PROJECTING FORWARD

A Framework for Groundwater Model Development Under the Sustainable Groundwater Management Act

November 2016 | Tara Moran

Stanford | Water in the West

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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. This report informed development of best management practices (BMPs) produced by the California Department of Water Resources to support implementation of the Sustainable Groundwater Management Act (SGMA).

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 Martin Gould Center for Conflict Resolution and California State University Sacramento’s (CSUS) 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 the 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.

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Note: Italicized terms are defined in the report glossary (Section 8).

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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 (California Department of Water Resources [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 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, water agencies will need to work collaboratively with one another, land-use planning agencies, and interested parties within the basin to develop 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 a 50-year planning and implementation horizon. Where there are multiple groundwater management agencies in a basin, basin management, data collection, and monitoring efforts must be closely coordinated. Additionally, agencies must ensure that their efforts to manage sustainably do not adversely impact neighboring basins. Groundwater models will play a critical role in achieving these goals.

While 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 water budgets, (3) ascertain future data collection needs, (4) forecast the outcome of future management actions on a groundwater basin, and (5) explore alternative management strategies (Barnett et al. 2012). Relatedly, models will play a critical role in simulating environmental changes during the 50-year planning and implementation horizon required under SGMA. Models provide the link between established management criteria and the management approaches necessary to achieve them. In many cases, models will form the basis of groundwater management decisions.

This report provides a framework for model development under SGMA. It offers 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 nontechnical audiences. While many of these practices are already occurring, there are additional opportunities during groundwater model development to encourage model coordination and the active engagement of the local entities who will be impacted by management decisions, as well as the state agencies responsible for evaluating Groundwater Sustainability Plans (GSPs) under SGMA. 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.

This report makes the following recommendations to promote consistency, transparency, and coordination during groundwater model development.

Groundwater models should be

1. **Developed through a collaborative, inclusive, and transparent process.** Local water agencies, county and municipal agencies, managers, advisory committees, 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 for water budget development and water management planning and its associated uncertainties.
2. **Developed in a manner that is consistent with model objectives and with the amount and type of data available.** Where the amount or quality of data is inadequate to meet model objectives goals, model limitations and uncertainty 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. **Communicated clearly to technical and nontechnical audiences.** Model results and uncertainty must be clearly articulated to decision-makers, stakeholders, and other technical and nontechnical users. Presenting model results as a range of possible outcomes rather than as a single “true” value can help to convey the uncertainty inherent in model results.
4. **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.
5. **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 review and evaluation. It also improves model access and may encourage coordination between adjacent basins. DWR’s IWFM and the USGS’ MODFLOW are two examples of public domain, open-source model codes.
6. **Developed at the system scale whenever possible.** Developing models of the hydrogeologic system as a whole, rather than modeling individual hydrologically connected basins can maximize efficiency, avoid conflicts over boundary issues, and provide the opportunity to share the financial and personnel costs of model development.
7. **Subject to thorough peer review.** Groundwater models should be reviewed by the state, independent hydrogeologists with modeling experience, neighboring jurisdictions, and other interested parties. Peer review of groundwater models helps ensure that a model is consistent with model objectives and with assumptions in adjacent basins. Model review should be a formal process undertaken after each model reporting milestone.
8. **Subject to thorough model reporting, documentation, and archiving.** Groundwater model reporting should be accessible to technical and nontechnical 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 and be in a format that can be easily viewed and shared among multiple model platforms. All relevant data files should be uploaded to the basin’s shared data platform.
9. **Developed with state assistance.** The state should provide technical and financial assistance to develop groundwater models that use a consistent, transparent, and collaborative model development framework and that have been subject to third-party review by a hydrogeologist with modeling experience.

2.0 LIST OF ACRONYMS

C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
CLC	Confidence Level Classification
CVHM	Central Valley Hydrologic Model
CVPM	Central Valley Production Model
BBGM	Butte Basin Groundwater Model
DWR	California Department of Water Resources
ET	Evapotranspiration
GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
IGSM	Integrated Groundwater-Surface Water Model
IHM	Integrated Hydrological Model
IWFM	Integrated Water Flow Model
MAGPI	Merced Area Groundwater Pool Interests
MODFLOW	Modular programming of groundwater flow
PDE	Partial differential equation
PVWMA	Pajaro Valley Water Management Agency
RDM	Robust Decision Making
SGMA	Sustainable Groundwater Management Act of 2014
SWAP	Statewide Agricultural Production Model
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 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***[1,2] 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.

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, data collection, 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 do not undermine those of their neighbors. ***Models*** will play a critical role in achieving these goals.

Box 1. Usage of the Term "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 that link surface water and groundwater processes. For simplicity, this report refers to both groundwater models and integrated hydrologic models as models or groundwater models.

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[1] This report uses the term basin to refer to a basin or subbasin, as identified in DWR's Bulletin 118 (DWR 2003).

[2] Terms shown in italics are defined in the glossary (Section 8).

[3] Twenty-one 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.

While 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 water budgets, (3) ascertain future data collection needs, (4) forecast the outcome of future management actions on a groundwater basin, and (5) explore alternative management strategies (Barnett et al. 2012). Relatedly, 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, models provide the link between established management criteria and the management approaches necessary to achieve them. In many cases, models will form the basis of groundwater management decisions.

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

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 model development and evaluation under SGMA.

4.0 THE ROLE OF GROUNDWATER MODELS IN SGMA

Models are likely to be used by local and state agencies to meet groundwater management actions 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 be developed using public domain, open-source software (Cal. Code of Regulations §352.4(f)(1-3)).

Table 1. Management Actions Pertaining to Model Development Under SGMA

Management actions pertaining to model development under SGMA 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 Action	**California Water Code Section**	**Implementing Agency**
Develop and meet a basin sustainability goal	Meet sustainability goal	• GSP(s) must be implemented to achieve a basin's 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	Collect and synthesize data for basin characterization	• 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). • GSAs must 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

Table 1. Management Actions Pertaining to Model Development Under SGMA (cont.)

	Management Action	California Water Code Section	Implementing Agency
Quantify projected water budgets and surface water depletions	Quantify projected water budgets and surface water depletions	• GSPs must use a numerical groundwater model or "an equally effective method, tool, or analytical model" to evaluate and quantify projected water budget conditions and to quantify surface water depletion (Cal. Code of Regulations §354.18 and §354.28(c)(6)).	GSA
Engage stakeholders	Engage stakeholders	• GSA(s) shall establish and maintain a list of persons interested in receiving notice regarding plan preparation (Cal. Water Code §10723.4). • 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)). • GSA(s) shall consider the interests of all beneficial uses and users of groundwater (Cal. Water Code §10723.2). • GSA(s) shall encourage the active involvement of a diverse population with the groundwater basin (Cal. Water Code §10727.8(a)).	GSA
Review and Evaluate GSPs	Review and Evaluate GSPs	Review GSPs:	
		1. To 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. And designate a basin as probationary, if	
		(a) In consultation with DWR, the SWRCB determines that a GSP is inadequate (Cal. Water Code §10735.2(3))	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
		(c) 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(a)(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).

Models are likely to play a critical role in translating the basin sustainability goals into measurable objectives and minimum thresholds (Christian-Smith & Alvord 2016). Because 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.

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 – 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 – 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 – 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 with-drawn annually from a groundwater supply with causing *undesirable results* (Cal. Water Code §10721(v)).

Planning and implementation horizon – 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 – 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 – 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)).

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 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.

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 systems 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 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. Models enable 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 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. Collect, Synthsize, and Coordinate Data

SGMA requires GSAs to monitor, manage, and report data necessary for sustainable groundwater management or to 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 joint 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 model development and refinement over the long term. Developing consensus on consistent data and methodologies at the basin-scale will not be easy. 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 help 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 hydrologically connected basins.

Developing functional groundwater models for hydrologically connected basins will require groundwater flow estimates from adjacent groundwater basins. While SGMA does not require it, 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" (Interbasin Flow Project [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 of boundaries where they do not 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 the Department of Water Resources (DWR) using its Integrated Water Flow Model (IWFM) code and the Central Valley Hydrological Model (CVHM), developed by the United States Geological Survey (USGS) using its 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, their use is not required (Cal. Code of Regulations §354.18). CVHM and C2VSim and their accompanying data can be readily accessed online. Using these regional models or the freely available model codes on which they are built may aid agencies in model coordination (see Table 2 for information on groundwater model codes).

4.4. Quantify Projected Water Budgets and Surface Water Depletions

GSAs are required to use a numerical model or "an equally effective method, tool, or analytical model" to quantify and evaluate projected water budgets and the potential impacts of beneficial uses and other users of groundwater, and to quantify surface water depletions (Cal. Code of Regulations §354.18 and §354.28(c)(6)).

Given the complexity of groundwater systems and the relatively long lag times associated with them, quantifying surface water depletions and impacts to beneficial users will be difficult without a numerical model. Unfortunately numerical model development may be hindered by the distinct lack of data on groundwater-surface connectivity in the state (Howard and Merrifield, 2010; Escriva-Bou et al., 2016; Moran et al., 2016), which stems from California's legal separation of groundwater and surface water, and has in many cases lead to fragmented management of the resource.

Whenever possible GSAs should begin working to identify areas of interconnected waters in their basin and develop monitoring networks and other field-based data that can be used for model calibration. Barlow and Leake (2012) summarize a breadth of field-based approaches for determining groundwater-surface water connectivity in USGS Circular 1376.

Agencies developing numerical model to assess quantifying impacts to surface water depletions and beneficial users must clearly show model uncertainty when presenting model results. Some agencies may choose to start with an analytical model of streamflow depletion while developing the data necessary for more advanced model development in the future. The Michigan Department of Natural Resources, in cooperation with the USGS developed a "screening tool" to evaluate proposed groundwater withdrawals and identify regions requiring more in-depth modeling or study (Reeves et al., 2009).

Here in California, The Nature Conservancy released a report entitled, "Groundwater and Stream Interaction in California's Central Valley" (The Nature Conservancy [TNC], 2014). The report uses the C2VSim model to identify the gaining and losing stream reaches in California's Central Valley. The report also explores the impacts of historical and current groundwater pumping on these river systems and may serve as useful first step for quantifying surface water depletion and impacts to beneficial users for many basins in California's Central Valley.

4.5. 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, environmental users, and others (Cal. Water Code §10723.2). We refer to these entities collectively throughout this report as stakeholders and/or interested parties. 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. The review periods also encourage evaluation of groundwater monitoring networks enabling agencies to modify or expand these networks or the monitoring protocols supporting them where necessary, 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 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.

4.6. 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. Additionally, 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).

SGMA does not require coordination of models within a basin or between adjacent basins. As a result, inconsistency in model development and the data underpinning model projections may hinder DWR's ability to effectively evaluate GSPs, particularly in basins developing multiple GSPs. Differences in choice of model code, data, and underlying model assumptions have the potential result in significant differences in model results. Whenever possible basins should work together to jointly determine modeling needs and coordinate model development. Coordinating model development, when done correctly, can promote an improved understanding of the basin, minimize conflicts, foster cost sharing, facilitate dialogue about the management actions necessary to achieve sustainability goals, and strengthen overall GSP development.

Coordinated model development is particularly important under SGMA because even where model use is required under the law and common projections are provided, agencies are not required to use them. For example, the quantification of projected water budgets must be done using a numerical model or “an equally effective method, tool or analytical model”, which must incorporate, among other things, historical and projected water use, climate change, population and land-use (Cal. Code of Regulations, §354.18(e)). While 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, require their use (Cal. Code of Regulations, § 354.18(d)). This potential lack of consistency in water budget and model development may significantly hinder consensus over the necessary management actions within basins, and DWR’s ability to evaluate GSPs within basins, as well as impacts between adjacent basins.

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 hydrologically connected. While some agencies will choose to coordinate voluntarily, as evidenced by the Interbasin Flow Agreement, other agencies will need legislative requirements to do so.

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); Michigan Department of Environmental Quality [DEQ] (2014); Bear and Cheng (2010); Bredehoeft (2002); and 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 (Bear and Cheng, 2010). Groundwater models have successfully been used for several decades to support informed groundwater management (Barnett et al., 2012).

Box 3. What is a Groundwater Model?

This report uses the term "model" or "groundwater model" to refer to a 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 its district. This model is referred to as the Santa Clara Valley Regional Ground-Water/Surface-Water Flow Model.

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).

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 lists some groundwater model codes commonly used in California.

5.1.1. 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 a highly simplified representation of boundary conditions. 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 that can serve as the basis for more complex numerical models in the future.

5.1.2. 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 or 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 as a powerful tool to simulate groundwater systems and forecast long-term changes to the system.

5.1.3.Public Domain, Proprietary, Open-Source, and Closed-Source Model Codes

Analytic and numerical model codes can be either 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 that 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 codes may be bound by rules within a licensing agreement requiring that the original author be credited or that any modifications be shared with the community.

SGMA requires all groundwater models developed in support of GSPs after August 15, 2016, to be developed using public domain, open-source software (Cal. Code of Regulations §352.4(f)(3)). DWR's IWFM and the USGS' MODFLOW are both public domain, open-source model codes that have been verified by subject-matter experts. Both model codes can be downloaded free from the agencies' websites. Learn more about these model codes in appendices A and B, respectively.

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 and irrigation, etc.) and sinks (i.e., flow from aquifers to surface water bodies and 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*** or 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 (3) 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 flow models and, as a result, are 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 (see Table 4).

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

Groundwater model codes commonly used in California. This list is not comprehensive.

Model Code	Developer	Model Code Categorization
GFLOW	Haitjema Software	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.

Table 2. Groundwater Model Codes Commonly Used in California (cont.)

Model Code	Developer	Model Code Categorization
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 ***parameters***; 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). 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 these variables help modelers 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. 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).

SGMA requires that models developed to support GSP planning under SGMA be based on field or laboratory measurements and be calibrated against site-specific field data (Cal. Code of Regulations §352.4(f)(2)). 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 re-examining the conceptual model and corresponding adjustments to the model setup or changing model parameters (aquifer parameters, boundary condition parameters).

6.0 A FRAMEWORK FOR GROUNDWATER MODEL DEVELOPMENT UNDER SGMA

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 that 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 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 interdependent impacts of all groundwater users on the system (Bredehoeft, 2002).

Groundwater models can help 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 are easier to use and maintain. 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 result in more-consistent models that can be used for local and regional management.

Groundwater models are generally 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 nontechnical 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 the state agencies 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 (Bay-Delta Modeling Forum [BDMF] 2000). Texas, which 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 (Texas Water Development Board [TWDB] 2016).

Three of the four framework phases pertain to model development; each phase is punctuated by a 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 experts into model development, including developing a model technical advisory committee that included board members, technical and modeling experts from PVWMA, 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, numerous decisions need to be made, many of which 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, water 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

A framework for groundwater model development under SGMA. Phases, steps, and specific tasks for groundwater model development under SGMA. Table Modified from Barnett et al. (2012).

Phases	Steps	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 GSA(s) should host public meetings to discuss model development options (i.e., who should develop the model, how model development should be funded, what technical and financial resources will be required to maintain the model long term, what the potential economic and planning advantages of coordinated model development are [particularly in basins with multiple GSAs or between hydrologically connected basins], etc.), the pros and cons of each option as well as the potential role of advisory committees in model development. Many GSAs will choose to pursue the remainder of the steps in consultation with an advisory committee, augmented by 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 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, understand the proposed future level of development, and 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 Table 4)
		2.5 The model developer should work with neighboring GSAs to determine how to best share data and coordinate 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 on 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.
		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; conceptual model development; 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, one or more independent hydrogeologists, neighboring basins, and interested parties.
Model Review # 1: Is model design adequate? If yes, proceed. If no, return to earliest stage necessary to correct deficiencies.		

Table 3. A Framework for Groundwater Model Development Under SGMA (cont.)

Phases	Steps	Specific Tasks
Phase 2: Construct, Calibrate, and Report	**5. Construct:** Construct model in a manner consistent with model objectives and design specifications	**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 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 the larger model development team.
	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 see confidence level classification in (see Table 4). 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 developer should present the model design report at one or more public meetings. Model construction and calibration should be reviewed by the state, one or more independent hydrogeologists, neighboring basins, and other interested parties.
Model 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 scenarios.	**7.1** The model developer should work with the larger model development team to develop scenarios and the underlying assumptions for each scenario (see Table 4).
	8. Assess and Report 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. Modeled scenarios should be compared to a baseline scenario to assess net impact of stresses.
		8.2 The model developer should develop a report of model scenarios. Whenever possible, predictions should be reported as the difference of two model outputs. Uncertainty in model predictions should be acknowledged, assessed, and clearly communicated to all parties (see section on uncertainty below).
		8.3 The model developer should present model scenarios and uncertainty estimates at one or more public meetings. Model scenarios and uncertainty estimates should be reviewed by the state, one or more independent hydrogeologists, 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.		

Table 3. A Framework for Groundwater Model Development Under SGMA (cont.)

Phases	Steps	Specific Tasks
Phase 4: Document and Archive	**9. Final Report and Archive:** Develop final model report and model archive.	**9.1** The model developer should produce 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 nontechnical audiences and clearly communicate model uncertainty.
		9.2 The model developer should develop a well-organized model archive to facilitate third-party review and enable model replication. Data files should be available electronically, include all necessary metadata and be in data formats that can be easily viewed and shared among multiple model platforms.
		9.3 The model developer should present the final model report and model archive at one or more public meetings. The final model report and archive should be reviewed by the state, one or more independent hydrogeologists, neighboring basins, and interested parties.
Final Model Review: Does the model meet the criteria outlined in the final model review checklist (Appendix C)? If yes, proceed. If no, return to earliest stage necessary to correct deficiencies.		

Table 4. Model Confidence Level Classification

Model confidence classification. Data requirements, calibration and prediction characteristics, model review criteria, and examples for groundwater model development. Table modified from Barnett et al. (2012).

Data	Calibration	Prediction	Key Indicator	Model Review	Examples of Specific Uses
Class 3					
Spatial and temporal distribution of groundwater head observations adequately define groundwater behavior, especially in areas of greatest interest and where outcomes are to be reported. Spatial distribution of bore logs and associated stratigraphic interpretations clearly define aquifer geometry. Reliable metered groundwater extraction and injection data is available. Rainfall and evaporation data is available. Aquifer-testing data to define key parameters. Streamflow and stage measurements are available with reliable baseflow estimates at a number of points. Reliable land-use and soil-mapping data available. Reliable irrigation application data (where relevant) is available. Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation.	Scaled RMS error or other calibration statistics are acceptable. Long-term trends are adequately replicated where these are important. Seasonal fluctuations are adequately replicated where these are important. Transient calibration is current (i.e., uses recent data). Model is calibrated to heads and fluxes.	Length of predictive model is not excessive compared to length of calibration period. Temporal discretization used in the predictive model is consistent with the transient calibration. Level and type of stresses included in the predictive model are within the range of those used in the transient calibration. Steady state predictions used when the model is calibrated in steady state only.	Key calibration statistics are acceptable and meet agreed targets. Model predictive time frame is less than 3 times the duration of transient calibration. Stresses are not more than 2 times greater than those included in calibration. Temporal discretization in predictive model is the same as that used in calibration. Mass-balance closure error is less than 0.5% of total. Model parameters consistent with conceptualization. Appropriate computational methods used with appropriate spatial discretization to model the problem.	The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modeling experience. Model is reviewed at all reporting milestones by the state and adjacent basins. Reviews are incorporated into the model development process. In many cases this will require model developers to revisit previous steps in the modeling process.	Suitable for predicting groundwater responses to arbitrary changes in applied stress or hydrological conditions anywhere within the model domain. Provide information for sustainable yield assessments for high- value regional aquifer systems. Evaluation and management of potentially high-risk impacts. Can be used to design complex mine¬ dewatering schemes, salt-interception schemes or water-allocation plans. Simulates the interaction between groundwater and surface water bodies to a level of reliability required for dynamic linkage to surface water models. Assessment of complex, large-scale solute transport processes.

Table 4. Model Confidence Level Classification (cont.)

Data	Calibration	Prediction	Key Indicator	Model Review	Examples of Specific Uses
Class 2					
Groundwater head observations and bore logs are available but may not provide adequate coverage throughout the model domain. Metered groundwater-extraction data may be available but spatial and temporal coverage may not be extensive. Streamflow data and baseflow estimates available at a few points. Reliable irrigation application data available in part of the area or for part of the model duration.	Calibration statistics are generally reasonable but may suggest significant errors in parts of the model domain(s). Long-term trends not replicated in all parts of the model domain. Transient calibration to historic data but not extending to the present day. Seasonal fluctuations not adequately replicated in all parts of the model domain.	Transient calibration over a short time frame compared to that of prediction. Temporal discretization used in the predictive model is different from that used in transient calibration. Level and type of stresses included in the predictive model are outside the range of those used in the transient calibration.	Key calibration statistics suggest poor calibration in parts of the model domain. Model predictive time frame is between 3 and 10 times the duration of transient calibration. Stresses are between 2 and 5 times greater than those included in calibration. Temporal discretization in predictive model is not the same as that used in calibration. Mass-balance closure error is less than 1% of total. Not all model parameters consistent with conceptualization. Spatial refinement too coarse in key parts of the model domain.	The model has been reviewed and deemed fit for purpose by an independent hydrogeologist.	Prediction of impacts of proposed developments in medium value aquifers. Evaluation and management of medium risk impacts. Providing estimates of dewatering requirements for mines and excavations and the associated impacts. Designing groundwater management schemes such as managed aquifer recharge, salinity management schemes and infiltration basins. Estimating distance of travel of contamination through particle-tracking methods. Defining water source protection zones.
Class 1					
Few or poorly distributed existing wells from which to obtain reliable groundwater and geological information. Observations and measurements unavailable or sparsely distributed in areas of greatest interest. No available records of metered groundwater extraction or injection. Climate data only available from relatively remote locations. Little or no useful data on land-use, soils or river flows and stage elevations.	Calibration is not possible or illustrates unacceptable levels of error, especially in key areas. Calibration is based on an inadequate distribution of data. Calibration only to datasets other than those required for prediction.	Predictive model time frame far exceeds that of calibration. Temporal discretization is different to that of calibration. Transient predictions are made when calibration is in steady state only.	Model is uncalibrated or key calibration statistics do not meet agreed targets. Model predictive time frame is more than 10 times longer than transient calibration period. Stresses in predictions are more than 5 times higher than those in calibration. Stress period or calculation interval is different from that used in calibration. Transient predictions made but calibration in steady state only. Cumulative mass-balance closure error exceeds 1% or exceeds 5% at any given calculation time. Model parameters outside the range expected by the conceptualization with no further justification. Unsuitable spatial or temporal discretization.	Model is reviewed internally or is not reviewed by external reviewers.	Designing observation bore array for pumping tests. Predicting long-term impacts of proposed developments in low- value aquifers. Estimating impacts of low-risk developments. Understanding groundwater flow processes under various hypothetical conditions. Providing first-pass estimates of extraction volumes and rates required for mine dewatering. Developing coarse relationships between groundwater extraction locations and rates and associated impacts. As a starting point from which to develop higher class models as more data is collected and used.

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 GSAs developing a GSP. Groundwater models are one of a number of tools that can help inform these 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 and 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 its 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 hydrologically 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 that 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 build the necessary capacity over several years for long-term model maintenance. 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 consultants.

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.

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. As discussed previously, there are pros and cons to different model codes. Developing clear model objectives helps model developers decide which model code will best meet management goals. 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 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 August 15, 2016, for GSP planning under SGMA must use public domain, open-source software.

After deciding which code to use 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 models 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 improving analyses and identifying future data needs. Over time, the model can be improved as more data become 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 stresses, and encompass the full geographic extent of the impact or area of stresses. For example, if the pumping drawdown from a well or series of wells extends beyond the model boundary, then the model cannot be used to sufficiently determine changes in groundwater storage or stream depletion resulting from this pumping. 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 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 and review. This report should include model objectives; data sources and key areas of uncertainty; an overview of the conceptual model; model type and code; ***model domain***, grid size and model time steps; an overview of model strengths, weaknesses and constraints; a 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. Table 4 provides information on the data requirements necessary to meet 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, one or more independent hydrogeologists with modeling experience, neighboring basins, and other interested parties.

6.2. Phase 2: Construct, Calibrate, and Report

Once feedback from the model design review has been adequately incorporated into model design, 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 for model developers to 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 and the larger model development team throughout the model development process will increase transparency and improve understanding of model constraints.

Once the model is constructed, the model developer should proceed with model calibration using site-specific field data (Cal. Code of Regulations §352.4(f)(2)). Model calibration should be assessed against predefined performance metrics that are consistent with both the amount and quality of data available for model construction and the model objectives (Table 4). Where basins are hydrologically connected, 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 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, one or more independent hydrogeologists with modeling experience, 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 hydrologically 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.

Assessing model uncertainty is complex, 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). It is important that model developers clearly articulate model limitations to water managers, stakeholders, and other decision-makers.

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 spatial or temporal uncertainty. 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 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 head 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 modeling scenarios and analysis are extended 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 nontechnical 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. Modeled scenarios and results from the uncertainty analysis should be documented in a publicly available report. 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 nontechnical stakeholders (Barnett et al., 2012). Results from this phase of model development should be and subject to review by the state, one or more independent hydrogeologists with modeling experience, 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 agency’s 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 nontechnical 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 and be in data formats that can be easily viewed and shared among multiple model platforms. All relevant data files should be uploaded to the basin’s shared data platform. In addition to facilitating review of the modeling process, proper and thorough data archiving facilitates in-house model maintenance and development. The final model report and corresponding model archive should be reviewed by the state, one or more independent hydrogeologists with modeling experience, neighboring basins, and other interested parties.

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.[4] The first two approaches have been discussed previously in the report.

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[4] 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).

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 incorporating learning from the management and monitoring of a system into the ongoing management process (Williams et al., 2009).

Groundwater models are a valuable tool in adaptive management 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 models, 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, ongoing model improvement, and ensure that model outputs are useful for making groundwater management decisions.

6.5.2. Coupling with Other Models and Model Comparison

Recent studies by Medellían-Azuara et al. (2016) , Medellían-Azuara et al. (2015) and Howitt et al. (2015) 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 nontechnical 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; decision-makers 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 two models developed for California’s Central Valley, CVHM and C2VSim, could provide important insights into model uncertainty and ultimately result in the 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 ensure consistency in model development, stakeholder engagement in the modeling process, and peer review of groundwater models at key points throughout their development.

Groundwater models should be

1. **Developed through a collaborative, inclusive, and transparent process.** Local water agencies, county and municipal agencies, managers, advisory committees, 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 for water budget development and water management planning and its associated uncertainties.
2. **Developed in a manner that is consistent with model objectives and with the amount and type of data available.** Where the amount or quality of data is inadequate to meet model objectives goals, model limitations and uncertainty 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. **Communicated clearly to technical and nontechnical audiences.** Model results and uncertainty must be clearly articulated to decision-makers, stakeholders and other technical and nontechnical users. Presenting model results as a range of possible outcomes rather than as a single “true” value can help to convey the uncertainty inherent in model results.
4. **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.
5. **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 review and evaluation. It also improves model access and may encourage coordination between adjacent basins. DWR’s IWFM and the USGS’ MODFLOW are two examples of public domain, open-source model codes.
6. **Developed at the system scale whenever possible.** Developing models of the hydrogeologic system as a whole, rather than modeling individual hydrologically connected basins can maximize efficiency, avoid conflicts over boundary issues, and provide the opportunity to share the financial and personnel costs of model development.
7. **Subject to thorough peer review.** Groundwater models should be reviewed by the state, independent hydrogeologists with modeling experience, neighboring jurisdictions, and other interested parties. Peer review of groundwater models helps ensure that a model is consistent with model objectives and with assumptions in adjacent basins. Model review should be a formal process undertaken after each model reporting milestone.
8. **Subject to thorough model reporting, documentation, and archiving.** Groundwater model reporting should be accessible to technical and nontechnical 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 and be in a format that can be easily viewed and shared among multiple model platforms. All relevant data files should be uploaded to the basin’s shared data platform.
9. **Developed with state assistance.** The state should provide technical and financial assistance to develop groundwater models that use a consistent, transparent, and collaborative model development framework and that have been subject to third-party review by a hydrogeologist with modeling experience.

8.0 GLOSSARY

Basin – This report uses the term “basin” to refer to a basin or subbasin, as identified in DWR’s Bulletin 118 (DWR 2003).

Boundary condition – The hydraulic head or flux assigned at the boundaries of model domain.

Conceptual model – A narrative and visual description of the geologic and hydrologic conditions in a basin (Anderson et al., 2015). Conceptual models commonly form the basis for groundwater model development.

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 – A model or model code that simulates water movement through the linked groundwater, surface water and land surface systems in an integrated manner.

Larger model development team – A groundwater model should be developed with feedback form GSAs, county and municipal agencies, managers, advisory committees and other interested parties. Because of the significant technical expertise required for model development, many GSAs and model developers will find it useful to work with advisory committee(s) for this purpose.

Measurable objectives – 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 §351(s)).

Minimum thresholds – A numeric value for sustainability indicator used to define undesirable results (Cal. Code of Regulations §351(t)).

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 “models or groundwater models.” This report uses the term 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 USGS, Santa Clara Valley Water District used the MODFLOW-2000 model code to develop a hydrologic model for its district. This model is referred to as the Santa Clara Valley Regional Ground-Water/Surface-Water Flow Model.

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

Model domain – 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.

Planning and implementation horizon – 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)).

Sensitivity analysis – A series of systematic tests performed during model calibration and scenarios to test the sensitivity of the model environment to changes in model parameters (Bear and Cheng, 2010).

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

Sustainable groundwater management – 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 – The Sustainable Groundwater Management Act defines this term 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))

Sustainability indicator – 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) (Cal. Code of Regulations §351(ah)).

Undesirable results – one or more of the following effects caused by groundwater conditions occurring throughout a basin:

(1) Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon.

(2) Significant and unreasonable reduction of groundwater storage.

(3) Significant and unreasonable seawater intrusion.

(4) Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies.

(5) Significant and unreasonable land subsidence that substantially interferes with surface land uses.

(6) Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water (Cal. Water Code §10721(w)).

Water budget – California 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.”

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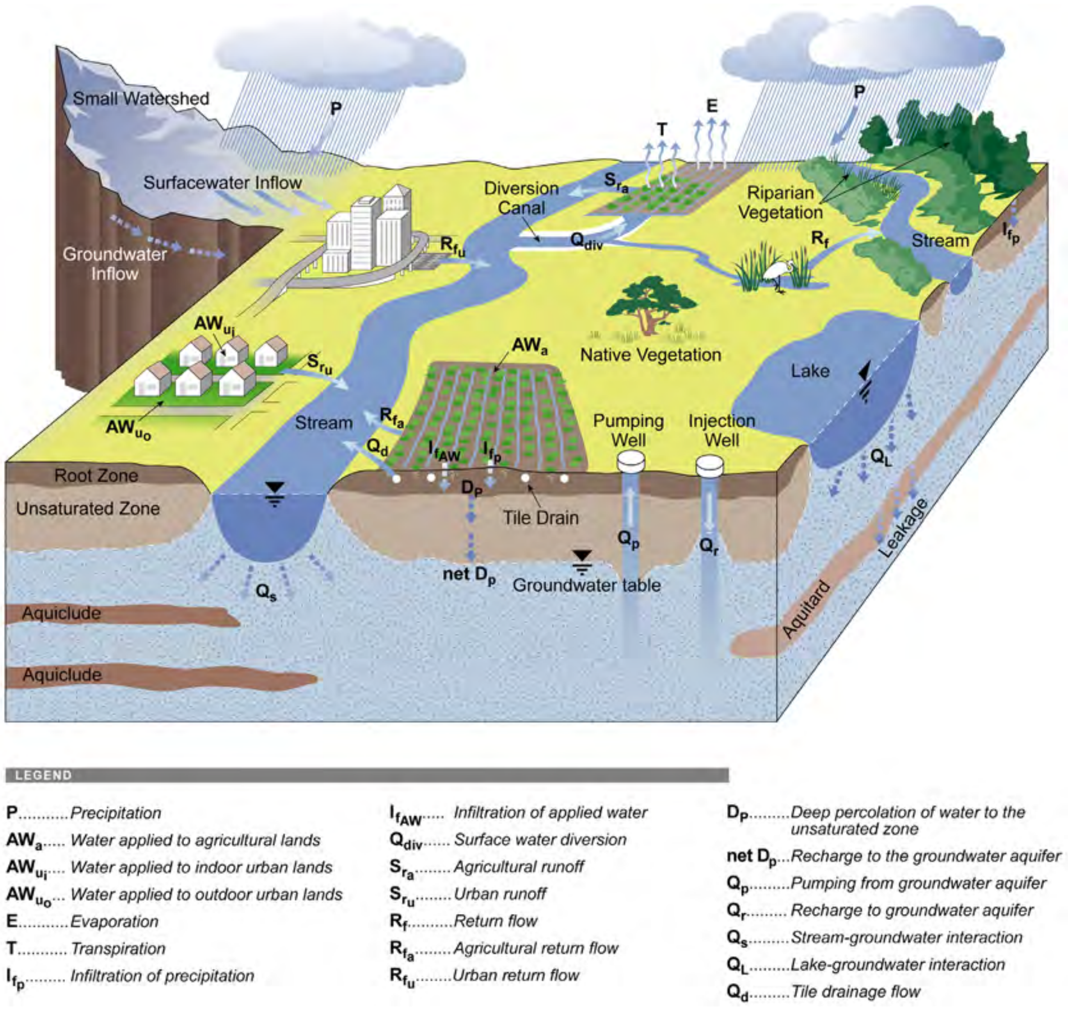
10.0 APPENDIX A: INTEGRATED WATER FLOW MODEL OVERVIEW

The Integrated Water Flow Model (IWFM) source code was adapted by the Department of Water Resources (DWR) 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, DWR, 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 (2014) to distinguish it from a variation of IGSM still in use by some private consulting firms (Taghavi et al., 2013).

Figure A1. 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 A1). 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 does 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 and Morel-Seytoux, 2013), 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 a 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 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" (Water Resources & Information Management Engineering [WRIME], 2007).

Butte Basin Groundwater Model (BBGM). The BBGM, developed using the IWFM model code, 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 Engineering, 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. The Yolo County IWFM was updated 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 operations in the cities of Davis and Woodland (ESA, 2015). It is currently 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 was recently updated 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 integrated regional water management 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 and 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 and 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 and 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 and 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 the hydraulic conductivity of different layers in the aquifer system, including the unsaturated zone, and location and thickness of confining layers.

3) **Hydraulic head 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 component simulated. These data can be output for each model cell, for subregions 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 nonlinear 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 (ET) estimates from a general circulation model. IWFM assumes that those ET rates already encompass climatic changes and changes to soil and crop management conditions (Harter and Morel-Seytoux, 2013). In some cases, users may need to develop 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 BBGM recommended using outputs from SWAP to estimate changes in cropping patterns for the Sacramento Valley in 2050 (Davids Engineering, 2013).

Are there any additional attributes?

IWFM is a public domain, open-source 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 IWFM's use through regular training workshops and users group meetings.

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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 appendix 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[5] and/or Processes.[6] 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?

The USGS has developed many groundwater models throughout the state (Figure B1). Some examples include

Central Valley Hydrologic Model (CHVM). 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 subregional 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). It uses the MODFLOW-2000 with the Farm Process (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 (Woodside and Westropp, 2015).

Santa Clara Valley Model. The SCVM is designed to assess management strategies to prevent subsidence in the Santa Clara Valley (Hanson et al., 2004).

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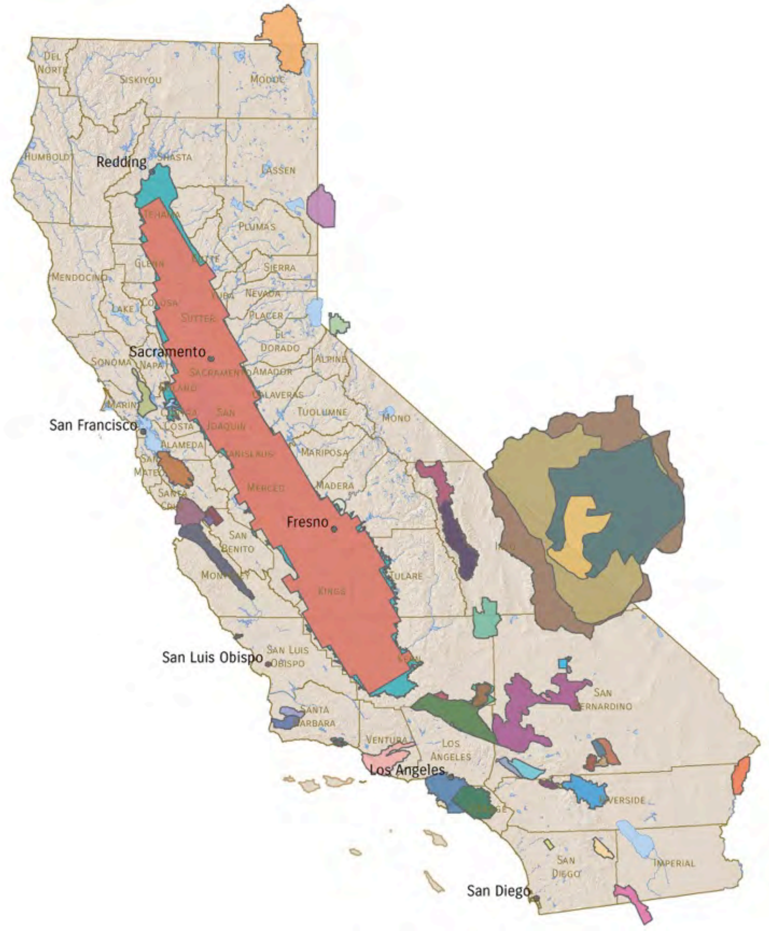
[5] Packages deal with a single aspect of the hydrologic system or with a specific method of simulation (Harbaugh, 2005). For example, the MODFLOW River Package (RIV) simulates the flow between rivers and the groundwater system using head-dependent flux boundaries.

[6] 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).

Figure B1. Groundwater Models Developed by the USGS in California

Colored areas indicate groundwater models developed by the USGS. 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 – 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 in fractured rock systems);
- With a constant groundwater density; and
- When 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.

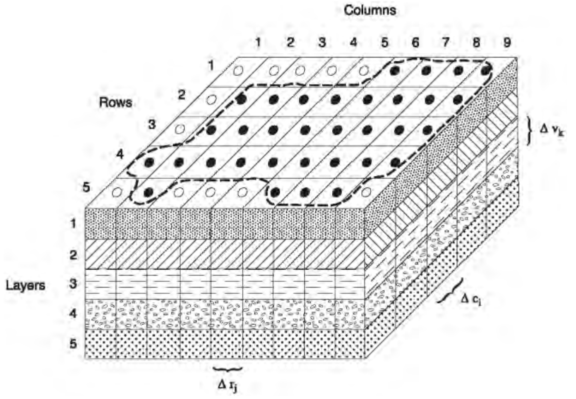
What inputs does a MODFLOW model require?

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 B2).

Figure B2. Conceptual Model of an Aquifer with a Model Grid

Conceptual model of an aquifer system with a model grid overlaid 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 (e.g., 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 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 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 SWR Process was developed to incorporate relatively complex surface-water problems. Also, the 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 FMP 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, come with greater potential error (uncertainty). By contrast, MODFLOW's FMP 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, open-source 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 graphical user interfaces 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.

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12.0 APPENDIX C: GROUNDWATER MODEL REVIEW CHECKLIST

Table C1. Groundwater Model Review Checklist

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

Question	Yes/No
1. Are the model objectives clearly stated?	☐ Yes ☐ No
2. Are the objectives satisfied and consistent with the model confidence level classification (CLC)?	☐ Yes ☐ No
3. Is the conceptual model based on all quality-assured data and reviewed by a third-party reviewer?	☐ Yes ☐ No
4. Is the conceptual model consistent with the model objectives and CLC?	☐ Yes ☐ No
5. Does the model design follow the model development framework and address all concerns raised during review?	☐ Yes ☐ No
6. Does the model calibration meet predefined model objectives?	☐ Yes ☐ No
7. Are the calibrated model parameter values and estimated fluxes plausible and is rationale for their use well documented?	☐ Yes ☐ No
8. Do the model predictions conform to the model development framework?	☐ Yes ☐ No
9. Is the uncertainty associated with the predictions reported?	☐ Yes ☐ No
10. Is the model being used for its intended purpose?	☐ Yes ☐ No

About the Author

Tara Moran, Sustainable Groundwater Program Lead at Stanford's Water in the West program, researches the technical requirements of water management, including data collection, sharing and integration. Moran is particularly interested in understanding the role of data and information in water management decisions. She works with interdisciplinary research teams to develop solutions to the legal, technical and governance challenges of sustainable groundwater management. Tara holds a first class honors B.Sc. in Environmental Science and a Ph.D. in Geography from the University of Calgary, Canada.

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