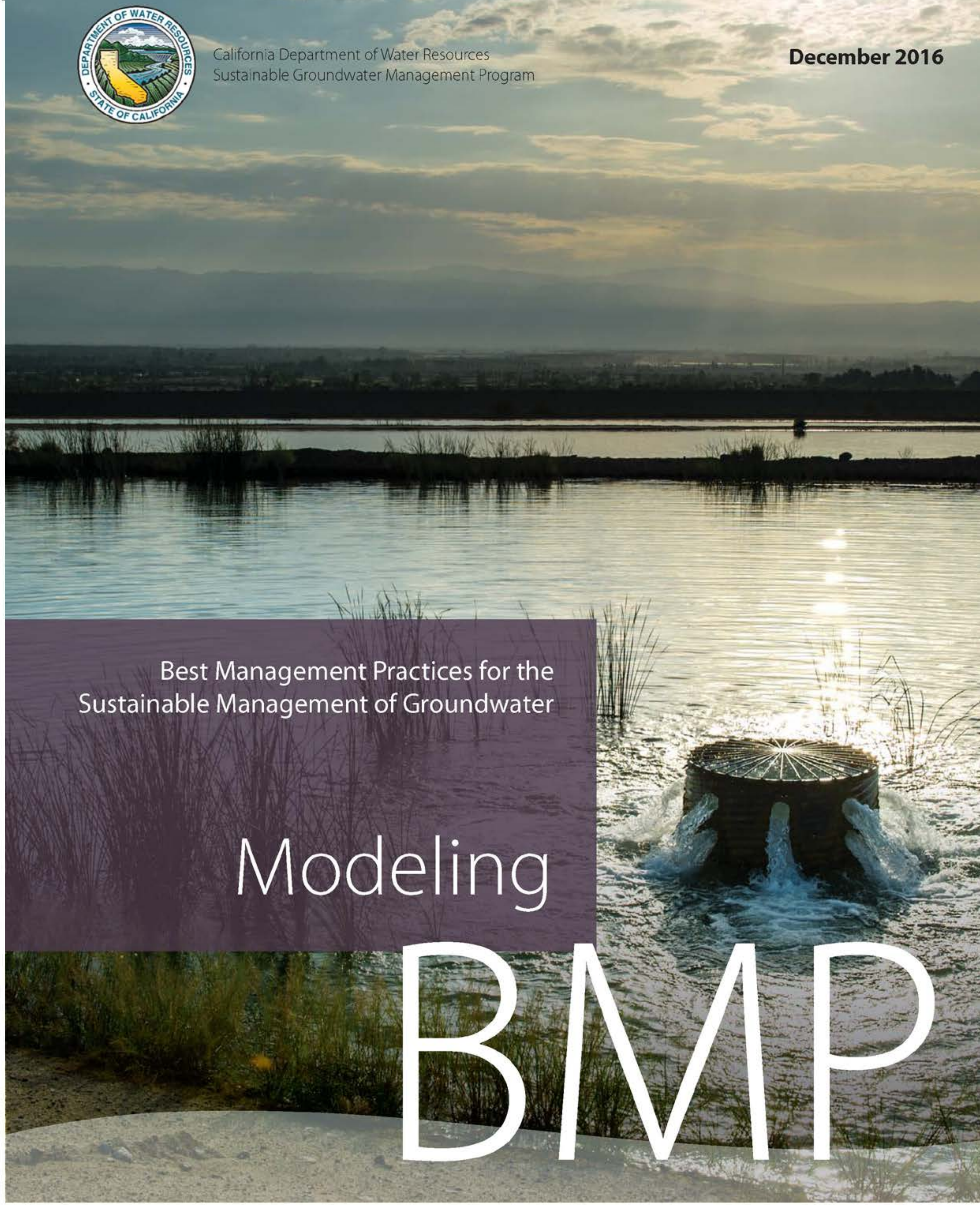

California Department of Water Resources
Sustainable Groundwater Management Program

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Best Management Practices for the Sustainable Management of Groundwater

Modeling BMP

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Modeling
Best Management Practice

1. Objective

The objective of this *Best Management Practice* (BMP) is to assist with the use and development of groundwater and surface water models. The California Department of Water Resources (the Department or DWR) has developed this document as part of the obligation in the Technical Assistance chapter (Chapter 7) of the Sustainable Groundwater Management Act (SGMA) to support the long-term sustainability of California's groundwater *basins*. Information in this BMP provides technical assistance to Groundwater Sustainability Agencies (GSAs) and other stakeholders on how to address modeling requirements outlined in the Groundwater Sustainability Plan (GSP) Emergency Regulations (GSP Regulations). This BMP identifies available resources to support the development of groundwater and surface water 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 for the development of a model, potential sources of information, and relevant datasets that can be used to further define model components.
6. Key Definitions. Definitions relevant for this BMP as provided in the GSP Regulations, Basin Boundary Regulations, and SGMA.
7. Related Materials. References and other materials related to the development of models.

2. Use and Limitations

BMPs developed by the Department provide technical guidance to GSAs and other stakeholders. Practices described in these BMPs do not replace the GSP Regulations, nor do they create new requirements or obligations for GSAs or other stakeholders. In addition, using this BMP to develop a GSP does not equate to an approval determination by the Department. All references to GSP Regulations relate to Title 23 of the California Code of Regulations (CCR), Division 2, Chapter 1.5, and Subchapter 2. All references to SGMA relate to California Water Code sections in Division 6, Part 2.74.

3. MODELING FUNDAMENTALS

As modified from Barnett and others (2012), a model is any computational method that represents an approximation of the hydrologic 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. Models can be useful tools for estimating the potential hydrologic effects of proposed water management activities.

Surface water and groundwater systems are affected by natural processes and human activity. They require targeted and ongoing management to maintain 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 management actions, 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. Such factors include 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. Often observational data are scarce (both in space and time), so understanding of the system remains limited and generally uncertain.

Models provide insight into the complex system behavior and (when appropriately designed) can assist in developing conceptual understanding. Models provide an important framework that brings together conceptual understanding, data, and science in a hydrologically and geologically consistent manner. In addition, models can estimate and reasonably bound future groundwater conditions, support decision-making about monitoring networks and management actions, and allow the exploration of alternative management approaches. However, there should be no expectation that a single 'true' model exists. All models and model results will have some level of uncertainty. Models can provide 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 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 described as a numerical model.

Each GSA is responsible for determining the appropriate modeling method, software, and the level of detail needed to demonstrate that *undesirable result*s can be avoided and the *sustainability goal* in each basin is likely to be achieved within 20 years of *GSP implementation*. A table of select, currently available, modeling codes (the model computation engine) and applications (the constructed model including inputs) is provided in Appendix A.

TYPES OF MODELS

Conceptual Models

A conceptual model is often considered the first step in understanding the groundwater flow system and 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, topographic boundary conditions are generally limited to simple geometric shapes 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.

However, analytical models and tools can successfully and inexpensively be employed to gain strong conceptual and general quantitative understanding of groundwater basin dynamics, which includes interactions with pumping, groundwater storage, groundwater quality, seawater intrusion, land subsidence, and interaction with surface water. Therefore, the applicability of this approach is most suited to initial scoping studies or basins with simple hydrologic conditions or easily idealized basins. This analysis may be limited when used as the only modeling tool.

Numerical Models and Tools

Numerical modeling tools are widely used in groundwater flow and transport analysis to evaluate the change to the groundwater system caused by changes in conditions due to management actions, changes in population and land use, climate change, or other factors. These numerical models allow for a more realistic representation of the physical system, including geologic layering, complex boundary conditions, and stresses due to pumping, recharge and land use demands. GSPs developed for complex basins with significant groundwater withdrawals and/or surface water - groundwater interaction may require the use of a numerical groundwater - surface water 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 Hydrologic Water Models

A fully integrated surface water and groundwater model refers to a suite of codes that jointly solve the numerical solutions for surface processes (such as irrigation deliveries and stream diversions), 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 uses separate models for 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.

Transport Models

Transport model codes add a layer of complexity beyond what is provided by groundwater-flow models. These models allow for the assessment of a variety of problems, including the potential migration of existing contaminant plumes due to management actions, or the changes in 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 impairs the use of groundwater as the source of supply and/or affect other areas of the basin now or as a potential result of future management actions.

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
- 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 of or in parallel with any of the above types of software
- A wide range of model codes to solve problems related to groundwater flow and/or transport, such as model codes that simulate farm water management, plant-water interactions, unsaturated zone flow and transport processes, stream flow processes, surface water - groundwater interactions, land subsidence, watershed processes, climate, geochemical reactions, economic water management optimization, or parameter calibration

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. Most model codes that solve the groundwater flow and/or transport equation have an integrated capability to also simulate some or many of the related processes listed above, such as surface water - groundwater interaction.

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 surface water and groundwater 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.

- Facilitating the estimate of sustainable yield for the basin.
- Optimizing proposed projects and management actions and evaluating the potential effects those activities have 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 measureable objectives.
- Helping identify potential projects and management actions and optimizing their design to achieve the sustainability goal for the basin within 20 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 determining sustainable groundwater management results in multiple benefits to GSAs and stakeholders. 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 predicting 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. 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 GSP 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 models should be used during GSP development is the question of the appropriate level of model complexity. Simple models require fewer data, less complex software, and are, therefore, often less expensive, and have much shorter run times. These characteristics are advantageous when focusing on a single undesirable result. However, simple models may overlook important system components and the interconnectedness of undesirable results, and may be difficult to calibrate to historical data. Complex models can incorporate more data and professional judgment. Therefore, they often result in a more accurate representation of the groundwater system. However, complex models are more expensive and difficult to build, require more data and more technical expertise, and the complexity can lead to a false impression of accuracy; a complex model may in fact be less accurate.

Fundamentally, a good model strategy is to follow the principle of parsimony: to build the simplest model that honors all relevant available data and knowledge, while providing a reasonable modeling tool to achieve the desired decision support at a desirable level of certainty. It may be necessary to use complex models to assess certain undesirable results, and it may be possible to use 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. Since significant professional judgment goes into the development of a model, two models of the same basin – even if they are built with the same model code - are likely to differ in their design and their outcome. Where multiple models exist, differences between model outcomes, after a careful assessment of the differences in model design and assumptions, may provide an important opportunity to further assess uncertainty in predicted outcomes and to further direct future data collection programs. Importantly, multiple models with differing outcomes should not be interpreted *a priori* as one model being (more) right and others being (more) wrong.

While models are useful and often invaluable tools for understanding a basin and predicting future basin conditions, in most cases, they are not the only available 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 purposes of modeling in the broader context of SGMA implementation include:

1. Supporting the development of the water budget
2. Establishing the Sustainable Management Criteria (sustainability goal, undesirable results, minimum thresholds, and *measurable objectives*)
3. Supporting identification and development of potential projects and management actions to address undesirable results that exist or are likely to exist in the future
4. 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 logical progression to sustainability as outlined in the GSP Regulations. The modeling BMP is part of the planning step in the GSP Regulations.

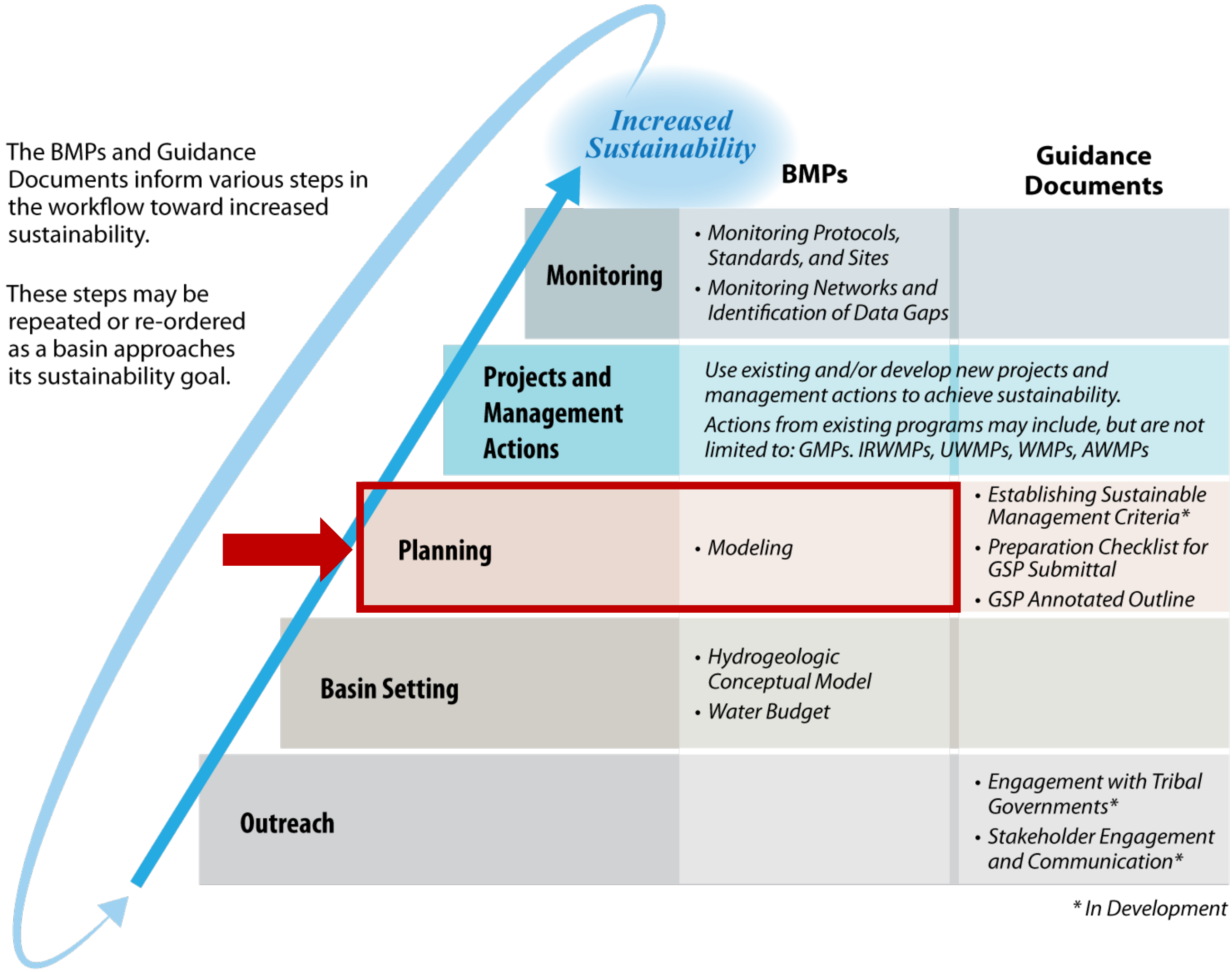

Figure 1 – Logical Progression of Basin Activities Needed to Increase Basin Sustainability

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. They help guide GSAs in their selection and use of models for sustainable groundwater management, and expedite Department review of GSP-related modeling analysis and findings.

1. Model documentation (documentation of model codes, algorithms, input parameters, calibration, output results, and user instructions) is publicly available at no cost. In particular, the model documentation should explain (or refer to available literature that explains) how the mathematical equations for the various model code components were derived from physical principles and solved, and 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 conceptual model, 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, provide the Department with a free working copy of the complete modeling platform (for example native MODFLOW and IWFM input files,

output files, and executables) that allows the Department to run the model, create and verify results, view input and output files, or perform any other evaluation and verification.

GENERAL MODELING REQUIREMENTS

23 CCR §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 GSP Regulations is to promote a consistent approach to the development and coordination of models in California. This will allow the Department 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 theoretical documentation, user instructions or manuals. This information should be referenced by the model developer 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 the conceptual model, simulation 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, e.g., 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. Calibration of the model should be performed by comparing simulated values to observed field data such as groundwater levels, groundwater flow directions, groundwater discharge rates, water quality concentrations, land subsidence observations, measurements of surface water and groundwater exchange, or chloride concentrations as an indicator for seawater intrusion. Additional information on these topics is provided 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 the Department, 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 model codes 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, case studies document 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 the Department and 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 GSP Regulations require that all new models developed in support of a GSP after the effective date of the GSP 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, and run the model, without using a proprietary code; this requirement 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**.

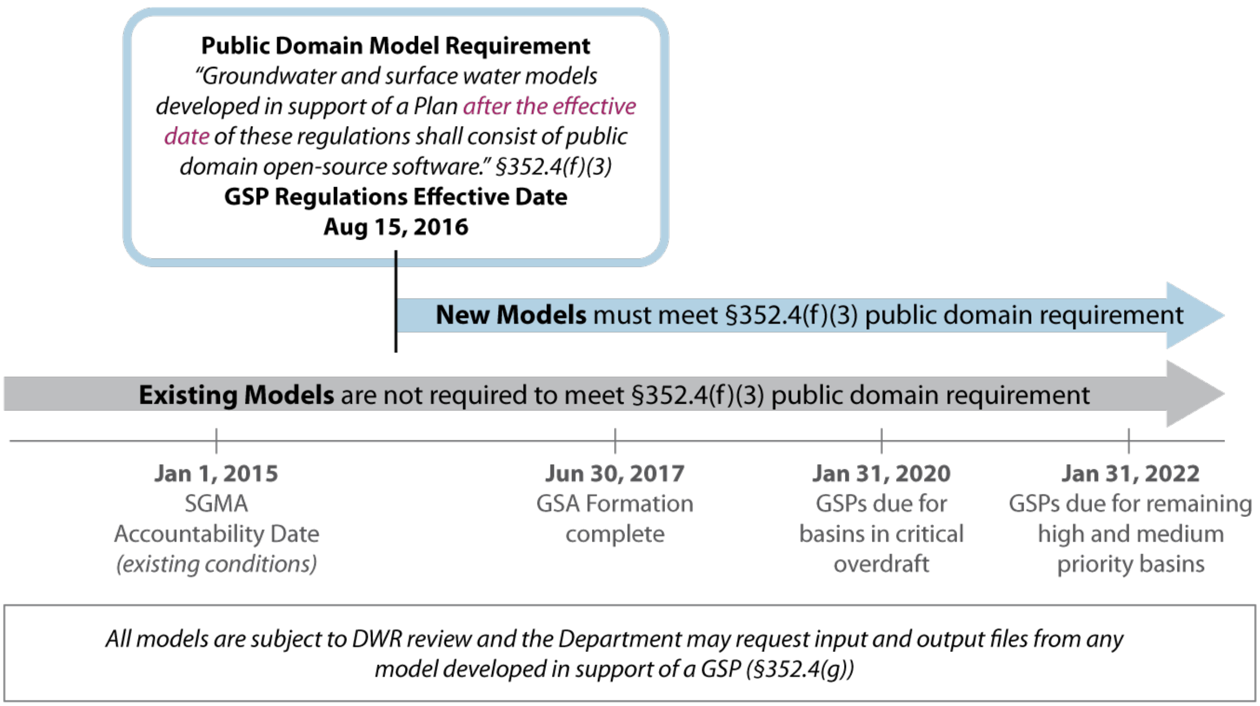

Figure 2 - GSP Regulations Effective Date and Model Development Timeline

The public domain and open-source software requirement only applies to model codes that solve the equations for groundwater flow and 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 boundary evaluation models or tools that provide input to the model or GSP, including watershed evaluation models, estimates of runoff, irrigation demand (if calculated outside the groundwater model), municipal demand (if calculated outside the groundwater model), or other related models.

23 CCR §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 Department review and the Department may request input and output files from any model developed in support of a GSP, including any software-specific files.

MODELING CONSIDERATIONS

A model should be selected and developed with clearly defined objectives to provide specific information in support of developing a GSP. Examples of the GSP needs and modeling objectives that should be considered when selecting and developing a model include the following.

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 improve 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 increase, 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 historical groundwater pumping on groundwater levels can be performed based on groundwater level measurements, forecasting future conditions that may differ from historical conditions will likely require the development of a model. All models are capable of simulating 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. However in basins where surface water - groundwater interaction plays a significant role in the basin water budget, the groundwater flow model selected to forecast basin conditions resulting from management actions should be capable of accounting for the effects of pumping on streamflow. 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. In addition, models are capable of providing the geographic distribution of changes in storage at specific locations. All transient groundwater and surface water models are capable of computing changes in groundwater storage within a basin due to particular management actions and, therefore, estimation of 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, particularly based on the types of management actions considered in the basin.

Seawater Intrusion

Basins adjacent to the ocean or parts of the Sacramento-San Joaquin Delta are susceptible to seawater intrusion. Seawater intrusion into a freshwater aquifer due to groundwater pumping 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, there are several types of model codes available for analyzing potential effects of seawater intrusion on a basin and associated basin management decisions (see Appendix A). For example, the groundwater budget can indicate whether water is generally flowing from onshore or offshore at the ocean boundary. Particle tracking can supplement the groundwater budget to show where water is flowing onshore and where water is flowing offshore. Sharp-interface approaches are also effective at estimating seawater intrusion fronts. Finally, there are model codes capable of accounting for or simulating the effects of density-driven flow in groundwater and that can simulate groundwater quality over time.

Degraded Water Quality

In basins with impaired water quality, the GSP's projects and management actions could cause impaired groundwater to flow 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, the resulting potential for drawdown-induced subsidence, and the loss of inelastic groundwater storage due to sediment compaction. If the historical subsidence has been significant, the GSA may want to select a model code that incorporates land subsidence directly into the groundwater flow process. If the amount of historical subsidence is not significant, controlling and abating subsidence could be estimated with simpler, one-dimensional calculations that are external to the groundwater flow model.

Depletion of Interconnected Surface Water

> *23 CCR §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 streambed 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 quantify the stream boundary conditions for use in the groundwater flow model simulations.

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

> *23 CCR §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 at varying scales 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, and the effects of climate change influencing meteorological conditions across the basin, and quantifying the uncertainty in these predictions.

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 best estimated 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. Simulations of future conditions, with or without projects, must include an assessment of prediction uncertainty about these simulated outcomes based on appropriate statistical analysis of parameter/boundary condition uncertainty during the sensitivity analysis and calibration process.

GSAs 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 GSAs to choose among various alternative strategies. Formal groundwater management optimization routines are one type of tool that may be used, in conjunction with groundwater (or integrated hydrologic) models, to achieve this goal.

Identifying Data Gaps and Monitoring Needs

Models can help GSAs 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: 1) which parameters have the greatest sensitivity on model estimates of key sustainability indicators, and 2) the magnitude of variability imparted in model forecasts of sustainability due to the level of uncertainty in the value of key model parameters. 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. In addition, focused field studies to estimate the physical values of associated model parameters, such as the streambed hydraulic conductivity for groundwater and surface water exchange, are valuable.

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 heads and 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 understanding of the basin is developed over time, through either additional characterization, monitoring efforts, or both, the predictive accuracy of the model (or models) 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 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 and Model Boundaries

A single GSP or multiple GSPs with a coordination agreement must be developed for an entire basin. Therefore, to predict whether undesirable results currently exist or may occur in the future, the model should at a minimum cover the entire basin. For some sustainability indicators, such as changing groundwater levels causing depletions of interconnected surface water, the model boundaries may need to extend beyond the basin boundary to accurately simulate the effects of pumping. 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. In many cases, the model needs to be large enough to encompass the entire area affected by the GSA's groundwater activities such as pumping and recharge projects that the model is intended to assess.

Regional scale models may not always be appropriate for basin management because the model grid might be too coarse to accurately assess local sustainability indicators. However, in these cases regional scale models can be used as a basis for basin-wide models. Regional models can provide boundary conditions that can be implemented into basin-wide models. Alternatively, fine grid models can be nested into regional models. This can be done by either locally refining the mesh structure of a regional model, or using tools such as the Telescopic Mesh Refinement (TMR) or Local Grid Refinement (LGR) packages.

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 surface water and groundwater use and potential issues in the basin. Hydrologic processes that may affect SGMA undesirable results also need to be considered for model development.

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 the Department 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. Where multiple models exist, an informed comparison to results from other models may be useful to confirm results or identify potential additional uncertainties.

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 expertise.

GUIs are commercially available for different types of model codes. These GUIs, in addition to other commonly used software, such as Microsoft Excel and ESRIs 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 GSP Regulations.

THE GROUNDWATER MODELING PROCESS

Modeling depends on and reflects the judgement and experience of the groundwater modeler(s). There is no formula or discrete 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.

1. **Establish the model's purpose and objectives**. 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 and near the end of the modeling process when various modeling scenarios are being considered.

2. **Collect and organize 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 density and integrity. 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).

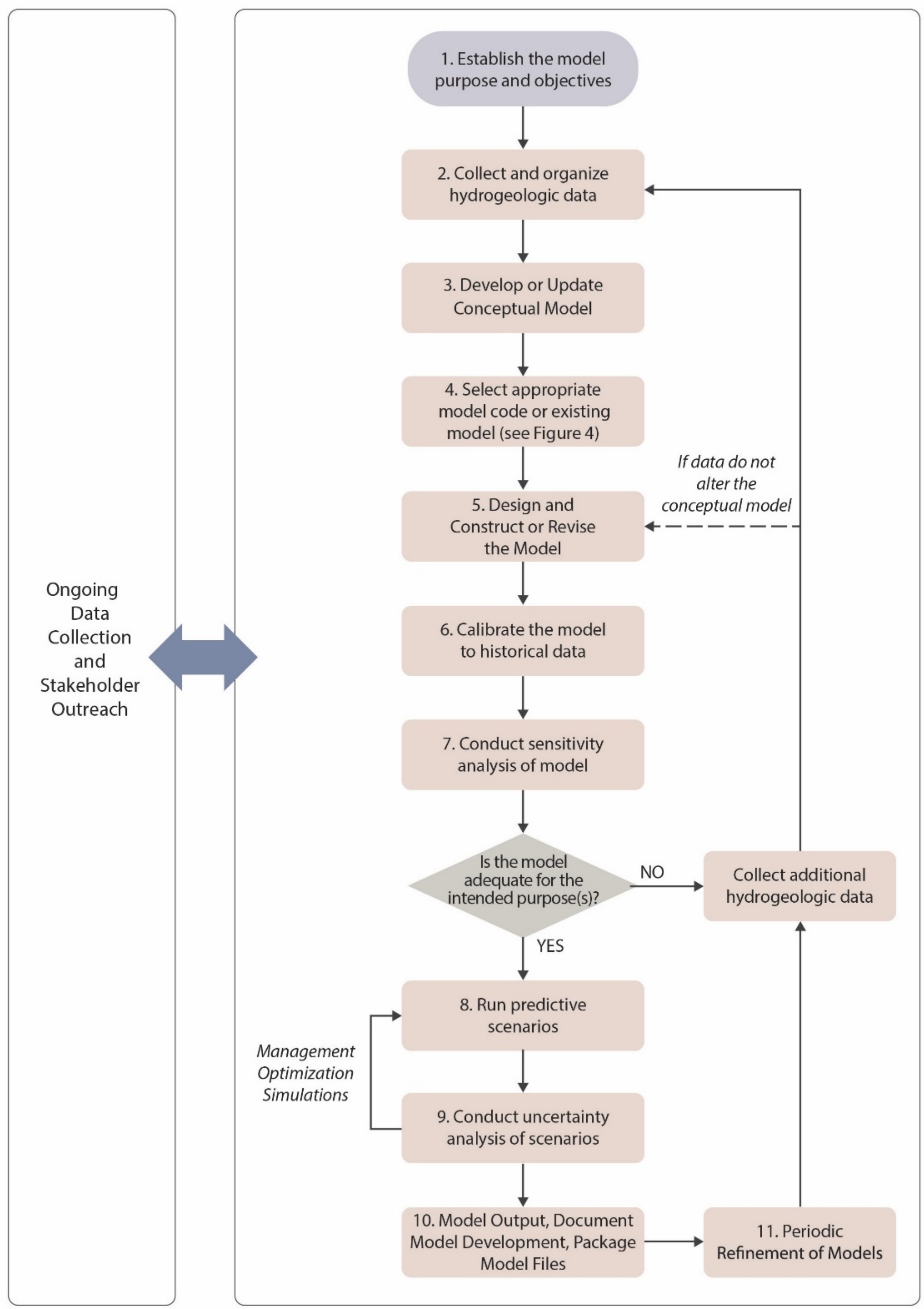

Figure 3: General Modeling Process

3. **Develop a conceptual model of the basin**. The conceptual model forms the structural, hydrogeologic, and hydrologic basis of the mathematical (analytical or numerical) model. The conceptual model identifies the key parameters of physical setting, aquifer structure and range of aquifer parameters, hydrologic processes, and boundary conditions that govern groundwater and surface water occurrence within the basin. The conceptual model provides the technical foundation of the model and an initial interpretation of a basin based on known characteristics and current management actions. In addition to aquifer characteristics and groundwater management activities, the conceptual model includes a conceptual understanding of the surface features, water uses, land uses, water management activities, and any other processes in the basin that affect surface and groundwater uses. Although a conceptual model does not necessarily include quantitative values, it should identify the range of reasonable parameter values for the aquifer materials that occur in the basin and that reflect the scale of the model. A sound and well-developed conceptual model is essential to the development of a reliable mathematical model. For more details on developing a *hydrogeologic conceptual model*, please refer to the HCM BMP.

   4. Select the appropriate model code or existing model. The selected model code or existing model 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. 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 for GSP development and implementation. If multiple models are used in a basin, GSAs should consider the potential overlap and differences between the models, and how the different model results could inform management uncertainty.

   Figure 4 provides a flowchart that may aid in the comparison and selection of an appropriate model if multiple models exist in a basin and GSAs opt to use a single model. In addition, two interactive maps of a select number of existing, available, model applications in California are available at the following links (DWR – http://www.water.ca.gov/groundwater/MAP_APP/index.cfm ; USGS – http://ca.water.usgs.gov/sustainable-groundwater-management/california-groundwater-modeling.html).

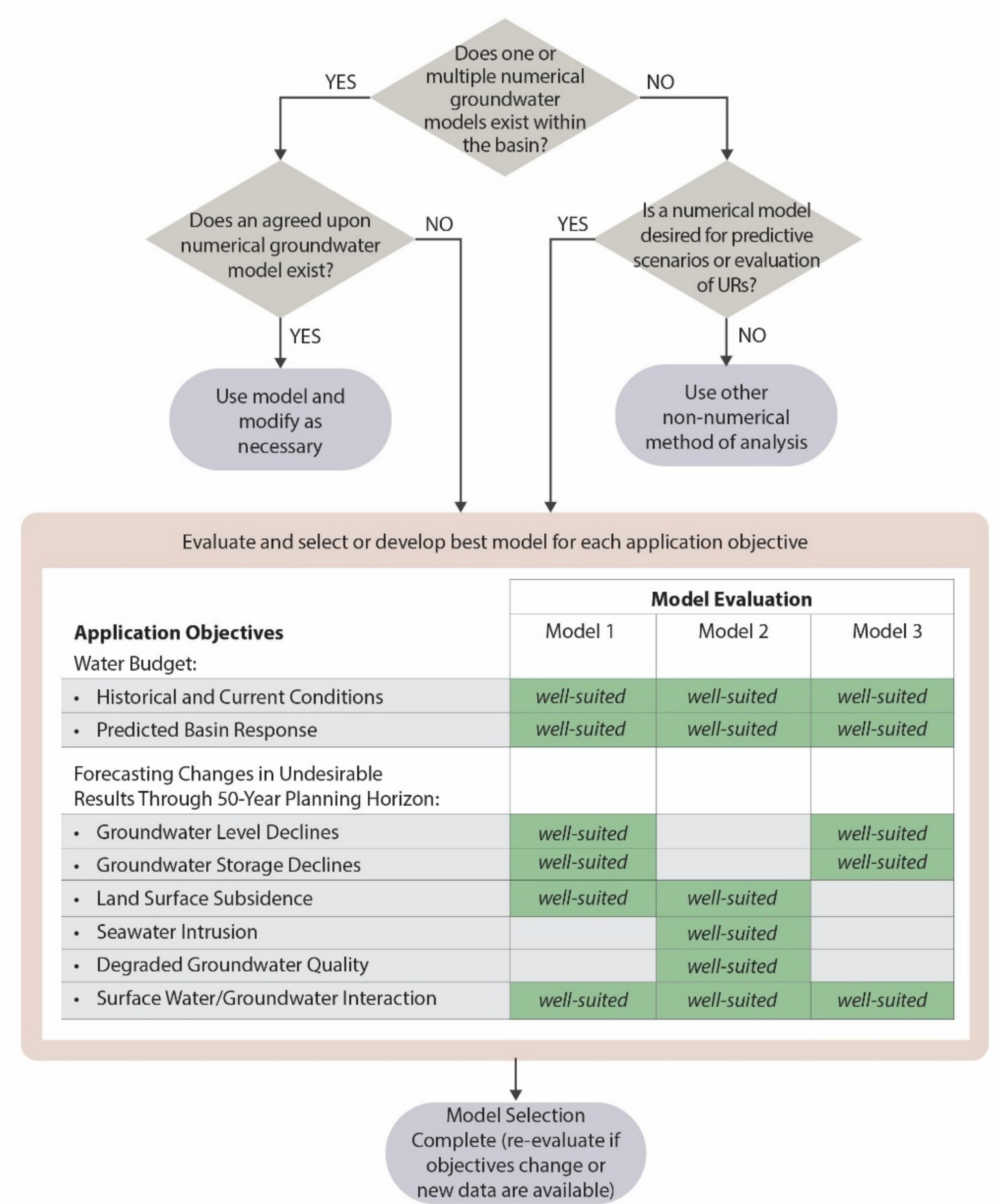

Figure 4: Generalized Model Selection Process

Note: Selected model needs to adhere to the public domain open source requirements.

5. **Design and construct (or revise) the model**. In this step, the conceptual model developed in step three is implemented in the selected model code. This step includes constructing the model grid, populating the model with hydrogeologic parameters, assigning 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, specific yield and leakance coefficients are often modified during model calibration. However, adjustment of parameter values must be constrained within the range of reasonable values for the aquifer materials identified in the conceptual model. Aspects of the water budget, such as recharge rate or private pumping rate, may also be modified during calibration.

   One of the primary values of model calibration is to identify problems in the hydrogeologic conceptual model. If a model fails to reproduce observed data, then the representation of the conceptual model in the numerical model contains inaccuracies. While the ability to achieve an acceptable calibration does not necessarily prove that a model is a good representation of the physical system, difficulties encountered during calibration can help identify areas where the conceptualization of the physical system is lacking and more data may be needed to improve the model conceptualization.

   No model is perfectly calibrated, and establishing desired calibration accuracy *a priori* is difficult. One criteria that could be considered 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. For example, the correlation coefficient between the simulated and observed groundwater elevations, for instance, can be used as a statistic to determine how well a model is calibrated. "Generally, a value of R that is greater than 0.90 indicates that the trends in the weighted simulated values closely match those of the weighted observations" (Hill and Tiedeman, 2007).

7. **Conduct sensitivity analysis of the model.** The model calibration process typically includes or is followed by a sensitivity analysis to identify parameters or boundary conditions to which model forecasts are particularly sensitive. Parameters that are both highly sensitive and poorly constrained may be good candidates for future data collection. Sensitivity analysis provides a measure of the influence of parameter uncertainty on model predictions. By systematically varying parameter values within reasonable ranges, GSAs can assess how sensitive the calibrated model is to uncertainty in these parameters, and where future data collection efforts could be focused. This step of the modeling process can also help to determine whether the calibrated model can conduct required simulations with the desired level of accuracy.

8. **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.

9. **Conduct an uncertainty analysis of the scenarios.** This is to identify the impact of parameter uncertainty on the use of the model's ability to effectively support management decisions and use the results of these analyses to identify high priority locations for expansion of monitoring networks. 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. A formal optimization simulation of management options may be employed, taking advantage of the predictive uncertainty analysis to minimize economic costs of future actions, while meeting regulatory requirements at an acceptable risk level.

10. **Model output, document model code and model application development, and package model files**. Model data outputs are used for GSP development and analysis of sustainability indicators and inform proposed management actions. The GSP needs to include documentation on the modeling tools used for GSP development. This documentation can be provided in the form of a technical appendix to the GSP and should include both information on the model code (i.e., referenced from user manuals) and detailed descriptions of the model application development. Model code information should include an explanation of the model code, associated mathematical equations, and assumptions, which are typically found in publicly available theoretical documentation, 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, final model files used for decision making in the GSP should be packaged for release to the Department.

11. **Revise and refine 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.

- "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)

- "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

The following links provide examples, standards, and guidance related to modeling. By providing these links, the Department 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.

REFERENCES FOR FURTHER 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

Brush, C.F., and Dogrul, E.C. June 2013. User Manual for the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG.

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

Harter T. and H. Morel-Seytoux, 2013. Peer Review of the IWFM, MODFLOW and HGS Model Codes: Potential for Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins. Final Report, California Water and Environmental Modeling Forum, August 2013, Sacramento. http://www.cwemf.org

Hill M.C. and C.R. Tiedeman. 2007. Effective Groundwater Model Calibration: With Analysis of Data, Sensitivities, Predictions, and Uncertainty. Wiley. 480 pages. January.

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

Moran, T., 2016. Projecting Forward, A framework for Groundwater Model Development Under the Sustainable Groundwater Management Act. Final Report, Stanford, Water in the West, November 2016. http://waterinthewest.stanford.edu/publications/groundwater-model-report

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

Peralta, R., 2012. Groundwater Optimization Handbook: Flow, Contaminant Transport, and Conjunctive Management 1st edition. Boca Raton, Florida, 474 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

United States Geological Survey (USGS). 2009. Groundwater Availability of the Central Valley Aquifer, California. U.S. Geological Survey Professional Paper 1766. Groundwater Resources Program. Reston, VA.

APPENDIX A - EXISTING MODEL CODES AND MODEL APPLICATIONS

There are many existing model codes and model applications being used in basins throughout the state. The Department and USGS have coordinated and compiled a table of available model codes (see Appendix A) and interactive maps displaying a select number of existing model applications in California.

- DWR: http://www.water.ca.gov/groundwater/MAP_APP/index.cfm
- USGS: http://ca.water.usgs.gov/sustainable-groundwater-management/california-groundwater-modeling.html

Currently, there are two existing, calibrated, and actively updated and maintained model applications that cover the Central Valley aquifer system. These models can be a great source of data and provide a good starting point for basins within the Central Valley that currently do not have a model. 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)

The Department 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 IWFM 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 groundwater and surface water flow, irrigated agriculture, and other key 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 irrigated agriculture. It can be used in a similar manner to C2VSim to simulate response to projected future stresses.
http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html

Summary of Commonly Used Groundwater Model Codes in California.					
Model Code	**Description**	**Download**	**Documentation**	**Maintained by**	**Applicability to SGMA Sustainability Indicator**
IWFM	Finite-element code for integrated water resources modeling.	http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/	DWR, 2016. *Integrated Water Flow Model: IWFM -2015, Theoretical Documentation*, 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://baydeltaoffice.water.ca.gov/modeling/hydrology/IDC/index_IDC.cfm	DWR, 2016. *IWFM Demand Calculator: IDC-2015, Theoretical Documentation and User's Manual*, Central Valley Modeling Unit Support Branch Bay-Delta Office	DWR	Land use water budget
MODFLOW	Finite-difference groundwater flow code; several versions available with related modules.	http://water.usgs.gov/ogw/modflow/	Current core version is MODFLOW -2005: *USGS. 2005. MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. USGS Techniques and Methods 6–A16*	USGS	Groundwater levels Storage Interconnected SW/GW Subsidence Seawater intrusion
MODFLOW - OWHM	MODFLOW based integrated hydrologic flow model (One Water Hydrologic Flow Model).	http://water.usgs.gov/ogw/modflow-owhm/	*USGS. 2014, One-Water Hydrologic Flow Model (MODFLOW-OWHM). U.S. Geological Survey Techniques and Methods 6-A51.*	USGS	Groundwater levels Storage Interconnected SW/GW Subsidence Seawater Intrusion

Summary of Commonly Used Groundwater Model Codes in California.					
Model Code	**Description**	**Download**	**Documentation**	**Maintained by**	**Applicability to SGMA Sustainability Indicator**
MODFLOW-USG	MODFLOW-USG: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation	http://water.usgs.gov/ogw/mfusg/	*Panday, Sorab, Langevin, C.D., Niswonger, R.G., Ibaraki, Motomu, and Hughes, J.D., 2015, MODFLOW-USG version 1.3.00: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation: U.S. Geological Survey Software Release, 01 December 2015, http://dx.doi.org/10.5066/F7R20ZFJ*	USGS	Groundwater levels Storage Interconnected SW/GW Subsidence
GSFLOW	GSFLOW: coupled groundwater and surface-water flow model	http://water.usgs.gov/ogw/gsflow/	*Regan, R.S., Niswonger, R.G., Markstrom, S.L., Maples, S.R., and Barlow, P.M., 2016, GSFLOW version 1.2.1: Coupled Groundwater and Surface-water FLOW model: U.S. Geological Survey Software Release, 01 October 2016, http://dx.doi.org/10.5066/F7WW7FS0*	USGS	Groundwater levels Storage Interconnected SW/GW
MT3D[1]	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, *MT3DMS v5.3 Supplemental User's Guide*, 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

[1] The USGS recently updated this code and released a newer version, *MT3D-USGS: Groundwater Solute Transport Simulator for MODFLOW*. More information can be found at: http://water.usgs.gov/ogw/mt3d-usgs/

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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#doc	Clement, P. T, 1997, *A Modular Computer Code for Simulating Reactive Multi-species Transport in 3-Dimensional Groundwater Systems*, 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, *Path3D, a groundwater pass and travel time simulator*, 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, *Users guide for mod-PATH3DU*; 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., *SEAWAT: a computer program for simulation of variable-density groundwater flow and multi-species solute and heat transport:* U.S. Geological Survey Fact Sheet FS 2009-3047, 2 p.	USGS	Seawater intrusion

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MODPATH	Particle-Tracking post-processing tool for MODFLOW.	http://water.usgs.gov/ogw/modpath/	*USGS. 2012, User guide for MODPATH version 6—A particle-tracking model for MODFLOW: U.S. Geological Survey Techniques and Methods, book 6, chap. A41*	USGS	Groundwater flow path tracking for groundwater quality, Seawater intrusion, and other flow-related processes
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:

- Additional DWR modeling tools and resources are available at: http://www.water.ca.gov/groundwater/sgm/index.cfm and http://baydeltaoffice.water.ca.gov/modeling/
- Additional USGS modeling tools and resources are available at: http://water.usgs.gov/software/lists/groundwater
- This list does not contain all available models in California and there are model codes in use in California that are currently proprietary (such as MicroFem, MODFLOW-Surfact, MODHMS) but may be allowed if the model applications were developed and used prior to the effective date of the GSP Regulations.