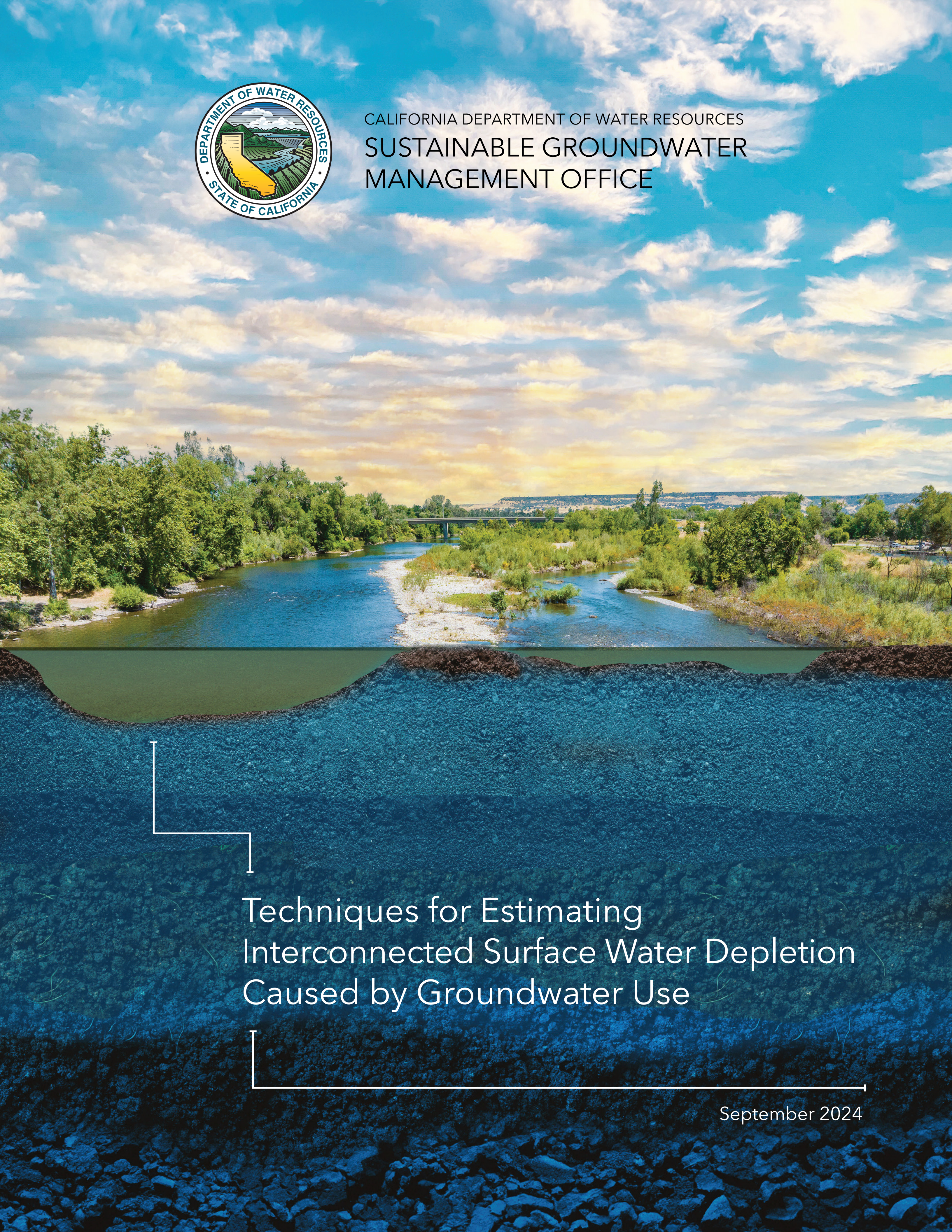

CALIFORNIA DEPARTMENT OF WATER RESOURCES
SUSTAINABLE GROUNDWATER
MANAGEMENT OFFICE

Techniques for Estimating Interconnected Surface Water Depletion Caused by Groundwater Use

September 2024

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1 Introduction

The California Department of Water Resources (DWR) developed a three-paper series on Interconnected Surface Water (ISW) and depletion of ISW to provide water managers with the tools necessary to determine the location, quantity, and timing of ISW depletion caused by groundwater use (i.e., groundwater pumping). Paper 1, "Depletions of Interconnected Surface Water: An Introduction," covers concepts associated with the interaction between surface water and groundwater and provides approaches for identifying ISW and defining depletion of ISW from groundwater pumping.

Paper 1 explains that groundwater pumping plays an important role in the interaction between ISW and groundwater. In areas identified as having ISW, groundwater pumping either reduces the flow from groundwater to the surface water bodies or increases the flow from the surface water bodies to the groundwater system. Both cases result in a reduction in the volume of surface water at a given time and location, which is referred to as 'ISW depletion.'

This paper continues the foundational concepts presented in Paper 1. It further explores the topic by discussing the data requirements for ISW depletion analyses, the methods that groundwater managers are likely to consider for analyzing ISW depletion caused by groundwater pumping, and the general process to implement those methods. The final paper in the series (Paper 3), "Examples for Estimating Interconnected Surface Water Depletion Caused by Groundwater Use," provides examples of applying numerical models to estimate ISW depletion.

This paper (Paper 2) is organized as follows:

- Section 2 discusses the types of data groundwater managers will need to evaluate ISW depletion.
- Section 3 identifies the quantitative approaches groundwater managers can use to evaluate ISW depletion and the factors they should consider when selecting an approach.
- Section 4 describes, at a high level, the application of one approach to quantify ISW depletion using a numerical model.
- Section 5 provides a summary of the concepts described in this paper.

2 Data Needed to Quantify ISW Depletion Caused by Groundwater Use

This section discusses the data and information needed to analyze and account for ISW depletion. Significantly, the data required to analyze ISW depletion often overlap with data needed to understand groundwater basin conditions, groundwater budgets, and other sustainability indicators such as lowering groundwater levels, reduction of groundwater storage, or land subsidence. Therefore, most, if not all, basins possess data to perform an initial evaluation of ISW depletion. However, as with all types of groundwater analyses, better data can be collected, and better, more refined methods can be employed to improve the assessment as groundwater management efforts progress. Understanding the data needs outlined in this section and their importance will help groundwater managers decide which methods to use for their current work and strategize for future data collection and prioritization.

Depletion is a function of two main types of data: the characteristics of pumping and the physical characteristics of the aquifers and surface water beds (e.g., streambeds) through which groundwater and surface water are interconnected. This section describes those two data types and ancillary data that groundwater managers may need to quantify depletion of ISW (e.g., through constructing or calibrating a numerical model).

2.1 Pumping Attributes

The attributes of groundwater use, or pumping, are fundamental data needed to characterize ISW depletion. The attributes of pumping, on a well-by-well basis, include:

- The quantity of pumping through time (e.g., monthly quantities of pumping), as well as an estimate of the portion of the pumping that is consumptively used (e.g., through crop transpiration, evaporation from the soil surface, domestic and industrial uses, or exported from the basin)
- The horizontal location of pumping (i.e., where wells are located or the estimated locations of pumping zones)
- The vertical location of pumping (i.e., the depth and aquifers from which pumping occurs)

In the ideal case, groundwater managers would have a detailed and accurate historical and current inventory of well locations, source aquifer(s), pumping quantities, and projections of future pumping by well or wellfield. The reality, however, is that few groundwater managers have comprehensive and reliable direct measurements (e.g., from meters on each well) of basinwide pumping. Instead, they may only have direct measurements from a subset of wells (e.g., from a particular water sector such as municipal water suppliers) or a subset of time, requiring them to use other methods to estimate the quantity and location of pumping.

Several methods exist to estimate pumping. Pumping in an agricultural area can be estimated by calculating the water demand by crop type, subtracting water supplied by other sources such as precipitation and surface water, and assuming that the remainder of the crop demand is supplied by groundwater pumping. These estimates are typically made at monthly time scales and can be prepared for spatial scales as small as individual fields or parcels. Pumping for domestic use in an area can be estimated by determining the population and assuming a per capita water use rate. The calculations described above can be implemented in relatively simple spreadsheets, or they can be built into a numerical model (e.g., the Integrated Water Flow Model [IWFM] Demand Calculator that is part of the IWFM code published by DWR or using the MODFLOW One-Water Hydrologic Model published by the United States Geological Survey [USGS]). Other methods exist to estimate pumping, such as determining a relationship between electricity usage and pumping rates and using historical electric meter readings to estimate pumping from wells with electrical pumps, although such data can be difficult to obtain for a basin.

2.1.1 Considerations for developing historical estimates of pumping rates and location: how far back in time to go?

One important question groundwater managers analyzing ISW depletion must answer is: How far back in time should they develop pumping estimates? A related question is: How far back in time should the analysis of depletion (or the numerical model used to analyze depletion) extend?

The answer to those questions depends on the characteristics of the basin. Groundwater pumping can, in some cases, deplete ISW relatively quickly (over days to weeks) and, in other cases, can deplete surface water over very long-time scales (years to decades). In relatively smaller basins, where the distances (horizontally and vertically) between pumping wells and surface water are shorter, or basins that are composed of materials that transmit groundwater quickly, groundwater managers may only need to estimate pumping for a relatively short historical period to understand the current stream depletion. However, in basins where pumping occurs in deeper, more distant, and more slowly transmitting aquifers, present-day depletion may be a function of pumping that happened decades ago; groundwater managers in those basins will need to utilize more extended analysis periods to estimate ISW depletion.

It is also a practical reality that the further back in time one goes, the less reliable and available the data is for either direct measurement of pumping or the data needed to estimate pumping, such as land use, hydrology, and surface water diversions. There may be instances where groundwater managers determine that they can only develop reasonably accurate estimates of pumping back to a certain time, even though they also recognize that pumping before that time may be responsible for a portion of the current depletion of ISW.

2.2 Aquifer and Surface-Water Interface Characteristics

The other fundamental data required to estimate depletion are the characteristics of the aquifers and surface water beds (e.g., stream beds) through which groundwater flows and interacts with surface water. These data include:

- Information on the horizontal and vertical hydraulic conductivity of aquifer and aquitard materials
- The thickness and geometry of the aquifers
- Aquifer storage parameters (i.e., the specific yield of unconfined aquifers and storage coefficient of confined aquifers)
- Conductance of the surface water beds
- The characteristics of faults that can influence the flow of groundwater

The data above can be inferred at point locations (e.g., through analysis of aquifer materials logged during well drilling or from information collected during aquifer testing) and then inferred to other parts of the basin by groundwater professionals. Newer methods, including geophysical techniques like those used in DWR's Statewide Airborne Electromagnetic (AEM) Surveys[1], allow for a more extensive assessment of aquifer geometry and properties. Knowledge of some aquifer characteristics, such as hydraulic conductivity and storage properties, is often refined in areas where numerical groundwater models are used. The model calibration process usually involves adjusting those parameters to achieve a reasonable match between simulated and historically observed groundwater and surface water conditions.

2.3 Other Data That May Be Needed to Estimate Depletion

While simpler analytical solutions for ISW depletion only require data related to pumping and aquifer characteristics, more complicated methods, particularly those relying on numerical models, have higher input data requirements. It is beyond the scope of this document to describe all the data that may be needed to develop a numerical model of a groundwater basin. However, DWR has developed resources that can be used to enhance the data collection processes. These include the Best Management Practices (BMPs) for sustainable groundwater management. The

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[1] https://water.ca.gov/Programs/Groundwater-Management/Data-and-Tools/AEM

following BMPs provide clarification, guidance, and examples of data collection and application:[2]

- BMP 1 – Monitoring Protocols Standards and Sites
- BMP 2 – Monitoring Networks and Identification of Data Gaps
- BMP 3 - Hydrogeologic Conceptual Model
- BMP 5 - Modeling

2.4 Assessment of Data Adequacy

As mentioned above, the fundamental data needed to assess ISW depletion in a basin (pumping and aquifer characteristics) have likely already been compiled for general basin understanding and for developing a basin's Groundwater Sustainability Plan (GSP). Groundwater managers can use that information to develop initial estimates of ISW depletion, but they face the question of whether the existing datasets are sufficient for the long-term characterization of ISW depletion. The answer to that question will vary from basin to basin and dataset to dataset.

Most basins likely have significant uncertainty with respect to the fundamental data, and DWR suggests that groundwater managers take practical steps to reduce those uncertainties.

- For pumping data, groundwater managers can use existing information such as well completion reports to refine the locations of existing wells, implement well inventories to track the locations of new or existing wells, and implement metering programs to understand the quantity and timing of pumping better.
- Where groundwater managers must rely on estimates of pumping, they should use the best available information to inform those estimates. Those sources of information could include better information on land use (see the DWR annual land use estimates or recently released code from the USGS to estimate land use in irrigated areas from pesticide use reports[3]) or evapotranspiration (such as data from CIMIS[4] or the new OpenET data[5]).
- For aquifer characteristics, groundwater managers can incorporate data from existing and new drillers logs, existing and new aquifer tests, and information

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[2] https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents

[3] https://code.usgs.gov/FEWS/calpur/-/tree/release

[4] https://cimis.water.ca.gov/

[5] https://etdata.org/

from data collection and analysis efforts like DWR's AEM[6] and basin characterization[7] projects.

While this section focuses on data adequacy, it is possible to use numerical models to make informed decisions about the priority of enhanced data collection (Dausman et al. 2010). These analyses, sometimes called data-worth analyses, do not appear to be widely used in California groundwater management planning. Still, they can be performed to evaluate the ability of additional, as-yet-uncollected observations to reduce the uncertainty of the numerical model predictions. Groundwater managers can use those assessments of data worth to prioritize collecting new data that will most significantly reduce the uncertainty in estimates of ISW depletion.

3 Methods to Estimate ISW Depletion

This section discusses the methods groundwater managers can use to evaluate ISW depletion and considerations for which method to select. Methods discussed include numerical models, analytical solutions, and statistical methods. Substantial literature exists describing the construction and application of tools using each of the methods, and it is beyond the scope of this document to comprehensively describe the intricacies and complexities of each. Instead, this section provides a basic description of each method. The subsections on considerations provide context that groundwater managers should know as they select a method to quantify ISW depletion.

3.1 Numerical Models

Numerical models, as used in this paper, are earth system models that employ one or more mathematical equations to describe the physical processes related to groundwater flow and are based on certain assumptions about the flow of water through aquifers and surface water systems. They are widely used to analyze groundwater flow, surface water conditions, and the interaction between the two systems. They can also evaluate changes in conditions due to changes in hydrology and climate conditions and the operation of the groundwater and surface water systems.

In the simplest terms and most cases, a numerical model generally represents an aquifer system, such as a groundwater basin or subbasin, with a spatially distributed grid that can be two- or three-dimensional and is composed of nodes, elements, or cells (as shown in **Figure 1**).

Developers of numerical groundwater models can refine the grid horizontally to represent features at the land surface, such as political and jurisdictional boundaries or hydrologic features like rivers. The grid can also be refined vertically with multiple

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[6] https://water.ca.gov/Programs/Groundwater-Management/Data-and-Tools/AEM

[7] https://water.ca.gov/Programs/Groundwater-Management/Bulletin-118/Basin-Characterization

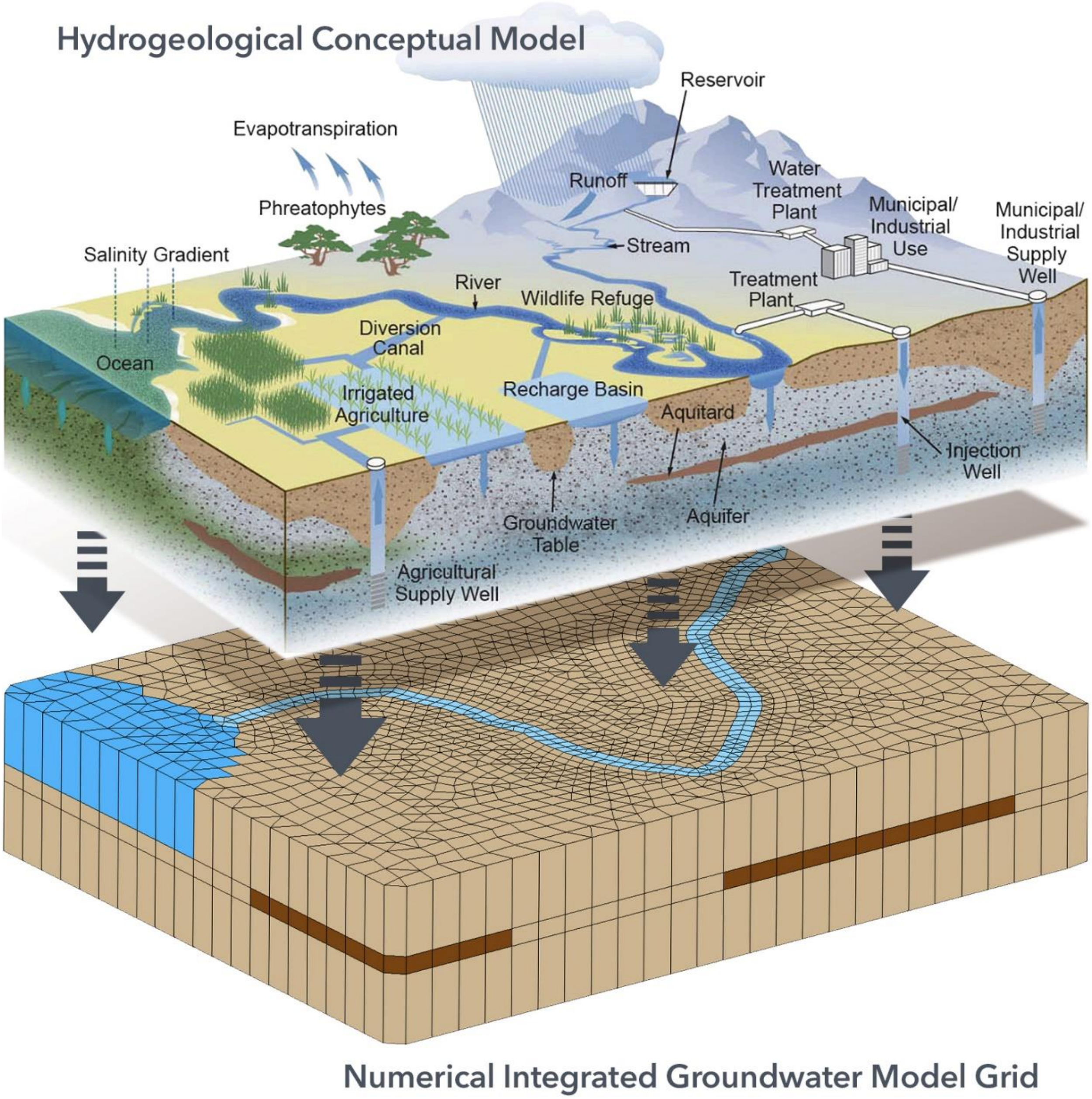
layers of varying thicknesses to represent geologic complexity (e.g., the vertical distribution of aquifers and aquitards) and to represent the vertical distribution of pumping. Hydrogeologic properties, such as hydraulic conductivity, are assigned to each cell or element in the grid to represent the complex physical properties of the basin. Boundary conditions are assigned to represent inflows (e.g., flow from mountain-front recharge or stream flow entering the numerical groundwater model area) and outflows (e.g., pumping). The numerical modeling code solves the groundwater flow equation at each node or cell in the grid to determine groundwater flow characteristics. Results of the numerical model can be assessed at specific locations and summarized by groups of elements or cells to determine groundwater conditions and budgets for larger areas such as an irrigation district, municipality, or subbasin.

In short, numerical models require subdividing the real world into a groundwater model grid, assigning data and parameters to each element or cell in that grid to represent the complexity of the land surface and groundwater systems, and using numerical methods to solve equations governing groundwater flow at each grid element or cell.

Numerical models can accommodate complexity and represent changing conditions in time and space. One example is groundwater systems with streams that are initially interconnected and later become disconnected as groundwater levels decline. That disconnection and change in stream-aquifer interaction introduces a non-linearity that numerical models can accommodate and which analytical methods, described below, generally cannot.

DWR’s Modeling BMP (BMP 5) (DWR, 2016) provides additional information on numerical models and their use in California groundwater management.

Figure 1. Example of a Numerical Model Grid



3.2 Analytical Methods

Like numerical models, analytical methods mathematically represent groundwater flow in aquifers and can be used to provide estimates of the quantity and timing of ISW depletion. However, unlike numerical models, analytical methods are often based on significant simplifying assumptions and can only account for limited complexity. Analytical methods can generally be run in a spreadsheet, website[8], or with a few lines of code.

Some of the simplifying assumptions that underpin the use of many analytical methods include:

- Constant aquifer transmissivity in space and time (i.e., the aquifer is assumed isotropic, homogeneous, and semi-infinite in areal extent and assumes that the drawdown is negligible compared to the aquifer's saturated thickness)
- Groundwater flow is horizontal with negligible vertical flow
- Pumping does not affect the stream stage
- The groundwater pumping rate is constant
- The stream is represented as an infinite straight line on a map

Some advanced analytical methods address simplifying assumptions, such as stream representation as a straight line (Zipper et al. 2019). However, those advanced methods only address some of the major simplifying assumptions inherent in analytical methods, and groundwater managers will need to carefully evaluate whether their use is appropriate for their basin or subbasin.

3.3 Statistical Methods

Statistical methods are data-driven approaches that use the relationship between stresses (pumping) on the system (surface water bodies) and impacts (depletion) experienced by the system. For example, given enough data, this method can evaluate the general effects of basinwide pumping on streamflow reductions. However, accounting for the specific effects of pumping at individual wells or helping understand how specific management actions might affect future depletion is not possible (Barlow and Leake 2012) using statistical methods.

3.4 Selecting a Method

Groundwater managers must consider many factors when selecting a method to analyze ISW depletion, some of which are described in the following subsections. The method chosen and the way it is applied may change over time. For example, a groundwater manager may initially decide to use a relatively simpler method (e.g., an

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[8] See e.g., https://mi.water.usgs.gov/software/groundwater/CalculateWell/index.html

analytical method or a relatively simpler numerical modeling approach) and then use more advanced methods and techniques (e.g., more complex numerical models) as their understanding of their basin increases, or as better data become available to support more complex analyses. The factors that go into selecting a particular method should be documented in a basin's GSP(s).

3.4.1 Regulatory Requirements

One important consideration when selecting a method to evaluate ISW depletion is the information the groundwater management agency will be required to provide to document compliance with their applicable management and regulatory requirements.

The Sustainable Groundwater Management Act (SGMA) and the GSP Regulations require GSAs to:

1. Estimate the quantity and timing of depletion of ISW systems identified in the basin[9]
2. Define conditions of ISW depletion that would have significant and unreasonable adverse impacts on surface water users and would, thus, be an undesirable result[10]
3. Set minimum thresholds for ISW depletion based on the rate or volume of those depletions caused by groundwater pumping that adversely impacts beneficial uses of the surface water and may lead to undesirable results[11]
    a. The minimum thresholds must be supported by information on the location, quantity, and timing of ISW depletion. The GSP must describe the groundwater and surface water model used to quantify the surface water depletion.
    b. If a numerical groundwater and surface water model is not used, the GSA must identify and describe a method or tool that is equally effective as a numerical model to accomplish the requirements for developing minimum thresholds.

To be "equally effective," other methods must be able to identify the location, quantity, and timing of ISW depletion to support the development of the minimum thresholds and other sustainable management criteria at the same quality as a numerical model.

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[9] 23 CCR § 354.16(f)

[10] Water Code § 10721(x)(6)

[11] 23 CCR § 354.28(c)(6)

In addition to the SGMA Requirements noted above, groundwater managers should consider any other applicable and appropriate legal and regulatory frameworks when considering the methods to estimate ISW depletion.

3.4.2 Complexity

A significant consideration when selecting among the methods to assess ISW depletion is the complexity of the basin or subbasin. In this case, complexity can include many items, such as hydrogeologic complexity, hydrologic and surface water complexity, and operational and management complexity. Groundwater managers should assess the inherent assumptions and simplifications of the various ISW depletion methodologies and compare them with their understanding of their basin. For example, numerical models can readily accommodate heterogeneity and anisotropy of the aquifer system under consideration, while most analytical methods to address stream-aquifer interaction and ISW depletion consider a homogeneous aquifer system. Most numerical models can also more readily accommodate dynamic conditions, such as streams that flow only for certain periods or are interconnected with groundwater for certain periods. Groundwater managers should describe in their GSPs how the selected methods are appropriate and commensurate with their basin's complexity.

3.4.3 Resource Requirements

Another consideration when selecting a methodology to evaluate ISW depletion is resource requirements, which can broadly include the types and amount of information (i.e., data) required to utilize the method and the time and expense needed to obtain that information and develop tools. This consideration includes the resources necessary to, for example, develop a numerical model and the resources that will be required to maintain and potentially improve analysis tools in the future.

In general, developing numerical models requires expertise and may require a substantial level of effort, depending on the level of complexity incorporated in the groundwater model, the quality of data available, the spatial and temporal scale of the area to be included in the model, and the level of calibration desired. DWR is aware that GSAs may have concerns about the cost and time required to use numerical models to evaluate ISW depletion. However, DWR has observed that most of California’s high- and medium-priority groundwater basins have existing numerical models used to develop their initial GSPs, even if they may not have been designed specifically to evaluate ISW depletion. In those cases, GSAs may decide that those numerical groundwater models represent the best *available* tools to assess ISW depletion, even if they do not represent the best *possible* tool for that purpose. For basins without existing numerical models but where groundwater managers have determined that a numerical modeling approach is the best option to evaluate ISW depletion, an incremental construction approach (i.e., starting simple and adding model features and capabilities as better information is obtained) is recommended to balance the requirement to quantify ISW depletion against the available time and resources needed to build a numerical model.

3.5 Conclusions about Selecting a Method to Evaluate ISW Depletion

As noted above, several potential methods can be applied to evaluate ISW depletion. Based on California's intricate hydrogeology, water operations, and management complexity, most basins will likely conclude that numerical modeling approaches are the most appropriate for ISW depletion analyses. Most basins already have existing numerical models; more than 90 percent of the basins that prepared GSPs to date used a numerical model for some portion of the plan. Many of those existing numerical models can be used to develop initial estimates of ISW depletion, and they can be updated in the future to improve their estimates of the location, quantity, and timing of depletion. DWR encourages this approach of using the best available methods and improving them as additional data and resources are available. If other, non-numerical-model techniques are used for ISW depletion estimates, groundwater managers must demonstrate that the alternate methods are “equally effective” as a numerical model. Because of the complexity noted above, such a finding is likely only in the simplest groundwater basins.

4 Applying Numerical Models to Estimate the Location, Quantity, and Timing of ISW Depletion

This section describes the application of the numerical modeling method to evaluate ISW depletion at a high level. Paper 3 provides additional descriptions and examples of how numerical models can evaluate ISW depletion. The approach described below is consistent with the process described by the USGS in Circular 1376 (Barlow and Leake, 2012) to account for surface water depletion due to pumping. The method allows for estimating the location, quantity, and timing of depletion, as required in the GSP Regulations, by isolating the effects of groundwater pumping from all other causes of depletion of ISW flow or stage (such as changes in hydrology or surface water diversion). The approach consists of three basic steps:

1. Run the model with pumping at the wells of interest and record model-computed flow rates to and from streams (i.e., the net stream gain) or other surface water bodies, as applicable. The wells of interest may be all wells in a (sub)basin, or smaller areas or groups of wells (e.g., in a management area).
2. Rerun the model without pumping from the wells of interest and record model-computed flow rates to and from streams.
3. Subtract model-computed flow rates to and from streams in step 1 from corresponding flow rates in step 2 to determine the net change in flow between the aquifer and streams, i.e., the depletion caused by groundwater use.

The following briefly discusses what this three-step process would look like in a hypothetical basin.

4.1 Description of Hypothetical Groundwater Basin

To support the discussion below, results from a numerical groundwater model representing a hypothetical groundwater basin are presented in the form of graphs depicting various water budget components. The intent of the hypothetical example is to illustrate concepts using a basin designed to “look and feel” like a California groundwater basin that a groundwater manager may encounter. The reader should not focus on the exact quantity or timing shown on these charts; rather, the focus should be on the broadly applicable concepts. Paper 3 includes a detailed description of the hypothetical basin, but for this paper, note that it is an alluvial basin with groundwater as the primary supply source and reaches of streams interconnected with surface water. All the results in this paper represent annual ISW depletion at the spatial scale of the entire hypothetical basin. Paper 3 describes other types of analyses, including evaluating ISW depletion in situations with multiple stream reaches and multiple subbasin areas and evaluating ISW depletion at different timescales (e.g., by month and water year types).

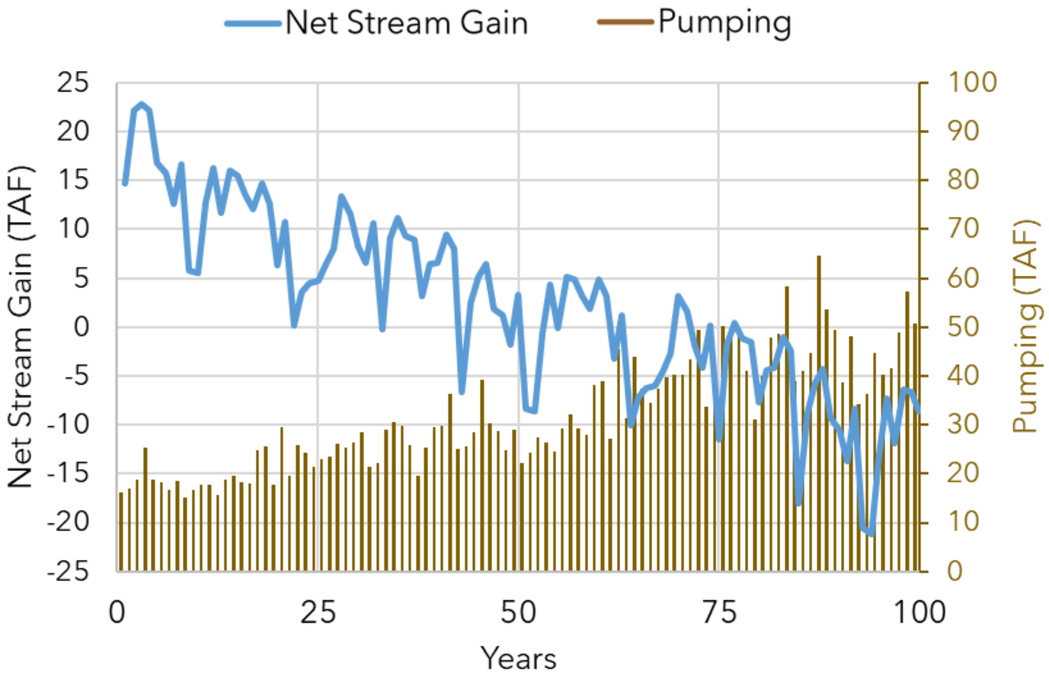
4.2 Application of a Numerical Model to Determine ISW Depletion

4.2.1 Step 1. With-Pumping Scenario

As noted above, the first step for using a numerical model to analyze ISW depletion analysis is to run the model in a with-pumping scenario. This scenario is likely the same scenario a basin with a numerical model would have used for its planning purposes (e.g., to document its historical and projected water budgets).

Outputs from the with-pumping scenario do not, on their own, contain the required information on the location, quantity, and timing of ISW depletion. However, groundwater managers may use this scenario to evaluate and present historical and projected pumping and stream-aquifer interaction information. **Figure 2** presents the stream-aquifer interaction as the net stream gain, which means the net amount of water that flows from groundwater to the ISW; negative values of net stream gain indicate periods where streams were losing to groundwater. Note that the net stream gain (or loss) is not the same quantity as the depletion of ISW due to groundwater pumping. In the case of the example shown in **Figure 2**, groundwater pumping increases steadily over the 100-year period. In the early portion of the simulated period, when pumping rates are relatively lower and before the effects of the early pumping fully affect the stream, the stream is gaining at all times. As pumping rates increase, the stream transitions from consistently gaining to consistently losing water to the aquifer in the latter half of the simulation period.

Figure 2. Annual Groundwater Pumping and Net Stream Gain in Thousand Acre-Feet (TAF).



4.2.2 Step 2. Without-Pumping Scenario

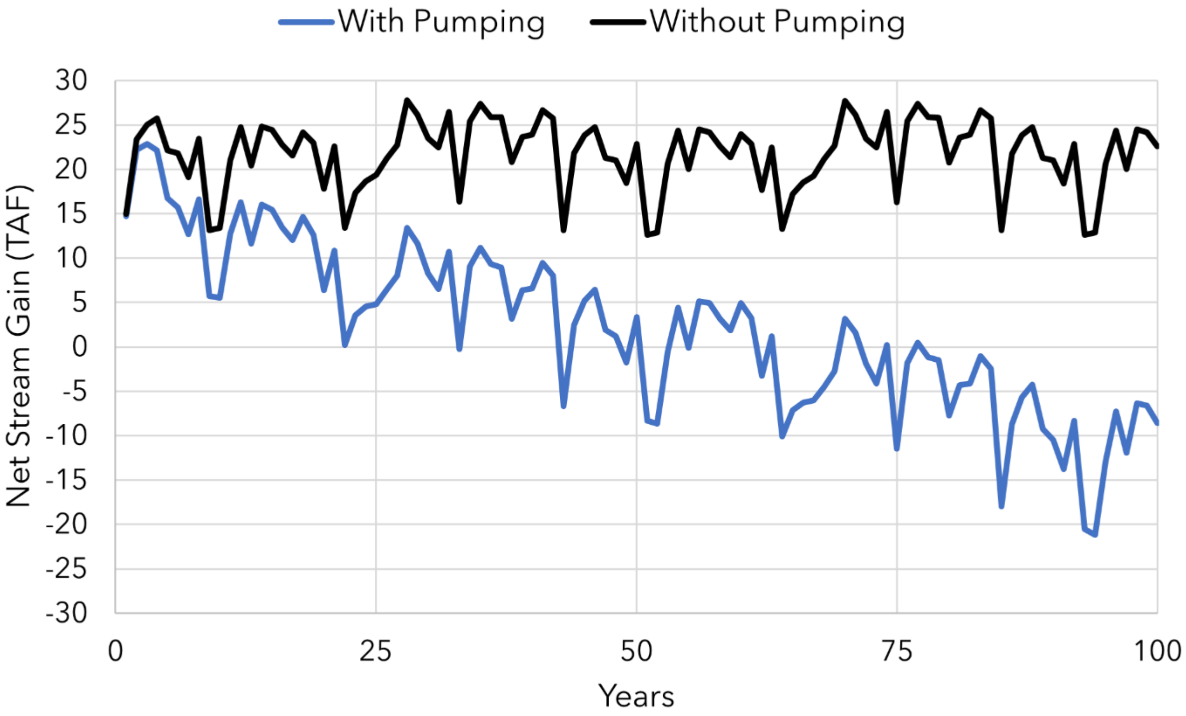
The second step consists of running a without-pumping scenario using the numerical model from Step 1. It is essential to address one potential misconception regarding a without-pumping scenario. The purpose of a without-pumping scenario is to satisfy the requirement to determine the location, quantity, and timing of depletion caused by groundwater use (i.e., pumping) within the basin. The without-pumping scenario is not intended to be a management scenario (i.e., groundwater managers are not likely to evaluate turning off all pumping in a basin as an actionable management scenario, nor is there an expectation that eliminating all pumping in a basin will be an outcome of sustainable management). In this context, the development of the without-pumping scenario facilitates the estimation of ISW depletion, which serves as the basis for subsequent management.

Groundwater managers must carefully consider the most appropriate options to develop a without-pumping scenario for their area. Developing a without-pumping scenario may be relatively easy for cases with simpler models and data processing. For example, if the quantity of groundwater pumping for a basin's numerical model is known or calculated in an external spreadsheet and then input into the model, then the model can be run with pumping in the basin of interest set to zero. In more complex cases, for example, where pumping is calculated internally by the numerical model based on other inputs such as crop type, crop evapotranspiration, rainfall, and surface water deliveries (as is the case with many IWFM-based models used in the

Central Valley), adjustment to other settings to limit pumping within a basin or area of interest may need to be considered. For instance, a without-pumping scenario could be performed by simulating the fallowing of agricultural land that relies on groundwater for water supplies (resulting in zero pumping and, by association, no percolation of applied groundwater). In urban areas, where water needs to be supplied to meet the urban population, a without-pumping scenario could be performed by assuming a hypothetical source of surface water as imported water to supply the urban demands, resulting in no groundwater withdrawals.

As in the with-pumping scenario, the without-pumping scenario does not quantify ISW depletion. However, groundwater managers can present stream-aquifer interaction information for the without-pumping scenario, as shown in**Figure** 3**.** In contrast to the without-pumping scenario,**Figure 3** shows that the stream would remain a gaining stream over the entire 100-year period in the absence of pumping.

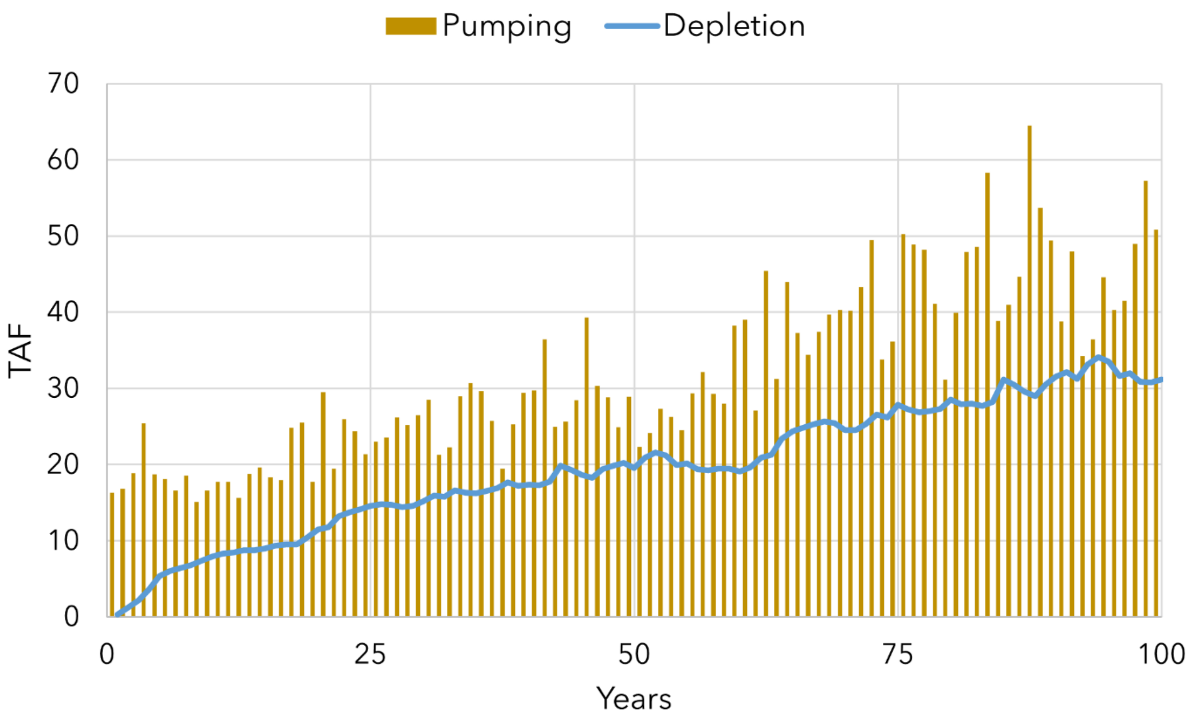
Figure 3. Net stream gain from the with-pumping and without-pumping scenarios.



4.2.3 Step 3. Calculating Depletion

Outputs from the with-pumping and without-pumping scenarios include the flow between surface water and groundwater. ISW depletion can be calculated as the difference between net inflow to streams from groundwater in the without-pumping scenario and the with-pumping scenario (i.e., the difference between the time series plotted in**Figure** 3). The annual ISW depletion quantity and pumping quantity are shown in **Figure 4**. Paper 3 includes additional examples of how the approach described herein can be used to estimate depletion at more refined spatial scales (e.g., by river reach), which helps address the ISW location impacts, and temporal scales (e.g., monthly average or by water year type).

Figure 4. Annual Depletion of Interconnected Surface Water and Annual Pumping Volume.



4.3 Factors to Consider when Using Numerical Models to Simulate ISW Depletion

While the three-step process (described in Section 4.2) for using a numerical model to quantify ISW depletion is relatively straightforward in concept, there are factors that groundwater managers should consider and address when using models for this purpose, several of which are described below. For each of these factors, there is no prescribed level beyond which the item has been adequately addressed; for example, there is not a certain number of groundwater model layers or thickness of groundwater model layers that are universally optimal for performing ISW depletion analysis. Whether working with existing numerical models or developing new ones, groundwater managers should consider the factors presented below and may need to evaluate multiple scenarios (e.g., with different layer configurations or levels of complexity) to determine the optimal model configuration to best match observed data and generate appropriate estimates of ISW depletion. Groundwater managers should describe the models sufficiently for interested parties to understand how these, and any other applicable factors, may affect the estimates of ISW depletion.

4.3.1 Model Code

Numerous modeling software or codes are available for integrated surface and groundwater systems. When properly developed, calibrated, and used, these are suitable for estimating the location, quantity, and timing of ISW depletion due to groundwater pumping.

DWR's Modeling BMP (DWR, 2016) lists several commonly used numerical modeling codes: IWFM (Dogrul et al., 2017), MODFLOW (Langevin et al., 2017), MODFLOW-OWHM (Boyce, 2022), MODFLOW-USG (Panday et al., 2017), and GSFLOW (Markstrom et al., 2008). Any of these codes, or others that meet SGMA requirements, can be used to build integrated surface water and groundwater numerical models for estimating ISW depletion.

4.3.2 Temporal Extent of Modeling Analysis

As noted above, it can take years or decades after the onset of pumping for groundwater systems to come into equilibrium and for the effects of ISW depletion to be fully realized (see e.g., Bredehoeft and Durbin 2009). Ideally, groundwater managers would extend the period of record used in their numerical models for the analysis of historical and current depletion far enough back in time to either coincide with the onset of significant groundwater development in their basin or to demonstrate that groundwater and surface water conditions are in equilibrium (i.e., that pumping-induced depletion of ISW has stabilized). In practice, achieving either of those conditions may not be practical for most basins in California because developing reliable estimates of pumping back to the onset of groundwater development (the 1920s in some basins) is likely not possible and because most basins in California are likely not in equilibrium. Therefore, groundwater managers may need to develop historical analyses as far back as they can reliably consider, given the uncertainties in the data and information available. One implication of using historical analyses shorter than the two conditions noted above is that the current (i.e., present-day) quantities of ISW depletion will likely be underestimated.

To estimate ISW depletion under projected conditions, modeling analyses should, ideally, have a long enough period of record to allow groundwater conditions to come into equilibrium with pumping. Again, that may be impractical in basins where the time to reach equilibrium is long. For SGMA purposes, projected conditions analyses should extend at least 50 years, consistent with the requirement to utilize 50 years of projected hydrology in analyzing projected water budgets in a GSP.[12]

4.3.3 Spatial Extent and Resolution of the Numerical Groundwater Model

Ideally, numerical groundwater models used for ISW depletion analysis would extend to the spatial limits of the basin and aquifers of interest. Models incorporating the entire defined basin and aquifer system are relatively common in smaller basins and

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[12] 23 CCR § 354.18(c)(3)(A)

those comprising a single basin with no defined subbasins. However, in many areas of California, such as the Central Valley, the large regional basin and aquifer systems have been subdivided into subbasins. In those areas, it is relatively common for one subbasin or a subset of subbasins to develop a numerical model solely for their area or their area plus a limited surrounding area (e.g., their jurisdictional area plus a buffer zone).

On the one hand, limiting the spatial extent of the groundwater model area is practical because it may be incredibly difficult and costly for one subbasin to independently develop a defensible numerical model for the entire basin in which they are located. On the other hand, limiting the groundwater model to only analyze conditions in one subbasin or a subset of subbasins limits the ability of that subbasin(s)-specific groundwater model to evaluate how pumping within the subbasin(s) can impact ISWs outside the modeled area (e.g., in neighboring subbasins). Groundwater managers with models that do not extend to basin boundaries may consider using regional modeling tools or collaborating with managers in adjacent subbasins to develop models with larger spatial extents or use other means to extrapolate the impacts to other subbasins. Several modeling platforms, such as IWFM, allow for the linkage of two neighboring models to facilitate the boundary issues between two neighboring management areas or subbasins.

In addition to spatial extent, the resolution of the numerical grid is an important consideration (Mehl and Hill, 2010). As described above, numerical models subdivide the model extent into smaller units, often called elements or cells. This spatial subdivision provides means to assign numerical model input data, such as precipitation, land use, cropping patterns, soil conditions, and aquifer hydraulic properties to each element or cell and for the groundwater model to calculate rainfall-runoff, deep percolation, recharge, and groundwater head and flow into and out of each element or cell. There is no correct answer for how refined a model grid should be near a stream or other feature of interest. The spatial resolution of the numerical model network around a stream is generally a balancing of:

- The level of detail that groundwater managers desire to analyze (e.g., stresses near the stream like pumping
- The level of available information on hydrologic and hydrogeologic properties
- The computational constraints that a more refined grid impose (e.g., longer model run times)

4.3.4 Vertical Extent and Resolution of the Numerical Groundwater Model

In addition to being subdivided horizontally into cells or elements, a numerical model grid is subdivided vertically into layers. The elevation and number of groundwater model layers can represent known or inferred hydrogeologic units, aquifers, or aquitards. Layers can also be defined to capture known or inferred details on the distribution of subsurface materials or texture. The number and distribution of layers is important for several reasons. First, the vertical distribution of groundwater pumping generally cannot be defined at resolutions smaller than the layer. For example, if a groundwater model layer is defined to represent the upper 300 feet of a groundwater basin and groundwater managers know that pumping only occurs in wells screened from 250 to 300 feet below ground, a single groundwater model layer cannot be used to analyze groundwater flow and head in a manner that honors the fact that pumping only occurs in the bottom portion of that layer. Second, aquifer properties like horizontal and vertical hydraulic conductivity are defined for each cell or element in each layer. A numerical model cannot generally accommodate more refinement of those properties at a sub-element or sub-cell scale. Using the above example of a groundwater model layer representing the upper 300 feet of a groundwater basin, if a groundwater manager knows that there is an important low-conductivity layer at 100 feet below the ground surface, then they may need to subdivide that first layer into two or more discrete layers to represent the groundwater system adequately.

When developing the Sacramento Valley Groundwater-Surface Water Simulation Model (SVSim), the DWR team experimented with different layering schemes to minimize the effect of vertical discretization on simulated stream-aquifer interactions (Cayar et al., 2015). They concluded that a nine-layer model, where the layers are thinner in the uppermost portions of the aquifer and thicker with increasing depth, was an ideal discretization to minimize errors and balance computational issues like long model run times. While their specific findings are limited to their study area and methodologies, they serve as a good example of the types of investigations that others may do to determine the appropriate discretization of models in other areas.

4.3.5 Surface Water Representation

Depending on which code and packages are used in numerical model development, models used for ISW depletion analyses need data and parameters for the surface water system, potentially including channel geometry; rating tables describing the relationships between streamflow, wetted perimeter, and stream stage; and a parameter representing streambed conductance, which can be a function of streambed thickness and hydraulic conductivity of the streambed. In a numerical model, these parameters can vary along the length of a surface water body. However, in the real world, the distribution of these parameters is typically either unknown or not readily available. Groundwater managers may need to engage with other experts in the basin, such as surface water managers and/or operators and hydrologists, to obtain the best available estimates of these data and parameters.

4.3.6 Numerical Model Calibration

Model calibration is, generally, the process of adjusting an initial set of numerical model parameters (e.g., horizontal and vertical hydraulic conductivity for aquifer processes, irrigation efficiency and target soil moisture for irrigation processes, or curve numbers and soil hydraulic conductivities for land surface processes) so that model outputs (e.g., modeled groundwater levels or streamflows) better fit observed data (e.g., reported groundwater levels or reported streamflows at specific gaging stations). The subject of numerical model calibration has been documented extensively (see e.g., Hill and Tiedeman 2007 or Doherty 2015).

For any groundwater model application, groundwater managers must ensure that their models (1) generate reasonable water budgets for the land-surface, surface water, and groundwater systems and (2) reasonably match observed data from the land-surface, surface water, and groundwater systems. Groundwater managers specifically interested in ISW depletion analyses may need to pay special attention to items such as:

- Surface water features, including reach-specific surface water budgets in areas susceptible to ISW depletion impacts and the ability of the model to reasonably simulate flow and stage for both high and low flow conditions
- Groundwater budgets to ensure that pumping estimates generated by models are reasonably aligned with local knowledge about the quantity and spatial distribution of pumping
- Calibration data to ensure that observed datasets that may have information particularly useful to ISW depletion estimates (e.g., groundwater elevation differences at paired or nested wells to evaluate vertical hydraulic conductivity or groundwater levels near stream gauges) are appropriately weighted during the numerical model calibration process

5 A Note on Uncertainty and the Timeliness of Estimating ISW Depletion

Groundwater managers will likely have concerns about the tension between the timeliness of developing ISW depletion estimates and the uncertainty of those estimates. For instance, a groundwater manager might believe their basin’s existing numerical model requires significant improvement to reduce the uncertainty in ISW estimates, which could only be initiated following significant new data collection, requiring planning and executing new field work. They might conclude, therefore, that it will take many years of new work before they could even initially estimate the location, quantity, and timing of depletion caused by groundwater use and, therefore, begin managing their basin for ISW depletion.

To be clear, in California’s groundwater basins with adopted GSPs, SGMA and the GSP Regulations required that information be developed for the initial GSP and that management of the basin begin immediately to achieve the sustainability goal within 20 years. Many basins did not estimate the location, quantity, and timing of ISW depletion in their initial GSP and DWR, acknowledging that the requirement to do so was new, recommended corrective actions in the assessment of those initial GSPs. DWR expects that groundwater managers expeditiously work to:

- Develop initial estimates of the location, quantity, and timing of depletion using the best available data and methods and document those estimates as part of their periodic evaluations and/or annual reports
- Develop plans to address the uncertainty in the ISW estimates in a timely manner
- Utilize the estimates of the location, quantity, and timing of ISW depletion to inform their sustainable management criteria, consistent with the requirements of the GSP Regulations

Consistent with best practices, DWR expects that GSAs will periodically update their models and include better and more complete information about the basin, and that this will usually result in changes to the output of those models.

6 Summary

This paper builds on the foundational information in Paper 1 to identify the types of data needed to characterize the location, quantity, and timing of ISW depletion caused by groundwater use; the types of methods available to characterize ISW depletion; and a description of applying numerical models to evaluate ISW depletion. The paper describes factors that should be considered by groundwater managers when deciding which method to use. It also describes several factors to consider when designing or using a numerical groundwater model for ISW depletion analyses.

As stated above, many, if not most, basins will likely conclude that numerical modeling approaches are the most appropriate for ISW depletion analyses. However, other methods or tools may be shown to be “equally effective,” though such a finding is likely only in the simplest of groundwater basins. Recognizing that all basins and subbasins are unique, there are no hard and fast rules for constructing a numerical model for ISW depletion analysis. Groundwater managers should weigh the factors described in this document and any other relevant factors that may apply to their basin when developing tools to characterize ISW depletion and should document the decisions made in their GSPs.

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