whether additional data or studies are necessary to achieve model objectives. Whenever possible GSAs should coordinate model design, development, and data collection with adjacent basins. Doing so will lead to more efficient and robust model development.

Table 4 provides guidance on data, calibration statistics, model review criteria and predictive characteristics for using model for specific groundwater management applications. For example, decision makers seeking to assess the sustainable yield of high-value aquifers (e.g., many of California's Central Valley groundwater basins) should have a breadth of information about the groundwater basin, including reliable estimates of pumping and recharge (estimated through crop land use, surface water deliveries, irrigation information and measured groundwater extraction where available).

DWR will provide a number of datasets relevant for model development, including current and projected land use information, current evapotranspiration, and projected climate change scenarios and population growth (Cal. Code of Regulations, § 354.18(2,3)). Having more specific basin information can improve the use of a model to address local conditions. In basins where these local-scale data are not available, model uncertainty will remain high and will limit a model's ability for predictive simulation (Barnett et al. 2012). Even if data is limited, developing a model can be an important start to improve analyses and identify future data needs. Over time, the model can be improved as more data becomes available.

Conceptual models serve as the basis for groundwater model development. As a result, the boundary conditions of the conceptual model should include the location of all present and anticipated future stresses. Additionally, any areas intended to serve as indicators of basin health should be included within the physical boundaries of the conceptual model. Finally, conceptual model development should incorporate all quality-assured data and be subject to review by the state, other experts, and other interested parties. If model development is not being undertaken with neighboring basins, these basins should also review the conceptual model for consistency between basins.

The first phase of the model development framework should culminate in a publicly available groundwater model design report. This report should include: model objectives; data sources and key areas of uncertainty; model type and code; model domain, grid size and model time steps; an overview of model strengths, weaknesses and constraints; timeline

for model development; key model development outputs; and the process for model reporting and development. In all cases, model design specifications and data requirements should be consistent with model objectives. (See Table 4 for more information on the data requirements for different model objectives.)

The model design report should be presented at one or more public meetings. Review of the model design should be encouraged from the state, neighboring basins, and other interested parties.

6.2. Phase 2: Construct, Calibrate and Report

Once feedback from the model design review has been adequately addressed, model construction and calibration can begin. It is important that model developers thoroughly document model construction, assumptions, and data sources. Model parameters should be based on data or laboratory analyses and/or physically-plausible parameterizations (Cal. Code of Regulations §352.4(f)(2)). Decisions on the parameters used should include an explanation of their origins.

It is not uncommon that model developers will need to modify model construction due to data constraints or other unanticipated factors. However, it is important that any substantial changes from model design be discussed and agreed upon with the larger model development team. Maintaining an open dialogue between the model developer, GSA(s), managers, advisory committees and other interested parties throughout the model development process will increase transparency in model development and improve understanding of model constraints.

Once constructed, the model developer should proceed with model calibration using site specific field data and the sensitivity analysis (Cal. Code of Regulations §352.4(f)(2)). Model calibration should include pre-defined performance metrics that are consistent with both the amount and quality of data available for model construction and the model objectives (Table 4). Model boundary conditions should roughly match neighboring basins and should follow similar trends.

Model construction and calibration should be documented in a publicly-available report. Deviations from the original design specifications should be noted in the report along with explanations for the deviations and any implications that they may have on model objectives. Similar to phase one, the model construction and calibration report should be presented at one or more public meetings. Review of model construction, calibration protocols and performance metrics should be encouraged from the state, other experts, neighboring basins, and other interested parties.

6.3. Phase 3: Predict and Assess Uncertainty

Developing and running scenarios are often at the heart of model development. During this phase of groundwater model development, model developers should work with the larger model development team to decide management scenarios of interest to the group. These scenarios should include a range of management actions currently being considered or other physical changes (like climate change or land use change) occurring in the basin that are likely to affect basin conditions in the future. Decisions about which scenarios to model should be informed by the basin's sustainability goal and the minimum thresholds and measurable objectives that support it.

Evaluating the impact of groundwater management between adjacent basins, is likely to be difficult, particularly where there are multiple GSPs developing in hydraulically-connected basins. Extending the GSP regulations to require the use of common projections (e.g., climate, land-use, population growth, etc.) for groundwater model development would facilitate model comparison and evaluation. In all cases, model projections should be compared against a baseline projection. Doing so minimizes the influence of model uncertainty and shows the net scenario impacts.

Assessing model uncertainty is complex. This is in part because uncertainty is inherent in many components of groundwater model development. During groundwater model development, modelers must make simplifying assumptions about the physical system they are representing. While necessary, this simplification results in an imperfect representation of the processes and properties being simulated, leading to uncertainty in model outputs (Hill and Tiedeman, 2007).

Model uncertainty also results because models are built and calibrated using imperfect data about the physical system they are representing. Model developers should work with local, regional, state and federal agencies to identify and incorporate existing data about the groundwater system into the model. Doing so will help improve model confidence while identifying potential gaps in knowledge and areas of uncertainty (spatial and/or temporal). This information can then be used to inform the development of more robust groundwater monitoring protocols or studies targeting areas of uncertainty. Working with model developers to ensure that groundwater data collection and monitoring programs are sufficient for model calibration and consistent with, and useful for, meeting modeling objectives will help to make the most of the limited funds that local agencies have for data collection and monitoring programs, while maximizing the benefits of groundwater modeling for groundwater planning purposes.

Additional uncertainty can result when models are used for predictive simulations. In groundwater flow models, the predictions might simulate hydraulic heads under future pumping conditions – conditions that may be different from those for which the model was calibrated. Predictive uncertainty can result because of limitations in the capacity of the calibrated model to predict future scenarios as well as from uncertainty about future hydrologic conditions themselves (Anderson et al. 2015).

Predictive uncertainty typically increases as you extend modeling scenarios and analysis into the future. As a result, it is important that model developers communicate additional uncertainty in projections and limit the duration of projections based on the timescale of data used in model calibration (see guidelines in Table 4).

Perhaps the most important part of model development is communication of model results and uncertainty to decision-makers, stakeholders and other technical and non-technical users. Involving and educating stakeholders on model development throughout the process can help interested parties understand the sources of model uncertainty and improve model transparency. Presenting model results as a range of possible outcomes rather than as a single “true” value can help to convey the inherent uncertainty in model results to non-technical stakeholders (Barnett et al. 2012).

Results from this phase of model development should be thoroughly documented and subject to review by the state, other experts, neighboring basins, and other interested parties.

Box 7. RDM: An Approach to Decision-Making in the Face of Uncertainty

Making decisions on how to proceed in the face of uncertainty can be challenging. Groves et al. 2013 demonstrate the use of the Robust Decision Making (RDM) approach for addressing climate change in local water agency plans. The RDM approach identifies a range of plausible future scenarios, assesses an agencies risk to each modeled scenario and, ultimately, identifies a "robust" strategy that is likely to perform well across all plausible outcomes. This approach can be particularly useful when there is a lack of consensus about future outcomes or even the issues at hand. Additionally, because RDM is an inherently adaptive approach, it eliminates the need for a "correct" solution in favor of a robust approach that can be adapted as information about the system evolves.

6.4. Phase 4: Model Documentation and Archiving

Thorough documentation of all phases of model development, including changes to the model resulting from the review process, should be included in the final model report. The report and supporting documentation should be publicly available (Cal. Water Code of Regulations §352.4(f)(1)). The final report should be tailored to a variety of audiences with an executive summary and non-technical overviews that include easy-to-read graphs and other visuals.

Data, parameters and source codes used for model development should be archived and publicly available in electronic format with the appropriate metadata. In addition to facilitating review of the modeling process, proper and thorough data archiving facilitates in-house model maintenance and development.

6.5. Additional Considerations

6.5.1. Adaptive Management

Gleeson et al. 2012 suggest three approaches for achieving sustainable groundwater management: setting long-term sustainably goals, backcasting – the practice of setting specific and defined goals and implementing management actions (often based on model results) to achieve these goals – and adaptive management.[6] The first two approaches have been discussed previously in the report.

Adaptive management is not written explicitly into SGMA; however, it is likely to play an equally important role in achieving sustainable groundwater management because of the uncertainty inherent in groundwater systems and future hydrologic conditions. In its simplest form, the term "adaptive management" refers to the iterative process of

[6] Adaptive management is an approach to resource management that "promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather emphasizes learning while doing." (Williams et al. 2009, p. 4)

incorporating learning from the management and monitoring of a system into the ongoing management process (Williams and Brown 2012).

Groundwater models are a valuable tool in adaptive management (Williams and Brown 2012) because they enable decision makers to experimentally compare selected policies or practices and evaluate alternative hypotheses about the system being managed (Pahl-Wostl 2007). Testing these scenarios over time, as new information about the system evolves, enables managers to respond to changes in the system and may prompt improvements to water budget estimates, conceptual model, or groundwater models themselves.

Refinements to the conceptual and groundwater models, may, in turn, lead to changes in basin management goals, data protocols or acquisition and future project design. Adaptive management strategies also ensure that groundwater data collection and monitoring efforts integrate long-term with groundwater model development and ongoing model improvement. Doing so will ensure that model outputs are useful for making groundwater management decisions.

6.5.2. Coupling with Other Models and Model Comparison

Recent studies by Howitt et al. (2015), Medellían-Azuara et al. (2015) and Medellían-Azuara et al. (2016) link groundwater model outputs with economic models to estimate the impacts of the recent drought on the agricultural industry in California. Linking groundwater model outputs with economic, regulatory or other models may help non-technical decision-makers make more informed decisions on how to manage the basin. However, care should be taken to ensure that decisions are not based purely on economics; they also need to consider the broader environmental and societal impacts of management decisions.

Finally, when groundwater models serve as the basis for high-risk decisions, it may be necessary to develop multiple models to ensure that decision-makers understand the range of potential outcomes from management actions. In such cases, however, it is essential that model developers work together to avoid competing models and instead use the process as an opportunity to improve understanding of the basin and the underlying model assumptions. This is similar to the approach taken in climate change science, where multiple models are developed in order to provide a more complete understanding of potential outcomes.

Identifying large discrepancies between models run using the same data and assumptions could provide an opportunity to identify areas of model uncertainty. Comparison of the CVHM and C2VSim could provide important insights into model uncertainty and ultimately result in improvement of both models.

7.0 Guiding Principles for Groundwater Model Development

Groundwater models will play a critical role in the development of GSPs under SGMA. The principles recommended below will help to ensure consistency in model development, stakeholder engagement in the modeling process, and peer-review of the groundwater models throughout their development.

Groundwater models should be:

1. **Developed through a collaborative, inclusive and transparent process**. Stakeholders and other interested parties should be actively involved in groundwater model development. In particular, they should have a role in defining groundwater model objectives, assumptions and the level of risk or uncertainty they are willing to tolerate for groundwater management planning purposes. Decision-makers and stakeholders should fully understand the purpose of using a model to address the water budget and water management planning.
2. **Used in a manner that is consistent with model objectives, and with the amount and type of data available.** Models should be developed and used in a manner that is consistent with model objectives. Where the amount or quality of data are inadequate to meet these goals, model limitations must be clearly articulated to decision-makers, stakeholders and other interested parties. Additional data and technical studies should be conducted to remedy data deficiencies.
3. **Developed using consistent datasets and projections.** The state should provide and require the use of consistent datasets for model development and projections under SGMA. These data and projections should include: climate, surface water, land use, regional water budgets, and population.
4. **Developed using public domain, open-source model codes.** Developing models using model codes that are public domain and open-source provides improved opportunity for model reviewed and evaluation. It also improves model access and may encourage coordination between adjacent basins. DWR's IWFM and the USGS's MODFLOW are two examples of public-domain, open-source model codes.
5. **Developed at the system scale whenever possible.** Developing models of the hydrogeologic system as a whole, rather than modeling individual hydraulically-connected basins can maximize efficiency, avoid conflicts over boundary issues and provide the opportunity to share the financial and personnel costs of model development.
6. **Reviewed by the state, other experts, neighboring jurisdictions and other interested parties**. Peer-review of groundwater models helps to ensure that a model is consistent with model objectives and consistent with assumptions in adjacent basins. Model review should be a formal process undertaken after each model reporting milestone.
7. **Subject to thorough model reporting, documentation and archiving.** Groundwater model reporting should be accessible to technical and non-technical audiences and should include an executive summary with easy-to-read visuals. Model data and source files should be publicly available, in electronic format with all necessary metadata. Data files should be uploaded to the basins shared data platform.
8. **Developed with state assistance.** The state should provide technical and financial assistance for groundwater models that are developed using a consistent, transparent and collaborative model development framework.

8.0 Glossary

Boundary condition - means the hydraulic head or flux assigned at the boundaries of model domain.

Conceptual model –Models are commonly developed based on a conceptual model of a system. The conceptual model is a narrative/visual description of the system that identifies components of the physical system to be included in the model. A conceptual model of a groundwater system is a descriptive representation of the system that incorporates an interpretation of the geological and hydrologic conditions (Anderson et al. 2015).

Finite difference method – the Michigan Department of Environmental Quality (2014), defines the finite difference method as a "discretization technique for solving a partial differential equation (PDE) by (1) replacing the continuous domain of interest by a finite number of regular-spaced mesh or grid-points (i.e. nodes) representative of the volume-averaged sub-domain properties; and (2) by approximating the derivatives of the partial differential equation for each of these points using a finite differences. The resulting set of linear or non-linear algebraic equations is solved using direct or iterative matrix solving." Finite difference models use this method to obtain approximate solutions to the governing model equations.

Finite element method – the Michigan Department of Environmental Quality (2014), defines the finite element method as being "similar to the finite difference method except that, (1) the mesh may consist of regular or irregular-spaced grid points which may have irregular shapes; and (2) the PDE is approximated using the method of weighted residuals to obtain a set of algebraic equations. These algebraic equations are solved using direct or iterative matrix-solving techniques." Finite element models use this method to obtain approximate solutions to the governing model equations.

Hydraulic conductivity – For groundwater applications, hydraulic conductivity (usually represented as K) is a measure of the substrate's ability to transmit water.

Integrated hydrologic model – refers to a model or model code that simulates water movement through the linked groundwater, surface water and land surface systems in an integrated manner.

Groundwater model – Groundwater and surface water are integrally linked. Similarly, groundwater systems should be modeled in a consistent manner using integrated hydrologic models or well-developed groundwater models. For simplicity, this report refers to both groundwater models and integrated hydrologic models as groundwater models.

This report use the term groundwater model to refer to a site-specific numerical groundwater model, using a particular set of governing equations, parameters, and model conditions, developed using a model code. For example, working with the United States Geologic Survey (USGS), Santa Clara Valley Water District used the MODFLOW-2000 model code to develop a hydrologic model for their district. This model is referred to as the Santa Clara Valley Regional Ground-Water/Surface-Water Flow Model.

Measurable objectives – refers to specific, quantifiable goals for the maintenance or improvement of specified groundwater conditions that have been included in an adopted groundwater sustainability plan to achieve the sustainability goal for the basin (Cal. Code of Regulations, Title 23, § 351.(s)).

Minimum thresholds – refers to a numeric value for sustainability indicator used to define undesirable results (Cal. Code of Regulations, Title 23, § 351.(t)).

Model code – The term model code refers to the spreadsheet or computer program that executes the governing equations representing the physical system.

Model domain - means the active area within the model grid; boundaries of the model domain should be based on the conceptual model.

Model grid – the system of connected nodal points superimposed over the problem domain to spatially discretize the problem domain into cells (finite difference method) or elements (finite element method) for the purpose of numerical modeling.

Parameter – a set of physical properties that determine the characteristics or behavior of a system.

Steady state –refers to systems where processes are stable with time.

Transient state – refers to systems where system inflows and outflows are variable and change over time.

Water budget – The Department of Water Resources (2015) defines the term water budget as "an accounting of the total groundwater and surface water entering and leaving a basin including the changes in the amount of water stored."

Sustainability indicator – refers to any of the effects caused by groundwater conditions occurring throughout the basin that, when significant and unreasonable, cause undesirable results, as described in Water Code Section 10721(x).

Sustainable yield – is defined in the Sustainable Groundwater Management Act, as "the maximum quantity of water, calculated over a base period representative of long-term conditions in the basin and including any temporary surplus, that can be withdrawn annually from a groundwater supply without causing undesirable results (Cal Water Code **§** 10721 (v))."

Stresses – refers to processes that affect the groundwater system in transient models. Common groundwater models stresses include: recharge, groundwater pumping, evapotranspiration, infiltration, etc.

9.0 References

Anderson, M.P., W. W. Woessner and R.J. Hunt. (2015). *Applied groundwater modeling, simulation of flow and advective transport*, *Second Edition.* Academic Press by Elsevier Inc.

Barfield, D. W. (2009) Collaborative Groundwater Model Development. World Environmental and Water Resources Congress, 2009: 1-3. doi: 10.1061/41036(342)477

Barnett, B., L. R. Townley, V. Post, R. E. Evans, R. J. Hunt, L. Peeters, S. Richarson, A. D. Werner, A. Knapton, and A. Boronkay. (2012). *Australian groundwater modeling guidelines,* Waterlines report, No. 82, National Water Commission, Canberra.

[BDMF 2000] Bay-Delta Modeling Forum. (2000). *Protocols for Water and Environmental Modeling.* Bay-Delta Modeling Forum Ad hos Modeling Protocols Committee. Available at: http://www.cwemf.org/Pubs/Protocols2000-01.pdf

Bredehoeft, J.D. (2002). The Water Budget Myth Revisited: Why Hydrogeologists Model. *Groundwater*, 40(4): 340—345.

Bredehoeft, J. (2012). Modeling Groundwater Flow-The Beginnings. *Groundwater*, 50(3): 324—329.

Christian-Smith, J. and A. Alvord. (2016). The Devil is in the Data: The Role of Science, Data, and Models in California's Historic Sustainable Groundwater Management Act. *California Journal of Politics and Policy,* 8(3): 1-6. doi:10.5070/P2cjpp8331696.

Dobbin, K., J. Clary, L. Firestone, and J. Christian-Smith. (2015). *Collaborating for Success: Stakeholder Engagement for Sustainable Groundwater Management Act Implementation.* Community Water Center. Available online at: http://waterfoundation.net/wp-content/uploads/2015/07/SGMA_Stakeholder_Engagement_White_Paper.pdf

[DEQ 2014] Michigan Department of Environmental Quality. (2014). *Groundwater Modeling: Remediation and Redevelopment Division Resource Materials*. Prepared by: Michigan Department of Environmental Quality Remediation and Redevelopment Division. RRD-Resource Materials -25-2013-01. February, 2014.

[DWR 2003] California Department of Water Resources. (2003). California's Groundw*ater. Bulletin 118, Update 2003,* California Department of Water Resources, Sacramento, CA.

[DWR 2013] California Department of Water Resources. (2013). *California Water Plan*, *Update 2013,* California Department of Water Resources, Sacramento, CA.

Fogg, G.E. and E.M. LaBolle. (2006). Motivation of synthesis, with an example on groundwater quality sustainability. *Water Resources Research,* 42:1-5. Doi:10.1029/2005WR004372.

Gleeson, T., W.A. Alley, D.M. Allen, M.A. Sophocleous, Y. Zhou, M. Taniguchi, and J. VanderSteen. (2012). Towards Sustainable Groundwater Use: Setting Long-Term Goals, Backcasting, and Managing Adaptively. *Groundwater*, 50(1): 19-26.

Groves, D. G., E. Bloom, D. R. Johnson, D. Yates, and V. Mehta. (2013). *Addressing Climate Change in Local Water Agency Plans, Demonstrating a Simplified Robust Decision Making Approach in the California Sierra Foothills.* Prepared for the California Energy Commission by The RAND Environment, Energy, and Economic Development Program. Available at: http://www.rand.org/pubs/research_reports/RR491.html

Harter, T. and H. Morel-Seytoux. (2013). Peer Review of the IWFM, MODFLOW, and HGS

Model Codes: Potential Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins. Final report, California Water and Environmental Modeling Forum, August 2013, Sacramento. Available at: http://groundwater.ucdavis.edu/files/171875.pdf

Hill, M.C., and C.R. Tiedeman. (2007). *Effective Groundwater Model Calibration: With Analysis of Data, Sensitivities, Predictions, and Uncertainty.* John Wiley & Sons, Inc. Hoboken, New Jersey.

Howitt, R., D. MacEwan, J. Medellían-Azuara, J. Lund. (2015). *Economic Analysis of the 2015 Drought for California Agriculture.* UC Davis Center for Watershed Sciences, ERA Economics and UC Agricultural Issues Center. Available at: https://watershed.ucdavis.edu/files/biblio/Economic_Analysis_2015_California_Drought_Main_Report.pdf

Hunt, R. and C. Zheng. (2012). The Current State of Modeling. *Groundwater*, 50(3): 329—333.

[IGFP 2016] Interbasin Flow Project. (2016). *Project Overview.* Available online at: https://www.buttecounty.net/waterresourceconservation/SpecialProjects/InterbasinGroundwaterFlowProject.aspx

Langsdale, S., A. Beall, E. Bourget, E. Hagan, S. Kudlas, R. Palmer, D. Tate, and W. Werick. (2013). Collaborative Modeling for Decision Support in Water Resources: Principles and Best Practices. *Journal of American Water Resources Association,* 49(3): 629-638.

Medellían-Azuara, J., D. MacEwan, R. Howitt, G. Koruakos, E. C. Dogrul, C.F. Brush, T.N. Kadir, F. Melton, and J. Lund. (2015). Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA. *Hydrogeology Journal,* 23(6); 1205-1216. 10.1007/s10040-015-1283-9.

Medellían-Azuara, J., D. MacEwan, R. E. Howitt, D. A. Sumner and J. Lund. (2016). *Economic Analysis of the 2016 California Drought on Agriculture. A report for the California Department of Food and Agriculture.* UC Davis Center for Watershed Sciences, ERA Economics and UC Agricultural Issues Center. Available at: https://watershed.ucdavis.edu/files/DroughtReport_20160812.pdf

Oreskes, N., K. Sharder-Frechette, K. Belitz. (1994). Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science,* 263: 641-646.

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water resources facing climate and global change*. Water Resources Management*, 21:49-62. doi.10.1007//s11269-006-9040-4.

[TWDB 2016] Texas Water Development Board, (2016). How to Submit a Groundwater Availability Model Run or Aquifer Assessment for the Development of Modeled Available Groundwater. Available online at: http://www.twdb.texas.gov/groundwater/docs/Guidelines_Submit_Model_Runs_for_DFCs

Tidwell, V.C. and C. van den Brink. (2008). Cooperative Modeling: Linking Science, Communication, and Ground Water Planning. *Groundwater*, 46(2): 174-182.

van den Brink, C., W. J. Zaadnoordijk, B. van der Grift, P. C. de Ruiter, and J. Griffioen. (2008). Using a groundwater quality negotiation support system to change land-use management

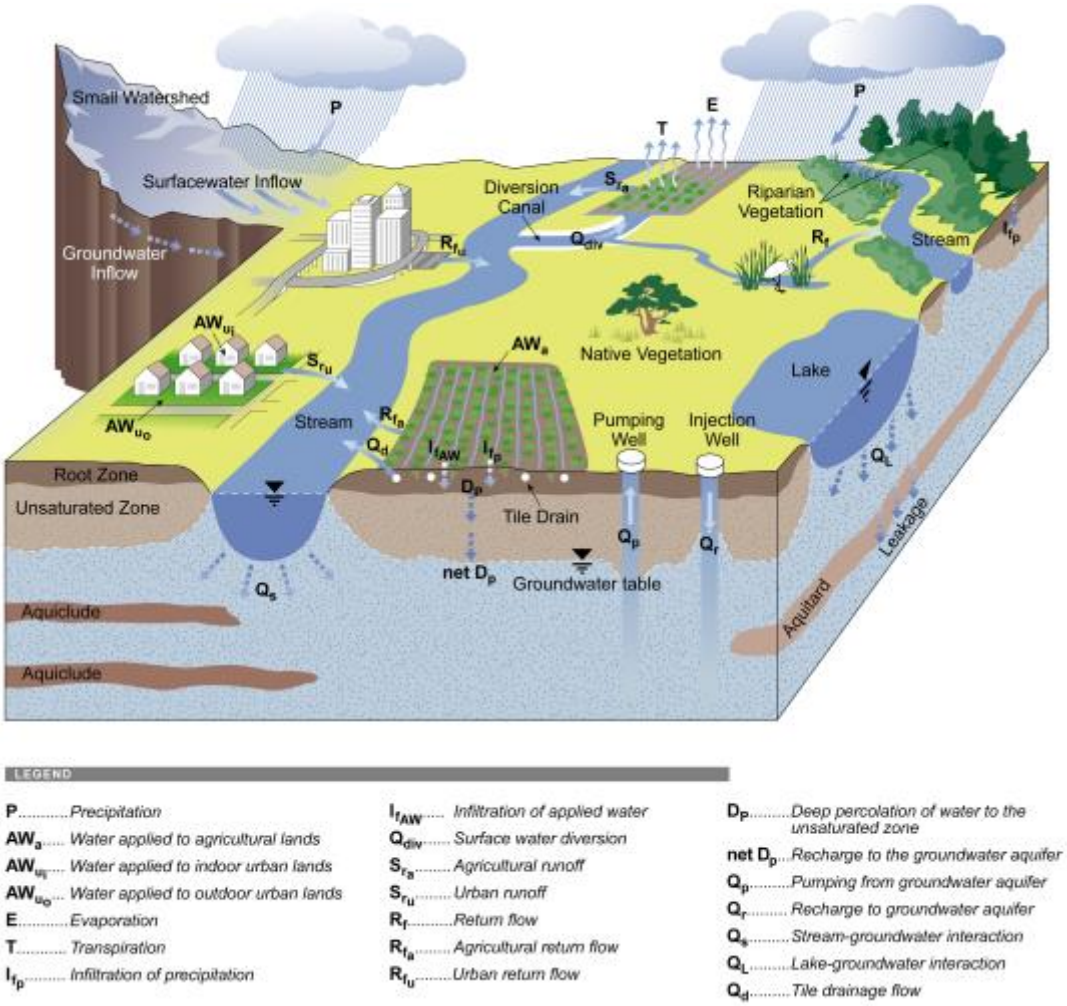
near a drinking-water abstraction in the Netherlands. *Journal of Hydrology,* 350(3-4):339-356.

Williams, B.K., and E.D. Brown. (2012). *Adaptive Management: The U.S. Department of the Interior Applications Guide*. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC. Available at: http://www.doi.gov/initiatives/AdaptiveManagement/TechGuide.pdf

10.0 Appendix A: Integrated Water Flow Model Overview

The Integrated Water Flow Model (IWFM) source code was adapted by the Department of Water Resources from a modified version of the Integrated Groundwater Surface water Model (IGSM) developed in 1990 by consultants for the State Water Resources Control Board, U.S. Bureau of Reclamation, Department of Water Resources, and Contra Costa Water District. After substantial revisions, the first public version was released by DWR in December 2002 called IGSM2. IGSM2 was renamed IWFM in September 2005 by DWR (DWR 2014) to distinguish it from a variation of IGSM still in use by some private consulting firms (Taghavi et al., 2013).

Figure 1. Hydrologic processes simulated by IWFM



IWFM is a water resource-planning model capable of simulating groundwater flow, surface water flow, groundwater-surface water interactions, subsidence and other hydrologic processes (Figure 1). These processes can be run in confined and/or unconfined groundwater aquifer systems that interact with surface water systems through simulation of surface water flows, rainfall runoff, recharge, irrigation water demand and supply, and other surface water processes that interact with the groundwater system. A key feature of IWFM is the optional balancing of

water supply (pumping and stream diversions) and agricultural and urban water demand, through automated adjustments. Also, although pumping at individual wells can be simulated, IWFM can also estimate groundwater pumping and recharge in a spatially distributed manner where information on specific well locations or pumping do not exist (i.e. the model does not require pumping location, rather pumping estimates can be distributed across a region) (Brush et al. 2013). While designed for regional-scale modeling applications (Harter & Morel-Seytoux 2013, Appendix 2), model outputs can be extracted for regional or local areas (Brush et al. 2013).

What are examples of groundwater models in California?

California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) – C2VSim is a regional water planning model developed for California's Central Valley. The model simulates water movement through linked land surface, groundwater and surface water flow system using historical precipitation, land use, crop acreage, river inflows, and surface water diversions (Brush et al. 2013).

In addition to being a stand-alone model, C2VSim also serves as the basis for the groundwater flow component of CalSim3.0 (a reservoir operation water planning model, developed by the California DWR and the Bureau of Reclamation, used to simulate operations of the State Water Project and Central Valley Project) (Brush et al. 2013). It has been used to investigate the impacts of groundwater pumping on surface water flows in California's Central Valley (Brush et al. 2013; TNC, 2014), the effects of Sacramento Valley water transfers on Sacramento-San Joaquin Delta flows (Brush et al. 2007), and the role of extended drought on groundwater flows (Miller et al. 2009). C2VSim has also been linked to the Central Valley Production Model (CVPM), an agricultural economics model, and its successor Statewide Agricultural Production Model (SWAP) to analyze the effects of extended droughts on California's agriculture as well as the economic cost of replacing surface water diversions with groundwater pumping (Dale et al. 2013; Medellin-Azuara et al. 2015). Brush et al. (2013) used C2VSim to estimate that groundwater withdrawals in California's Central Valley exceeded replenishment by nearly 130 million acre-feet for the period 1921-2009.

Merced Area Groundwater Pool Interests (MAGPI) Groundwater Model – In 2007, the Merced Area Groundwater Pool Interests (MAGPI) initiated the development of a regional-scale hydrologic model using IWFM to inform "the planning and analysis of conjunctive use management strategies, design and evaluation of specific water supply projects, management of the Basin operations, and the development of financing mechanisms and cost sharing arrangements among MAGPI members." (WRIME, 2007).

Butte Basin Groundwater Model (BBGM) – The Butte Basin Groundwater Model using IWFM is currently being updated and further developed to support evaluation of projected water demands and the effects of changing climatic conditions on local water resources (Davids 2013). These modeling efforts will be coordinated with water balance analyses being undertaken by the Feather River Regional Agricultural Water Management Plan.

Yolo County Integrated Water Flow Model (YCIWFM) The YCIWFM was mapped over from the original IGSM model application for the area, and improved by the University of California at Davis and consulting companies. The model has been used to study the implications of aquifer storage and recovery (ASR) operations in the cities of Davis and Woodland (ESA 2015). It is also being used to develop conjunctive use strategies in aquifer-flood plain recharge operations, to

evaluate the effects of changes in irrigation practices on groundwater and in developing transfer functions to estimate change in aquifer storage based on monitoring data.

Kings Integrated Water Flow Model (Kings IWFM) The Kings IWFM has recently been updated and improved to study the groundwater management strategies in the Kings Basin region, and to model the future impacts and water balance scenarios with an emphasis on IRWM planning.

What are useful applications of IWFM in groundwater management in California?

Aquifer Sustainable Yield - Determine the sustainable yield of a groundwater basin by simulating surface water and groundwater systems and the interactions between them under a variety of scenarios such as climate change, extended droughts, changes in agricultural cropping patterns and farm water management practices, substitution of stream diversions with groundwater, etc.

Conjunctive Use - Simulate the groundwater flow and groundwater storage changes that result from various conjunctive use management practices such as recharging groundwater from surface water supplies in wet years (Harter & Morel-Seytoux 2013), or substitution of stream diversions with groundwater pumping.

Subsidence - Calculate the vertical displacement of the land surface due to permanent compaction of low permeable clay layers (subsidence) and its impact on water flow within the aquifers (Harter & Morel-Seytoux 2013).

Integration of Land Use-Driven Urban and Agricultural Water Management - Predict future land uses based on water supply and predict future water demand based on land uses. Because land use and water availability are interconnected, IWFM simultaneously models both the water management decision-making process and the groundwater and surface water flow and storage processes as they move forward in time (Harter & Morel-Seytoux 2013).

Incorporate Regulatory and Policy Aspects - Evaluate groundwater systems while enforcing water rights and maximum pumping limitations as well as environmental flow constraints on surface water demands (Harter & Morel-Seytoux 2013).

Informational - Imbedded in the historical run of C2VSim (application of IWFM to California's Central Valley) is the time series evolution of the different components of water resources development in California's Central Valley including the changes to the agricultural and urban landscape and demands, and the interplay between surface water diversions and ground water pumping and their impacts. (Brush et al. 2013).

What assumptions are inherent to IWFM?

IWFM can be run in a variety of configurations with varying degrees of complexity. As a result, model assumptions will vary depending on the model configuration.

Core assumptions include:

- Aquifers contain groundwater of a constant density
- Darcy's Law applies (e.g., groundwater flow is laminar, aquifer is within fine-grained sedimentary unit, not fractured rock system)

What inputs does an IWFM model require?

Model inputs and data requirements vary depending on the model objectives and complexity. However, all IWFM models require the following inputs:

1) Model Grid: During model development, the modeler must first define the area being modeled. During this phase a modeler will define: 1) the natural or institutional boundaries of the model area (e.g., faults, mountains, streams, water districts, counties, cities), and 2) the mesh that will be used to represent the area. IWFM simulates groundwater flow using the finite element method, which divides the modeled area into smaller cells (referred to as the mesh). The modeler can control the size of the cells in order to represent the aquifer and surface flow processes at varying accuracy at different areas of the model domain (smaller cell sizes represent flow processes more accurately than coarser cell sizes).

Once the model area and mesh have been constructed, additional data are *required*:

2) Geologic and hydrogeologic data: Geologic and hydrogeologic inputs providing stratigraphic information on aquifer layers and soil characteristics. These data can be entered directly using measured values or indirectly using user-defined parameters for every cell within the model. This information includes: hydraulic conductivity (a measure of the ease with which water flows through the system) of different layers in the aquifer system including the unsaturated zone, and location and thickness of confining layers.

3) Hydraulic data: Initial groundwater heads at the beginning of the simulation period as well as the aquifer boundary conditions (groundwater heads or flows specified at the model boundary) are all required model input data.

Depending on the components being modeled, *optional* data requirements may include:

1) Surface characteristics data: Surface characteristics encompass all processes that affect groundwater. Data describing these characteristics include land use type and distribution (agricultural, urban, native vegetation or riparian vegetation), soil type, urban and agricultural water demand (or data to calculate these demands), stream flows, stream and lake bed hydraulic properties, and surface water diversions and deliveries.

2) Climate data: Climate data can be entered into the model as a time series of precipitation rates and distributions and evapotranspiration data.

What information can an IWFM model generate?

IWFM can produce water budget outputs for each specific model components simulated. These data can be output for each model cell, for sub-regions of the model, or can be integrated across the entire model domain. These data include information on water budgets (groundwater budget, stream budget, lake budget, root zone budget, and unsaturated zone budget), information on water demand and supply, hydrographs (groundwater, stream flow and tile drain hydrographs), subsidence at selected locations, and groundwater head in all model elements.

Common questions

Can IWFM integrate surface water?

Yes. At its core IWFM is an integrated surface water groundwater model. IWFM uses non-linear conservation equations to iteratively solve groundwater and surface water flow equations.

How does IWFM use projected climate and land use data?

Climate projections can be included in IWFM by using downscaled precipitation and evapotranspiration estimates from General Circulation Model (GCM). IWFM assumes that those evapotranspiration rates already encompass changes to climatic, soil, and crop management conditions (Harter and Morel-Seytoux 2013, *Appendix 2*). In some cases, users may need to develop evapotranspiration (ET) estimates using a local ET model.

IWFM divides land use cover into four different types (agricultural crops, urban, native and riparian vegetation). Changing land use conditions can be estimated using modeled land use change projections (e.g. Dale et al. 2013, Medellin-Azuara et al. 2015). A report prepared for the Butte County Department of Water and Resource Conservation on the Butte Basin Groundwater Model recommended using outputs from the Statewide Agricultural Production Model (SWAP) to estimate changes in cropping patterns for the Sacramento Valley in 2050 (Davids 2013).

Are there any additional attributes?

IWFM is a public-domain code developed in such a way that it can easily be linked to other types of simulation tools such as reservoir system analysis models (e.g. CalSim), or agricultural economics models (e.g. CVPM and SWAP) to address complex water management issues under changing regulatory, climatic and agro-economic conditions. The input and output files used and generated by IWFM are user-friendly and several pre- and post-processing tools are freely available for efficient model building and results analysis. DWR provides technical support to existing and new IWFM users, and promotes its use through regular training workshops and users group meetings.

References

Brush, C.F., E.C. Dogrul, T.N. Kadir, and F.I. Chung. (2007). *Applying the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM), an integrated hydrologic model of California's Central Valley, to assess local and regional impacts of conjunctive use projects*. California Department of Water Resources, Sacramento, California. Available at: http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/Publications/downloadables/Posters/Brush_2007_AGU_C2VSIM.pdf

Brush, C.F., E.C. Dogrul, and T.N. Kadir. (2013). DWR Technical Memorandum: Development and calibration of the California Central Valley Groundwater-Surface Water Model (C2VSim), Version 3.02-CG. California Department of Water Resources, Sacramento, California. Available at: http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/download/C2VSim_Model_Report_Final.pdf

Christian-Smith, J., and A. Alvord. (2016) The Devil is in the Data: The Role of Science, Data, and Models in California's Historic Sustainable Groundwater Management Act. *The California Journal of Politics & Policy,* 8(3): 1-6.

Dale, L. L., E. C. Dogrul, C. F. Brush, T. N. Kadir, F. I. Chung, N. L. Miller, and S. D. Vicuna. (2013). Simulating the impact of drought on California's Central Valley hydrology, groundwater and cropping. *British Journal of Environment and Climate Change* 3, (Jul-Sep): 271-291.

[Davids 2013]. *Technical Memorandum: Recommended Methodologies for the update of Butte County Water Inventory and Analysis and Butte Basin Groundwater Model*. (2013). Prepared for: Butte County Department of Water and Resource Conservation. (2013). Prepared by: Davids Engineering, Inc. October, 2013. Available at: https://www.buttecounty.net/Portals/26/Reports/Inventory%20Analysis/Methodologies%20TM%20131011%20final.pdf

Dobbin, K., J. Clary, L. Firestone, and J. Christian-Smith. (2015). *Collaborating for Success: Stakeholder Engagement for Sustainable Groundwater Management Act Implementation.* Community Water Center, Sacramento, California. Available at: http://waterfoundation.net/wp-content/uploads/2015/07/SGMA_Stakeholder_Engagement_White_Paper.pdf

[DWR 2014]. Department of Water Resources. (2014). *Integrated Water Flow Model: IWFM-2015 – Theoretical Documentation*. Central Valley Modeling Unit, Modeling Support Branch, Bay-Delta Office, CADWR, Sacramento, California. http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IWFM-2015/v2015_0_260/downloadables/IWFM-2015.0.260_TheoreticalDocumentation.pdf

[ESA 2015]. *Davis-Woodland Water Supply Aquifer Storage and Recovery: Supplemental Environmental Impact Report, State Clearinghouse No. 2015012062*. (2015). Prepared for Woodland Davis Clean Water Agency. Prepared by: ESA. July, 2015. Available at: http://www.wdcwa.com/images/uploadsdoc/Davis-Woodland_Water_Project_ASR_SEIR.pdf

Harter, T., and H. Morel-Seytoux. (2013). *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*. Final Report, California Water and Environmental Modeling Forum, August 2013, Sacramento.

Medellin-Azuara, J., D. MacEwan, R. E. Howitt, G. Koruakos, E. C. Dogrul, C. F. Brush, T. N. Kadir, T. Harter, F. Melton, J. R. Lund. 2015. *Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA*. Hydrogeology Journal, DOI: 10.1007/s10040-015-1283-9.

[WRIME 2007]. Merced Basin Hydrologic Modeling Objectives and Strategy: Technical Memorandum. (2007). Prepared for: The Merced Area Groundwater Pool Interests and The California Department of Water Resources. Prepared by: Water Resources & Information Management Engineering (WRIME), Inc. February, 2007. Available at: http://project.wrime.com/Merced/pdf/Modeling%20objectives%20and%20strategy%20Draft_022607.pdf

Miller, N. L., L. L. Dale, C. F. Brush, S. D. Vicuna, T. N. Kadir, E. C. Dogrul, and F. I. Chung. (2009). *Drought resilience of the California Central Valley surface-ground-water-conveyance system*. Journal of the American Water Resources Association 45(4): 857-866.

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

11.0 Appendix B: MODFLOW Overview

Originally developed in 1984, MODFLOW has had five major releases of the core version: The original MODFLOW, MODFLOW-88, MODFLOW-96, MODFLOW-2000, and MODFLOW-2005 (Harbaugh 2005). MODFLOW-6 is currently under development and will be released in late 2016. Other versions of MODFLOW have been developed in recent years to meet specific needs, including:

- MF2005-FMP2 – Includes the Farm Process, which estimates dynamically integrated supply-and-demand components of irrigated agriculture (Schmid and Hanson 2009)
- MODFLOW-LGR – Supports local refinement of the model grid (Mehl and Hill 2013)
- MODFLOW-NWT – Improved simulation of unconfined groundwater flow problems (Niswonger et al. 2011)
- MODFLOW-OWHM – Ties the above capabilities together as an integrated hydrologic flow model (Hanson et al. 2014a)
- GSFLOW – A coupled version of MODFLOW-2005 and the USGS Precipitation-Runoff Modeling System (Markstrom et al. 2008)
- MODFLOW-USG – An unstructured-grid version of MODFLOW (Panday et al. 2013)

This report focuses on MODFLOW-2005 – the current core version of MODFLOW – unless otherwise specified, with the aim that this will provide readers with a proficient degree of fluency to discuss other codes in the MODFLOW family.

MODFLOW is a groundwater flow model that can simulate confined and unconfined groundwater aquifer systems. Surface water groundwater interactions, groundwater recharge from irrigation and/or precipitation, reservoirs, rivers, wells and a breadth of other processes are simulated in MODFLOW through the use of Packages[7] and/or Processes[8]. MODFLOW's modular design enables model code users to develop groundwater (or groundwater/surface water) models that are tailored to specific groundwater management goals (McDonald and Harbaugh 2003). This is done by selecting the Packages and/or Processes most suitable for the model area's conditions, as well as for the desired groundwater management scenarios to be evaluated. In some cases, Package or Process incompatibilities may require the use of more than one version of a model to evaluate all groundwater management scenarios being considered; however, most capabilities are included within MODFLOW-OWHM.

What are examples of MODFLOW models in California?

[7] Packages deal with a single aspect of the hydrologic system, or with a specific method of simulation (Harbaugh 2005). For example, the MODFLOW River Package (RIV) simulates the flow between rivers and the groundwater system using head-dependent flux boundaries.
[8] Processes are defined as parts of the code that solve a major equation or set of related equations (Harbaugh 2005). For example, the Farm Process (FMP2) was developed to simulate the integrated supply- and demand-side components of irrigated agriculture (Schmid and Hanson 2009).

The USGS has developed many groundwater models throughout the state (Figure 1). Some examples include:

Central Valley Hydrologic Model (2009) – The CVHM is designed to be coupled with forecasts from Global Climate Models to help predict surface-water supply and groundwater demand. The CVHM can be used to help evaluate sub-regional issues such as conjunctive-use projects or water transfers, or to support smaller-scale modeling investigations, such as the restoration of salmon habitat in the San Joaquin River (Traum et al. 2014). Uses MODFLOW-2000 with FMP (Faunt 2009).

Orange County Water District – Orange County uses a basin model that is updated every three to five years to estimate the effects of potential future pumping and recharge projects on groundwater levels, storage, and the water budget. Uses MODFLOW-1988 (Woodside and Westropp 2015).

Santa Clara Valley Model (2004) – The SCVM is designed to assess management strategies to prevent subsidence in the Santa Clara Valley. Uses MODFLOW-2000 (Hanson et al. 2004).

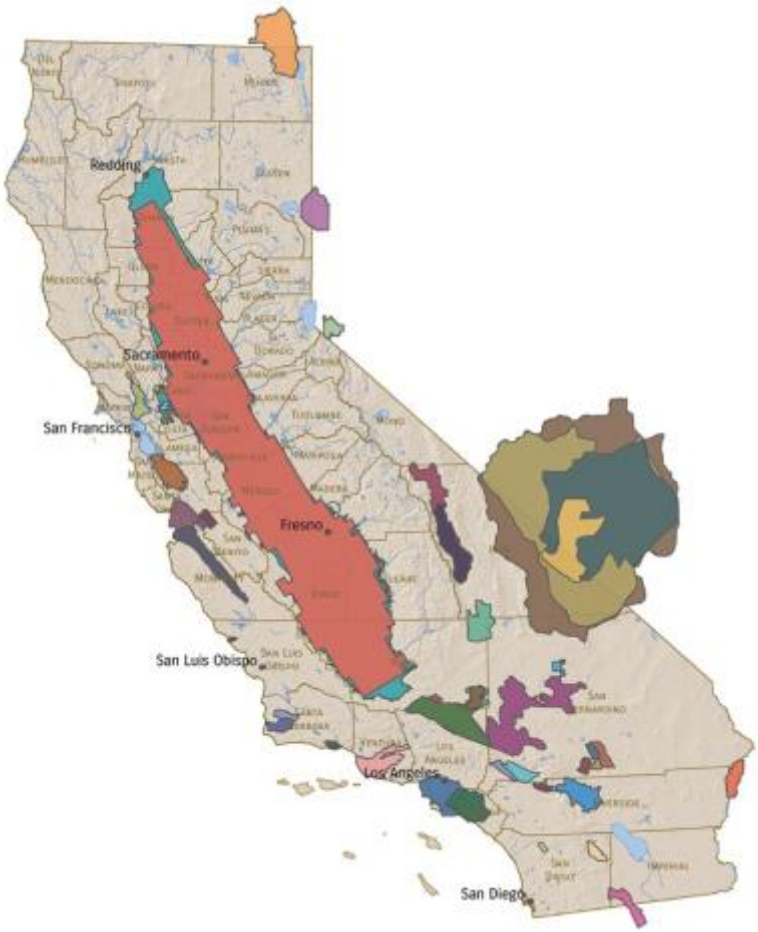


Figure 1. Map of different groundwater models developed by the USGS in California. Figure from: USGS California Water Science Center.

What are some useful applications of MODFLOW in groundwater management in California?

Aquifer Sustainable Yield - Determine the long-term behavior of a groundwater basin and the groundwater-surface water interactions within it. Groundwater systems are naturally in a dynamic balance with their surroundings. When the system is perturbed, the flow within the aquifer changes. For example, pumping may cause less groundwater to flow into streams, less groundwater uptake by plants, and/or more surface water to recharge groundwater. The sustainable yield is the maximum extraction rate that will avoid causing an undesirable level of harm to the aquifer, environment, and community.

Conjunctive Use - Simulate the groundwater flow and groundwater storage changes that result from various conjunctive-use management practices, such as recharging groundwater using surface-water supplies during wet years (Phillips et al. 2003).

Subsidence - Calculate the vertical displacement of the land surface due to permanent compaction of fine-grained clay layers (subsidence) and its impact on water flow within the aquifers (Siade et al. 2014).

Seawater Intrusion - MODFLOW can be used in a variety of ways to simulate the intrusion of seawater into an aquifer system. The companion USGS code SEAWAT is a variable-density transport code that can simulate seawater intrusion explicitly (Langevin et al. 2007).

Integration of Land Use-Driven Urban and Agricultural Water Management - Predict future land uses based on water supply and predict future water demand based on land uses. Because land use and water availability are interconnected, MODFLOW (with Farm Process) simultaneously simulates both the water management decision-making process and the groundwater and surface-water flow and storage processes as they move forward in time (Hanson et al. 2014b).

Contaminants tracking - Simulate contaminant transport processes in groundwater to evaluate changes in groundwater quality (Halford et al. 2010).

Incorporate Regulatory and Policy Aspects
Evaluate groundwater systems while enforcing water rights and maximum pumping limitations as well as environmental flow constraints on surface-water demands.

What assumptions are inherent to MODFLOW?

In its simplest form, MODFLOW is designed to simulate confined and/or unconfined groundwater aquifer systems with:

- Saturated flow (i.e., below the water table);
- Where Darcy's Law applies (e.g., not valid in fractured rock systems);
- A constant groundwater density; and
- The principal directions of horizontal hydraulic conductivity or transmissivity do not vary (Leake 1997).

These assumptions are valid for many confined and unconfined aquifer systems where there is an interest in groundwater flow or contaminant movement (Leake 1997). However, Packages or Processes can be added to MODFLOW to lift some of these constraints (e.g., Unsaturated Zone Flow, MT3D) or to add new capabilities (e.g., Recharge, Subsidence), making MODFLOW broadly applicable for modeling groundwater flow conditions in many environments for a breadth of applications.

What inputs does a MODFLOW model require?

During model development, the modeler must first define the area being modeled. During this phase a modeler will define: 1) the area's natural boundaries (e.g., faults, mountains, streams), and 2) the grid that will be used to represent the area.

MODFLOW simulates groundwater flow using the finite difference method, which divides the modeled area into a series of smaller rectangular blocks that form the model grid. These blocks are arranged in user-specified columns, rows, and layers (Figure 1).

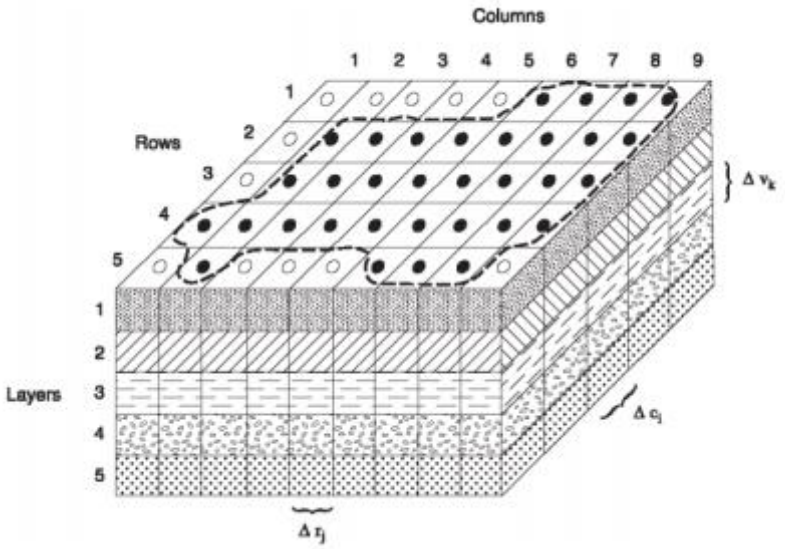


Figure 1. A conceptual model of an aquifer system with a model grid overlayed on the surface. The dotted line surrounding the black dots on the surface indicates the active portion of the groundwater model. Figure from Harbaugh 2005.

Once the model grid has been developed, modelers input specific information about the system into each active model cell. The inputs to MODFLOW vary depending on the Packages or Processes being used. In most cases, users are required to input information about: 1) initial conditions, 2) hydraulic properties of the aquifer system, and 3) hydrologic stresses and other boundary conditions.

1) Initial conditions: This describes the hydrologic conditions at the beginning of the simulation period. All models require hydraulic head (a measure of how much potential energy is stored in water, equivalent to the water-level elevation in a well) to be defined in every cell.

2) Hydraulic properties of the aquifer system: These properties can be derived from measured values and input directly, or derived using user-defined parameters for every cell within the model. Hydraulic properties include the hydraulic conductivity (a measure of the ease with which water flows through the geologic materials within a model cell) and the storage properties for each cell. If other processes are simulated, additional hydraulic properties will be needed; for example, if streams are simulated, the vertical hydraulic conductivity of the streambed will be needed.

3) Hydrologic stresses and other boundary conditions: These refer to conditions along the outer boundaries of the model, and features such as wells, rivers, and drains within the model domain. The input requirements vary depending on the Packages or Processes being used in the model. For example, if the user wants simulate groundwater surface water interactions, then one of several Packages may be used to simulate surface-water features. Inputs for such packages might include stream or lake locations, the vertical hydraulic conductivity of the bed materials, flow-stage relations, bed geometry, etc. Input for simulating pumping in wells would require, at a minimum, the cell(s) associated with the well screen and the pumping rate for each time period simulated.

What information can a MODFLOW model generate?

The modular nature of MODFLOW means that it can provide a breadth of information about the groundwater system being modeled depending on the Packages or Processes used. During a model run, MODFLOW solves the code's equations at each cell. This results in outputs for every cell, which can be reentered into the equations as inputs at that cell. This can be repeated for the designated number of time steps. In this way, MODFLOW can generate an output file of the system's conditions at every cell as time passes. The standard output includes:

- Head
- Drawdown
- Composite water budgets
- Cell-by-cell flows

If the GAGE package is used, "gages" can be placed where groundwater and surface water are interconnected to generate output files for that particular location. Outputs can include:

- Stage
- Stream outflow
- Streambed seepage
- Unsaturated storage
- Change in unsaturated storage
- Groundwater recharge

There are additional packages and post-processors for generating various types of output, including information needed to generate hydrographs of simulated heads for specified model cells (OBS, HYDMOD).

What are examples of Packages and Processes?

There are a variety of Packages that can be used in MODFLOW. Their functions encompass the abilities to:

- Simulate surface-water features (SFR, LAK, STR, RES, RIV)
- Incorporate evapotranspiration (EVT, ETS, RIP)
- Specify recharge (RCH)
- Create wells (WEL, MNW1, MNW2)
- Account for unsaturated zone flow (UZF)
- Simulate subsidence (SUB, IBS, SWT)

- Add drains (DRN, DRT)
- Incorporate faults (HFB)
- Simulate seawater intrusion (SWI2)

Processes group these functions so that they interact by creating feedbacks. The Groundwater-Flow Process contains the core MODFLOW code, and the Observation Process allows simulated data to be compared with observed data (Winston, 2015). The Farm Process (FMP) is a useful tool for investigating conjunctive use since it simulates agricultural water use and its effects on groundwater and surface water (Schmid and Hanson 2009). The Surface Water Routing (SWR) Process (Hughes and White 2014) was developed to accurately simulate stages, surface-water flows, and surface-water/groundwater interactions in areas where surface-water gradients are small and (or) there is significant management of surface water.

Common questions

Can MODFLOW integrate surface water?

Yes. Although MODFLOW was initially designed primarily to simulate groundwater flow, the need to incorporate surface water processes has led to the development of a series of Packages that expand the capabilities of the original River (RIV) Package, including Stream (STR), Streamflow-Routing (SFR), and the Lake (LAK) and Reservoir (RES) Packages. The Surface Water Routing (SWR) Process was developed to incorporate relatively complex surface-water problems. Also, the Farm Process (FMP) relates surface water and groundwater flow in areas where vegetation has a large influence on the water budget (Schmid 2009). FMP goes through a series of steps to estimate how much groundwater is being pumped for irrigation, partly on the basis of surface water diverted for irrigation. It integrates several existing Packages to calculate this value. These include: HYDMOD, MNW, MULT, SFR, SUB, UZF, and ZONEBUDGET (Schmid and Hanson 2009). In addition, GSFLOW is a linkage of MODFLOW and PRMS, a USGS precipitation-runoff model, allowing for more explicit simulation of surface-water flow where needed.

How does MODFLOW incorporate climate and land use data?

Most versions of MODFLOW do not directly use data associated with climate (e.g., temperature and precipitation) or land-use (e.g., crop, natural or urban categories); instead, these data are used externally in spreadsheets or other tools to estimate recharge, which then serves as input to MODFLOW. Versions of MODFLOW that include the Farm Process do explicitly use climate, land-use, and other landscape data to estimate recharge in agricultural, natural and urban settings, uptake of groundwater by plants, and groundwater pumpage for irrigation. Decisions about which model code or Packages/Processes to use depend on modeling objectives. Models with fewer input requirements, and therefore greater ease of use, comes with greater potential error (uncertainty). By contrast, MODFLOW's Farm Process takes a significant amount of time and data to develop, but can achieve lower model uncertainty.

Are there any additional attributes?

Other useful aspects of MODFLOW are (a) it is a public-domain code, and is by far the most used (and tested) groundwater model code in the world; (b) it can be coupled with other model codes to expand the model's function [this is a primary enhancement of the upcoming MODFLOW-6]; (c) many free and commercial GUIs and other programs are available to format data into the appropriate input style; and (d) lots of people know how to work with MODFLOW, so users are not beholden to a few individuals with expertise on the code in case they need to troubleshoot.

References

Faunt, C.C., ed. (2009). *Groundwater Availability of the Central Valley Aquifer, California*, U.S. Geological Survey Professional Paper 1766.

Gerber, R.E., and K. Howard. (2002). Hydrogeology of the Oak Ridges Moraine aquifer system: implications for protection and management from the Duffins Creek watershed. *Can. J. Earth Sci.* 39: 1333-1348. DOI: 10.1139/E02-058.

Halford, K. J., C.L. Stamos, T. Nishikawa, and P. Martin. (2010), Arsenic Management Through Well Modification and Simulation. *Groundwater*, 48: 526–537. doi: 10.1111/j.1745-6584.2009.00670.x

Hanson, R.T., S.E. Boyce, W. Schmid, J.D. Hughes, S.M. Mehl, S.A. Leake, T. Maddock III, and R.G. Niswonger. (2014a). *One-Water Hydrologic Flow Model* (MODFLOW-OWHM): U.S. Geological Survey Techniques and Methods. Available at: http://dx.doi.org/10.3133/tm6A51

Hanson, R.T., W. Schmid, C.C Faunt, J. Lear, and B. Lockwood. 2014b, *Integrated hydrologic model of Pajaro Valley, Santa Cruz and Monterey Counties, California*: U.S. Geological Survey Scientific Investigations Report 2014–5111. Available at: http://dx.doi.org/10.3133/sir20145111

Hanson, R.T., Z. Li, and C.C. Faunt. (2004). *Documentation of the Santa Clara Valley regional ground-water/surfacewater flow model, Santa Clara County, California*: U.S. Geological Survey Scientific Investigations Report 2004–5231.

Harbaugh, A.W. (2005). MODFLOW-2005, *The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process,* U.S. Geological Survey Techniques and Methods.

Hughes, J.D., and J.T. White. (2014). *Hydrologic conditions in urban Miami-Dade County, Florida, and the effect of groundwater pumpage and increased sea level on canal leakage and regional groundwater flow,* U.S. Geological Survey Scientific Investigations Report 2014-5162. Available at: http://dx.doi.org/10.3133/sir20145162

Leake, S.A. (1997). *Modeling Ground-Water Flow with MODFLOW and Related Programs*: U.S. Geological Survey Fact Sheet FS-121-97.

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

Markstrom, S.L., R.G. Niswonger, R.S. Regan, D.E. Prudic, and P.M. Barlow. (2008). *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.

McDonald, M.G., and A.W. Harbaugh. (2003). The History of MODFLOW. *Groundwater,* 41(2): 280-283.

Mehl, S.W., and M.C. Hill. (2013). *MODFLOW-LGR -- Documentation of ghost node local grid refinement (LGR2) for multiple areas and the boundary flow and head (BFH2) package*: U.S. Geological Survey Techniques and Methods 6-A44, 43 p.

Niswonger, R.G., S. Panday, and M. Ibaraki. (2011), *MODFLOW-NWT, A Newton formulation for MODFLOW-2005*: U.S. Geological Survey Techniques and Methods 6-A37.

Panday, S., C.D. Langevin, R.G. Niswonger, M. Ibaraki, and J.D. Hughes. (2013). *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, book 6, chap. A45.

Phillips, S.P., C.S. Carlson, L.F. Metzger, J.F. Howle, D.L. Galloway, M. Sneed, M.E. Ikehara, K.W. Hudnut, and N.E. King. (2003). *Analysis of tests of subsurface injection, storage, and recovery of freshwater in Lancaster, Antelope Valley, California,* U.S. Geological Survey Water-Resources Investigations Report 03-4061. Available at: http://pubs.er.usgs.gov/usgspubs/wri/wri034061

Schmid, W., and R.T. Hanson. (2009). *The Farm Process Version 2 (FMP2) for MODFLOW-2005—Modifications and Upgrades to FMP1,* U.S. Geological Survey Techniques and Methods 6-A-32.

Siade AJ, T. Nishikawa, D.L. Rewis, P. Martin, S.P. Phillips. (2014). *Groundwater-flow and land-subsidence model of Antelope Valley, California*, U.S. Geological Survey Scientific Investigations Report 2014–5166.

Traum, J.A., S.P. Phillips, G.L. Bennett, C. Zamora, and L.F. Metzger. (2014). *Documentation of a groundwater flow model (SJRRPGW) for the San Joaquin River Restoration Program study area, California*, U.S. Geological Survey Scientific Investigations Report 2014–5148. Available at: http://dx.doi.org/10.3133/sir20145148

Valerio, A., H. Rajaram, and E. Zagona. (2010), Incorporating Groundwater-Surface Water Interaction into River Management Models. *Groundwater*, 48: 661–673. doi: 10.1111/j.1745-6584.2010.00702.x

Winston, R.B. (2015). Online Guide to MODFLOW. Available at: http://water.usgs.gov/nrp/gwsoftware/modflow2000/MFDOC/

Woodside, G., and M. Westropp. (2015). *Draft Orange County Water District Groundwater Management Plan 2015 Update*. Available at: http://www.ocwd.com/media/3622/groundwatermanagementplan2015update_20150624.pdf

12.0 Appendix C. Groundwater Model Review Checklist

Table C1. Groundwater model checklist. Modified from Barnett et al. (2012).

Question	Yes/No

1. Are the model objectives clearly stated?	
2. Are the objectives satisfied and consistent with the model confidence level classification (CLC)?	
3. Is the conceptual model based on all quality-assured data, and reviewed by a third-party reviewer?	
4. Is the conceptual model consistent with the model objectives and CLC?	
5. Does the model design follow the model development framework and address all concerns raised during review?	
6. Does the model calibration meet predefined model objectives?	
7. Are the calibrated model parameter values and estimated fluxes plausible, and rationale for their use well documented?	
8. Do the model predictions conform to the model development framework?	
9. Is the uncertainty associated with the predictions reported?	
10. Is the model for its intended purpose?	

Back Matter

About Water in the West

Water in the West is a partnership of the faculty, staff and students of the Stanford Woods Institute for the Environment and the Bill Lane Center for the America West. The mission of Water in the West is to design, articulate, and advance sustainable water management for the people and environment of the American West. Linking ideas to action, we accomplish our mission through cutting-edge research, creative problem solving, collaboration with decision-makers and opinion leaders, effective public communication and hands-on education of students. To learn more visit waterinthewest.stanfrod.edu

About the Gould Center for Conflict Resolution

The Martin Gould Center for Conflict Resolution is located at the Stanford Law School. The center is home for both the Gould Negotiation & Mediation Program and a series of research projects on a range of negotiation, public policy, and system design applications including sustainable groundwater management, online dispute resolution, and international comparative dispute resolution.

About the Center for Collaborative Policy

The Center for Collaborative Policy is a program of California State University, Sacramento. The mission of the Center is to build the capacity of public agencies, stakeholder groups, and the public to use collaborative strategies to improve policy outcomes. The Center provides services to private and public stakeholders to address complex public policy challenges through collaborative processes, conflict resolution, public involvement, strategic planning, visioning, and training.