

California Department of Water Resources
Best Management Practices for the Sustainable Management of Groundwater

DRAFT
Modeling
Best Management Practice



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Modeling Best Management Practice

1. OBJECTIVE

The objective of this *Best Management Practice* (BMP) is to provide technical assistance on the use and development of groundwater and surface water models (with an emphasis on the groundwater modeling processes) in accordance with the Groundwater Sustainability Plan (GSP) Emergency Regulations (Regulations) that supports the long-term sustainability of the *basin* under the Sustainable Groundwater Management Act (SGMA). Information provided in this BMP is meant to provide technical assistance to Groundwater Sustainability Agencies (GSAs) and other stakeholders on how to address modeling requirements outlined in the Regulations, including identifying available resources to support the development of groundwater and surface water models (models).

This BMP includes the following sections:

1. [Objective](#). The objective and outline of the contents of this BMP.
2. [Use and Limitations](#). A description of the use and limitation of this BMP.
3. [Modeling Fundamentals](#). A description of fundamental modeling concepts.
4. [Relationship of modeling to other BMPs](#). A description of how modeling relates to other BMPs and is a tool used to develop other GSP requirements.
5. [Technical Assistance](#). A description of technical assistance to support the development of a model, potential sources of information, and relevant datasets that can be used to further define each component.
6. [Key Definitions](#). Definitions relevant for this BMP as provided in the GSP Regulations, Basin Boundary Regulations, and the SGMA.
7. [Related Materials](#). References and other materials that provide supporting information related to the development of models.

2. USE AND LIMITATIONS

BMPs developed by the Department are intended to provide technical guidance to GSAs and other stakeholders. Practices described in these BMPs do not replace or serve as a substitute for the GSP Regulations, nor do they create new requirements or obligations for GSAs or other stakeholders. While the use of BMPs is encouraged, adoption of BMPs does not guarantee that a GSP will be approved by the Department.

3. MODELING FUNDAMENTALS

As modified from Barnett and others (2012), a model is any computational method that represents an approximation of the surface water and groundwater system. While models are, by definition, a simplification of a more complex reality, they have proven to be useful tools

over several decades for addressing a range of groundwater problems and supporting the decision-making process.

Surface water and groundwater systems are affected by natural processes and human activity, and require targeted and ongoing management to maintain the condition of surface water and groundwater resources within acceptable limits, while providing desired economic and social benefits. *Sustainable groundwater management* and policy decisions must be based on knowledge of the past and present behavior of the surface and groundwater system, the likely response to future changes, and the understanding of the *uncertainty* in those responses.

The location, timing and magnitude of hydrologic responses to natural or human-induced events depend on a wide range of factors—for example, the nature and duration of the event that is impacting groundwater, the subsurface properties and the connection with surface water features such as rivers and oceans. Through observation of these characteristics a conceptual understanding of the system can be developed, but often observational data is scarce (both in space and time), so understanding of the system remains limited and uncertain.

Models provide additional insight into the complex system behavior and (when appropriately designed) can assist in developing conceptual understanding. Furthermore, they can estimate and reasonably bound future groundwater conditions, support decision-making, and allow the exploration of alternative management approaches. However, there should be no expectation of a single ‘true’ model exists and all models and model results will have some level of uncertainty. As such, another valuable role that models can play is providing decision-makers an estimate of the predictive uncertainty that exists in model forecasts. By gaining a sense of the magnitude of the uncertainty in model predictions, decision makers can better accommodate the reality that all model results are imperfect forecasts and actual basin responses to management actions will vary from those predicted by modeling.

GENERAL TYPES OF MODELS AND MODELING SOFTWARE

There are various modeling approaches, methods, and modeling software that can be used for GSP development and implementation. This section provides a general description of a few widely used types of models and the variety of software typically used for modeling. These model types are not mutually exclusive: for example an integrated groundwater and surface water model can also be a numerical model. Each GSA is responsible for determining the appropriate modeling method, software, and the level of detail needed to demonstrate that *undesirable results* can be avoided and the *sustainability goal* in each basin is likely to be achieved within 20 years of *GSP implementation*. A table of currently available modeling codes and applications is provided in Appendix A.

TYPES OF MODELS

Conceptual Models

A conceptual model is often considered the first step in developing a mathematical model. A conceptual model includes a narrative interpretation and graphical representation of a basin based on known characteristics and current management actions. Conceptual models do not necessarily include quantitative values. For more details on developing a conceptual model, please refer to the Hydrogeologic Conceptual Model (HCM) BMP.

Mathematical Models

A model that simulates *groundwater flow* or solute transport by solving an equation, or series of equations, that reasonably represents the physical flow and transport processes is referred to as a mathematical model. Mathematical models differ from conceptual models in that they are capable of providing quantitative estimates of the *water budget* components. Mathematical models are often divided into two categories: analytical and numerical models or tools.

Analytical Models and Tools

Analytical models generally require assumptions that significantly simplify the physical system being evaluated. For example, physical boundary conditions are generally omitted in these solutions, and aquifer properties are often required to be homogeneous and isotropic. The physical configuration of the management action is also typically idealized for the purposes of analysis and therefore influences related to project geometry are ignored. Often only one component (a measured or simulated value or relationship) of the groundwater system is evaluated at a time, and this approach omits the evaluation of potential interactions with other components. For example, a spreadsheet could use a simple equation to estimate the aquifer drawdown in one location based on pumping at another location, without considering the potential influence on nearby streams. Therefore, the applicability of this approach is limited to basins with less complex hydrologic conditions or groundwater use that can be more easily idealized for this type of analysis.

Numerical Models and Tools

Numerical modeling tools are widely used in groundwater flow and contaminant transport analysis to evaluate the change to the groundwater system due to changes in external stresses related to the implementation of management actions. These numerical models allow for a more realistic representation of the physical system, including geologic layering, complex boundary conditions, and stresses due to pumping and recharge and land use demands. GSP development for complex basins with significant groundwater withdrawals and/or surface water-groundwater interaction will likely require the use of a numerical groundwater model to demonstrate that the GSP will avoid undesirable results and achieve the sustainability goal within the basin. Several of the available modeling codes and associated applications are discussed in more detail in Appendix A.

Integrated Groundwater and Surface Water Models

A fully integrated surface water and groundwater model refers to a suite of codes that jointly solve the numerical solutions for surface flows and groundwater heads together. Many models include the ability to simultaneously simulate streamflow and its interconnection with the aquifer system.

Coupled Groundwater and Surface Water Models

A coupled groundwater and surface water model refers to the use of separate models for the surface water and the groundwater systems. Coupled models are set up such that the solution from one model (i.e., surface water modeling output) can be used as input into the second model (i.e., groundwater model) to solve the groundwater flow equations and to consider the stresses (boundary conditions) imposed by the surface water information.

Contaminant Transport Models

Contaminant transport model codes add a layer of complexity beyond what is provided by groundwater flow models. These models allow for the assessment of the potential migration of existing contaminant plumes due to management actions, or the resulting groundwater quality over time after a remediation project is implemented. These types of models are not as widely used for water resources planning, but need to be considered for basins in which existing contamination plumes impair the use of groundwater as the source of supply and/or affect other areas of the basin.

TYPES OF MODELING SOFTWARE

Groundwater modeling typically requires the use of a number of software types, including the following (modified from Barnett and others, 2012):

- The model code that solves the equations for groundwater flow and/or solute transport, sometimes called simulation software or the computational engine
- A graphical user interface (GUI) that facilitates preparation of data files for the model code, runs the model code and allows visualization and analysis of results (model predictions)
- Software for processing spatial data, such as a geographic information system (GIS), and software for representing hydrogeological conceptual models
- Software that supports model calibration, sensitivity analysis and uncertainty analysis
- Programming and scripting software that allows additional calculations to be performed outside or in parallel with any of the above types of software

Some software is public domain and open source (freely available and able to be modified by the user) and some is commercial and closed (proprietary design that is only available in an executable form that cannot be modified by the user).

Some software fits several of the above categories; for example, a model code may be supplied with its own GUI or a GIS may be supplied with a scripting language. Some GUIs support one model code while others support many.

COMMON MODEL USES

The following provides a partial list of general and SGMA-related uses for models:

General Uses (modified from Barnett and others, 2012)

- Improving hydrogeological understanding (synthesis of data)
- Aquifer simulation (evaluation of aquifer behavior)
- Calculating and verifying water budget components, such as recharge, discharge, change in storage and the interaction between groundwater and surface water systems (water resources assessment)
- Predicting impacts of alternative hydrological or development scenarios (to assist decision-making)
- Managing resources (assessment of alternative policies)
- Sensitivity and uncertainty analysis (to guide data collection and risk-based decision-making)
- Visualization (to communicate aquifer behavior)
- Providing a repository for information and data that influence groundwater conditions

GSP-Related Uses

- Developing an understanding and assessment of how historical conditions concerning hydrology, water demand, and surface water supply availability or reliability have impacted the ability to operate the basin within *sustainable yield*.
- Assessing how annual changes in historical inflows, outflows, and changes in basin storage vary by water year type (hydrology) and water supply reliability.
- Evaluating how the surface and groundwater systems respond to the annual changes in the water budget inflows and outflows.
- Identifying which management actions and water budget situations commonly result in overdraft conditions or undesirable results.
- Estimating the sustainable yield for the basin.
- Evaluating the effect of proposed projects and management actions on achieving the sustainability goal for the basin.
- Evaluating future scenarios of water demand uncertainty associated with projected changes in local land use planning, population growth, and climate.
- Informing monitoring requirements.
- Informing development and quantification of sustainable management criteria, such as the sustainability goal, undesirable results, *minimum thresholds*, and measurable objectives.
- Helping identify potential projects and management actions to achieve the sustainability goal for the basin within twenty years of GSP implementation.

- Identifying *data gaps* and uncertainty associated with key water budget components and model forecasts, and developing an understanding of how these gaps and uncertainty may affect implementation of proposed projects and water management actions.

MODELS IN REFERENCE TO THE GSP REGULATIONS

Developing and applying models to aid in sustainable groundwater management yields multiple benefits to GSAs and stakeholders. The process of constructing and calibrating the model improves understanding of the critical processes that influence *sustainability indicators* within the basin. The application of the model to forecast the influence of projects and management actions on basin conditions provides a framework within which a GSA can screen and select appropriate projects and management actions that lead to the achievement of the sustainability goal for the basin. Additionally, models can play a critical role in simulating the changing climate conditions that may occur during the 50-year planning and implementation horizon required under SGMA. It should be noted that in general, groundwater and surface water models are more effective at comparing the benefits and impacts of various management strategies with respect to one another rather than to predict exact management outcomes. So while a model can assist in selecting the best alternative from a variety of options, uncertainty will still remain in the forecasted outcome of a particular alternative, and adaptive management will always be a necessary component of program implementation.

A significant consideration that must be addressed by all GSAs is whether modeling is necessary or required for developing and implementing its GSP. In most basins, the spatial and temporal complexity of the data will require some application of modeling to accurately assess the individual and cumulative effects of proposed projects and management actions on avoiding or eliminating undesirable results and achieving the basin's sustainability goal. It is each GSA's role to carefully consider if changing basin conditions and proposed projects and management actions have the potential to trigger undesirable results within the basin or in adjacent basins, and whether a model is necessary to demonstrate that the proposed projects and management actions will achieve the sustainability goal. Therefore, the use of models for developing a GSP is highly recommended, but not required. The use of a model will ultimately depend on the individual characteristics and complexity of the *basin setting*, the presence or absence of undesirable results, and the presence or absence of *interconnected surface water* systems. As stated in Regulation sections 354.18 (f) and 354.28(c)(6), "if a numerical groundwater and surface water model is not used to quantify the water budget and depletions of interconnected surface water, the GSP shall identify and describe an equally effective method, tool, or analytical model to accomplish these requirements".

Similar to the question of whether or not models should be used during GSP development is the question of the appropriate level of model complexity. Simple models are often less expensive, have shorter run times, and have the advantage of focusing on a single undesirable result. However, simple models may overlook important system components, be difficult to calibrate to historical data, and therefore carry unacceptable levels of uncertainty. Complex models can

incorporate more data and professional judgment, and therefore often result in better calibration. However, complex models are more expensive and difficult to build, and the complexity can lead to a false impression of accuracy. It may be possible to use complex models to assess certain undesirable results, and simple models to assess other undesirable results. Some guidance on what might influence model complexity is provided in the modeling considerations section of this BMP.

While models are useful and often invaluable tools for understanding a basin and predicting future basin conditions, in most cases, they are not the means for demonstrating that a basin has met its sustainability goal. Satisfactorily demonstrating that all undesirable results have been avoided, and the sustainability goal has been met, will be a function of the data collected and reported during GSP implementation.

4. RELATIONSHIP OF MODELING TO OTHER BMPs

The purpose of modeling in the broader context of SGMA implementation include supporting the development of the water budget, establishment of the Sustainable Management Criteria (sustainability goal, undesirable results, minimum thresholds, and *measurable objectives*), supporting identification and development of potential projects and management actions to address undesirable results that exist or are likely to exist in the future, and supporting the refinement of the monitoring network in the basin over time. Modeling is also linked to other related BMPs as illustrated in **Figure 1**. This figure provides the context of the BMPs as they relate to the various steps to sustainability as outlined in the Regulations. The modeling BMP is part of the planning step in the Regulations.

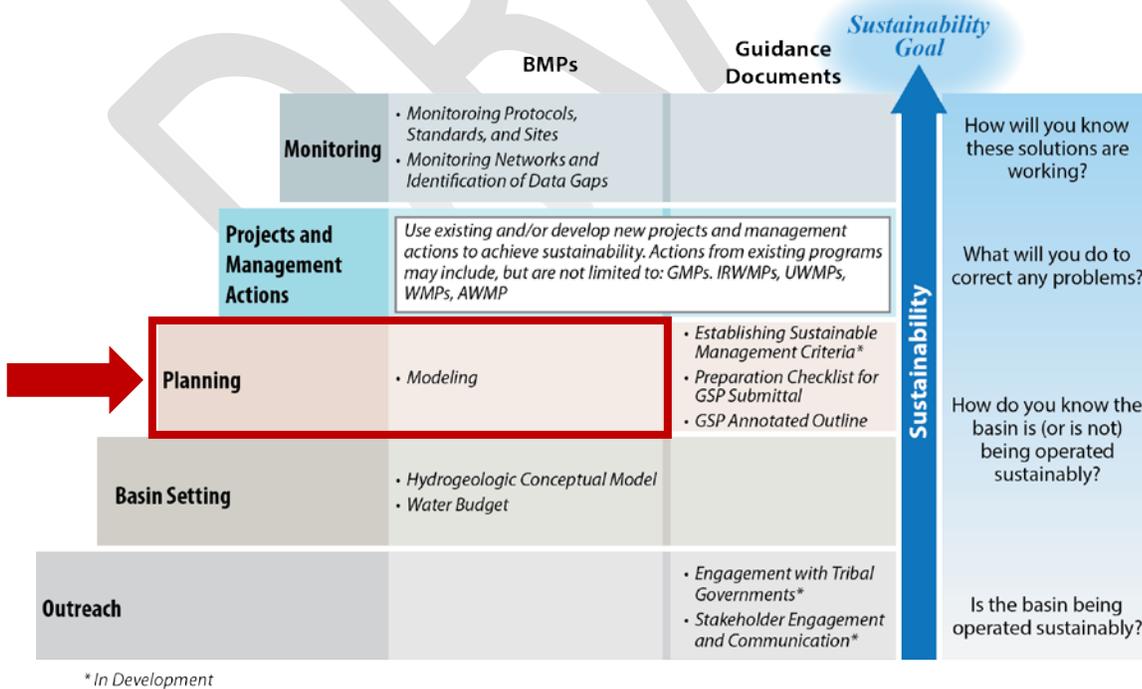


Figure 1 - Steps to Sustainability under SGMA

5. TECHNICAL ASSISTANCE

This section provides technical assistance and guidance to support the development of models under SGMA and the GSP Regulations, including potential sources of information and relevant datasets that can be used to develop and implement the various modeling components.

GUIDING PRINCIPLES FOR MODELS USED IN SUPPORT OF GSPs

The Department is providing the following four modeling principles to help foster SGMA's intent to promote transparency, coordination, and data sharing; to help guide GSAs in their selection and use of models for sustainable groundwater management; and to help expedite Department review of GSP-related modeling analysis and findings.

1. Model documentation (explanation of code, algorithms, input parameters, calibration, output results, and user instructions) is publicly available at no cost. In particular, the model documentation should explain how the mathematical equations were derived from physical principles and solved, and any guidance on limitations of the model code.
2. The mathematical foundation and model code have been peer reviewed for the intended use. Peer review is not intended to be a "stamp-of-approval" or disapproval of the model code. Instead, the goal of peer review is to inform stakeholders, and decision-makers as to whether a given model code is a suitable tool for the selected application, and whether there are limits on the temporal or spatial uses of the model code, or other analytic limits.
3. The GSP descriptions of the site-specific model assumptions, input parameters, calibration, application scenarios, and analytical results demonstrate that the quantification of the forecasted water budget, sustainable management criteria (sustainability goal, undesirable results, minimum thresholds, and measurable objectives), proposed projects and management actions are reasonable and within the range of identified uncertainties, to evaluate the GSP-identified outcomes of sustainability for the basin.
4. If requested, a free working copy of the complete modeling platform is provided to DWR for further evaluation and verification.

GENERAL MODELING REQUIREMENTS

352.4(f) Groundwater and surface water models used for a Plan shall meet the following standards:

- (1) The model shall include publicly available supporting documentation.*
- (2) The model shall be based on field or laboratory measurements, or equivalent methods that justify the selected values, and calibrated against site-specific field data.*
- (3) Groundwater and surface water models developed in support of a Plan after the effective date of these regulations shall consist of public domain open-source software.*

The intent of requiring standards for models in the Regulations is to promote a consistent and sound approach to the development and coordination of models in California, which will allow DWR to evaluate these models and related GSPs within basins and between basins across the state. A description of the specific modeling standards listed in §352.4(f) is provided below.

(1) The model shall include publicly available supporting documentation.

Models used for a GSP are required to provide publicly available supporting documentation in the form of:

1. An explanation of the modeling code, the physical processes simulated by the code, associated mathematical equations, and assumptions, which are typically found in publicly available user instructions or manuals. This information should be referenced by the model user in their documentation of the model application.
2. A description of the model application, including the construction of the model by the GSA that describes model development, assumptions, data inputs, boundary conditions, calibration, uncertainty analysis, and other applicable model application elements. This documentation should be a component of a GSP, and included as an appendix to characterize the technical work that went into developing and applying the model for GSP development and implementation. The California Water and Environmental Modeling Forum (CWEMF) has developed a framework for documenting and archiving a groundwater flow model application that can be tailored for GSA use (CWEMF, 2000).

(2) The model shall be based on field or laboratory measurements, or equivalent methods that justify the selected values, and calibrated against site-specific field data.

The development of a mathematical model starts with assembling applicable information relevant to the basin or site-specific characteristics. A detailed HCM forms the basis of the model by providing relevant physical information of the aquifer and surface systems, as well as applicable boundary conditions of the basin and stressors (such as pumping and artificial recharge). Previous field evaluations, studies and literature may provide additional data for the model development. For more site-specific information, field testing can be performed, such as targeted aquifer tests to determine parameters such as hydraulic conductivity, transmissivity, and storage coefficients. In addition, field tests allow for the calibration of the model to field data. In addition, calibration of the model should be performed by comparing simulated values to observed field data (water levels, groundwater flow directions, groundwater discharge rates, water quality concentrations). Additional information on these topics is provided below in the modeling considerations and modeling process sections.

(3) Groundwater and surface water models developed in support of a Plan after the effective date of these regulations shall consist of public domain open-source software.

Public domain codes published through government agencies like DWR, the U.S. Army Corps of Engineers Hydrologic Engineering Center, and United States Geological Survey (USGS) are often widely distributed, relatively inexpensive, and generally accepted models with features that can be and have been used to simulate a wide range of hydrogeological conditions. Public domain codes, including many listed in Appendix A, have received extensive peer review, and case histories documenting their general applicability; and their limitations have been published in the scientific literature. Many were originally developed, and are continually being refined, by government agencies such as DWR and the USGS. Proprietary codes may share many attributes with public domain codes; however the source code is not generally available for review, they require the purchase of a license to use the software, and the peer review may be limited.

The regulations require that all new models developed in support of a GSP after the effective date of the regulations (August 15, 2016) use public domain open-source software to promote transparency and expedite review of models by the Department. The requirement to use public domain open-source software allows for different agencies, stakeholders, and the Department to view input and output data without using a proprietary model, and may help encourage collaborative actions and data sharing that could lead to increased coordination within and between basins. Models developed and actively used in groundwater basins prior to the GSP Regulations effective date can be used for GSP development and implementation, even if they do not use public domain and open-source software as shown in **Figure 2**.

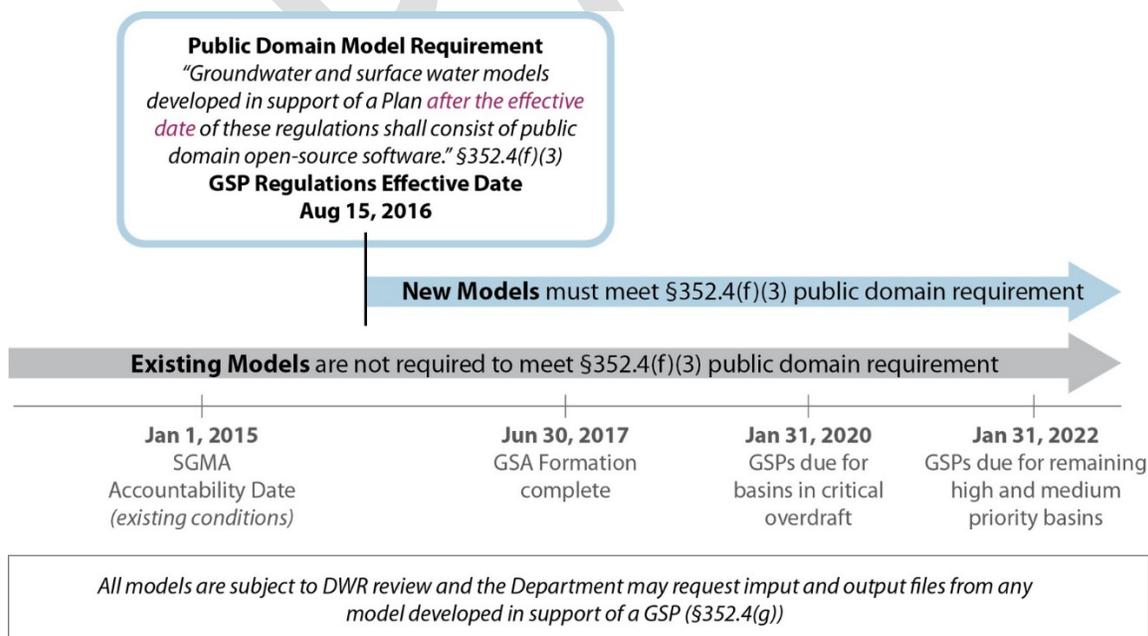


Figure 2 - GSP Regulations Effective Date and Model Development Timeline

The public domain and open-source software requirement only applies to model codes that solve the equations for groundwater flow and contaminant transport, and does not apply to other supporting software used to generate model input files or process model output data (such as Microsoft Excel, various GUIs, or GIS mapping software). In addition, the public domain and open-source software requirement does not apply to other watershed evaluation models or tools that provide input to the model or GSP including estimates of runoff, irrigation demand (if calculated outside the groundwater model), municipal demand (if calculated outside the groundwater model), or other related models.

352.4(g) The Department may request data input and output files used by the Agency, as necessary. The Department may independently evaluate the appropriateness of model results relied upon by the Agency, and use that evaluation in the Department's assessment of the Plan.

All models are subject to DWR review and DWR may request input and output files from any model developed in support of a GSP.

MODELING CONSIDERATIONS

A model should be selected and developed that provides specific information in support of developing a GSP. Examples of the GSP needs that should be considered when selecting and developing a model are included below.

Addressing Sustainability Indicators

The management of each sustainability indicator poses unique technical challenges. Each GSA will need to characterize the current and projected status of each sustainability indicator in the basin, and identify the point at which conditions in the basin cause undesirable results. Models must be selected and developed that provide GSAs ample information about the future condition of each sustainability indicator relevant to the basin, and the GSA's ability to avoid undesirable results and achieve the Sustainability Goal in the basin.

The need to model each sustainability indicator will be specifically related to the current and potential presence and magnitude of undesirable results in the basin. As the magnitude and distribution of undesirable results increases, the complexity associated with adequately identifying appropriate projects and management actions to achieve sustainability may surpass the ability of simple analytical tools and lead towards the need to apply more complex numerical modeling techniques. Models are also tools that can help establish the Sustainable Management Criteria. Specific modeling considerations for each of the sustainability indicators are described below.

Lowering of Groundwater Levels

One of the most common effects of unsustainable groundwater management is the chronic lowering of groundwater levels. While an assessment of current and/or historic groundwater

pumping on groundwater levels can be performed based on groundwater level measurements, forecasting future conditions that may differ from historic conditions will likely require the development of a model. All models are capable of predicting the effects of groundwater pumping on groundwater levels and, therefore, forecasts of groundwater level impacts due to basin management actions are readily available from any model of adequate detail and complexity. Addressing this sustainability indicator does not promote or exclude any particular models. Instead, the GSA should assess which modeling tool will provide estimates of groundwater levels at the appropriate spatial distribution to support GSP development and implementation.

Reduction of Groundwater Storage

Estimates of changes in groundwater storage volume can be computed based on observed groundwater level changes, along with knowledge of the geometry and hydraulic and hydrogeologic properties of the aquifer system. Therefore, historical changes in groundwater storage can be estimated from aquifer and groundwater monitoring data. However, forecasting future storage changes due to projects and management actions will likely require a modeling tool of some type. All transient groundwater models are capable of computing changes in groundwater storage within a basin due to particular management actions and, therefore, estimating change in groundwater storage is readily available from any transient model of adequate detail and complexity. Addressing this sustainability indicator does not promote or exclude any particular model. Instead, the GSA should assess which modeling tool will provide estimates of groundwater storage changes at the appropriate spatial distribution and accuracy to support GSP development and implementation.

Seawater Intrusion

Basins adjacent to the ocean or parts of the Sacramento Delta are susceptible to seawater intrusion. Seawater intrusion into a freshwater aquifer due to future groundwater pumping under changing climate, sea levels, population and land use is a complex process that very likely will need to be addressed with a model. If seawater intrusion may be a threat to long-term groundwater quality in a basin, then the model code or codes (see Appendix A) selected to support basin management must be capable of simulating the effects of density-driven flow in groundwater and should be capable of simulating groundwater quality over time.

Degraded Water Quality

In basins with impaired water quality, the GSP's projects and management actions could redirect the impaired groundwater towards municipal or other water supply wells. In these basins, the model code or codes (see Appendix A) should be capable of simulating the extent and flow direction of the impaired groundwater. This could require a model with particle tracking capabilities or a model with chemical transport capabilities. To satisfy the requirement that an open-source public domain flow model code be used for all new models under SGMA, groundwater quality will likely be simulated with open source particle tracking or transport codes that can be coupled to the flow model, such as PATH3D or MT3D.

Land Subsidence

Groundwater basins may be subject to subsidence from groundwater pumping. In these basins, the GSA should implement a model code or codes (see Appendix A) capable of accurately simulating significant groundwater level changes over time and the resulting potential for drawdown-induced subsidence. If the amount of groundwater released by subsidence could be significant, the GSA may want to select a model code that incorporates land subsidence directly into the groundwater flow process. If the amount of groundwater released by subsidence is not significant, future subsidence could be estimated with simpler, one-dimensional calculations that are external to the groundwater flow model.

Depletion of Interconnected Surface Water

354.28 (b) *The description of minimum thresholds shall include the following:*

(1) The information and criteria relied upon to establish and justify the minimum thresholds for each sustainability indicator. The justification for the minimum threshold shall be supported by information provided in the basin setting, and other data or models as appropriate, and qualified by uncertainty in the understanding of the basin setting.

...

(6) Depletions of Interconnected Surface Water. The minimum threshold for depletions of interconnected surface water shall be the rate or volume of surface water depletions caused by groundwater use that has adverse impacts on beneficial uses of the surface water and may lead to undesirable results. The minimum threshold established for depletions of interconnected surface water shall be supported by the following:

(A) The location, quantity, and timing of depletions of interconnected surface water.

(B) A description of the groundwater and surface water model used to quantify surface water depletion. If a numerical groundwater and surface water model is not used to quantify surface water depletion, the Plan shall identify and describe an equally effective method, tool, or analytical model to accomplish the requirements of this Paragraph.

Depletion of interconnected surface water occurs when groundwater levels decline beneath a surface water system that is hydraulically connected at any point by a continuous saturated zone between the underlying aquifer and the overlying surface water system. The pattern of surface water depletion can be complex, both spatially and temporally, depending on the characteristics of the stream sediments and the distribution of drawdown in the underlying aquifer system. If groundwater in a basin is in hydraulic connection with the surface water system, the selected model code or codes (see Appendix A) used to evaluate basin sustainability must be capable of accurately depicting the effects of changing groundwater levels and stream stages on the resulting depletion of interconnected surface water. This objective could be met by either using a fully-integrated surface water/groundwater model, or coupling a groundwater flow model with an external set of equations or surface water model that can adequately simulate the surface water depletion from groundwater management activities.

If a numerical groundwater and surface water model is not used to quantify surface water depletions, an equally effective method, tool, or analytical model must be identified and described in the GSP (§354.28(b)(6)(B)).

Developing Water Budgets

354.18 (e) Each Plan shall rely on the best available information and best available science to quantify the water budget for the basin in order to provide an understanding of historical and projected hydrology, water demand, water supply, land use, population, climate change, sea level rise, groundwater and surface water interaction, and subsurface groundwater flow. If a numerical groundwater and surface water model is not used to quantify and evaluate the projected water budget conditions and the potential impacts to beneficial uses and users of groundwater, the Plan shall identify and describe an equally effective method, tool, or analytical model to evaluate projected water budget conditions.

(f) The Department shall provide the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM) and the Integrated Water Flow Model (IWFM) for use by Agencies in developing the water budget. Each Agency may choose to use a different groundwater and surface water model, pursuant to Section 352.4.

Groundwater and surface water models are useful tools to develop water budgets as they have the ability to account for all inflows and outflows to the basin and estimate changes in storage over time. Specifically, a model can be used to predict water budgets under future conditions and climate change, as well as with the inclusion of management scenarios. The Water Budget BMP includes more details on the development of surface water and groundwater budget and the associated required components.

If a numerical groundwater and surface water model is not used to quantify and evaluate the projected water budget conditions, an equally effective method, tool, or analytical model must be identified and described in the GSP (§354.18(e)).

Forecasting Future Conditions

One significant and important benefit of using a model is the computational ability to forecast and evaluate multiple basin conditions over time. Any modeling approach should be capable of readily simulating reductions in available surface water supplies, changes in land use and associated water demands, or the effects of climate change influencing meteorological conditions across the basin.

Assessing Impacts of Potential GSP Projects and Management Actions

Each GSP must demonstrate how the selected projects and management actions will achieve the sustainability goal for the basin within 20 years of GSP implementation. Impacts on sustainability indicators from the various projects and management actions in a GSP can be predicted by an appropriately developed and calibrated model. Model simulations can include a variety of potential projects and management actions, and identify those that appear to be

successful at achieving the sustainability goal for the basin. Furthermore, the model simulations can demonstrate sustainability over the range of climatic patterns that may occur in the future.

GSAAs may additionally want to weigh a number of alternative strategies that can all achieve sustainability and identify those that can be implemented at the lowest cost. The selected model should be accurate and detailed enough to demonstrate the different impacts on various parties from proposed projects and management actions, and allow GSAAs to choose among various alternative strategies.

Identifying Data Gaps and Monitoring Needs

Modeling can help GSAAs identify additional data that could reduce uncertainty in the GSP development and implementation. Models can perform a large number of simulations, each with a different set of hydrogeologic parameters, to assess how the parameter uncertainty affects the ability to achieve sustainability. Results from a model's uncertainty analysis can be used to prioritize data collection activities according to which parameters are most influential on various sustainability indicators. For example, if modeling results indicate that achieving sustainability is heavily dependent on infiltration of surface water, it will be important to focus characterization activities on better understanding the rate and variability of surface water infiltration, and what actions influence these processes.

Uncertainty analysis can provide useful input in the following areas::

- Prioritization of data collection efforts to target key basin characteristics driving the potential for undesirable results with the goal of reducing the level of remaining uncertainty.
- The selection of a reasonable margin of operational flexibility in specifying measurable objectives, minimum thresholds, and proposed projects and management actions, (allowable surface water diversions, pumping quantities, etc.).
- A platform for integrating the uncertainty of the effects of climate change and sea-level rise on sustainable basin operations.

Assessing Impacts on Adjacent Basins

Coordination of modeling efforts between adjacent basins is critical in assessing the current understanding of the basin inflows and outflows, and evaluating the potential effects from projects and management actions in one basin on adjacent basins. For example, boundary flows computed by different models need to be checked for consistency. Boundary conditions and general parameter values for adjacent models are expected to be consistent. Interagency *coordination agreements*, as required under the GSP Regulations (357.4), stress the importance of basin-wide planning and modeling. Interbasin agreements are optional, but are recommended in the GSP Regulations (357.2) to help with establishing a consistent understanding of basin conditions across adjacent basins, and to aid in development of models with consistent assumed properties and boundary conditions. Items that may be affected and need to be coordinated

among adjacent basins relate to existing undesirable results, basin sustainability goals, water budgets, minimum thresholds and measurable objectives, and general land use plans.

Model Adaptability

Modeling to support sustainable groundwater management is an ongoing effort. The initial model developed to support a sustainability assessment must be based on the best available information, the level of expert knowledge about the basin, and the *best available science* at the time of model development. As new data are collected and an improved basin understanding is developed over time, through either additional characterization, monitoring efforts, or both, the predictive accuracy of the model should be improved through a refinement of the underlying model assumptions (aquifer properties, stratigraphy, boundary conditions, etc.), as well as more robust calibration due to a larger database of calibration targets (groundwater levels, surface water flows, a more robust climatic dataset, etc.). The model selected to provide long-term support of a groundwater basin should be able to adapt to refined hydrogeologic interpretations and incorporate additional data.

Incorporating model adaptability allows a GSP to be start with relatively simple models, and add complexity over time. It may be beneficial to initially defer to simple yet adaptable models. As the amount of information and expert knowledge about a basin increases, complexity can be added to these simple models to reduce the amount of predictive uncertainty.

Spatial Extent of the Model

GSPs or multiple GSPs with a coordination agreement are required to be developed for an entire basin. Therefore, to predict whether undesirable results currently exist or may occur in the future, the model should cover the entire basin. Additionally, the model must be capable of evaluating whether the basin's projects and management actions adversely affect the ability of adjacent basins to implement their Plan or achieve and maintain their sustainability goals over the planning and implementation horizon. Important areas of consideration that may call for an expanded model domain are: 1) the ability to simulate the magnitude and variability in the exchange of groundwater and surface water systems between a basin of interest and adjacent groundwater basins; and 2) the ability to simulate boundary conditions that may lie outside of the basin of interest, but still have an influence on the water budget of the basin under consideration.

Data Availability

The availability of basin-specific information may influence model selection and construction. Basins with a large amount of data may support a more complex modeling platform than a basin with a paucity of available data. However, the complexity of the model should be based on the groundwater use and potential issues in the basin.

Importance of Land Use Practices in Agricultural Basins

It is important that models developed for basins with significant agricultural water use be responsive to changes in agricultural practices. These changes may entail changes in crop types, irrigation practices, irrigation water source, or other changes related to land use practices.

Some model codes, such as DWR's Integrated Water Flow Model (IWFm) and the USGS' One Water Hydrologic Model (OWHM) explicitly simulate the effects of changing agricultural practices and surface water uses. Agricultural practices may also be addressed in model pre-processors such as GIS tools or spreadsheets for other model codes.

Model Results Presentation

Models are important tools that can aid with stakeholder engagement and common understanding of the basin, as well as the establishment of sustainable management criteria, and projects and management actions, through the presentation of outputs in graphical and mapping formats. Using model results in coordination with HCM graphical representations provides a means of communication with interested parties in the basin by providing detailed basin information.

Models developed for management support should provide clear information to decision makers, and must be capable of efficiently and effectively conveying simulation output in a format that is understandable by a wide variety of stakeholders with varying levels of technical experience.

GUIs are commercially available for different types of model codes. These GUIs, in addition to other commonly used software such as Microsoft Excel and ESRI's software, are powerful tools to help with processing data into model input formats, more efficiently run models, and provide a platform to visualize model outputs and create figures for stakeholder communication and reporting needs. These GUIs are not part of the model code itself, but are an external software that can be used to make the modeling process more streamlined. Therefore, GUIs do not fall under the "public domain and open source" definition that the model codes need to adhere to per the Regulations.

THE GROUNDWATER MODELING PROCESS

Modeling depends on and reflects the judgement and experience of the groundwater modeler(s). There is no formula or discreet set of steps that will ensure that a model is accurate or reliable. However, there are recommended steps and protocols that groundwater modelers should follow. The general steps are shown graphically in **Figure 3**, and discussed below.

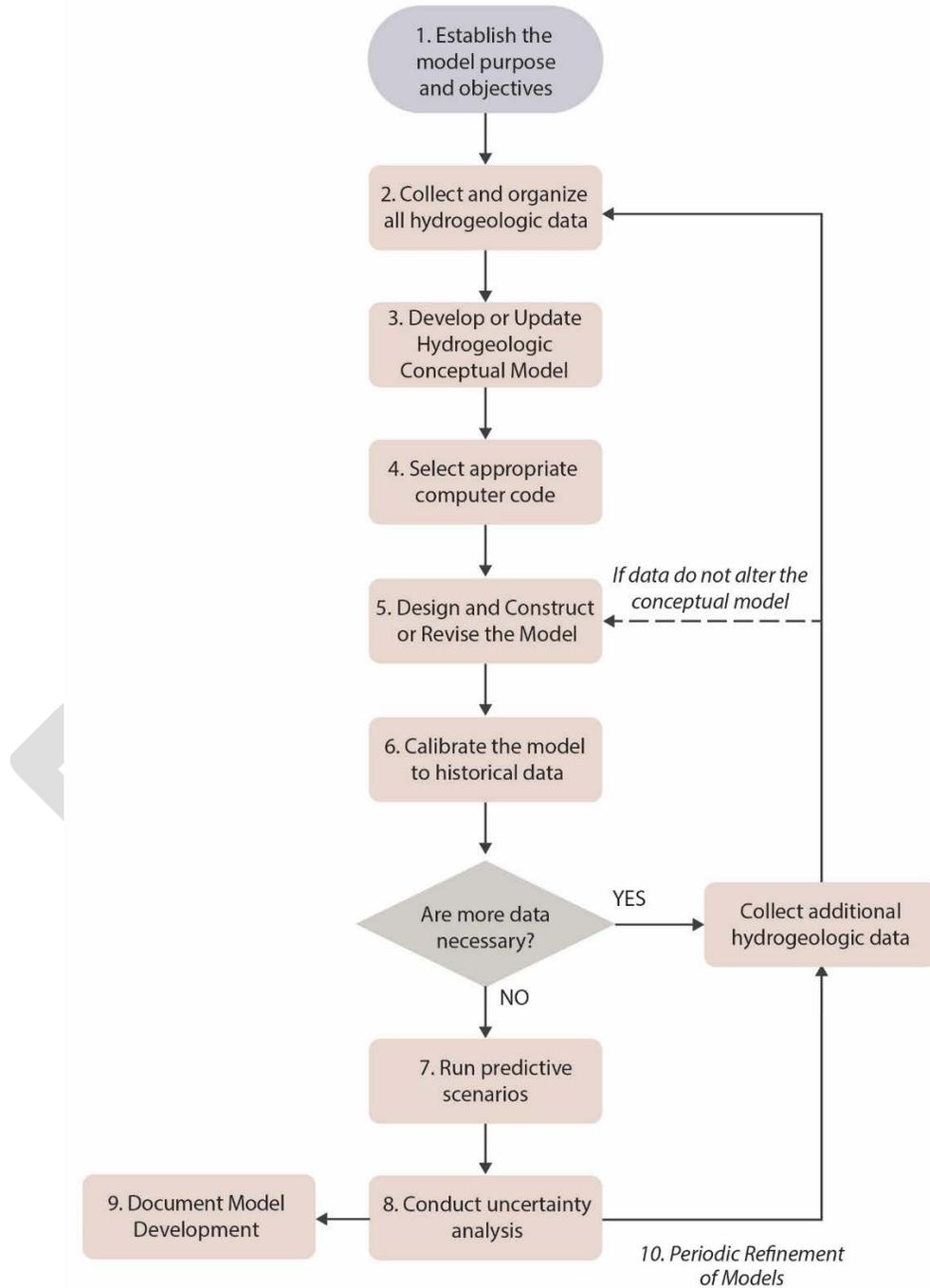


Figure 3: General Modeling Process

1. **Establish the model's purpose and intended use.** Models generally cannot reliably answer all questions about groundwater behavior. For the purposes of SGMA, the GSA should assess which sustainability indicators need to be simulated by the model (or models), and develop the model purpose to address these. GSAs should also establish protocols at this stage for where the model will be housed, how the model will be updated, and the terms of model use by various GSA members. Stakeholder input is an important component of model development. Specifically, during the early planning phase of model development when the purpose and objectives of the model are being considered.
2. **Collect and organize all hydrogeologic data.** The amount of available data and accuracy of available data will drive the complexity and detail included in both the conceptual model and mathematical model. All GSA members should, to the degree possible, provide data of similar accuracy and completeness to ensure that the entire model reflects a similar level of data collection. Raw data collected as part of the basin setting and HCM development should be organized at this stage. Once these data are organized into a database, they are processed into input files for modeling, with specific file formats as required by the chosen code. As an example, the Central Valley Hydrologic Model (CVHM) website has a framework for the organization of the raw data with links to the data sources, as well as related GIS shapefiles and CVHM input files of the processed data (<http://ca.water.usgs.gov/projects/central-valley/central-valley-spatial-database.html>).
3. **Develop a conceptual model of the basin.** A conceptual model allows for the narrative interpretation and graphical representation of a basin based on known characteristics and current management actions. Conceptual models do not necessarily include quantitative values. For more details on developing a conceptual model, please refer to the HCM BMP.
4. **Select the appropriate computer code.** The selected computer code must be able to simulate all the processes that might significantly influence the various sustainability indicators. However, modelers should practice pragmatism and avoid unnecessary model complexity. For example, it may be practical to analyze future land subsidence with one-dimensional analytical calculations, rather than selecting a three-dimensional model that includes land subsidence.

In many basins, there may be one or multiple existing models already in use. It is preferable to avoid competing models that perform similar functions in a single basin. The GSA should compare existing models, and decide if one of these models is better suited to GSP development and implementation. The following figure provides a flowchart that may aid in the comparison and selection of an appropriate model if multiple models exist in a basin. In addition, an interactive map of a select number of

existing, available, model applications in California is available at the following link: <https://gis.water.ca.gov/app/gicima/> (in development, not currently available).

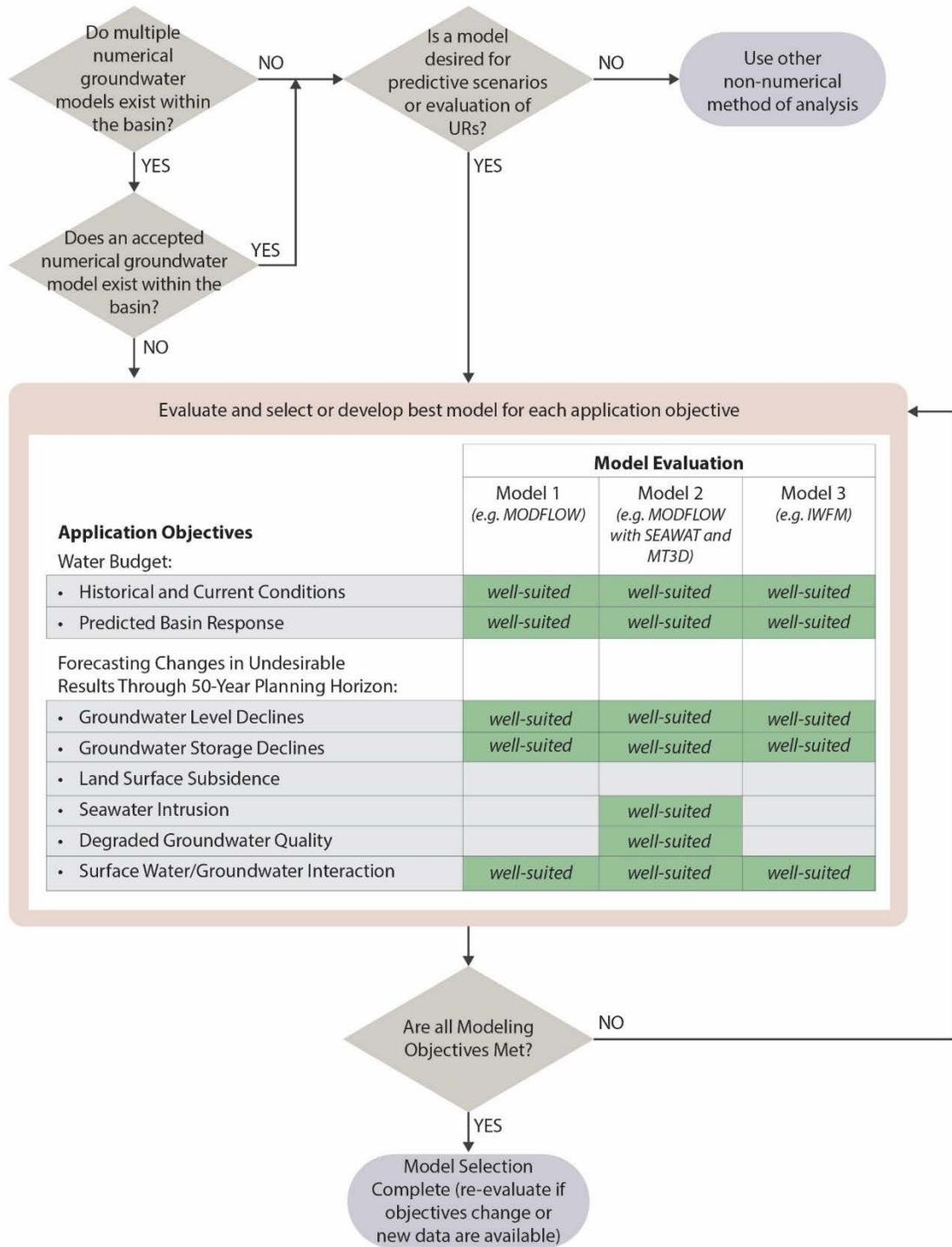


Figure 4: Model Code Selection Flowchart

5. **Design and construct the model.** In this step, the conceptual model developed in step three is implemented in the selected model code. This step includes developing model layers, developing the model grid, populating the model with hydrogeologic parameters, developing boundary conditions, and adding water budget components to the model. Models should maintain simplicity and parsimony of hydrogeologic parameters, while simultaneously simulating the important hydrogeologic details that will drive basin sustainability.
6. **Calibrate the numerical model to historical data.** Model calibration is required by the GSP Regulations (352.4(f)(2)). Calibration is performed to demonstrate that the model reasonably simulates known, historical conditions. Calibration generally involves iterative adjustments of various model aspects until the model results match historical observations within an agreed-to tolerance. Hydrogeologic parameters such as hydraulic conductivity and specific yield are often modified during model calibration. Aspects of the water budget such as recharge rate or pumping depth may also be modified during calibration.

No model is perfectly calibrated, and establishing desired calibration accuracy *a priori* is difficult. One guideline that could be implemented is whether additional calibration would change a GSA's approach to achieving sustainability. If a more accurate model does not change the decision a GSA would make, then additional calibration is not necessary. The USGS has published calibration guidelines (Reilly and Harbaugh, 2004), and other modeling guidelines exist to help estimate calibration adequacy.

7. **Develop and run predictive scenarios** that establish expected future conditions under varying climatic conditions, and implementing various projects and management actions. Predictive scenarios should be designed to assess whether the GSP's projects and management actions will achieve the sustainability goal, and the anticipated conditions at five-year interim milestones. Predictive scenarios for the GSP should demonstrate that the sustainability goal will be maintained over the 50-year planning and implementation horizon.
8. **Conduct a predictive uncertainty analysis to identify the impact of parameter uncertainty on the use of model's ability to effectively support management decisions.** Predictive uncertainty analysis provides a measure of the likelihood that a reasonably constructed and calibrated model can still yield uncertain results that drive critical decisions. It is important that decision makers understand the implications of these uncertainties when developing long-term basin management strategies. As discussed in other sections of this BMP, this type of analysis can also identify high-value data gaps that should be prioritized to improve confidence in model outputs, and yield a tool that has an increased probability of providing useful information to support effective basin management decisions.

9. **Document model code and model application development.** The GSP needs to include documentation on the modeling tools used for the sustainability analysis. This documentation can be provided in the form of a technical appendix to the GSP and should include both information on the model code (referenced from user manuals, for instance) and detailed descriptions of the model application development. Model code information should include an explanation of the modeling code, associated mathematical equations, and assumptions, which is typically found in publicly available user instructions or manuals. This information should be referenced by the model user in their documentation of the model application. The description of the model application should include detailed information on the model conceptualization, assumptions, data inputs, boundary conditions, calibration, sensitivity and uncertainty analysis, and other applicable modeling elements such as model limitations. In addition, all final model files used for decision making in the GSP should be packaged for release to DWR.
10. **Revise model regularly during implementation.** After GSP development and during the implementation of the GSP, new data will be available through monitoring and collection from local agencies. As new data are made available through annual updates and the 5-year review process, models can be updated and refined. These new data will be useful for regular model updates and recalibration to reduce model uncertainties and better assess the future effects of management actions on the basin's sustainability indicators.

6. KEY DEFINITIONS

The key definitions related to surface water and groundwater modeling outlined in this BMP are provided below for reference.

SGMA Definitions ([CALIFORNIA WATER CODE 10721](#)):

- “Basin” refers to a groundwater basin or subbasin identified and defined in Bulletin 118 or as modified pursuant to Chapter 3 (commencing with Section 10722).
- “Coordination agreement” means a legal agreement adopted between two or more groundwater sustainability agencies that provides the basis for coordinating multiple agencies or groundwater sustainability plans within a basin pursuant to this part.
- “Condition of long-term overdraft”: The condition of a groundwater basin where the average annual amount of water extracted for a long-term period, generally 10 years or more, exceeds the long-term average annual supply of water to the basin, plus any temporary surplus. Overdraft during a period of drought is not sufficient to establish a condition of long-term overdraft if extractions and recharge are managed as necessary to

ensure that reductions in groundwater levels or storage during a period of drought are offset by increases in groundwater levels or storage during other periods.

- “Groundwater” refers to water beneath the surface of the earth within the zone below the water table in which the soil is completely saturated with water, but does not include water that flows in known and definite channels.
- “Groundwater recharge” refers to the augmentation of groundwater, by natural or artificial means.
- “Planning and implementation horizon” means a 50-year time period over which a groundwater sustainability agency determines that plans and measures will be implemented in a basin to ensure that the basin is operated within its sustainable yield.
- “Recharge area” is the area that supplies water to an aquifer in a groundwater basin.
- “Sustainability goal” means the existence and implementation of one or more groundwater sustainability plans 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.
- “Sustainable groundwater management” means the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results.
- “Sustainable yield” means 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 an undesirable result.
- “Undesirable result” refers to: One or more of the following effects caused by groundwater conditions occurring throughout the basin:
 1. Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon. Overdraft during a period of drought is not sufficient to establish a chronic lowering of groundwater levels if extractions and recharge are managed as necessary to ensure that reductions in groundwater levels or storage during a period of drought are offset by increases in groundwater levels or storage during other periods.
 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.

- “Water budget” is an accounting of the total groundwater and surface water entering and leaving a basin including the changes in the amount of water stored.
- “Water year” refers to the period from October 1 through the following September 30, inclusive.

Groundwater Basin Boundaries Regulations ([CALIFORNIA CODE OF REGULATIONS 341](#)):

- “GIS”: Geographic Information System that collects, stores, analyzes, and displays spatial or geographically referenced data.
- “Hydrogeologic conceptual model” is a description of the geologic and hydrologic framework governing groundwater flow through and across the boundaries of a basin and the general groundwater conditions in a basin.

Groundwater Sustainability Plan Regulations ([CALIFORNIA CODE OF REGULATIONS 351](#)):

- “Basin setting” refers to the information about the physical setting, characteristics, and current conditions of the basin as described by the Agency in the hydrogeologic conceptual model, the groundwater conditions, and the water budget, pursuant to Subarticle 2 of Article 5.
- “Best available science” means the use of sufficient and credible information and data, specific to the decision being made and the time frame available for making that decision that is consistent with scientific and engineering professional standards of practice.
- “Best management practice” refers to a practice, or combination of practices, that are designed to achieve sustainable groundwater management and have been determined to be technologically and economically effective, practicable, and based on best available science.

- “Data gap” refers to a lack of information that significantly affects the understanding of the basin setting or evaluation of the efficacy of Plan implementation, and could limit the ability to assess whether a basin is being sustainably managed.
- “Groundwater flow” refers to the volume and direction of groundwater movement into, out of, or throughout a basin.
- “Interconnected surface water” refers to surface water that is hydraulically connected at any point by a continuous saturated zone to the underlying aquifer and the overlying surface water is not completely depleted.
- “Interim milestone” refers to a target value representing measurable groundwater conditions, in increments of five years, set by an Agency as part of a Plan.
- “Measurable objectives” refer to specific, quantifiable goals for the maintenance or improvement of specified groundwater conditions that have been included in an adopted Plan to achieve the sustainability goal for the basin.
- “Minimum threshold” refers to a numeric value for each sustainability indicator used to define undesirable results.
- “Plan implementation” refers to an Agency’s exercise of the powers and authorities described in the Act, which commences after an Agency adopts and submits a Plan or Alternative to the Department and begins exercising such powers and authorities.
- “Sustainability indicator” refers to any of the effects caused by groundwater conditions occurring throughout the basin that, when significant and unreasonable, cause undesirable results, as described in Water Code Section 10721(x).
- “Uncertainty” refers to a lack of understanding of the basin setting that significantly affects an Agency’s ability to develop sustainable management criteria and appropriate projects and management actions in a Plan, or to evaluate the efficacy of Plan implementation, and therefore may limit the ability to assess whether a basin is being sustainably managed.

7. RELATED MATERIALS AND KEY DEFINITIONS

The following links provide examples, Standards, and guidance related to modeling. By providing these links, DWR neither implies approval, nor expressly approves of these documents.

STANDARDS

- ASTM D5718-95: Standard Guide for Documenting a Groundwater Flow Model Application.
- ASTM D5880-95: Standard Guide for Subsurface Flow and Transport Modelling.
- ASTM D5981-96: Standard Guide for Calibrating a Groundwater Flow Model Application.

GUIDANCE

Anderson, M.P., and W.W. Woessner, 1992. *Applied groundwater modeling: simulation of flow and advective transport*, Academic Press, 381 p.

Barnett B., L.R. Townley, V. Post, R.E. Evans, R.J. Hunt, L. Peeters, S. Richardson, A.D. Werner, A. Knapton, and A. Boronkay, 2012. *Australian groundwater modelling guidelines*, National Water Commission, Canberra, June, 191 p.

<http://archive.nwc.gov.au/library/waterlines/82>

CWEMF (formerly - Bay-Delta Modeling Forum), 2000, Protocols for Water and Environmental Modeling, <http://www.cwemf.org/Pubs/Protocols2000-01.pdf>

Merz, S.K. 2013. *Australian groundwater modelling guidelines: companion to the guidelines*, National Water Commission, Canberra, July, 31 p.

<http://archive.nwc.gov.au/library/waterlines/82>

Murray–Darling Basin Commission (MDBC) 2001, Groundwater flow modelling guideline, report prepared by Aquaterra, January 2001.

Reilly, T.E., 2001, System and boundary conceptualization in ground-water-flow simulation. Techniques of Water Resources Investigations of the U.S. Geological Survey Book 3, Applications of Hydraulics, Chapter B8, 30 p.

Reilly, T.E., 2001. *System and boundary conceptualization in groundwater flow simulation: Techniques of water resource investigations of the United States geological survey, book 3, applications of hydraulics, Chapter B8*, Reston, VA, 38 p.

http://pubs.usgs.gov/twri/twri-3_B8/

Reilly, T.E., and A.W. Harbaugh, 2004. *Guidelines for evaluating ground-water flow models: USGS scientific investigations report 2004-5038*, Reston, VA, 30 p.

<http://pubs.usgs.gov/sir/2004/5038/PDF.htm>

APPENDIX A - EXISTING MODEL CODES AND MODEL APPLICATIONS

There are many existing model codes and model applications being used in basins throughout the state. DWR and USGS have coordinated and compiled a table (see Appendix A) and interactive map (<https://gis.water.ca.gov/app/gicima/>, *in development, not currently available*) of a select number of existing model codes and model applications in California. Currently, there are two existing, calibrated, and actively updated and maintained model applications that cover the Central Valley aquifer system. A brief description of these models is provided below. Other regional applications of these models have also been developed for specific purposes.

California Central Valley Groundwater-Surface Water Simulation Model (C2VSim)

DWR developed, maintains, and regularly updates C2VSim. It has been used for several large-scale Central Valley studies. C2VSim is an integrated numerical model based on the finite element grid IWFEM that simulates the movement of water through a linked land surface, groundwater, and surface water flow systems. The C2VSim model includes monthly historical stream inflows, surface water diversions, precipitation, land use, and crop acreage data from October 1921 through September 2009. The model simulates the historical response of the Central Valley's groundwater and surface water flow system to historical stresses, and can also be used to simulate response to projected future stresses (DWR, 2016).

http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm

Central Valley Hydrologic Model (CVHM)

CVHM is a three-dimensional numerical groundwater flow model developed by USGS and documented in Groundwater Availability of the Central Valley Aquifer, California (USGS, 2009). CVHM simulates primarily subsurface and limited-surface hydrologic processes over the Central Valley at a uniform grid-cell spacing of 1 mile on a monthly basis using data from April 1961 to September 2003. CVHM simulates surface water flows, groundwater flows, and land subsidence in response to stresses from water use and climate variability throughout the Central Valley. It uses the MODFLOW-2000 (USGS, 2000) finite-difference groundwater flow model code combined with a module called the farm process (FMP) (USGS, 2006) to simulate groundwater and surface water flow, irrigated agriculture, and other key hydrologic processes. It can be used in a similar manner to C2VSim.

<http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html>

Summary of the most commonly used groundwater models in California water resources management.					
Model Code or Application	Description	Download	Documentation	Maintained by	Applicability to SGMA Undesirable Results
MODFLOW	Finite-difference groundwater flow code; several versions available with related modules.	http://water.usgs.gov/ogw/modflow/	Current core version is MODFLOW-2005: <i>USGS. 2005. MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. USGS Techniques and Methods 6-A16</i>	USGS	Groundwater levels Storage Interconnected SW/GW (with certain modules)
CVHM	MODFLOW application for the Central Valley Aquifer.	http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html	United States Geological Survey. 2009. <i>Groundwater Availability of the Central Valley Aquifer, California</i> . U.S. Geological Survey Professional Paper 1766. Groundwater Resources Program. Reston, VA.	USGS	Groundwater levels Storage Interconnected SW/GW Subsidence
MODFLOW - OWHM	MODFLOW based integrated hydrologic flow model (One Water Hydrologic Flow Model).	http://water.usgs.gov/ogw/modflow-owhm/	<i>USGS. 2014, One-Water Hydrologic Flow Model (MODFLOW-OWHM). U.S. Geological Survey Techniques and Methods 6-A51.</i>	USGS	Groundwater levels Storage Interconnected SW/GW Subsidence
<i>MODFLOW-Surfact (MODHMS)</i>	<i>Groundwater flow and transport simulation software based on MODFLOW.</i>	<i>https://www.hgl.com/expertise/modeling-and-optimization/software-tools/modflow-surfact/</i> <i>http://www.ssttechnology.com/novamatrix/index.php?option=com_k2&view=item&id=7:modflow-surfact-flow-and-transport</i>	<i>Panday, S. and Huyakorn, P.S., 2008. MODFLOW SURFACT: A state-of-the-art use of vadose zone flow and transport equations and numerical techniques for environmental evaluations. Vadose Zone Journal, 7(2), pp.610-631.</i>	<i>HydroGeoLogic Inc.</i>	<i>Groundwater levels Storage Interconnected SW/GW Water quality</i>

Summary of the most commonly used groundwater models in California water resources management.					
Model Code or Application	Description	Download	Documentation	Maintained by	Applicability to SGMA Undesirable Results
MT3D	Modular 3-D Multi-Species Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems. Post-processing code to MODFLOW for transport modeling.	http://hydro.geo.ua.edu/mt3d/	Zheng, Chunmiao, 2010, <i>MT3DMS v5.3 Supplemental User's Guide</i> , Technical Report to the U.S. Army Engineer Research and Development Center, Department of Geological Sciences, University of Alabama, 51 p	University of Alabama	Water quality/contaminant plumes
RT3D	Modular Code for Simulating Reactive Multi-species Transport in 3-Dimensional Groundwater Systems. Post-processing code to MODFLOW for transport modeling.	http://bioprocess.pnnl.gov/rt3d.downloads.htm#docs	Clement, P. T., 1997, <i>A Modular Computer Code for Simulating Reactive Multi-species Transport in 3-Dimensional Groundwater Systems</i> , Pacific Northwest National Laboratory	Pacific Northwest National Laboratory	Water quality/contaminant plumes
Path3D	A particle-tracking program for MODFLOW that can simulate advective transport	http://www.sspa.com/software/path3d	Zheng, C., 1992, <i>Path3D, a groundwater pass and travel time simulator</i> , S.S. Papadopulos & Associates, Inc..	S.S. Papadopulos & Associates	Water quality/contaminant plumes
mod-PATH3DU	Groundwater path and travel time simulator for unstructured model grids	http://www.sspa.com/software/mod-path3du	Muffles, C, M. Tonkin, M. Ramadhan, X. Wang, C. Neville, and J.R. Craig, 2016, <i>Users guide for mod-PATH3DU</i> ; a groundwater pass and travel time simulator, S.S. Papadopulos & Assoc. Inc, and the University of Waterloo.	S.S. Papadopulos & Associates	Water quality/contaminant plumes
SEAWAT	MODFLOW MT3D based model designed to simulate three-dimensional variable-density groundwater flow.	http://water.usgs.gov/ogw/seawat/	Langevin, C.D., <i>SEAWAT: a computer program for simulation of variable-density groundwater flow and multi-species solute and heat transport</i> : U.S. Geological Survey Fact Sheet FS 2009-3047, 2 p.	USGS	Seawater intrusion
MODPATH	Particle-Tracking post-processing tool for MODFLOW.	http://water.usgs.gov/ogw/modpath/	USGS. 2012, <i>User guide for MODPATH version 6—A particle-tracking model for MODFLOW</i> : U.S. Geological Survey <i>Techniques and Methods</i> , book 6, chap. A41	USGS	Groundwater flow path tracking for groundwater quality

Summary of the most commonly used groundwater models in California water resources management.					
Model Code or Application	Description	Download	Documentation	Maintained by	Applicability to SGMA Undesirable Results
IWFM	Finite-element code for integrated water resources modeling.	http://baydelt.aoffice.water.ca.gov/modeling/hydrology/IWFM/	DWR, 2016. <i>Integrated Water Flow Model: IWFM -2015, Theoretical Documentation</i> , Central Valley Modeling Unit Support Branch Bay-Delta Office	DWR	Groundwater levels Storage Interconnected SW/GW Subsidence
IDC	Stand-alone executable version of IWFM root zone component (IWFM Demand Calculator).	http://baydelt.aoffice.water.ca.gov/modeling/hydrology/IDC/index_IDC.cfm	DWR, 2016. <i>IWFM Demand Calculator: IDC-2015, Theoretical Documentation and User's Manual</i> , Central Valley Modeling Unit Support Branch Bay-Delta Office	DWR	Land use water budget
C2VSIM	IWFM application for the Central Valley Aquifer.	http://baydelt.aoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSim.cfm	Brush, C.F., and Dogrul, E.C. <i>June 2013</i> . User Manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG.	DWR	Groundwater levels Storage Interconnected SW/GW Subsidence
<i>MicroFEM</i>	<i>Finite-element groundwater flow code.</i>	http://www.microfem.com/	<i>Hemker, C.J., MicroFEM for Windows – Short User's Guide</i>	<i>Dr. C.J. Hemker</i>	<i>Groundwater levels Storage Interconnected SW/GW</i>
<i>SACFEM</i>	<i>MicroFEM application for the Sacramento Valley Groundwater Basin.</i>		<i>USBR. 2015. SACFEM2013: Sacramento Valley Finite Element Groundwater Flow Model User's Manual</i>	<i>CH2M</i>	<i>Groundwater levels Storage Interconnected SW/GW</i>
INFIL 3.0	Watershed model to estimate net infiltration below the root zone.	http://water.usgs.gov/nrp/gwsoftware/infil/Infil.html	U.S. Geological Survey, 2008, Documentation of computer program INFIL3.0-A distributed-parameter watershed model to estimate net infiltration below the root zone: U.S. Geological Survey Scientific Investigations Report 2008-5006.	USGS	

Notes:

Models highlighted in red and italicized are currently proprietary but may be allowed if these models were developed and used prior to the effective date of the regulations. This list does not contain all available models in California.